THE UNEP
LARGE MARINE ECOSYSTEMS
REPORT

A PERSPECTIVE ON CHANGING CONDITIONS IN LMES OF THE WORLD'S REGIONAL SEAS

UNEP

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A Message from the Executive Director of UNEP

The world's 64 Large Marine Ecosystems are as much economic as they are environmental assets contributing around 12 trillion dollars annually to the global economy.

Increasingly the management of these assets is beginning to reflect that importance. Combined efforts among coastal countries in Africa, Asia, Latin America, and eastern Europe are now contributing to assessment and management actions aimed at tackling coastal pollution, restoration of degraded habitats, and recovery of depleted fish stocks.

They have been joined by United Nations agencies, the Global Environment Facility, and a growing number of northern hemisphere countries and principle stakeholders in fish and fisheries, coastal transportation, tourism, gas and oil production, and diamond and mineral extraction operations.

The effort to reverse the degraded status of LMEs will take time, well-focused and creative policies and funding. However it is clear that with the financial assistance of the GEF and in partnership with the UN the effort has begun, especially among the economically developing nations.

The work reflects the targets put forward at the World Summit on Sustainable Development in Johannesburg in 2002 to achieve substantial reductions in land-based sources of pollution; introduce an ecosystems approach to marine resource assessment and management by 2010; designate a network of marine protected areas by 2012 and restore and maintain fish stocks to maximum sustainable yield levels by 2015. UNEP is among several agencies and donors assisting developing countries to achieve these targets.

Climate change adds new urgency to this effort. Indeed the original findings in this report have been up-dated to reflect new findings showing that in many of the LMEs warming is proceeding at two to three times the global rate. Some of this most rapid warming is being witnessed in northeastern North Atlantic and around Europe and in the East Asian seas.

Pollution, such as high levels of nutrients coming from the land and the air, may be aggravating the effect. So we must not only secure a deep and decisive climate regime post 2012 but also tackle the wider sustainability issues to ensure the abundant productivity of not only LMEs but the Regional Seas and oceans in general for this and future generations.

Achim Steiner,UN Under-Secretary General and UNEP Executive Director

A Message from the Chief Executive Officer, GEF

We live on the land yet we often forget the sea. We forget that 70% of our planet is made up of coastal and marine ecosystems and that our coastal economies depend on these ecosystems to generate sustainable communities.

Many do not know that more than half of the carbon sequestered on the planet is attributed to marine ecosystems; our planet's temperature is regulated by the oceans. We take them for granted as we do the fact that international trade in coastal and marine fisheries is a $70 billion a year business that drives coastal economies.

While we tend to focus on a plethora of terrestrial environmental problems over the last 35 years, we have neglected coastal and marine water pollution. The Large Marine Ecosystems (LMEs) of our planet that span the continental shelves and enclosed marine waters are warming, over-fished, and becoming ever more degraded with nitrogen.

This book represents the first attempt at establishing the baseline environmental conditions of the world's LMEs and comes from a partnership among the United Nations Environment Programme, the U.S. National Oceanic and Atmospheric Administration, the Intergovernmental Oceanographic Commission of UNESCO, and the Global Environment Facility. Eighty percent of marine capture fisheries are taken in these LMEs where billions of people reside in coastal areas.

The satellite-based time series of warming of LMEs presented in this baseline assessment presents a stark picture. The trend of over-fishing of valuable and less desirable species of fish based on many decades of data from the Food and Agriculture Organization and the University of British Columbia's Sea Around Us Project shows vast depletion of species in many LMEs to the point of overexploitation and collapse. The authors also found there is an increased trend expected for nitrogen pollution from land-based sources—this promises to create more dead zones of oxygen depletion and hazardous algal blooms that threaten human, ecosystem, and economic health.

We at the Global Environment Facility hope that the release of this global assessment will call attention to the degraded state of many coasts and marine waters as well as the high risk that human behavior is placing on loss of perhaps trillions of dollars of annual goods and services. We need to stop taking these precious resources for granted.

Monique Barbut, CEO Global Environment Facility

A Message from the Director of the Environment & Energy Group, UNDP

Climate change is a critical global issue. Without action, climate change could negate decades of development progress and undermine efforts for advancing sustainable development. As the UN's global development network, UNDP recognizes that climate change calls for a new development paradigm—a paradigm that mainstreams climate change into development planning at all levels, links development policies with the financing of solutions and helps countries move toward less carbon intensive sustainable economies.

The integrity of all 64 of the World's LMEs and the livelihoods of billions of people that depend upon them are under threat not only from climate change, but also from overfishing, toxic pollution, nutrient over-enrichment, invasive species, habitat degradation, and biodiversity loss. The large majority of these LMEs are shared by two or more countries, underscoring the need for regional cooperation to advance sustainable LME management. The UNDP Environment and Energy Group is pleased to partner with the Global Environment Facility, UNEP, and other UN agencies and US-NOAA in providing capacity building, scientific and technical assistance to over 75 developing countries executing ten Large Marine Ecosystem (LME) projects in Asia, Africa, Latin America, and Europe. Through these and other projects, UNDP also provides technical support to strengthen the capacities of coastal developing countries bordering LMEs to adapt to the effects of climate change on vital LME resources.

A firm scientific basis is essential in developing options for mitigating and adaptive actions during the present period of global warming. This volume presents, for the first time, an intercomparable global baseline of information at the LME management scale of changing states of productivity, fish and fisheries, pollution and ecosystem health, and socioeconomic and governance conditions. The information presented provides a clear assessment of the global extent of overfishing, nutrient overenrichment, habitat loss, and the progressive warming rates of surface water in LMEs around the globe, against which the success of climate change mitigation and adaptive actions to advance sustainable development of marine goods and services can be measured.

UNDP welcomes this volume as a key contribution to improving global knowledge and understanding of LMEs, their significant economic value, and the principal threats to LME sustainability including climate change. Through the continued cooperative efforts of a growing number of countries that have initiated joint LME management programmes and support from the international community, these vital environmental and economic assets can be sustained for future generations.

Veerle Vandeweerd, Environment & Energy Group, UNDP

The UNEP Large Marine Ecosystems Report

A Perspective on Changing Conditions in LMEs of the World's Regional Seas

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Preface

The world's coastal ocean waters continue to be degraded by unsustainable fishing practices, habitat degradation, eutrophication, toxic pollution, aerosol contamination, and emerging diseases. Against this background is a growing recognition among world leaders that positive actions are required on the part of governments and civil society to redress global environmental and resource degradation with actions to recover depleted fish populations, restore degraded habitats and reduce coastal pollution. No single international organization has been empowered to monitor and assess the changing states of coastal ecosystems on a global scale, and to reconcile the needs of individual nations to those of the community of nations for taking appropriate mitigation and management actions. However, the World Summit on Sustainable Development convened in Johannesburg in 2002 recognized the importance for coastal nations to move more expeditiously toward sustainable development and use of ocean resources. Participating world leaders agreed to pursue 4 marine targets: (i) to achieve substantial reductions in land-based sources of pollution by 2006; (ii) to introduce an ecosystems approach to marine resource assessment and management by 2010; (iii) to designate a network of marine protected areas by 2012; and (iv) to maintain and restore fish stocks to maximum sustainable yield levels by 2015. At present, 110 developing countries are moving toward these targets in joint international projects supported, in part, by financial grants by the Global Environment Facility (GEF) in partnership with scientific and technical assistance from UN partner agencies, donor countries and institutions, and non-governmental organizations including the World Conservation Union (IUCN). Many of these projects are linked to ecosystem-based initiatives underway in Europe and North America.

This report is a result of a collaborative effort to promote a global view of conditions within LMEs across the North-South divide. It was generously coordinated by UNEP Regional Seas Programme, and the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA Coordination Office) in The Hague, Netherlands. In summer 2005 it was agreed that UNEP, in partnership with the GEF-supported Global International Waters Assessment (GIWA) project, and NOAA's Large Marine Ecosystem Program, would provide synopses of ecological conditions for each of the worlds' Large Marine Ecosystems (LMEs). In accordance with the outcome of a series of consultations among the three parties, it was concluded that the five-module LME assessment framework of productivity, fish and fisheries, pollution and ecosystem health, socioeconomics, and governance, would provide a useful basis for describing ecological conditions within the world's LMEs.

The synopses are relatively brief for the LMEs adjacent to the more economically developed countries where ecological conditions are fairly well documented by periodically released reports, published in print or electronically, on various sectoral interests including: fisheries, pollution, habitats, tourism, shipping, oil and gas production and mineral extraction. Sources for this summary information are provided for the reader. Whereas, for the LMEs bordering countries less economically developed in Africa, Asia, and Latin America, the synopses are longer. They are based on information collected through GIWA and the GEF-LME project planning and implementation process using information that would otherwise not be readily available in the published marine assessment and management literature. The synopses were prepared by two principal authors, Dr. Sherry Heileman and Dr. Marie Christine Aquarone. For several LME synopses, where one or more of the peer reviewers added substantially to the description of ecological conditions, they are listed as co-authors of the synthesis. Each of the 64 synopses of ecological conditions includes standardized information on productivity ($gCm^{-2}y^{-1}$), ocean fronts, multi-decadal time series of trends in annual fishery yields, and changes in mean annual trophic levels of fish catch, as well as data on the physical extent (km^2) of LMEs, the presence of sea mounts, coral reefs and linked rivers, watersheds and estuaries.

Chapters I, through XVIII describe conditions of LMEs within the Regional Seas areas, followed by chapter XIX on the LMEs bordering Regional Seas areas. Three generic issues recur in the synopses: (1) the issue of encroachment of industrial fisheries into near coastal community based fisheries in Africa, Asia, and Latin America, and the need for application of the precautionary principle to protect the food security and livelihood of coastal communities; (2) the need for improved forecasting of climate driven events affecting LME resources, especially during present extensive global climate change, and (3) the global scale increasing frequency and extent of eutrophication stress on ecosystem integrity and health. Examples of these issues are included in the introductory chapter.

The substantial contribution in start-up funding by the GEF to 110 developing countries is enabling a global effort to go forward in initiating movement in Asia, Africa, and Latin America towards the WSSD marine targets. Although the way ahead is costly, a concerted and focused effort has been initiated. Within the context of the baseline initiated in this report, UNEP in partnership with other actors in the conservation and management of the marine and coastal environment will aim at measuring progress regularly through further editions of this report or through contributing to other reports such as the Global Marine Assessment (GMA).

The Editors

Acknowledgments

Preparation of this initial report on the ecological conditions of the LMEs in the Regional Seas has been a collaborative effort. We are greatly indebted to the GEF-LME Programme Managers for their pioneering contributions to the LME assessment and management process and their willingness to take the time from busy schedules to provide reviews of the LME descriptions in this report. Special appreciation is extended to: Andrew Cooke (Canary Current LME), Gerardo Gold-Bouchot (Gulf of Mexico LME), Chidi Ibe (Guinea Current LME), Yihang Jiang, Qisheng Tang and Hyung Tack Huh (Yellow Sea LME), Robin Mahon (Caribbean Sea LME), Jan Thulin (Baltic Sea LME), and Michael O'Toole (Benguela Current LME).

The GEF had tasked the Global International Waters Assessment (GIWA) to identify the ecological conditions of the GEF-eligible LMEs, thereby allowing, on the basis of these assessments, the GEF to prioritize the activities or areas needing more financial, scientific and technical support. The reports on the ecological condition for 34 LMEs, for which bordering countries are eligible for GEF financial support, were prepared by Dr. Sherry Heileman, marine and fisheries biologist, Paris, France. We are indebted to Dr. Heileman for her carefully prepared reports and to Dag Daler, Ulla Li Zweifel and Kristin Bertilius of GIWA for their contributions and support in the preparation of this report. We are indebted to Dr. Marie Christine Aquarone for her expert synthesis of ecological conditions in the 30 LMEs bordering the more economically advanced countries. We are indebted as well to Dr. Sara Adams, Technical Editor, for recent updates to LME descriptions and for extraordinary care and expertise in producing this volume for publication.

The following experts gave much of their time, effort, and considerable expertise to review the LME reports in Africa, Asia, Latin America and eastern Europe: Dr. Johann Augustyn (South Africa), Dr. Andrew Bakun (USA), Dr. Ratana Chuenpagdee (Nova Scotia), Dr. Andrew Cooke (Senegal), Brian Crawford (South Africa), Dr. Werner Ekau (Germany), Dr. Li Haiqing (China), Dr. Kwame Koranteng (Kenya), Dr. Daniel Lluch Belda (Mexico), Johann Lutjeharms (South Africa), Dr. Robin Mahon (Barbados), Dr. Gennady G. Matishov (Russia), Dr. Laurence Mee (United Kingdom), Dr. Sunilkumar Kolliyil Mohamed (India), Dr. Dirar Nasr (Saudi Arabia), Dr. Michael O'Toole (Namibia), Dr. Nancy Rabalais (USA), Dr. Claude Roy (France), Rodolfo Serra (Chile), Jerker Tamelander (Sri Lanka), Dr. Jan Thulin (Sweden), Professor Dr. Matthias Wolff (Germany), Jiang Yihang (Korea) and Dr. Sinjae Yoo (Korea).

The LME descriptions for North America, Europe and East Asia were originally made possible by LME experts who prepared syntheses of ecosystem productivity, fish and fisheries, pollution and ecosystem health, socioeconomics, and governance that have been published in the 14 LME volumes. These experts include P. Cury, S. J. Heymans, P. Hoagland, S. Levin, P.A. Livingston, J.M. McGlade, J.E. Overland, J. Rice, V. Shannon, H. R. Skjoldal, Q. Tang, and K.C.T. Zwanenburg.

We thank Dr. Daniel Pauly and other members of the Sea Around Us Project (Fisheries Centre, University of British Columbia, Vancouver, Canada), for contributing graphs of fisheries catch time series and related statistics for each of the LMEs covered here, and embedding these graphs and their explanatory text into the LME descriptions. We extend special appreciation to Dr. Sybil Seitzinger of Rutgers University and her team of experts for their work on modeling nutrient inputs to the world's LMEs.

Finally, we acknowledge with gratitude the support and encouragement of Dr. Veerle Vandeweerd, former coordinator of UNEP/GPA and Head of the Regional Seas Program in the Hague and now serving as Director of the Environment & Energy Group, Bureau

for Development Policy for the UNDP in New York, and Anjan Datta, Officer in Charge of the UNEP/GPA Coordination Office, Nairobi, Kenya, and Annie Muchai of UNEP, Nairobi, Kenya.

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BACKGROUND REPORTS

Perspectives on Regional Seas and the Large Marine Ecosystem Approach

K. Sherman and G. Hempel

UNEP REGIONAL SEAS PROGRAMME LINKS WITH LARGE MARINE ECOSYSTEMS ASSESSMENT AND MANAGEMENT

A new partnership has been developed that links the coastal and marine activities of the global Regional Seas Programme (RSP), coordinated by the United Nations Environment Programme (UNEP), with the Large Marine Ecosystem (LME) approach to the assessment and management of living marine resources and environments. The joint initiative assists developing countries in using LMEs as operational units for translating the Regional Seas Programme into concrete actions. With substantial support in over one billion dollars in financial grants from the Global Environment Facility (GEF) and investment funds from the World Bank in partnership with other UN agencies and government and industrial donors, countries in Africa, Asia, the Pacific, Latin America and the Caribbean, and Eastern Europe are presently engaged in LME assessment and management projects that implement actions to restore and sustain living marine resources in coastal waters.

THE LARGE MARINE ECOSYSTEM APPROACH

The LME approach to the assessment and management of marine resources and their environments was first introduced at an international symposium convened at the annual meeting of the American Association for the Advancement of Science, in 1984. At the outset, it was understood that the LME approach would provide a framework for utilizing ecologically defined Large Marine Ecosystems as place-based areas around the globe, to focus the methods of marine science, policy, law, economics and governance on a common strategy for assessing, managing, recovering, and sustaining marine resources and their environments (Sherman and Alexander 1986).

There are two important features in the LME approach. ***First and foremost, the physical extent of the LME and its boundaries are based on 4 linked ecological rather than political or economic criteria. These are: (i) bathymetry, (ii) hydrography, (iii) productivity, and (iv) trophic relationships.*** It is the bathymetry or bottom topography that greatly influences water column structure and flow. Within the water column, the nutrient flux, vertical circulation and advective processes determine to a large extent the levels of primary productivity of the phytoplankton of the LME—productivity that is a determinant of zooplankton biomass and species composition (biodiversity), and subsequent energy-flow (trophodynamics), from plankton to fish and shellfish to marine birds and marine mammals, through the food web of the LME. Based on the 4 ecological criteria, 64 distinct LMEs have been delineated around the coastal margins of the Atlantic, Pacific, and Indian Oceans (Figures 1a and 1b).

Frontal maps and quantitative assessments of the sea surface temperature (SST) and temperature anomalies for each of these LMEs are provided by Dr. Igor Belkin. SST was selected as the only thermal parameter routinely measured worldwide that can be used to characterize thermal conditions in each and every LME. Subsurface hydrographic data, albeit important, lack spatial and temporal density required for reliable assessment of thermal conditions at the LME scale worldwide.

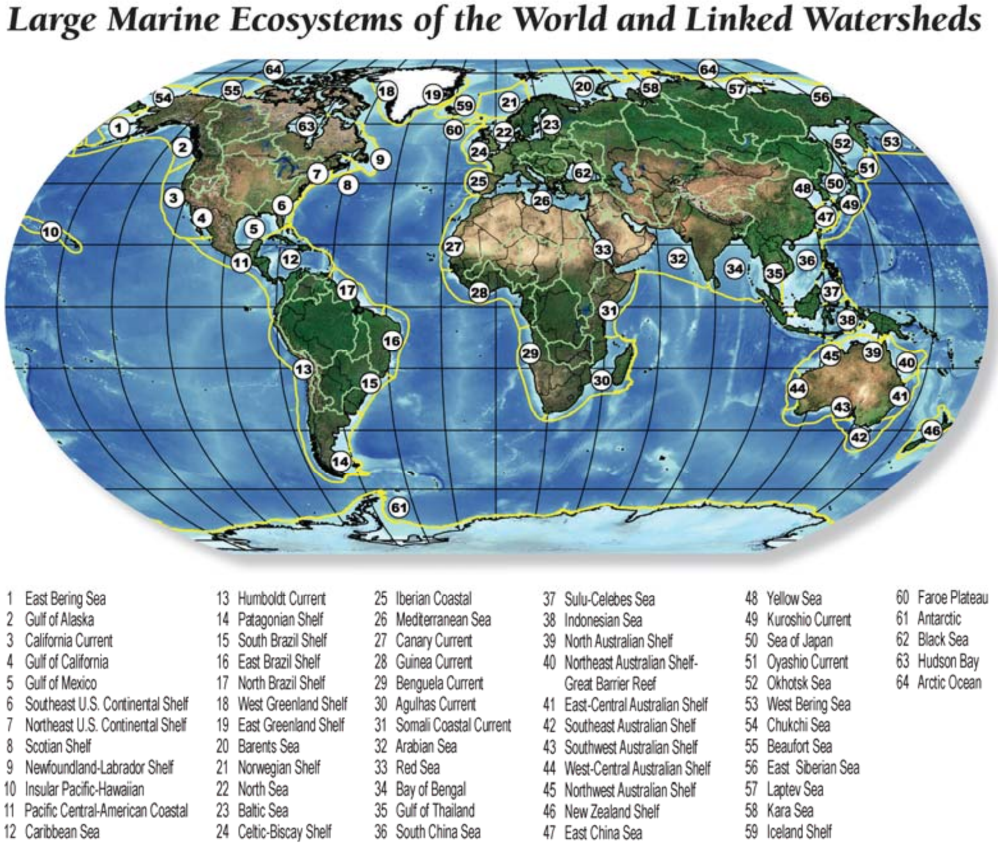


Figure 1a. Map showing 64 Large Marine Ecosystems of the world. LMEs in this map are numbered as they are on the LME website, www.lme.noaa.gov.

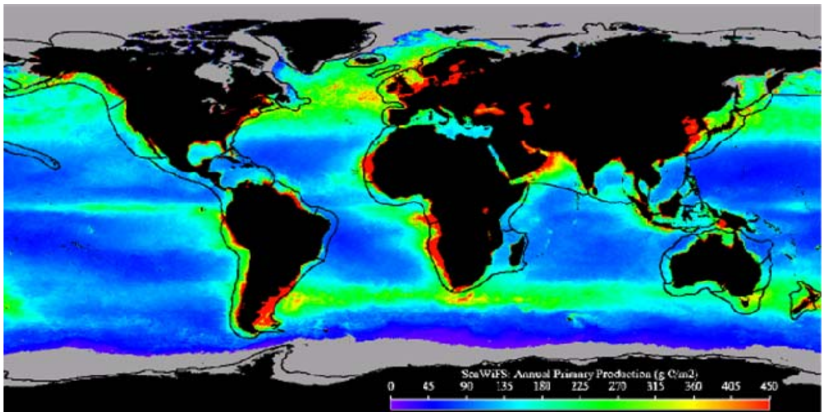


Figure 1b. Global map of average primary productivity and the boundaries of the 64 Large Marine Ecosystems (LMEs) of the world, available at www.lme.noaa.gov. The annual productivity estimates are based on Sea WiFS satellite data collected between September 1998 and August 1999, and the model developed by M. Behrenfeld and P.G. Falkowski (Limnol. Oceangr. 42(1): 1997, 1-20). The color-enhanced image provided by Rutgers University depicts a shaded gradient of primary productivity from a high of 450 $gCm^{-2}yr^{-1}$ to a low of $10gCm^{-2}y^{-1}$.

All LMEs are relatively large areas of ocean space, of approximately 200,000 km^2 or greater, adjacent to the continents in coastal waters where primary productivity is generally higher than in open ocean areas. It is within the boundaries of the LMEs that 80% of the world's annual marine fish catch is produced, degraded habitats are most prevalent and the frequency and effects of pollution and eutrophication of ocean waters are most severe. The LMEs are also centers of marine gas and oil production; mining for sand, gravel, diamonds and other extractive minerals; coastal shipping; and tourism.

A second important feature of the LME approach is the use of a 5-module strategy for measuring the changing states of the ecosystem and for taking remedial actions toward recovery and sustainability of degraded resources and environments. From a management perspective it is essential to establish a baseline condition against which to measure the success or failure of management actions directed toward recovery of degraded conditions within the LMEs. The 5 modules are focused on the application of suites of indicators measuring LME (1) productivity, (2) fish and fisheries, (3) pollution and ecosystem health, (4) socio-economics, and (5) governance.

LMES AND THE UNEP REGIONAL SEAS PROGRAMME

Since 1984, the LME approach has matured into the planning and implementation activities of 16 projects in 110 countries bordering on LMEs in Africa, Asia, Latin America and countries in economic transition in eastern Europe (Sherman et al. 2007). The projects are country driven, wherein the direction and priorities of assessment and management actions are "driven" by nations sharing the transboundary goods and services of the LMEs.

There is a growing body of peer-reviewed published reports on the application of the LME approach to the assessment and management of marine resources. As of 2006, the American Association for the Advancement of Science, Westview Press, Blackwell Science, and Elsevier Science have published a total of fourteen peer-reviewed volumes with contributions by 445 authors (www.noaa.lme.gov).

The LME approach is a way forward for advancing ecosystem-based management of coastal and marine resources within a framework of sustainable development. Country-driven GEF-LME assessment and management projects are linked to the WSSD Plan of Implementation and to the global Regional Seas Programme, coordinated by UNEP. The descriptions in this report of the general ecological conditions of the LMEs, with regard to their productivity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance, are arranged in accordance with the Regional Seas designations (Figure 2**)**.

Regional Seas, LMEs and the 2002 World Summit on Sustainable Development

In December 2004, at the 6th Global Meeting of the Regional Seas Conventions and Action Plans, new strategic directions were adopted, in order to strengthen the Regional Seas Programme at the global level and address evolving challenges and priorities, while continuing to implement the individual work programmes of the Conventions and Action Plan secretariats. One of the directions calls to ***"Develop and promote a common vision and integrated management, based on ecosystem approaches, of priorities and concerns related to the coastal and marine environment and its resources in Regional Seas Conventions and Action Plans, introducing amongst others proactive, creative and innovative partnerships and networks and effective communication strategies."*** In 1982, UNEP began to address issues related to impacts on the marine environment from land-based activities. Some 80% of the pollution load in the oceans originates from land-based activities (municipal, industrial and agricultural wastes, run-off, and atmospheric deposition). These contaminants affect the most productive areas of the marine environment, including estuaries and near-shore coastal waters.

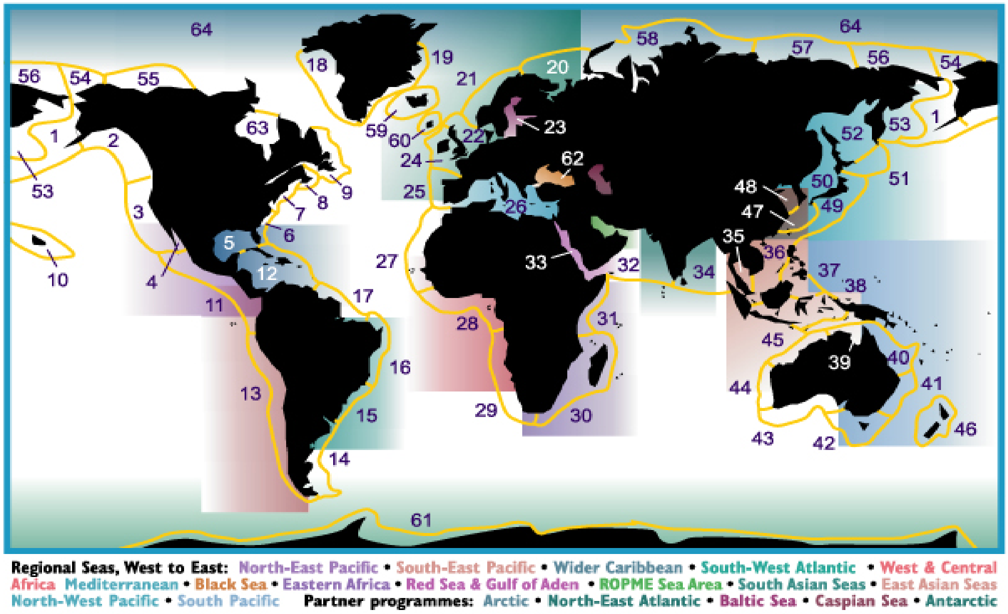


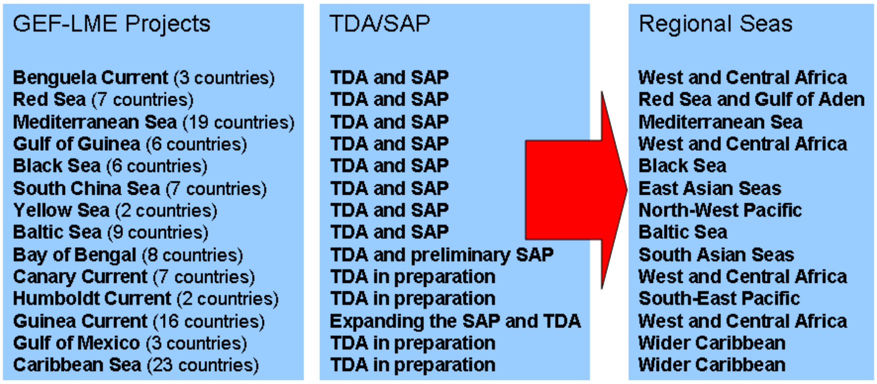
Figure 2. Regional Seas map with boundaries (in yellow) of the 64 Large Marine Ecosystems. Numbers correspond to the LME map numbers for the 64 LMEs.

The health and, in some cases, the very survival of coastal populations depend upon the health and well being of coastal systems such as estuaries and wetlands. In response to intense pressures put on coastal systems, 108 governments and the European Commission adopted the 1995 Washington Declaration, to establish a Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA). To support the GPA activity, a UNEP/GPA office was established in The Hague, Netherlands.

During the World Summit on Sustainable Development (WSSD), held in Johannesburg in 2002, participating world leaders agreed to pursue 4 marine targets: (i) to achieve substantial reductions in land-based sources of pollution by 2006; (ii) to introduce an ecosystems approach to marine resource assessment and management by 2010; (iii) to designate a network of marine protected areas by 2012; and (iv) to maintain and restore fish stocks to maximum sustainable yield levels by 2015. In an effort to encourage the global movement toward the 4 WSSD targets, UNEP along with other partnering UN and non-governmental organizations (NGOs), and the GEF and its partners, is assisting developing countries in operationalizing LME projects to serve as operational and management units for translating the legal frameworks and objectives of the Regional Seas Programmes into concrete actions to restore, sustain, protect and manage coastal environments and linked watersheds. Assessments of the state of most LMEs in GEF eligible regions were carried out by the Global International Waters Assessment (GIWA) between 2000 and 2005. The GIWA Regional Reports can be downloaded from their website www.giwa.net/publications/.

TRANSBOUNDARY DIAGNOSTIC ANALYSIS AND STRATEGIC ACTION PROGRAM

The GEF Operational Strategy recommends that nations sharing an LME begin to address coastal and marine issues by jointly undertaking strategic processes for analyzing science-based information on transboundary concerns, their root causes, and by setting priorities for action on transboundary concerns. This process is referred to as a Transboundary Diagnostic Analysis (TDA) and it provides a useful mechanism to foster participation of policy makers, scientists, management experts, stakeholders, and civil society at local, regional, national and international levels of interest. Countries then determine the national and regional policy, legal, and institutional reforms and investments needed to address the priorities, and based on the strategies prepare and initiate an LME wide Strategic Action Program (SAP). This allows sound science to assist policy making within a specific geographic location for an ecosystem-based approach to management that can be used to engage stakeholders (Figure 3).



GEF-LME Projects	TDA/SAP	Regional Seas
Benguela Current (3 countries)	**TDA and SAP**	**West and Central Africa**
Red Sea (7 countries)	**TDA and SAP**	**Red Sea and Gulf of Aden**
Mediterranean Sea (19 countries)	**TDA and SAP**	**Mediterranean Sea**
Gulf of Guinea (6 countries)	**TDA and SAP**	**West and Central Africa**
Black Sea (6 countries)	**TDA and SAP**	**Black Sea**
South China Sea (7 countries)	**TDA and SAP**	**East Asian Seas**
Yellow Sea (2 countries)	**TDA and SAP**	**North-West Pacific**
Baltic Sea (9 countries)	**TDA and SAP**	**Baltic Sea**
Bay of Bengal (8 countries)	**TDA and preliminary SAP**	**South Asian Seas**
Canary Current (7 countries)	**TDA in preparation**	**West and Central Africa**
Humboldt Current (2 countries)	**TDA in preparation**	**South-East Pacific**
Guinea Current (16 countries)	**Expanding the SAP and TDA**	**West and Central Africa**
Gulf of Mexico (3 countries)	**TDA in preparation**	**Wider Caribbean**
Caribbean Sea (23 countries)	**TDA in preparation**	**Wider Caribbean**

Figure 3. Summary of Transboundary Diagnostic Analyses (TDA) and Strategic Action Plans (SAP) for GEF sponsored LME projects planned and underway. An additional 2 projects outside the Regional Seas areas have completed TDAs.

In the GEF-LME projects either approved or in the preparation stage, 110 countries are moving to meet WSSD ecosystem-related targets and to address overfishing, fishing down food webs, destruction of habitat and accelerated nitrogen export. Countries engaged in the TDA process have already begun to scientifically characterize the LME, to identify the root causes of trends in LME biomass yields and the most pressing transboundary characteristics of coastal pollution, damaged habitats and depleted fish stocks, in order to prioritize these issues. Seven country-driven GEF-LME Projects are advancing to the drafting of the SAP, in which the countries commit to making institutional arrangements and taking policy actions, based on sound science, to address the issues identified in the TDA. The SAP addresses actions to correct institutional fragmentation, ecosystem assessment gaps, lack of cooperation and weak coastal policies and is signed by high-level government authorities of each participating country. The strategic framework for developing TDAs and SAPs is guided by the geographic area of LMEs and the application of the 5-module approach to LME assessment and management. Examples of TDA and SAP documents for the Benguela Current LME Project are available at www.bclme.org.

These processes are critical for integrating science into management in a practical way and for establishing appropriate governance regimes. The five modules consist of 3 that are science-based indicators focused on: productivity, fish/fisheries, pollution/ecosystem health; the other two, socio-economics and governance, are focused on economic benefits to be derived from a more sustainable resource base and implementing governance mechanisms for providing stakeholders and stewardship interests with legal and administrative support for ecosystem-based management practices (Figure 4). The first four modules support the TDA process while the governance module is associated with periodic updating of the Strategic Action Program or SAP (Duda and Sherman, 2002; Wang 2004). Adaptive management regimes are encouraged through periodic assessment processes (TDA updates) and updating of SAPs as gaps are filled.

CHANGING STATES OF THE LMES: INDICATOR MODULES

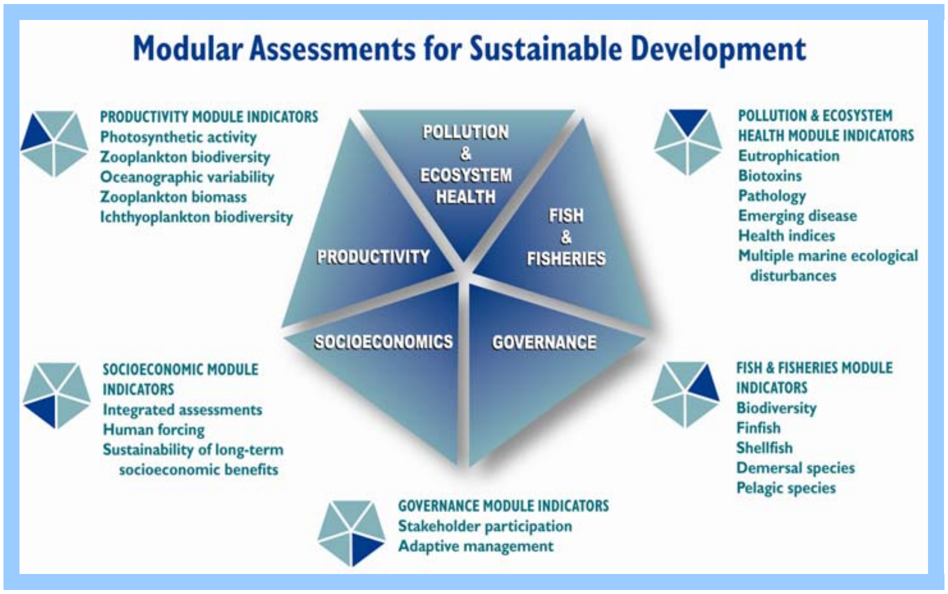


Figure 4. The Large Marine Ecosystem (LME) approach to sustainable development includes 5 modules with indicators.

The five-module indicator approach to the assessment and management of LMEs has proven useful in ecosystem-based projects. The modules are customized to fit the situation within the context of the TDA process and SAP development process for the groups of nations or states sharing an LME.

Productivity module indicators

Primary productivity can be related to the carrying capacity of an ecosystem for supporting fish resources (Pauly & Christensen 1995). Measurements of ecosystem productivity can be useful indicators of the growing problem of coastal eutrophication. In several LMEs, excessive nutrient loadings to coastal waters have been related to algal blooms implicated in mass mortalities of living resources, emergence of pathogens (e.g., cholera, vibrios, red tides, and paralytic shellfish toxins), and explosive growth of non-indigenous species (Epstein 1993, Sherman 2000). The ecosystem parameters measured and used as indicators of changing conditions in the productivity module are zooplankton biodiversity and species composition, zooplankton biomass, water-column structure, photosynthetically active radiation, transparency, chlorophyll-*a*, nitrite, nitrate, and primary production, (Aiken 1999, Berman & Sherman 2001, Melrose *et al*. 2006), (Figure 5).

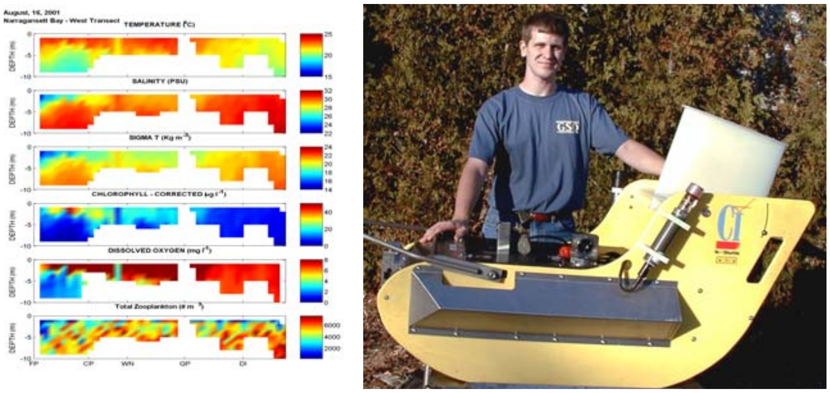


Figure 5. A Mariner Shuttle, towed behind a ship is used to collect measurements for assessing changing conditions of temperature, salinity, density, chlorophyll and primary productivity, oxygen and zooplankton within LMEs.

Fish and Fisheries module indicators

Changes in biodiversity and species dominance within fish communities of LMEs have resulted from excessive and selective exploitation, environmental shifts due to climate change and coastal pollution. Changes in biodiversity and species dominance in a fish community can cascade up the food web to apex predators and down the food web to plankton and benthos components of the ecosystem.

The Fish and Fisheries Module includes both fisheries-independent bottom-trawl surveys and pelagic-species acoustic surveys to obtain time-series information on changes in fish biodiversity and abundance levels (Figure 6). Standardized sampling procedures, when employed from small, calibrated trawlers, can provide important information on changes in fish species (Sherman 1993). The fish catches on the surveys provide biological samples for stock identification, stomach content analyses, age-growth relationships, fecundity, and for coastal pollution monitoring, based on pathological examinations.

Figure 6. The Norwegian Research Vessel *Dr. Fridtjof Nansen* readies to depart from Accra, Ghana on the Third Guinea current LME Survey (June 4 – July 15, 2005) of the fish and fisheries of the Guinea Current LME Project (GCLME). Scientists and technicians from all of the GCLME countries participated in this survey. The countries represented were Angola, Benin, Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Ghana, Equatorial Guinea, Guinea, Liberia, Nigeria, Sierra Leone and Togo.

Fish stock demographic data are used for preparing stock assessments (NAFO 2005) and for clarifying and quantifying multispecies trophic relationships (NAFO 2005). NOAA Fisheries information is available at http://nft.nefsc.noaa.gov (username: nft; password: nifty) for development of a standard suite of methods for standardizing assessment tasks. The survey vessels can also be used as platforms for obtaining water, sediment, and benthic samples for monitoring harmful algal blooms, diseases, anoxia, and structure of benthic communities.

Pollution and Ecosystem Health module indicators

In semi-enclosed LMEs, pollution and eutrophication can be important driving forces of change in biomass yields. Assessing the changing status of pollution and health of an entire LME is scientifically challenging. Ecosystem health is a concept of wide interest for which a single precise scientific definition is difficult. The health paradigm is based on multiple-state comparisons of ecosystem resilience and stability, and is an evolving concept that has been the subject of a number of meetings (Sherman 1993). To be healthy and sustainable, an ecosystem must maintain its metabolic activity level and its internal structure and organization, and must resist external stress over time and space scales relevant to the ecosystem (Costanza 1992). The modules are all used to a greater or lesser extent in the US, in ICES, and are now being introduced in the GEF-LME Projects.

The Pollution and Ecosystem Health Module measures pollution effects on the ecosystem through the pathobiological examination of fish, and through the estuarine and nearshore monitoring of contaminant effects in the water column, the substrate, and selected groups of organisms. Where possible, bioaccumulation and trophic transfer of contaminants are assessed, and critical life history stages and selected food web organisms are examined for indicators of exposure to, and effects from, contaminants. Effects of impaired reproductive capacity, organ disease, and impaired growth from contaminants are measured. Assessments are made of contaminant impacts at both species and population levels. Implementation of protocols to assess the frequency and effect of harmful algal blooms, emergent diseases, and multiple marine ecological disturbances (Sherman 2000) are included in the pollution and ecosystem health module. In the United States, the Environmental Protection Agency (EPA) has developed a suite of 5 coastal condition indicators: water quality index, sediment quality index, benthic index, coastal habitat index, and fish tissue contaminants index (Figure 7) as part of an ongoing collaborative effort with the National Oceanic and Atmospheric Administration (NOAA), the U.S. Fish and Wildlife Service (FWS), the U.S. Geological Survey (USGS), and other agencies representing states and tribes.

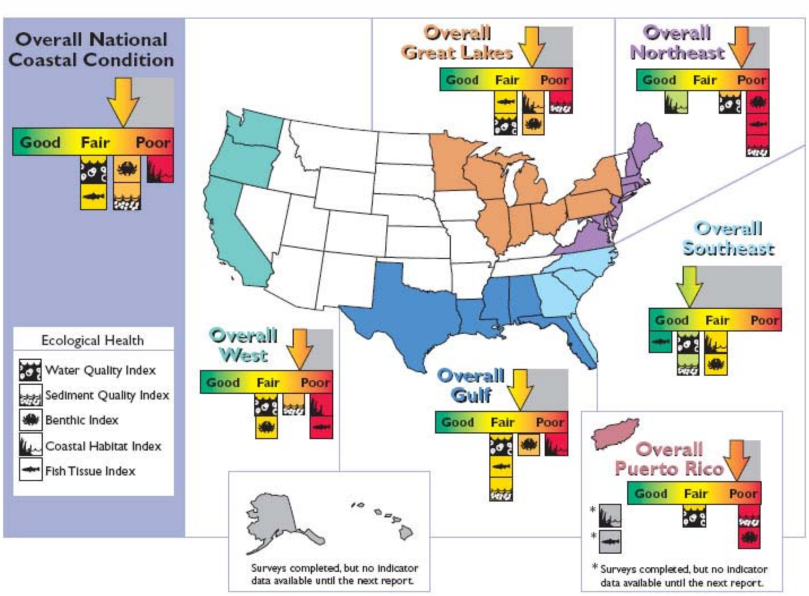


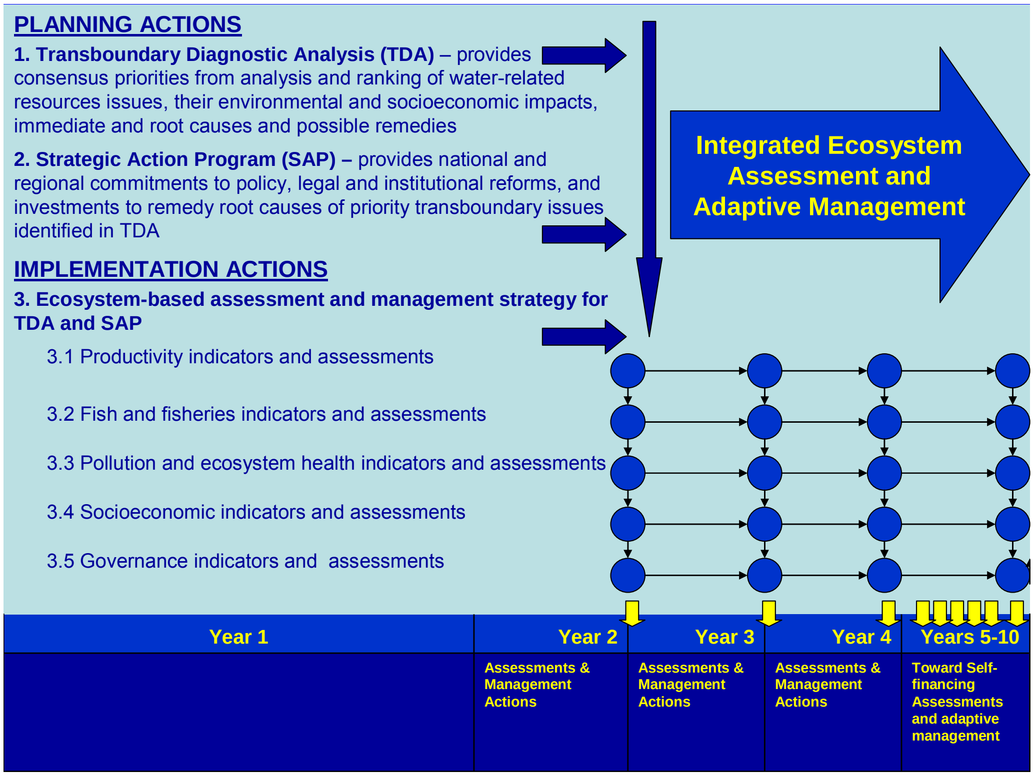
Figure 7. The U.S. Environmental Protection Agency (EPA) 2004 indicators of coastal condition A stoplight approach is used to indicate relative conditions: poor (red), moderate (orange) or good (green). (National Coastal Condition Report II. 2004).

The 2004 report, “National Coastal Condition Report II,” includes results from EPA’s analyses of coastal condition indicators and NOAA’s fish stock assessments by LMEs aligned with EPA’s National Coastal Assessment (NCA) regions (USEPA 2004). Several GEF supported LME projects are adapting EPA’s 5 coastal condition indicators for assessing the health of near coastal areas of LMEs (Figure 7).

Socioeconomic module indicators

This module emphasizes the practical application of scientific findings to the management of LMEs and the explicit integration of social and economic indicators and analyses with all other scientific assessments to assure that prospective management measures are cost-effective. Economists and policy analysts work closely with ecologists and other scientists to identify and evaluate management options that are both scientifically credible and economically practical with regard to the use of ecosystem goods and services.

In order to respond adaptively to enhanced scientific information, socioeconomic considerations must be closely integrated with science findings. Both the socioeconomic and governance indicators are used in the planning and implementation actions as summarized in Figure 8.



PLANNING ACTIONS

1. Transboundary Diagnostic Analysis (TDA) – provides consensus priorities from analysis and ranking of water-related resources issues, their environmental and socioeconomic impacts, immediate and root causes and possible remedies

2. Strategic Action Program (SAP) – provides national and regional commitments to policy, legal and institutional reforms, and investments to remedy root causes of priority transboundary issues identified in TDA

IMPLEMENTATION ACTIONS

3. Ecosystem-based assessment and management strategy for TDA and SAP

3.1 Productivity indicators and assessments

3.2 Fish and fisheries indicators and assessments

3.3 Pollution and ecosystem health indicators and assessments

3.4 Socioeconomic indicators and assessments

3.5 Governance indicators and assessments

Figure 8. Integrated Ecosystem-based assessment and adaptive management planning actions over 10 years.

The new ecosystem accounting paradigm requires that resource managers of the different sectors of stakeholder interests incorporate the cumulative assessments of changing ecosystem productivity, fish and fisheries, pollution and ecosystem health and their effects on socioeconomic conditions and governance jurisdictions, as both additive and integrative effects on ecosystem conditions. These latter components of the LME approach to marine resources management have recently been described as the human dimensions of LMEs (Hennessey & Sutinen 2005). A framework has been developed by the Department of Natural Resource Economics at the University of Rhode Island for monitoring and assessment of the human dimensions of LMEs and for incorporating socioeconomic considerations into an adaptive management approach for LMEs (Sutinen et al. 2000; Juda et al. 2006, Olsen et al. 2006). One of the more critical considerations, a method for economic valuations of LME goods and services, has been developed using framework matrices for indexing economic activity (Sherman et al. 2005, Hoagland & Jin 2006).

Governance module indicators

The Governance Module is evolving, based on demonstration projects now underway in several ecosystems, that are being managed from an ecosystem perspective. In LME assessment and management projects supported by the Global Environment Facility for the Yellow Sea, the Guinea Current, and the Benguela Current LMEs, agreements have been reached among the several ministries in each country bordering the LMEs (ministries responsible for ocean resources for the environment, fisheries, energy, tourism, finance and foreign affairs, for example), to enter into joint resource assessment and management activities as the framework for ecosystem-based management practices. Elsewhere, the Great Barrier Reef LME and the Antarctic LME are also being managed from an ecosystem perspective, the latter under the Commission for the Conservation of Antarctic Marine Living Resources. Governance profiles of LMEs are being explored to determine their utility in promoting long-term sustainability of ecosystem resources (Juda and Hennessey 2001). In each of the LMEs, governance jurisdiction can be scaled to ensure conformance with existing legislated mandates and authorities. An example of multiple governance-related jurisdictions that includes areas designated for fisheries management, pollution control and marine protected areas, is described in Sherman *et a*l. (2004).

Within the context of ecosystem-based management the integration of data and information for decision making is additive and vertically integrated for the five modules, and adaptive contingent on annual assessment findings horizontally across years. From Year 1, the GEF supported projects move toward the goal of self-financing of the ecosystem assessment and management process by year 10 (Figure 8).

GEF-SUPPORTED LME PROJECTS

An increasing number of countries and organizations are engaged in LME projects aimed at moving toward the WSSD marine targets. The LME approach to the assessment and management of marine resources and their environments is being applied with financial assistance from GEF to developing countries who are planning and implementing LME projects focused on introducing an ecosystem-based approach to the (1) recovery of depleted fish stocks; (2) restoration of degraded habitats; and (3) reduction of coastal pollution and eutrophication. GEF-LME projects are presently located in 16 LMEs that provide goods and services in bordering countries containing over half the world's population. These LMEs produce 46% of the world's annual marine fish catch while also being subjected to significant eutrophication in near coastal waters. These stressors have been identified during the TDA and SAP process. Taken together, the 16 projects represent a significant movement toward the WSSD targets, and will be the subject of future UNEP and partners' ecological condition reports.

The new generation

The LME projects themselves as well as their academic, administrative and political environment have to be scientifically and technically strong. The complexity of the modern ecosystem oriented approach of fisheries and other marine activities calls for a new generation of professionals addressing the sustainability issue in a much broader sense than before. Not only do the preservation of the fish stocks and the other goods and services of the ecosystem including the protection of marine biodiversity have to be taken care of, but also the socio-economic development of the region. Management goals have to be defined and defended under the pressure of conflicting ecological interests and societal and political constraints.

On the one hand, in order to address all five modules of the LME concept, specialists are needed like ichthyologists and oceanographers and plankton experts, fish stock assessment biologists, sociologists, economists and experts in international law. There is an increasing demand for reliable data sets of adequate length and resolution in space and time to feed modern data-driven models on the medium- and long-term consequences of various management strategies. On the other hand experienced generalists and modelers are required to put the facts and findings together and to create such management scenarios. Those generalists are rather rare and not easy to recruit. Therefore, capacity development has to be continued in all parts of the world, not only in developing countries. Much of it can now be done in the regions themselves through mutual assistance.

To a certain extent a fair division of research work between the rich and the poorer countries might be envisaged. Rich countries have the capacity and hence the responsibility of advancing science in the broadest possible way in natural and social sciences per se but also in theory and analysis of the interactions in the sustainability triangle of environment, economy and society. Those interactions differ in structure from region to region. Working in collaboration with colleagues and institutions in poorer parts of the world, including developing countries with their rich and diverse perspectives, is a win-win situation.

In a nutshell

The LME approach is the pathway towards sustainable use of marine ecosystems provided the interaction between the various players becomes much stronger amongst the various science sectors and between scientists and stakeholders, the general public and the national and international administration. Partnership and communication are required on all levels and on all geographical scales. What is lacking is not so much the money but rather the political will and the vision of enthusiastic and competent experts on the way to apply the LME concept for the sustainable development of the use and conservation of the marine environment in many parts of the World Ocean.

TECHNICAL DESCRIPTION OF THE DATA SETS CONTAINED IN THIS REPORT

ECOLOGICAL INDICATORS OF LME CONDITION AND METHODOLOGY

Ocean front maps

Igor Belkin of the University of Rhode Island provided descriptions and maps of LME oceanographic fronts for each of the 64 LMEs (Belkin *et al*. 2009, Belkin & Cornillon 2003). An oceanographic front is a relatively narrow zone of enhanced horizontal gradients of physical, chemical and biological properties (e.g. temperature, salinity, nutrients). Fronts occur on a variety of scales, from several hundred meters up to many thousand kilometers. Some of them are short-lived, but most are quasi stationary and seasonally persistent: they emerge and disappear at the same locations during the same season, year after year. The temperature and salinity ranges across the strongest fronts can be as high as 10-15 degrees C and 2 to 3 parts per thousand (ppt) salinity, although somewhat smaller numbers, such as 5 degrees C and 1 ppt, are far more common. The width of fronts varies widely: from less than 100 m to 200 km. Vertically, many fronts extend several hundred meters in depth. Major fronts can extend as deep as 2,000 m. Fronts are crucial in various processes that evolve in the ocean and at the ocean interfaces with the atmosphere, sea ice and sea bottom. Fronts are important for climate change monitoring and prediction, the fishing industry, pollution control, waste disposal and hazards mitigation, marine transportation, marine mining, including the oil and gas industry, submarine navigation and integrated coastal management.

- Fronts are associated with current jets, so that any frontal pattern represents a circulation pattern;
- The along-frontal current jets are accountable for the bulk of water/heat/salt transport;
- Fronts separate different water masses and spawn rings responsible for the bulk of cross-frontal and meridional transport of water, heat and salt;
- Fronts usually coincide with major biogeographical boundaries associated with zones of enhanced bio-productivity, including fisheries grounds;
- The surface heat fluxes, wind stress and other meteorological parameters may differ drastically between the warm and cold sides of a front. Fronts strongly interact with the marine atmospheric boundary layer and separate regions with different response to atmospheric forcing, so they are crucial for weather forecasting and climate monitoring;
- Some high-latitude fronts are directly related to sea ice conditions, so the front locations are determined by the maximum extent of the sea ice cover;
- Fronts profoundly influence acoustic environment so that solving any sound propagation problem requires knowledge of the fronts' locations and characteristics;
- Ocean sedimentation regimes are largely determined by the circulation (hence frontal) pattern, therefore the interpretation of paleo-oceanographic and paleoclimatic information recorded in marine sediments requires *a priori* knowledge of the modern frontal situation;
- Because fronts are associated with convergent currents, oceanic and riverine pollutants can be concentrated thousands of times on fronts, thus endangering the fish, sea birds and marine mammals that inhabit the frontal zones.

The descriptions and maps provide both textual and visual summaries of dominant frontal patterns and principal individual fronts. The frontal schematics are annual long-term means, based largely on a 12-year data set of frontal maps assembled at the University of Rhode Island. They are the result of a comprehensive global analysis, based on Pathfinder Sea Surface Temperatures. The maps show the most robust and well-defined fronts, regardless of the seasons during which they develop and peak.

Sea Surface Temperature

All SST time series in this report have been calculated by Igor Belkin (University of Rhode Island) from the U.K. meteorological Office Hadley Centre SST climatology data (Belkin, 2009). The U.K. Meteorological Office Hadley Center SST climatology data was selected for its superior resolution (1 degree latitude by 1 degree longitude globally); for the historic reach of the data; and for its high quality. A highly detailed, research-level description of this data set has been published by Rayner *et al.* (2003). The Hadley data set consists of monthly SSTs calculated for each 1° x 1° rectangular cell (spherical trapezoid, to be exact) between 90°N-90°S, 180°W-180°E. To calculate and visualize annual SSTs for each LME, the annual SST for each 1° x 1° cell was calculated and the area-averaged annual 1° x 1° SSTs within each LME. Since the square area of each trapezoidal cell is proportional to the cosine of the middle latitude of the given cell, all SSTs were weighted by the cosine of the cell's middle latitude. After integration over the LME area, the resulting sum of weighted SSTs was normalized by the sum of the weights, that is, by the sum of the cosines. Annual anomalies of annual LME-averaged SSTs were calculated by computing the long-term LME-averaged SST for each LME by a simple long-term averaging of the annual area-weighted LME-averaged SSTs. Then, annual SST anomalies were calculated by subtracting the long-term mean SST from the annual SST. Both SST and SST anomalies were visualized using adjustable temperature scales for each LME in order to bring out details of temporal variability that otherwise would be hardly noticeable if a unified temperature scale were used. The resulting plots of SST and SST anomalies are for 63 LMEs. Ice cover precludes a meaningful assessment of the LME-averaged SST for the Arctic Ocean. John O'Reilly (NOAA) kindly provided a data set of the LME coordinates for these processes.

Primary productivity data

The LME descriptions include primary productivity estimates derived from satellite borne data of NOAA's Northeast Fisheries Science Center, Narragansett Laboratory. These estimates originate from SeaWiFS (satellite-derived chlorophyll estimates from the Sea-viewing Wide Field-of-view Sensor), Coastal Zone Color Scanner (CZCS), a large archive of *in situ* near-surface chlorophyll data, and satellite sea surface temperature (SST) measurements to quantify spatial and seasonal variability of near-surface chlorophyll and SST in the LMEs of the world. Daily binned global SeaWiFS chlorophyll *a* (CHL, mg m^{-3}), normalized water leaving radiances, and photosynthetically available radiation (PAR, Einsteins m^{-2} d^{-1}) scenes at 9 km resolution for the period January 1998 through December 2006) are obtained from NASA's Ocean Biology Processing Group. Daily global SST (^{o}C) measurements at 4 km resolution are derived from nighttime scenes composited from the AVHRR sensor on NOAA's polar-orbiting satellites and from NASA's MODIS TERRA and MODIS AQUA sensors. Daily estimates of global primary productivity (PP, gC m^{-2} d^{-1}) are calculated using the Ocean Productivity from Absorption and Light (OPAL) model (Marra, personal communication), a derivative of the model first formulated in Marra et al. (2003). The OPAL model generates profiles of chlorophyll estimated from the SeaWiFS chlorophyll using the algorithm from Wozniak et al. (2003) and uses the absorption properties in the water column to vertically resolve estimates of light attenuation in approximately 100 strata within the euphotic zone. Absorption by pure water is assumed to be a constant value over PAR wavelengths; chlorophyll-specific phytoplankton absorption is parameterized empirically (Bricaud et al., 1998); absorption by photosynthetic pigments is distinguished from total absorption; and absorption by colored dissolved organic matter (CDOM) is calculated according to Kahru and Mitchell (2001). The chlorophyll-specific phytoplankton absorption is used to calculate productivity, while absorption by photosynthetic pigments, water, and CDOM are used to vertically resolve light attenuation. SST, which is used as a proxy for seasonal changes in the phytoplankton community, is related to the chlorophyll-specific absorption coefficient. The quantum efficiency is obtained from a hyperbolic tangent and a constant φmax. Productivity is calculated for the 100 layers in the euphotic zone and summed to compute the integral daily productivity (gC m^{-2} d^{-1}).

Monthly and annual means of PP were extracted for each LME and a simple linear regression of the annual PP was used to determine the rate of change over time. The significance (alpha = 0.01 and 0.05) of the regression coefficient was calculated using a t-test according to Sokal and Rohfl (1995)(Table 1). The data allowed for classifying the LMEs into 3 categories: **Class I**, high productivity (>300 gCm^{-2} $year^{-1}$), **Class II**, moderate productivity (150-300 $gCm^{-2}year^{-1}$), and **Class III,** low (<150 gCm^{-2} $year^{-1}$) productivity.

LME	Chl	PP
Barents Sea	+ **	
Bay of Bengal		- *
California Current	+ *	
East Greenland Shelf	+ *	
East Siberian Sea	- *	
Hudson Bay	+ **	+ *
Humboldt current		+ *
Indonesian Sea	+ *	
New Zealand Shelf	+ *	
North Australian Shelf	+ *	
Red Sea	+ **	+ *
Sea of Okhosk	+ *	

Table 1. Significance of T test on chlorophyll (Chl) and primary productivity (PPD) regression coefficients for SeaWiFS time series data on chlorophyll and primary productivity (1998-2006). Only cases where p<.05 are listed. All other comparisons were nonsignificant. Plus and minus signs are used to designate the direction of the slope of the trend line. * Indicates P<.05 ** Indicates P<.01

Fisheries catch and values trends, and ecosystem state indicators

Trends in fisheries biomass yields and catch value, provided by the Sea Around Us Project, Fisheries Centre, University of British Columbia (see www.seaaroundus.org), are also included in the LME descriptions. The datasets and methods used for deriving the catch trends and the concepts behind the indicators are described in Pauly *et al.* (this volume).

THE GLOBAL INTERNATIONAL WATERS ASSESSMENT

The assessments presented in this volume on state and trends in LMEs in GEF eligible regions are based mainly on the data collections and regional reports compiled by the Global International Waters Assessment (GIWA), supplemented by information from other sources (see Appendix 2). GIWA was designed as a globally comparable assessment of the present state and future trends of transboundary aquatic resources in the world‘s shared waters. On a regional basis, a bottom-up and multidisciplinary approach was adopted that involved nearly 1,500 natural and social scientists from around the world, particularly in developing regions (Hempel & Daler 2004, UNEP 2006).

The GIWA project divided the world into transboundary water regions, each comprising one or more major drainage basin(s) with adjacent LMEs. Regional teams conducted the assessment based on existing regional data and information, and adapted the methodology to the local conditions. In many GIWA regions, the assessment process has strengthened communication between social and natural scientists, as well as managers. It has also fostered new partnerships within the regions and between neighbouring regions. The GIWA project was initiated and largely funded by GEF and led by UNEP. The key products of GIWA are 35 regional reports, most of them published in print and/or electronically. The GIWA Final Report (UNEP 2006) summarises the findings of the regional reports in a global perspective and provides information on GIWA’s methodology and theoretical background.

Globally comparable results were achieved by a common and consistent methodology applied by all of the regional teams. The GIWA methodology provides criteria for assessing water-related environmental concerns, and for identifying their immediate and root causes and potential policy options. Regional experts assessed and compared the severity of impacts from a regional perspective (Belausteguigoitia 2004).

The numerous and complex transboundary water-related environmental problems were grouped into five major concerns:

1) Freshwater shortage
2) Pollution
3) Overfishing and other threats to aquatic living resources
4) Habitat and community modification
5) Global change

The GIWA methodology is comprised of four major steps:

1) Scaling defines the geographic boundaries of the GIWA region, boundaries generally demarcated by a large drainage basin and its adjacent marine areas. The boundaries of the marine parts of the GIWA regions often correspond with those of LMEs.
2) Scoping assesses and scores the severity of present and predicted environmental and socioeconomic impacts caused by each of the GIWA concerns.
3) Causal chain analysis traces the cause and effect pathways from the socio-economic and environmental impacts back to their root causes.
4) Wherever possible, the causal chain analysis was followed by policy option analysis which outlined potential courses of action that aim to mitigate or resolve environmental and socioeconomic problems in the region.

The GIWA provided baseline information at the regional level for the preparation of TDAs and SAPs initiated by GEF. At the same time, many GIWA regional assessments have benefited from completed TDAs. GIWA has been the largest global assessment of ecosystem-wide water issues from a transboundary perspective, linking international river basins to their adjacent LMEs. It was designed to provide policy makers and managers with the information they need to improve transboundary resources management.

RECENT TRENDS IN LMES WITHIN REGIONAL SEAS, IDENTIFIED THROUGH THE 5-MODULE ASSESSMENTS

During the review of the LME condition descriptions, three major challenges emerged: (1) the need to apply the precautionary approach, especially in LMEs with limited access to science-based stock assessments, to control the industrial fishing effort that threatens the community-based artisanal fisheries, (2) The need to improve forecasts of climate effects on abundances of key species, and (3) the need to reduce nutrient inputs into estuaries to levels that protect coastal waters from eutrophication.

Need for Precautionary Approach:

One example illustrating the need for a precautionary approach is the encroachment of industrial globalized fisheries on artisanal fisheries in the Guinea Current LME. Findings from a time series analysis of Catch-Per-Unit-Effort for both small-sized inshore artisanal-type vessels and industrialized fishing fleets from the European Union showed that the large industrialized trawlers are fishing species in near-shore areas previously not fished by the industrial fishmeal extraction enterprises that provide product to industrialized farms in the developed world as animal feed or fertilizer (Figure 9). The analysis found a consistent rise in industrial trawling coinciding with a downward trend during the late

1980s in inshore seasonal artisanal fishing, which raises concerns for the community-based fish harvest, available to meet the growing nutritional needs of the 300 million people living along the Guinea Current coast (Korentang 2002, Figure 9).

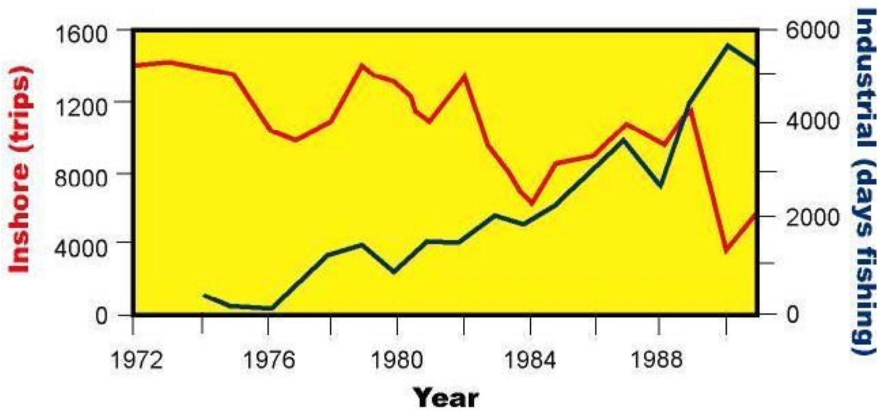


Figure 9. Negative influence of industrial fisheries (days fished) on catch based in shore fishing fishing trips along the coast of Ghana in the Guinea Current LME (from Koranteng, 2002)

Need for improved forecasts of fishery fluctuations during climate change:

The variability in mean-annual fisheries catch of Humboldt Current LME provides one illustration of the need for improved forecasts of fishery fluctuations in order to move toward long-term sustainability of pelagic and demersal fish stocks. The Humboldt Current LME contains the world's largest upwelling system and is the world's most productive marine ecosystem, providing between 15% and 20% of the world's annual marine catch. Anchovy, sardine and horse mackerel are used for fish meal and for human consumption. Fishing sustains thousands of fishermen and their families. The sharp decline in landings in the early 1970s and increases in the late 1980s and 1990s are related to El Niño climate effects (see Humboldt Current description, this volume).

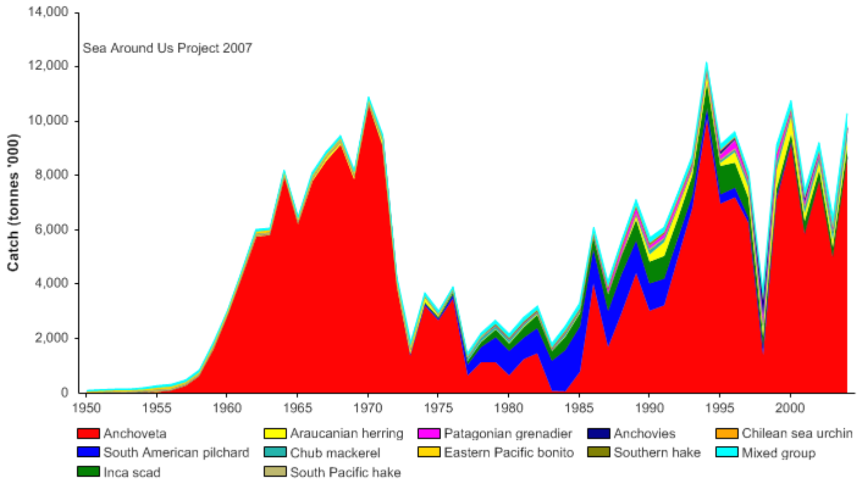


Figure 10.--Humboldt Current LME multi-decadal fish catch (1950-2004). Source: Sea Around Us Project 2007.

While the high productivity of the Humboldt Current LME is the result of upwelling processes governed by strong trade winds, the upwelling is subjected to considerable annual climatic variability, which causes variations in marine populations and catch (Figure 10). The normal seasonal upwelling can be interrupted by the El Niño-Southern Oscillation (ENSO), which results in intrusions of warm water. For the long-term sustainability of the pelagic and demersal fish stocks of this LME, improved forecasts of climate-driven fishery fluctuations are required. Polar region LMEs are now also changing from extensive global climate warming and ice melt (see East Bering Sea and Gulf of Alaska descriptions, this volume).

Need to curb excessive nitrogen loading:

Models of nitrogen affecting LMEs predict significant increases. Excessive levels of nitrogen contribution to coastal eutrophication constitute a growing global environmental problem that is cross-sectoral in nature. Excessive nitrogen loadings have been identified as problems *inter alia* in the Baltic Sea, Black Sea, Adriatic portion of the Mediterranean, Yellow Sea, South China Sea, Bay of Bengal, Gulf of Mexico, and Patagonian Shelf LMEs.

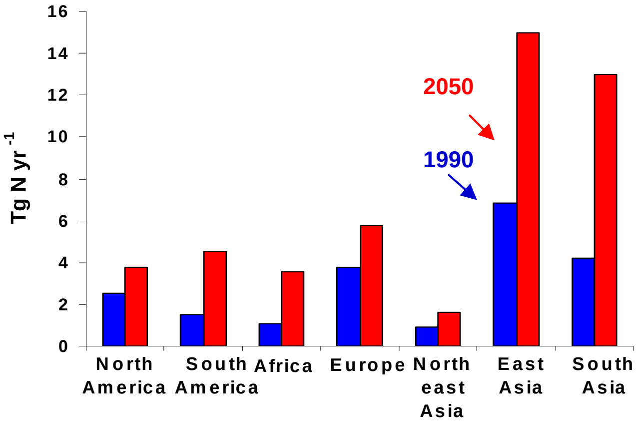


Figure 11. Model-predicted nitrogen (dissolved inorganic N) export by rivers to coastal systems in 1990 and in 2050—based on a business-as-usual (BAU) scenario. Figure modified from Kroeze and Seitzinger (1998).

Model-predicted global estimates of dissolved inorganic nitrogen (DIN) export from freshwater basins to coastal waters in 1990 and 2050 have been developed by Kroeze and Seitzinger (1998). These estimates, based on a business-as-usual (BAU) scenario, are cause for concern for the future condition of LME coastal waters with expected nitrogen exports doubling between 1990 and 2050 (Figure 11). Given the expected future increases in human population size and in fertilizer use, without significant nitrogen mitigation efforts, LMEs will be subjected to a future of increasing harmful algal bloom events, reduced fisheries, and hypoxia that will further degrade marine biomass and biological diversity.

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Fisheries in Large Marine Ecosystems: Descriptions and Diagnoses

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Abstract

We present a rationale for the description and diagnosis of fisheries at the level of Large Marine Ecosystems (LMEs), which is relatively new, and encompasses a series of concepts and indicators different from those typically used to describe fisheries at the stock level. We then document how catch data, which are usually available on a smaller scale, are mapped by the Sea Around Us Project (see www.seaaroundus.org) on a worldwide grid of half-degree lat.-long. cells. The time series of catches thus obtained for over 180,000 half-degree cells can be regrouped on any larger scale, here that of LMEs. This yields catch time series by species (groups) and LME, which began in 1950 when the FAO started collecting global fisheries statistics, and ends in 2004 with the last update of these datasets. The catch data by species, multiplied by ex-vessel price data and then summed, yield the value of the fishery for each LME, here presented as time series by higher (i.e., commercial) groups. Also, these catch data can be used to evaluate the primary production required (PPR) to sustain fisheries catches. PPR, when related to observed primary production, provides another index for assessing the impact of the countries fishing in LMEs. The mean trophic level of species caught by fisheries (or 'Marine Trophic Index') is also used, in conjunction with a related indicator, the Fishing-in-Balance Index (FiB), to assess changes in the species composition of the fisheries in LMEs. Also, newly conceived 'Stock-Catch Status Plots' are presented which document graphically, for each LME, both the increase in the number of stocks that moved from the fully exploited to the overexploited and collapsed stages, and the relative biomass of fish extracted from stocks in these various stages. Finally, original time series of estimated catch data are presented for the six LMEs of the coast of North Siberia, Arctic Alaska and Arctic Canada (all entirely contained within FAO Statistical Area 18), for which even crude catch estimates were previously unavailable. Altogether these descriptors of fisheries and ecosystem states over the last 50+ years allow a diagnosis of the fisheries of each LME, and inferences on global trends, as LMEs are the source of 80% of the global marine catch.

Introduction

Fisheries have been seen traditionally as local affairs, largely defined by the range of the vessel exploiting a given resource (Pauly & Pitcher 2000). The need for countries to manage all fisheries within their Exclusive Economic Zones (EEZ), a consequence of the United Nations Convention on the Law of the Sea (UNCLOS), led to attempts to derive indicators for marine fisheries and ecosystems at the national level (see e.g., Prescott-Allen 2001). Also, it was realized that, given the large scale migrations of some exploited stocks, and of distant-water fleets (Bonfil *et al.* 1998), an even better integration of fisheries could be achieved at the level of Large Marine Ecosystems (LMEs)(Sherman *et al.* 2003, Sherman & Hempel, this vol.).

However, no national or international jurisdiction reports, at the LME level, for catches and other quantities from which fisheries sustainability indicators could be derived were available. Indeed, if the fisheries of LMEs are to be assessed, and if comparisons of the fisheries in, and of their impact on LMEs, are to be performed, then the fisheries within LMEs must be documented for this explicit purpose, mainly by assembling data sets from national and other sources.

The Sea Around Us Project was created in 1999 with the explicit purpose of assessing the impact of fisheries on marine ecosystems and of developing policies which can mitigate this impact (Pauly 2007). Thus, we set ourselves, from the very beginning, the task of assembling data on all the fisheries that impacted on a 'place', i.e., any area of the sea, since whatever one's definition of an 'ecosystem' is, it must include reference to a place. Indeed, the concept of place has a profound implication on our ability to implement ecosystem based management of fisheries (Pauly 1997; Sumaila 2005).

When dealing with the fisheries of places such as LMEs, the physical and other features that are relevant to the fisheries must also be expressed at the LME scale. The Sea Around Us website provides such statistics, which are used in the LME-specific accounts in this volume. These are:

1) The percentage of global coral reef area in a given LME (rather than the area itself, which is highly variable between authors), based on a global map produced by the World Conservation Monitoring Centre (www.unep-wcmc.org);
2) The percentage of seamounts in a given LME (rather than their number, for the same reason), based on a global map of Kitchingman & Lai (2004);
3) The percentage of the area of a given LME that is part of a Marine Protected Area (MPA), based on an MPA database documented in Wood *et al*. (in press).

Other fisheries-relevant information, not used here, but available through the 'Biodiversity' option on our website (www.seaaroundus.org), are fish species by LME (from www.fishbase.org), and of marine mammals and other marine organisms, to be consolidated in SeaLifeBase (www.sealifebase.org). Additionally, the 'Ecosystem' option allows access to maps of primary production (see Sherman & Hempel, this vol. for details), major estuaries (Alder 2003), ecosystem models, and other features of LMEs.

However, the major exhibit of the website, and the major product of the Sea Around Us Project are time series of fisheries catches by LME. They were obtained using a method developed by Watson *et al.* (2004), which relies on splitting the world oceans into more than 180,000 spatial cells of ½ degree lat.-long., and mapping onto these cells, by species and higher taxa, all catches that are extracted from such cells. The catches in these spatial cells can then be regrouped into higher spatial aggregates, for example, the EEZs of maritime countries or, as is relevant here, the LMEs that have been so far defined in the world's oceans (Watson *et al* 2004).

As these aggregates of spatial cells can then be combined with other data, for example, the price of the fish caught therein, or their trophic level, one can straightforwardly derive other time series, e.g., of indicators of the value, or the state of fisheries in any area. In the following, we present how the primary (i.e., 'catch') time series were obtained, along with a set of four derived time series included in this volume for all (except some of the Arctic) LMEs. As these time series are presented through graphs (the tabular data are available from www.seaaroundus.org); each section below refers to the graph that presents one of these time series. A final section is devoted to the newly derived catch graphs for the six Arctic LMEs that are entirely within FAO Statistical Area 18, and which are the sole fisheries-related exhibit presented for these LMEs.

Graph 1 - Reported landings by species, per LME

The method used by the Sea Around Us Project to map catches onto ½ degree lat.-long. spatial cells has been described by Watson *et al.* (2003, 2004, 2005) in some detail. Here, we summarize it in 5 steps:

1) Assemble the 'catch' data to be mapped. Data were sourced from FISTAT, the database of the United Nations Food and Agriculture Organization (FAO; www.fao.org), the STATLANT database and selected reports of the International Council for the Exploration of the Sea's (ICES, www.ices.int/fish/statlant.htm), the Northwest Atlantic Fisheries Organization (NAFO; www.nafo.ca/), FAO Regional bodies (Southeast Atlantic, Mediterranean and Black Sea (GFCM), Eastern Central Atlantic (CECAF) and RECOFI), Cuban fisheries catch data (Baisre *et al.* 2003); Estonian fisheries catch data (Ojaveer 1999), 'nationally disaggregated' catch data for the components of the former USSR (Zeller & Rizzo *in press*) and the former Yugoslavia (Rizzo & Zeller *in press*), Guam, and the Commonwealth of the Northern Mariana Islands (Zeller *et al.* 2007), American Samoa (Zeller *et al.* 2006), and, for the Antarctic, from the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR; www.ccamlr.org). These data consist of marine finfish, brackishwater and diadromous finfish, and marine invertebrates. They exclude marine mammals, and reptiles (i.e., sea turtles), algae, and invertebrates harvested for purposes other than food (e.g., corals harvested as construction material). All freshwater organisms are excluded, as are fish and invertebrates produced in mariculture operations. The latter is not always clear-cut, due to the similarity between sea ranching and capture fisheries, and it may be the cause for some of the large recent 'catch' increases in some LMEs, notably those along the Chinese coast. Another cause of catch mis-estimation (although one with reversed sign) is discarded by-catch (Zeller & Pauly 2005), and Illegal, Unregulated and Unreported (IUU) fishing, which is generally not accounted for by our sources of 'catch' data. For this reason, we nearly always refer to 'reported landings'. Thus, when encountering 'catches', readers should be aware that these are not really catches, i.e., landings + discards + IUU, etc. Finally, in the case of some countries for which the FAO database does not provide catches, or reports without correcting the unrealistic figures submitted by member countries, the Sea Around Us Project has attempted to reconstruct or correct the catch, using concepts initially presented by Pauly (1998). However, for the analyses presented in this volume, this concerned only the following areas: China (Watson & Pauly 2001); Cuba, Estonia and US flag territories in the Pacific (see references above), and the seven Arctic LMEs in FAO area 18, for which we provide preliminary catch time series, to replace the landings of zero that FAO often reports for this area (see below). For all other countries, we stress again, the catches reported here originated from FAO and other official sources.
2) Create, for each taxon (species, genera, families and orders) for which at least one country reports landings, a distribution range map, constrained by an external polygon, based on the known depth and latitudinal range, and within which account is taken of the habitat preference of this taxon (Watson *et al*. 2004, Close *et al.* 2006). These range maps rely heavily on data extracted from FishBase (www.fishbase.org) for fish, and from various sources, all consolidated in SeaLifeBase (www.sealifebase.org) for invertebrates. The range maps were all revised for the catch allocation used here (see Close *at al.* 2006; www.seaaroundus.org). Also, a new procedure, which we call 'demersal creep', was implemented which accounts (only in demersal taxa, generally caught by trawling) for the fact that when exploitation is light (and catches low), only the

near-shore part of the distribution is fished, with the fraction of the distribution range covered increasing ratchet-like when catches increase, up to the entire distribution being covered when the catch reaches its maximum (and remaining there when catches subsequently decrease).

3) Combine the landings reported by various countries and species (or higher taxa) with the corresponding distribution range maps, and allocate these landings to spatial cells, subject to fishing access status (does country A fish in the EEZ of country B?), and other constraints (Watson *et al.* 2004). The procedure used here considers where countries have been fishing, which can be in their own waters (or EEZ, since the early 1980s), in the waters (EEZ) of countries to which they have legal access (as documented by access agreements), or to which they have traditional or illegal access (as documented by other sources). The allocation procedure thus uses a large database of access agreements, which grew from a smaller database called FARISIS (FAO 1999), which was kindly made available by FAO to the Sea Around Us Project. Published or online reports of countries observed fishing in the waters of other countries, even without any known access agreements, were also considered and incorporated in the access agreement database.

4) When under these rules the landings of a given taxon reported by a given country cannot be allocated to its own waters (because that taxon does not occur there), or to the waters of other countries (because no access agreement is known, nor is it known to fish there traditionally or illegally), the case is investigated until resolution is found.

5) Once the landings by species is allocated to ½ degree lat.-long. spatial cells and the landings reported by different countries are thus reassigned to the ecosystem(s) from which they originated, a procedure is implemented which attempts to reduce the fraction of the reported landing assigned to the 'miscellaneous fish' category. These miscellaneous fish, particularly abundant in reports from tropical developing countries and from China, make it extremely difficult to understand what happens to the underlying stocks. The procedure used for this, which relies on a set of simple heuristics, does not affect total catch levels. Rather, it only reassigns fish from the 'miscellaneous fish' category to some of the identified taxa already reported by either the country itself or its neighbors. As presently implemented, these rules disaggregate > 50 % of the reported 'miscellaneous fish' landings of the world (R. Watson, Sea Around Us Project, August 2007, unpublished data).

These steps, though they typically do not modify the reported landings by FAO statistical areas, produce a radically different view of landings at the level of the EEZ of individual countries. Thus, in the Mauritanian EEZ, for example, which is a component of the Canary Current LME, the landings derived from this procedure are much higher than suggested by looking at the FAO data for Mauritania because we 'put back' into the Mauritanian EEZ fish that was landed in other countries, but which was caught in Mauritanian waters (Watson *et al.* 2005). Another feature of Mauritanian landings (and of landings elsewhere in the world) is that since 2007, they do not include the ex-USSR, even for the period from 1950-1991, when its fleets were active through the oceans. This is so because we have retroactively re-assigned ex-USSR catches to its components maritime republics (Estonia, Georgia, Latvia, Lithuania, Russian Federation and Ukraine), based on their relative reported landings in the first years of the post-dissolution period, and rules about who tended to fish where (Zeller & Rizzo). Thus, we show Russian, Estonian, etc. catches from 1950 onward. However, their sum, it must be stressed, still adds up to the FAO catch for the ex-USSR. An analogous procedure was used for the relevant components of the former Yugoslavia, i.e., Croatia, Slovenia and Montenegro (Rizzo & Zeller).

Our procedure was recently tested independently by Gascuel (2007), who found that our approach approximates well the values that would have been generated by Mauritania, were it to also report the landings by all the distant water fleets operating in its EEZ.

Figure 1 shows the landings, by species for all LMEs in the world. Since this graph is normalized to show the 11 most abundant species (with the remainder pooled into 'mixed group'), and not many species are globally important, this graph exhibits more 'mixed group' landings (as 12th category) than typically occur in any specific LME. Also, it will be noted that LMEs account for the overwhelming part of the world catch, i.e., between 76% (1990) and 91% (1968) of global catch. However, the average contribution of LME catches appears to have slightly declined over time, from around 89-90% in the early decades to around 78-81% for recent time periods. Indeed, the only major group not caught primarily in LMEs is represented by large pelagic fishes, primarily tunas.

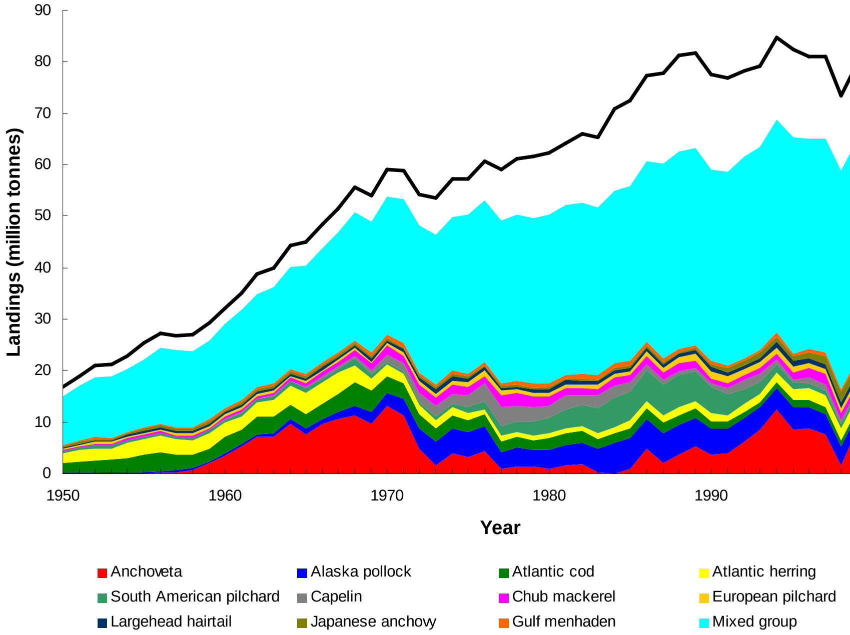


Figure 1. Landings by species in all LMEs (colored time series), and in the world ocean (black line). As this graph individually identifies only the 11 species with the highest global catch (with the remainder pooled into 'mixed group'), this graph exhibits more 'mixed group' landings (as 12th category) than reported from any specific LME. The only major group not caught primarily in LMEs is large pelagic fishes, primarily tunas. Our website (www.seaaroundus.org) also presents catches by 'Commercial groups' (as used in Figure 2), 'Functional Groups, as used in Ecopath models (see www.ecopath.org), 'Country fishing', and 'Gear', based on Watson *et al.* (2006).

In addition to the catch by species, the website of the Sea Around Us Project presents, for all but the six Arctic LMEs located fully in FAO Area 18 (see section 'Catch graphs for Arctic LMEs in FAO Statistical Area 18' below), catches by 'Commercial groups' (as used in 'Graph 2', see below), 'Functional groups, as used in Ecopath models (see www.ecopath.org), 'Country fishing' (not to be mistaken for the PPR by, or footprint of countries, see Graph 3 below), and 'Gear', based on Watson *et al.* (2006a, 2006b).

Graph 2 - Value of reported landings by major commercial groups, per LME

Fishing is an economic operation and the ex-vessel value of the landings has to cover all fixed and variable costs of fishing and still generate a profit, except when fisheries are subsidized (Sumaila & Pauly 2006). To be able to evaluate the ex-vessel value of fisheries worldwide, a database of ex-vessel fish price data was constructed, based on 1) observed prices in different countries at different times for different species; and 2) inferred prices, based on observed prices and an averaging algorithm which took taxonomic affinity, adjacency of countries and time into account (Sumaila *et al.* 2007). As observed prices were available for the most important commercial species, the inferred prices have little influence on the total value of landings from any LME fishery.

The year-, species- and time-specific prices in the database were then adjusted for inflation to year 2000 real prices in US$, using consumer price index (CPI) data from the World Bank, and multiplied by the spatially allocated landings for the corresponding years and species (groups). This yielded time series of the value of fisheries landings in year 2000 inflation adjusted prices, which can be compared in time and space (Sumaila *et al.* 2007), and which, in the aggregate, match, for example, estimates of the ex-vessel values of fisheries catches produced by the OECD.

Here we present graphs of reported landing value by 'Commercial groups', to facilitate comparison between LMEs which may not share species. This may also facilitate their interpretation by readers who do not know biological details on the various species caught in different LMEs, but know market categories. Again, we stress that all values presented here are based on real 2000 prices, i.e., deflated nominal prices (Sumaila *et al* 2007). Figure 2 shows the value by major commercial groups of reported landings in all LMEs of the world. As might be seen, LMEs account for most of the value of marine fisheries catches in the world with values ranging from 71-90% of global landings value. However, this is a slightly smaller fraction than for catch biomass, as many of the offshore fishing grounds for extremely valuable tunas are not included in LMEs.

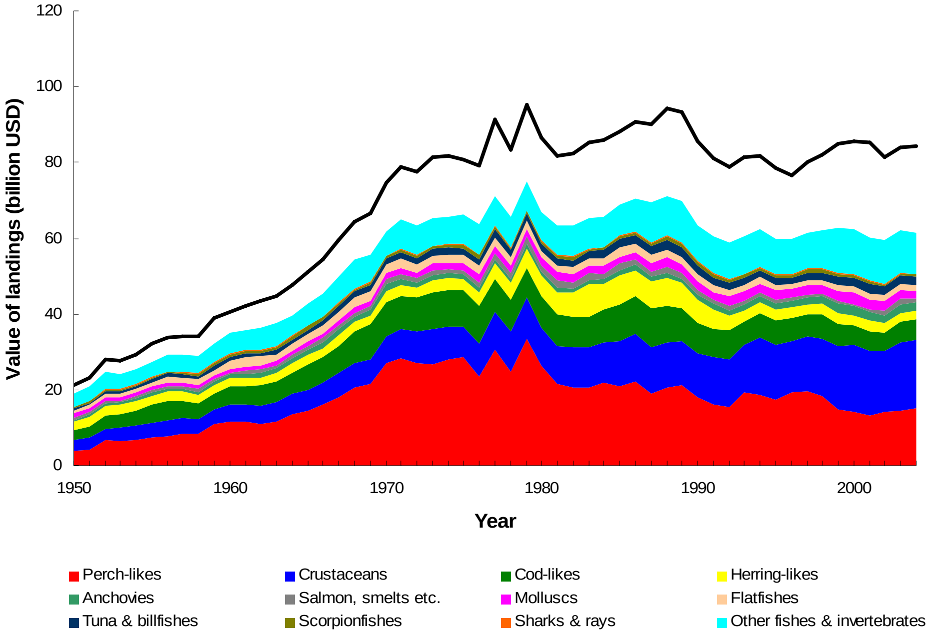


Figure 2. Ex-vessel value of reported landings in all LMEs of the world, by 'Commercial groups' (colored time series), with the value of the global marine catch also added (black line). All values presented are based on real 2000 prices, i.e., deflated prices (Sumaila *et al.* 2007).

Graph 3 – Primary production required to sustain fisheries within LMEs

Footprint analysis consists essentially of expressing all human activities in terms of the land area required for generating products that are consumed by us, or for absorbing the waste generated in the course of supplying these products. Numerous conversion tables exist which allow footprint analysis, for example for producing crops, or absorbing carbon emissions, and these are being used to account for the human impact on ecosystems in standardized fashion (Wackernagel & Rees 1996). Also important to the footprint concept is that, generally, they are expressed in relative terms, i.e., in terms of the surface area of a country. Thus, a country which has a footprint exceeding its surface area relies on resources from other countries. The footprint concept, and conversion tables which are used to implement it, are, however, tied to land areas. There has been to date no published application of this concept to LMEs.

Here, we present extensions of the footprint concept to LMEs. However, the productivity of a given area of ocean is determined by the local primary production, which can vary tremendously over small distances, depending on local mixing processes (Longhurst 2007). Thus we shall not consider the surface area of LMEs, but their average primary production as reference for footprint analysis; hence the concept of Primary Production Required (PPR) (Christensen & Pauly 1993) used here.

The Primary Production Required (PPR) by fisheries landings is a function of the trophic level of the fishes that are caught. Thus, far more primary production is required to produce one tonne of a high-level trophic fish, for example tuna, than a tonne of a low level- trophic fish, for example sardine. This is because the transfer efficiency between trophic levels in the ocean is relatively low, estimated at 10 % on the average (Pauly & Christensen 1995). Thus, to calculate the primary production that was required to produce a given tonnage of fish, we need the average trophic level of the fish in question, an assumption about trophic efficiency (here 10%) and the equation $PPR = \text{landings} \cdot 10^{(TL-1)}$ (Christensen and Pauly 1995).

The landings data used to estimate footprints are those presented above. PPR is calculated separately for each species (or group of species) for the fleets of all countries operating in the LME in question, expressed in terms of the primary production in that LME. The combined footprint of different countries fishing in a given LME area can thus be assessed. To facilitate comparisons between LMEs, the ‘maximum fraction’ (of PPR, in terms of primary production in each LME) is also shown. It is computed as the mean of values for the five years with the highest PPR value.

The primary production data used here refer to the average from October 1997 to September 1998 and will not be representative of observed primary production in specific years, nor of the average primary production from 1950 to 2004 in each LME. While this may cause some errors, there is no reason to believe it should cause any systematic bias, and we consider it warranted to use the PPR measure for comparisons between LMEs. Thus the low level of relative PPR in Australian LMEs compared with the high values in the north Atlantic is likely not an artifact, nor will the relative contribution of various countries’ fleets to the overall footprint within a given LME be an artifact.

On the other hand, extremely high values of PPR (above a fraction of 0.5) point at serious problems, including:

1) The assumptions and data used for implementing the method itself (i.e., the use of one year’s worth of SeaWifs global remote sensing data as a proxy for primary production for all years from 1950 to 2004, everywhere);
2) Over-reported landings;

3) Extensive range extension in periods of peak abundance, e.g., in Japanese sardine (Watanabe *et al.* 1996), or migration of targeted species, especially feeding migrations, extending beyond the limits of an LME;
4) High reported landings from exploitation of accumulated biomass, rather than exploitation of annual surplus production.

Which of these problems is likely to apply is indicated in the LME-specific chapters. By way of generalization, however, we may mention here that (2) tends to occur in East Asian LMEs (Watson & Pauly 2001), (3) in the Kuroshio LME, and some of the smaller LMEs of the North Atlantic, and (4) with regard to Atlantic cod in the Northwest Atlantic in the earlier periods. The problem in (1), on the other hand, occurs throughout the world. However, it is not likely to be the cause of the geographic pattern just mentioned.

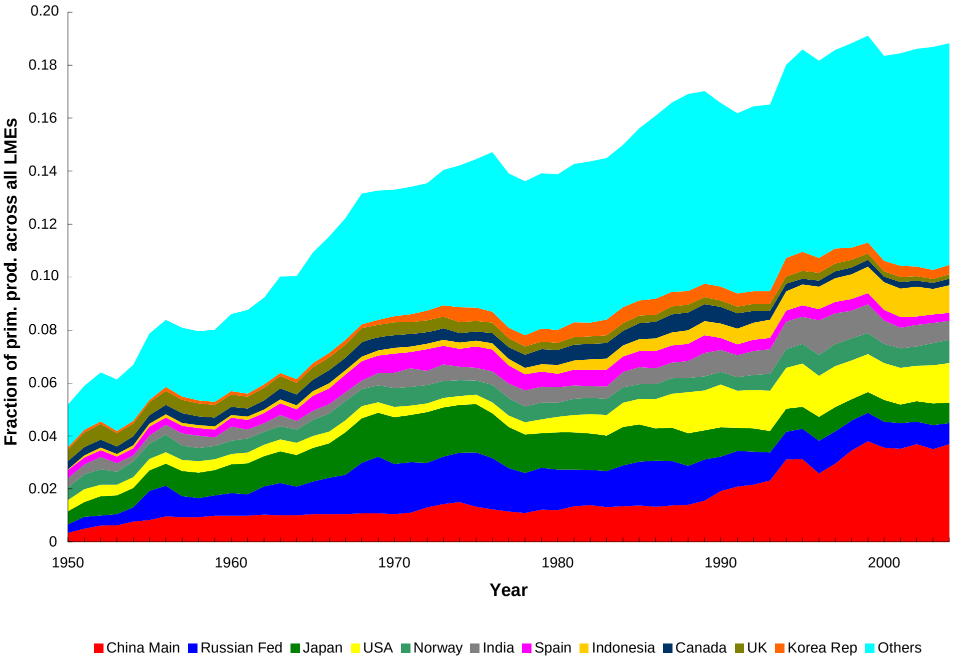


Figure 3. Primary Production Required (PPR; Pauly & Christensen 1995) to sustain fisheries in the 57 most important LMEs of the world, an expression of their 'footprint' (Wackernagel & Rees 1996). PPR is calculated separately for each species (or group of species) caught by the fleets of all countries operating in a LME (or here: in 57 of 64 LMEs). The 'maximum fraction' (of PPR, in terms of primary production in each LME) is computed as the mean of values for the five years with the highest PPR value.

Figure 3 shows the fraction of primary production required to sustain the landings reported by countries fishing within 57 LMEs of the world, as fractions of their combined primary production. (The Arctic LMEs exclusive to FAO Area 18 are not included here, due to their small catches and variable ice-free zones). The fraction of primary production required has increased steadily over the years, in line with increasing reported landings, and is approaching 20%. In recent years, the countries with the largest footprint in all LMEs combined were China, USA and Indonesia, with China outpacing all others (even with correction of over-reporting of landings, Watson & Pauly 2001).

Graph 4 – The Marine Trophic Index and the FiB index, by LME

When a fishery begins in a given area, it usually targets the largest among the accessible fish, which are also intrinsically most vulnerable to fishing (Cheung *et al*. 2007). Once these are depleted, the fisheries then turn to less desirable, smaller fish. This pattern has been repeated innumerable times in the history of humankind (Jackson *et al.* 2001) and also since the 1950s, when landing statistics began to be collected systematically and globally by FAO.

With a trophic level assigned to each of the species in the FAO landings data set, Pauly *et al* (1998) were able to identify a worldwide decline in the trophic level of fish landings. This phenomenon, now widely known as ‘fishing down marine food webs’, has been since shown to be ubiquitous when investigated on a smaller scale, e.g., in countries such as Greece (Stergiou & Koulouris 2000) or subdivisions of large countries, e.g. India (Bhathal 2005). This ubiquity of fishing down is one of the reasons why the Convention on Biological Diversity (CBD) adopted the mean trophic level of fisheries catch, which it renamed Marine Trophic Index (MTI) as one of eight biodiversity indicators for “immediate testing” (CBD 2004, Pauly & Watson 2005).

Diagnosing fishing down the food web from the mean trophic level of landings is problematic, however. Landings reflect abundances only crudely. Also, a fishery that has overexploited its resource base, e.g., on the inner shelf, will tend to move to the outer shelf and beyond (Morato *et al.* 2006). There, it accesses hitherto unexploited stocks of demersal or pelagic fish, and the MTI calculated for the whole shelf, which may have declined at first, increases again, especially if the ‘new’ landings are high. Thus, at the scale of an LME, a trend reversal of the MTI may occur when the fisheries expand geographically. This is the reason why the diagnosis as to whether fishing down occurs or not, performed for many of the LMEs in this volume, generally depends on the species composition of the landings, which may indicate whether a geographic expansion of the fishery has taken place.

To facilitate this evaluation, a time series of the Fishing-in-Balance (FiB) index is also presented for each LME. Pauly *et al.* (2000) defined the FiB index such that its value remains the same when a downward trend in mean trophic level is compensated for by an increase in the volume of ‘catch’, as should happen given the pyramidal nature of ecosystems and the transfer efficiency of about 10% between trophic levels alluded to above.

The FIB index will decline, obviously, when both the MTI and landings decline, as now happens, unfortunately, in many LMEs. On the other hand, the FIB index will increase if landings increases more than compensate for a declining MTI. In such cases (and obviously also in the case when landings increases and the MTI is stable or increases), the FiB index increases indicate that a geographic expansion of the fishery has taken place, i.e., that another part of an ecosystem is being exploited (Bhathal & Pauly *in press*). Note that the absolute value of the FiB index can be applied to assess the change of the FiB index from any baseline we like. It is here standardized to have a value of zero in 1950.

Figure 4 presents the trophic level and FIB index for all LMEs combined, but with Peruvian anchoveta (*Engraulis ringens*) and large pelagic fishes (large tunas and billfishes) excluded. The very localized fishery for Peruvian anchoveta, a low trophic level species, is the largest single-species fishery in the world, and it exhibits extreme fluctuations in landings (see Figure 1, top, and Chapter XVII-56 Humboldt Current LME), which mask the comparatively more subtle patterns in trophic level changes by the rest of the world's fisheries. The reason for excluding large tunas and billfishes is that much of their catch is taken in pelagic waters outside of the currently defined LMEs. Thus, the inclusion of these landings from only part of their stock-exploitation ranges would artificially inflate trophic level patterns, especially in recent decades, where the tuna fisheries expanded tremendously (Pauly and Palomares 2005). The trend in mean trophic level for all LMEs combined (Figure 4, top) indicates a decline in the MTI from a peak in the 1950s to a low in the mid 1980s. This is attributed to 'fishing down marine food webs' (Pauly et al. 1998, Pauly and Watson 2005), attenuated by an offshore expansion of the fisheries (Figure 4, bottom, and see Morato *et al.* 2006). In the mid 1980s, the continued offshore expansion, combined with declining inshore catches led to a trend reversal in the MTI, i.e., to the fishing down effect being completely occulted. Analyses at smaller scales (i.e., as documented in the LME-specific chapters, or in smaller-scale studies, see above) confirm this.

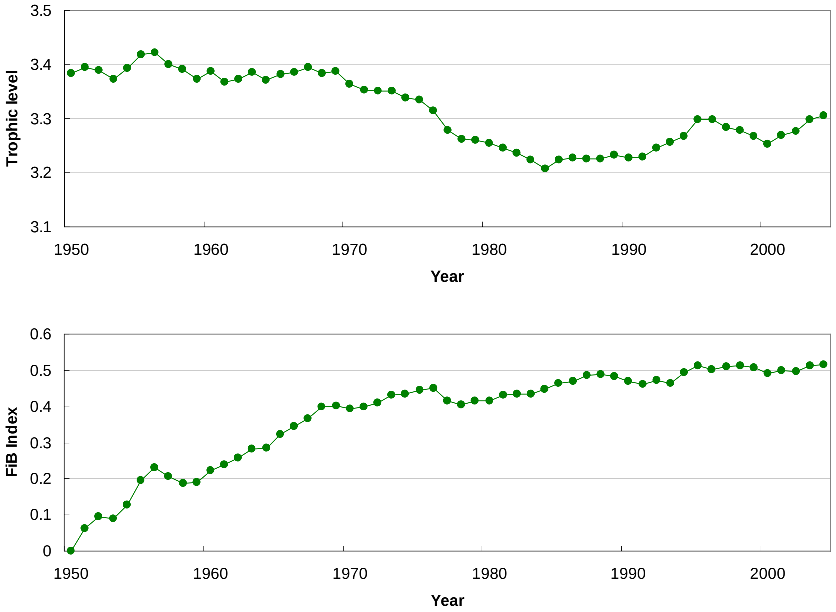


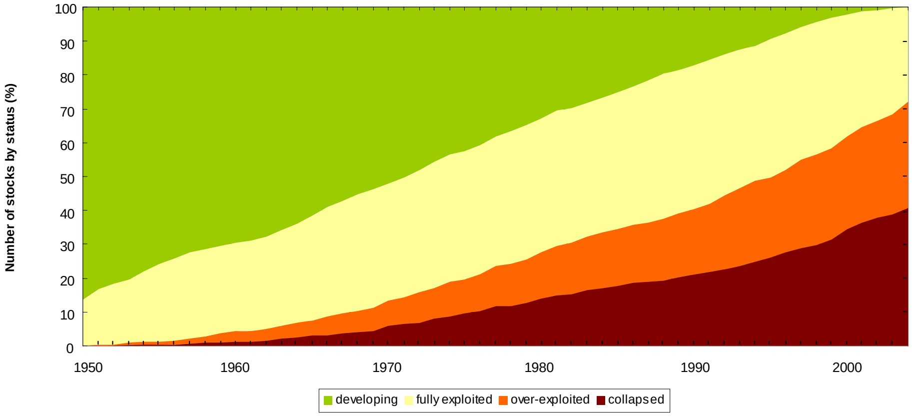
Figure 4. Two indicators based on the trophic levels (TL) of exploited fish, used to characterize the fisheries in the LMEs of the world. Top: trend of mean TL, indicating 'fishing down marine food webs', recently masked by offshore expansion of the fisheries (Pauly *et al.* 1998, Pauly & Watson 2005). Bottom: corresponding trend of the Fishing-in-Balance (FiB) index, which is defined such that its increase in the face of stagnating or increasing MTI suggests a geographic expansion of the fisheries (see text and Bhatal & Pauly, *in press*).

Graph 5 – Stock-Catch Status Plots, by LME

These graphs have their origin in the work of Granger & Garcia (1996), who fitted time series of landings of the most important species in the FAO database with high-order polynomials, and evaluated from their slopes whether the fisheries were in their 'developing', 'fully utilized' or 'senescent' phases. Froese & Kesner-Reyes (2002) simplified these graphs by defining for any time series, five phases relative to the maximum reported landing in that time series, representing a 'stock'. They are:

- **Undeveloped**: Year of landing is before the year of maximum landing, and landing is less than 10% of the overall maximum;

- **Developing**: Year of landing is before the year of maximum landing, and landing is between 10 and 50 % of the overall maximum;
- **Fully exploited**: Landing is greater than 50% of maximum year's landing;
- **Overexploited**: Year of landing is after year of maximum landing, and landing is between 10 and 50% of the overall maximum; and
- **Collapsed**: Year of landing is after the year of maximum landing, and landing is below 10% of the overall maximum.



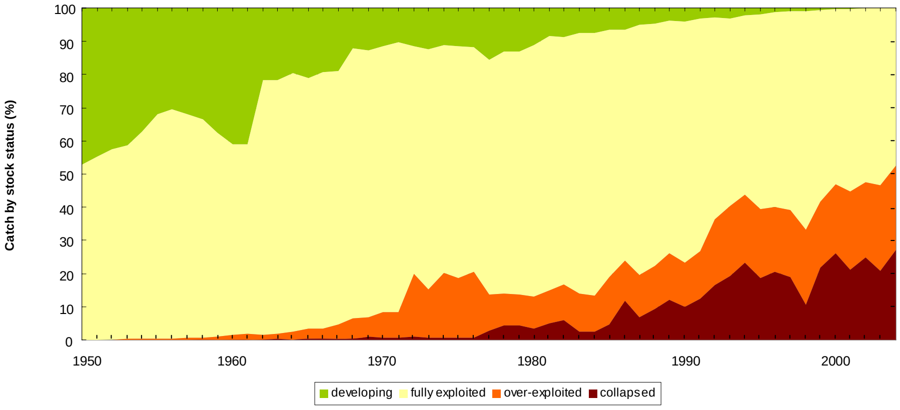


Figure 5. A newly proposed type of paired 'Stock-Catch-Status Plots' (here presented for all LMEs in the world), wherein the status of stocks, i.e., species with a time series of landings in an LME, is assessed, based on Froese & Kesner-Reyes (2002), using the following criteria (all referring to the maximum catch in the series): Developing (catches < 50 %); Fully exploited (catches >= 50%); Overexploited (catches between 50% and 10%); Collapsed (catches < 10%). Top: Percentage of stocks of a given status, by year, showing a rapid increase of the number of overexploited and collapsed stocks. Bottom: Percentage of catches extracted from stocks of a given status, by year, showing a slower increase of the percentage of catches that originate from overexploited and collapsed stocks. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded.

The fisheries in a given area can then be diagnosed by plotting time series of the fraction of 'stocks' in any of these categories (Froese & Kesner-Reyes, 2002). Such graphs were used in a paper by Froese & Pauly (2004) documenting the state of the North Sea LME. This method of diagnosis suggests that the number of collapsed stocks (as defined in Figure 5) is increasing alarmingly throughout the world, as can be seen in the LME-specific 'Stock-Catch Status Plots' included in this book. Here, a 'stock' is defined as a time series of one species, genus or family for which the first and last reported landings are at least 10 years apart, for which there are at least 5 years of consecutive catches and for which the catch in a given LME is at least 1000 tonnes.

Here, we propose a variant of what may be called ‘stock number by status plots’: a ‘catch by status plot’, defined such that it documents, for a series of years, the fraction of the reported landings biomass that is derived from stocks in various phases of development (as opposed to the number of such stocks). As might be seen in Figure 5, such a plot of relative ‘catch’ by status (lower panel) is quite different from the stock number by status plots (upper panel). We call the combination of these two plots ‘Stock-Catch-Status Plots’ (Figure 5).

Figure 5 illustrates the dual nature of the newly derived Stock-Catch Status Plots, for all LMEs in the world combined. It illustrates that, overall, 70 % of global stocks within LMEs are deemed overexploited or collapsed, and only 30% fully exploited (Figure 5, top). However, the latter stocks still provide 50% of the globally reported landings biomass, with the remainder produced by overexploited and collapsed (Figure 5, bottom). This confirms the common observation that fisheries tend to affect biodiversity even more strongly than they affect biomass.

Catch graphs for Arctic LMEs in FAO Statistical Area 18

The Arctic, generally defined as the area within the 10^o Celsius summer isotherm, has about four million human inhabitants. FAO Statistical Area 18, ranging from Novaya Zemlya in the west to the Hudson Bay in the east, is comprised of the Siberian coast (Russia), the Arctic coast of Alaska (USA), the Arctic coast of Canada, and parts of the northern coast of Greenland, or about two-third of what is generally defined as the Arctic. FAO Area 18 is also an area with extremely low fish catches. However, landings are not as low as the FAO data from that area would have it, and the negligible (often zero) catches officially reported from this area are mainly the result of Russia, the USA and Canada not reporting adequately on the small-scale fisheries in their section of the Arctic. This obviously affects the seven LMEs presently defined for this area, i.e., from west to east, the Kara, Laptev, East Siberian, Chukchi and Beaufort Seas, Hudson Bay, and the large Arctic LME (soon to be differentiated into [Canadian] Arctic Archipelago, Baffin Bay/Davis Strait as ‘new’ Arctic LMEs). Six of these seven LMEs are located entirely within FAO Area 18, while the Arctic LME has substantial coverage also in FAO Areas 21 (NW Atlantic) and 27 (NE Atlantic).

Thus, to complete our coverage of the world’s LMEs, and to produce a baseline against which future fisheries development in the Arctic can be assessed, the Sea Around Us Project undertook a reconstruction of catch time series for FAO Area 18. We present here key results from this work on northern Siberia (Pauly & Swartz *2007*) and Arctic Canada (Booth & Watts *2007*), and from an ongoing study on Arctic Alaska (S. Booth and D. Zeller, Sea Around Us Project, unpublished data). These results are summarized, for the Arctic LMEs, in Table 1 and Figure 6, and are presented individually in their respective chapters.

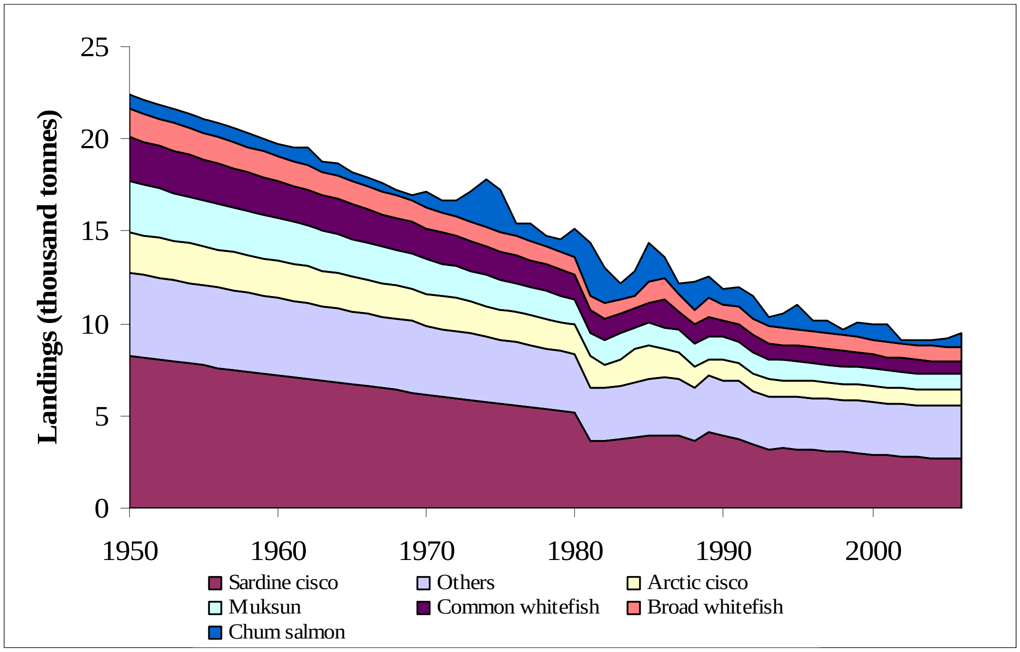


Figure 6. Estimated catches from the six LMEs fully comprised within FAO Statistical Area 18, and based on Pauly & Swartz (*2007*), Booth & Watts (*2007*) and Booth & Zeller (unpubl. data). These conservative estimates of (small-scale fisheries) catches are considerably higher than reported by FAO for the same area, an extreme case of the tendency, by FAO member countries, of underreporting the catches of their small-scale fisheries (see also Zeller *et al.* 2006, 2007).

Because the catches in Figure 6 are usually not destined for commercial markets, and relatively small, we abstain here from presenting their ex-vessel value, and indeed, from deriving any catch-based indicators (MTI, PPR, etc). Consequently, the LME-specific accounts do not include graphs illustrating catch-based indicators, either.

Table 1: Estimated average annual catches (1950-2004) and major taxa for LMEs within FAO Statistical Area 18, arranged from west to east.

LME	**Average catch (tonnes·year^{-1})**	**Major taxa**
Kara Sea	7,239	*Coregonus sardinella*, *C. lavaretus*, *C. nasus*
Laptev Sea	3,667	*Coregonus sardinella, C. autumnalis, C. muksun*
East Siberian Sea	2,717	*Coregonus nasus, C. sardinella, C. autumnalis*
Chuckchi Sea	1,727	*Oncorhynchus keta*, *Coregonus* spp., *Stenodus leucichthys*
Beaufort Sea	127	*Coregonus* spp., *Stenodus leucichthys, Clupea pallasii*
(Canadian) Arctic Sea[1]	1,066	*Salvelinus alpinus*, Gadidae, *Salmo salar*
Hudson Bay	484	*Salvelinus alpinus,* Gadidae, *Salmo salar*

[1] These data apply only to that part of the currently defined Arctic LME that comprises the (Canadian) Arctic Archipelago, and are not included in Figure 6. These data exclude the much higher catches from the Arctic LME areas within FAO areas 21 (Baffin Bay, Davis Strait) and 27 (NE Atlantic waters).

Discussion

Traditionally, the local and sectoral focus of fisheries science, monitoring and management has precluded the development and use of indicators at large spatial scales. With the advent of ecosystem-based concerns and concepts such as the Large Marine Ecosystems (Sherman *et al.* 2003), it has become evident that such indicators will be needed for better integration of fisheries in ecosystem-based management approaches.

However, existing national and international institutions, due to their historic sectoral, local and national focus, are not in a position to report fisheries information, i.e., catches, their values and associated indicators at an ecosystem level, such as LMEs. In contrast, the Sea Around Us Project was specifically established to assess the impacts of fisheries at an ecosystem level. We therefore developed tools and concepts to present available fisheries data via ½ degree lat.-long. spatial cells, allowing consideration of various spatial scales, such as LMEs. It is this 'place'-based, rather than sector-based approach which allows us to document fisheries impacts at the scale of LMEs. We have also derived a standard set of indicators and graphical representations, presented here on a global scale (i.e., for all currently defined LMEs combined). They are presented in LME-specific format in the various chapters of this book, and as well, through our website (www.seaaroundus.org).

The five types of graphs presented here allow comprehensive overviews of the general status of fisheries and ecosystem of each LME, as they account for the characteristics of fisheries, biology and ecology of the exploited species and ecosystem. Catch and catch values indicate status and trends of the fisheries, e.g., through changes in species composition and catches. These relate strongly to the status of stocks in the LME, as indicated by the Stock-Catch Status Plots developed here. Changes in fisheries and stock status have direct impacts on the ecosystem which can be indicated by the MTI and FiB. These also determine the footprint of fisheries – an indicator of sustainability, as shown here through the Primary Production Required by fisheries within LMEs.

All of these indicators require accurate and complete catch data. Such catch data, however, are not available for all LMEs. The methods we use for re-expressing FAO's global reported landings dataset on a spatial basis, here through LMEs, cannot compensate for these limitations. Rather, it makes them visible, and emphasizes the need for catch reconstruction at the national level (*sensu* Zeller *et al.* 2006, 2007), from which LME catch time series can then be derived. This was here specifically illustrated by reconstructed catch time series from Northern Siberia (Russian Federation), Arctic Alaska (USA), and parts of Arctic Canada, with the help of which the fisheries of six arctic LMEs could be characterized for the first time. In the next years, the Sea Around Us Project, working in close collaboration with national scientists, will radically expand its coverage of countries with reconstructed catches, to overcome the data problems highlighted in the LME-specific chapters. Also, we will expand our list of indicators, and include several that do not rely on catch trends, but on biomass (or catch/effort) trends, which are far more informative.

The LME framework, populated with relevant and current catch and related fisheries data, is set to provide the information needed to develop policies for ecosystem-based fisheries management. It provides a neutral platform for jurisdictions (national and sub-national) to come together to discuss resource management issues as a single ecological unit and look at the consequences of policies, irrespective of boundaries. This information will also provide guidance on information gaps (e.g., spatial effort data) and areas for research (e.g., large scale fisheries-independent biomass estimation), so that ecosystem based management of fisheries and marine areas can be strengthened in many of the world's coastal regions.

The LME system can also enhance the global assessments of marine areas and resources. Until now, large-scale assessments have primarily focused on ocean basins (Pauly *et al.* 2005) or FAO Statistical Areas (Pauly *et al.* 1998, Alder *et al. 2007*). However, these are large areas, and the important differences needed for developing policy can be lost in such a large scale management unit. Assessments based on LMEs can give much better resolution. LME units also lend themselves to ecosystem modeling software such as Ecopath with Ecosim (EwE), which can be used to simulate developments scenarios (Christensen & Walters 2004). Recent experience with EwE and FAO Statistical Areas as modelling units has highlighted that these areas are too large for meaningful treatment (Alder et al. 2007). For example, FAO area 21 includes the Barents Sea and the North Sea, which are strongly divergent ecosystems in terms of structure and fisheries (Alder *et al*. 2007*)*. LMEs do not have this problem. Also, they can be interfaced with other spatial entities, e.g., 'ecoregions' (Spalding *et al.* 2007), i.e., with smaller scale systems defined in terms of their biodiversity.

Thus, the present volume presents globally, and for the first time, comprehensive fisheries data and indicators assembled at a large spatial ecosystem scale, namely for all 64 currently defined Large Marine Ecosystems.

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Accelerated Warming and Emergent Trends in Fisheries Biomass Yields of the World's Large Marine Ecosystems

K. Sherman, I. Belkin, K.D. Friedland, J. O'Reilly and K. Hyde

Introduction

The heavily exploited state of the world's marine fisheries has been well documented (FAO 2004; Garcia and Newton 1997; González-Laxe 2007). Little, however, is known of the effects of climate change on the trends in global fisheries biomass yields. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change stated with "high confidence" that changes in marine biological systems are associated with rising water temperatures affecting shifts in pelagic algae and other plankton, and fish abundance in high latitudes (IPCC 2007). The Report also indicated that adaptation to impacts of increasing temperatures in coastal systems will be more challenging in developing countries than in developed countries due to constraints in adaptive capacity. From a marine resources management perspective, the 8 regions of the globe examined by the IPCC (i.e. North America, Latin America, Europe, Africa, Asia, the Australia and New Zealand region and the two Polar regions), are important fisheries areas but at a scale too large for determination of temperature trends relative to the assessment and management of the world's marine fisheries biomass yields produced principally in 64 large marine ecosystems (LMEs) (Figure 1). These LMEs, in coastal waters around the globe, annually produce 80% of the world's marine fisheries biomass (Figure 2).

Large Marine Ecosystems are areas of an ecologically based nested hierarchy of global ocean biomes and ecosystems (Watson et al. 2003). Since 1995, LMEs have been designated by a growing number of coastal countries in Africa, Asia, Latin America, and eastern Europe as place-based assessment and management areas for introducing an ecosystems approach to recover, develop, and sustain marine resources. The LME approach to the assessment and management of marine resources is based on the operationalization of five modules, with suites of indicators for monitoring and assessing changing conditions in ecosystem: (i) productivity, (ii) fish and fisheries (iii) pollution and ecosystem health, (iv) socioeconomics, and (v) governance (Duda and Sherman 2002). The approach is part of an emerging effort by the scientific community to relate the scale of place-based ecosystem assessment and management of marine resources to policy making and to tighten the linkage between applied science and improved management of ocean resources within the natural boundaries of LMEs (COMPASS 2005; Wang 2004).

Since 1995, international financial organizations have extended explicit support to developing coastal countries for assessing and managing goods and services using the modular approach at the LME scale. At present, 110 countries are engaged in LME projects along with 5 UN agencies and $1.8 billion in financial support from the Global Environment Facility (GEF) and the World Bank. Sixteen LME projects are presently focused on introducing an ecosystems approach to the recovery of depleted fish stocks, restoration of degraded habitats, reduction and control of pollution, conservation of biodiversity, and adaptation to climate change. In recognition of the observational evidence of global warming from the 4th Assessment Report of the (IPCC 2007) and the lack of information on trends in global warming at the LME scale where most of the world's marine fisheries biomass yields are produced, we undertook a study of the physical extent and rates of sea surface temperature trends in relation to fisheries biomass yields and SeaWiFS derived primary productivity of the world's LMEs.

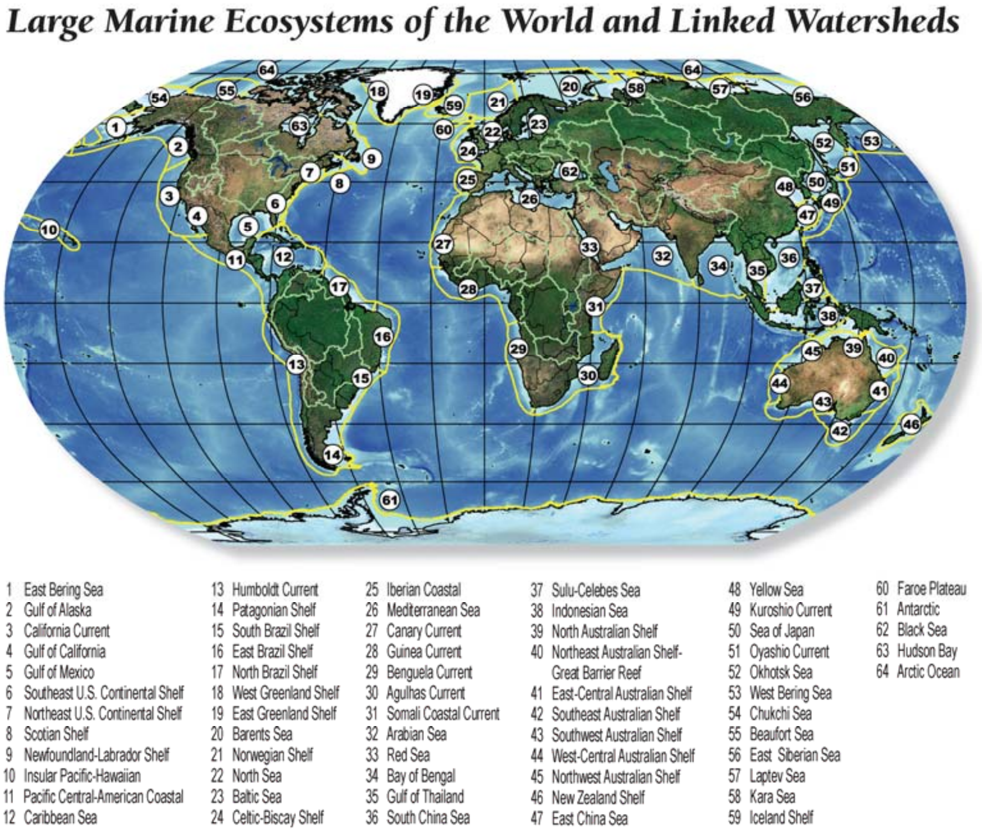


Figure 1. Large Marine Ecosystems of the World

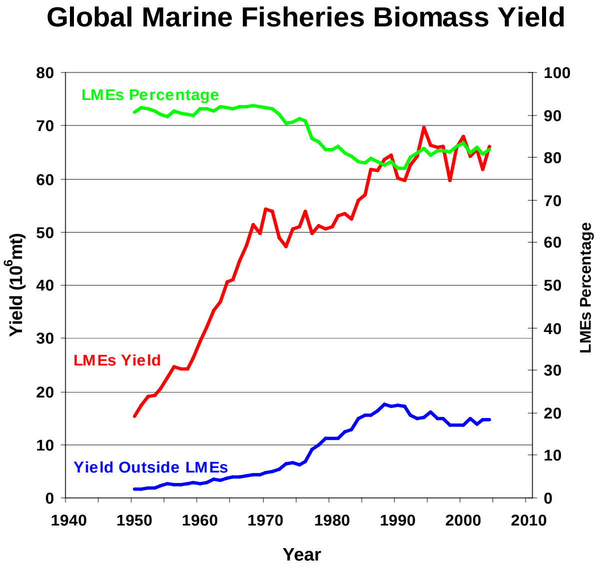


Figure 2. **Annual global marine fisheries biomass yields in metric tons of the world's LMEs. From the University of British Columbia's Sea Around us Project (SAUP).**

METHODS

Fisheries biomass yields are not presented here as representative of individual fish stock abundances. They are representative of fisheries catches and are used here to compare the effects of global warming on the fishery biomass yields of the World's LMEs. The comparative analysis of global temperature trends, fisheries biomass yields, and primary productivity is based on available time-series data at the LME scale on sea surface temperatures, marine fisheries biomass yields, and Sea WiFS derived primary productivity values.

LME Sea Surface Temperatures (SST)

Sea surface temperature (SST) data is a thermal parameter routinely measured worldwide. Subsurface temperature data, albeit important, are limited in the spatial and temporal density required for reliable assessment of thermal conditions at the Large Marine Ecosystem (LME) scale worldwide. The U.K. Meteorological Office Hadley Center SST climatology was used in this analysis (Belkin 2009), as the Hadley data set has resolution of 1 degree latitude by 1 degree longitude globally. A detailed description of this data set has been published by Rayner et al. (2003). Mean annual SST values were calculated for each 1° x 1° cell and then were area-averaged by annual 1° x 1° SSTs within each LME. Since the square area of each trapezoidal cell is proportional to the cosine of the middle latitude of the given cell, all SSTs were weighted by the cosine of the cell's middle latitude. After integration over the LME area, the resulting sum of weighted SSTs was normalized by the sum of the weights, that is, by the sum of the cosines. Annual anomalies of annual LME-averaged SST were calculated. The long-term LME-averaged SST was computed for each LME by a simple long-term averaging of the annual area-weighted LME-averaged SSTs. Annual SST anomalies were calculated by subtracting the long-term mean SST from the annual SST. Both SST and SST anomalies were plotted using adjustable temperature scales for each LME to depict temporal trends. Comparisons of fisheries biomass yields were examined in relation to intervals of 0.3°C of increasing temperature.

LME Primary Productivity

The LME primary productivity estimates are derived from satellite borne data of NOAA's Northeast Fisheries Science Center, Narragansett Laboratory. These estimates originate from SeaWiFS (satellite-derived chlorophyll estimates from the Sea-viewing Wide Field-of-view Sensor), Coastal Zone Color Scanner (CZCS), a large archive of *in situ* near-surface chlorophyll data, and satellite sea surface temperature (SST) measurements to quantify spatial and seasonal variability of near-surface chlorophyll and SST in the LMEs of the world. Daily binned global SeaWiFS chlorophyll *a* (CHL, mg m^{-3}), normalized water leaving radiances, and photosynthetically available radiation (PAR, Einsteins m^{-2} d^{-1}) scenes at 9 km resolution for the period January 1998 through December 2006 were obtained from NASA's Ocean Biology Processing Group. Daily global SST (^{o}C) measurements at 4 km resolution were derived from nighttime scenes composited from the AVHRR sensor on NOAA's polar-orbiting satellites and from NASA's MODIS TERRA and MODIS AQUA sensors. Daily estimates of global primary productivity (PP, gC m^{-2} d^{-1}) were calculated using the Ocean Productivity from Absorption and Light (OPAL) model, a derivative of the model first formulated in Marra et al. (2003). The OPAL model generates profiles of chlorophyll estimated from the SeaWiFS chlorophyll using the algorithm from Wozniak et al. (2003) that uses the absorption properties in the water column to vertically resolve estimates of light attenuation in approximately 100 strata within the euphotic zone. Productivity is calculated for the 100 layers in the euphotic zone and summed to compute the integral daily productivity (gC m^{-2} d^{-1}). Monthly and annual means of primary productivity (PP) were extracted and averaged for each LME. Significance levels (alpha=0.01 and 0.05) of the regression coefficients of the nine years of Sea WiFS mean annual primary productivity data were determined using a t-test according to Sokal and Rohfl (1995). Time series trends plotted for each LME are available online (www.lme.noaa.gov).

Fisheries Biomass Yield Methods

Prior to the Sea Around Us Program, projections of marine fisheries yields at the LME scale, were largely defined by the range of vessels exploiting a given resource (Pauly and Pitcher 2000). The need for countries to manage fisheries within EEZ's under UNCLOS initiated efforts to derive fisheries yields at the national level(Prescott-Allen 2001) and consistent with the emergence of ecosystem-based management at the LME scale(Sherman et al. 2003) (Pauly et al. 2008). The time series of fisheries biomass yields (1950-2004) used in this study are based on the time-series data provided at the LME scale by the Sea Around Us Project at the University of British Columbia (Pauly et al. 2008) The method used by the Sea Around Us Project to map reported fishery catches onto 180,000 global spatial cells of ½ degrees latitude and longitude was applied to produce profiles of 54-yr. mean annual time-series of catches (biomass yields) by 12 species or species groups for the world's LMEs (Pauly et al. 2008; Watson et al. 2003). In addition, plots on the status of the stocks within each of the LMEs according to their condition (e.g. undeveloped, fully exploited and overexploited) in accordance with the method of Froese and Kesner-Reyes (2002), and illustrated by Pauly et al. (2008), were used to examine trends in yield condition among the LMEs. Fisheries biomass yields were examined in relation to warming trends for 63 LMEs for the period 1982 to 2004. Fisheries biomass yield trends were plotted for each LME using the LOESS smoothing method (tension=0.5) and the emergent increasing and decreasing patterns examined in relation to LME warming data (Cleveland and Devlin 1988). Observed trends were compared to earlier studies for emergent spatial and temporal global trends in LME fishery biomass yields.

RESULTS

Comparative SST Clusters

The LME plots of SST and SST anomalies are presented in 2 sets of 4 plates, with each set containing a total of 63 figures: four plates for SST and four plates for SST anomalies 1957-2006. These can be viewed at www.lme.noaa.gov. The Arctic Ocean LME was not included in this analysis because of the perennial sea ice cover. Other Arctic LMEs also feature sea ice cover that essentially vanishes in summer, thus making summer SST assessment possible. The 1957-2006 time series revealed a global pattern of long-term warming however, the long-term SST variability since 1957 was not linear over the period. Specifically. most LMEs underwent a cooling between the 1950s and the 1970s, replaced by a rapid warming from the 1980s until the present. Therefore we re-calculated SST trends using only the last 25 years of data (SST data available at www.lme.noaa.gov, where SST anomalies are calculated for each LME. Net SST change in each LME between 1982 and 2006 based on SST trends is summarized in Table 1 (after Belkin 2009).

The most striking result is the consistent warming of LMEs, with the notable exceptions of two, the California Current and Humboldt Current. These LMEs experienced cooling over the last 25 years. Both are in large and persistent upwelling areas of nutrient rich cool water in the Eastern Pacific. The SST values were partitioned into 0.3°C intervals to allow for comparison among LME warming rates. The warming trend observed in 61 LMEs ranged from a low of 0.08°C for the Patagonian Shelf LME to a high of 1.35°C in the Baltic Sea LME (Table 1). The relatively rapid warming exceeding 0.6°C over 25 years is observed almost exclusively in moderate- and high-latitude LMEs. This pattern is generally consistent with the model-predicted polar-and-subpolar amplification of global warming (IPCC 2007). The warming in low-latitude LMEs is several times slower than the warming in high-latitude LMEs (Table 1). In addition to the Baltic Sea, the most rapid

Table 1. SST change in each LME, 1982-2006 (sorted in descending order)

LME#	SST Change (°C) 1982-2006	Slope of Linear Regression (°C/year)	Standard Error of Slope (°C/year)
LME23='BALTIC SEA';	1.35	0.0563	0.0151
LME22='NORTH SEA';	1.31	0.0544	0.0099
LME47='EAST CHINA SEA';	1.22	0.0509	0.0077
LME50='SEA OF JAPAN'/'EAST SEA';	1.09	0.0453	0.0098
LME9='NEWFOUNDLAND-LABRADOR SHELF';	1.04	0.0435	0.0108
LME62='BLACK SEA';	0.96	0.0401	0.0124
LME8='SCOTIAN SHELF';	0.89	0.0370	0.0105
LME59='ICELAND SHELF	0.86	0.0360	0.0091
LME21='NORWEGIAN SEA';	0.85	0.0356	0.0072
LME49'KUROSHIO CURRENT';	0.75	0.0312	0.0062
LME60='FAROE PLATEAU';	0.75	0.0311	0.0078
LME33='RED SEA';	0.74	0.0309	0.0048
LME18='WEST GREENLAND SHELF';	0.73	0.0304	0.0064
LME24='CELTIC-BISCAY SHELF';	0.72	0.0301	0.0076
LME26='MEDITERRANEAN SEA';	0.71	0.0294	0.0055
LME54='CHUKCHI SEA';	0.70	0.0290	0.0087
LME25='IBERIAN COASTAL';	0.68	0.0283	0.0072
LME48='YELLOW SEA';	0.67	0.0279	0.0097
LME17='NORTH BRAZIL SHELF';	0.60	0.0252	0.0049
LME51='OYASHIO CURRENT';	0.60	0.0250	0.0086
LME15='SOUTH BRAZIL SHELF';	0.53	0.0221	0.0068
LME27='CANARY CURRENT';	0.52	0.0217	0.0082
LME12='CARIBBEAN SEA';	0.50	0.0208	0.0050
LME19='EAST GREENLAND SHELF';	0.47	0.0197	0.0074
LME28='GUINEA CURRENT';	0.46	0.0194	0.0063
LME10='INSULAR PACIFIC HAWAIIAN';	0.45	0.0187	0.0056
LME36='SOUTH CHINA SEA';	0.44	0.0182	0.0063
LME53='WEST BERING SEA';	0.39	0.0162	0.0064
LME2='GULF OF ALASKA';	0.37	0.0154	0.0081
LME40='NE AUSTRALIAN SHELF-GREAT BARRIER REEF';	0.37	0.0153	0.0101
LME56='EAST SIBERIAN SHELF';	0.36	0.0149	0.0092
LME41='EAST-CENTRAL AUSTRALIAN SHELF';	0.35	0.0145	0.0056
LME55='BEAUFORT SEA';	0.34	0.0140	0.0066
LME46='NEW ZEALAND SHELF';	0.32	0.0135	0.0105
LME4='GULF OF CALIFORNIA';	0.31	0.0130	0.0069
LME5='GULF OF MEXICO';	0.31	0.0130	0.0161
LME52='SEA OF OKHOTSK';	0.31	0.0129	0.0053
LME16='EAST BRAZIL SHELF';	0.30	0.0126	0.0062
LME63='HUDSON BAY';	0.28	0.0117	0.0076
LME1='EAST BERING SEA';	0.27	0.0113	0.0070
LME32='ARABIAN SEA';	0.26	0.0110	0.0048
LME29='BENGUELA CURRENT';	0.24	0.0100	0.0072
LME34='BAY OF BENGAL';	0.24	0.0098	0.0061
LME38='INDONESIAN SEA';	0.24	0.0098	0.0067
LME45='NORTHWEST AUSTRALIAN SHELF';	0.24	0.0098	0.0049
LME7='NORTHEAST U.S. CONTINENTAL SHELF';	0.23	0.0096	0.0043
LME37='SULU-CELEBES SEA';	0.23	0.0096	0.0125
LME30='AGULHAS CURRENT';	0.20	0.0085	0.0079
LME42='SOUTHEAST AUSTRALIAN SHELF';	0.20	0.0084	0.0042
LME31='SOMALI COASTAL CURRENT';	0.18	0.0074	0.0059
LME39='NORTH AUSTRALIAN SHELF';	0.17	0.0070	0.0068
LME6='SOUTHEAST U.S. CONTINENTAL SHELF';	0.16	0.0067	0.0061
LME35='GULF OF THAILAND';	0.16	0.0067	0.0064
LME58='KARA SEA';	0.16	0.0066	0.0065
LME11='PACIFIC CENTRAL-AMERICAN COASTAL';	0.14	0.0059	0.0101
LME20='BARENTS SEA';	0.12	0.0051	0.0092
LME57='LAPTEV SEA';	0.12	0.0048	0.0088
LME43='SOUTHWEST AUSTRALIAN SHELF';	0.09	0.0039	0.0057
LME44='WEST-CENTRAL AUSTRALIAN SHELF';	0.09	0.0038	0.0093
LME14='PATAGONIAN SHELF';	0.08	0.0034	0.0059
LME61='ANTARCTIC';	0.00	0.0001	0.0011
LME3='CALIFORNIA CURRENT';	-0.07	-0.0030	0.0119
LME13='HUMBOLDT CURRENT';	-0.10	-0.0042	0.0112
LME64='ARCTIC OCEAN';			

warming exceeding 0.96°C over 25 years is observed in the North Sea, East China Sea, Sea of Japan/East Sea, and Newfoundland-Labrador Shelf and Black Sea LMEs. Comparisons of warming were made among three temperature clusters of LMEs. 1) Super fast warming LMEs with D(SST) between >0.96°C -1.35°C are combined with fast warming LMEs .67°C – 0.84°C. Moderate warming LMEs have D(SST) between >0.3-0.6°C; slow warming LMEs, have D(SST) between 0.0°C-0.28°C. Of the fast warming LMEs (0.67°C to 1.35°C), 18 are warming at rates 2x to 4x times higher than the global air surface temperature increase of 0.74°C for the past 100 years as reported by the IPCC (2007) (Figure 3).

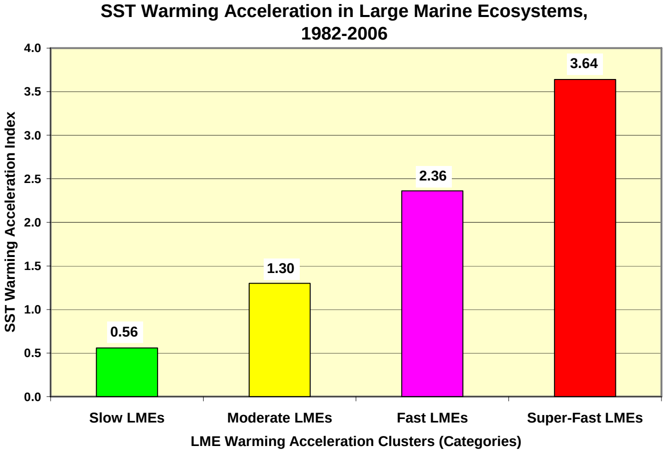


Figure 3. Accelerated warming of sea surface temperature in Large Marine Ecosystems, 1982-2006. Shown is the Warming Acceleration Index (WAI) for four clusters of LMEs grouped according to their net SST change between 1982 and 2006, categorized as slow (0.0-0.3°C, net SST change), moderate (0.3-0.6°C), fast (0.6-0.9°C) and super-fast (>0.9°C) (Table 1). The WAI (shown at the top of each bar) is calculated as the ratio of the cluster's average SST warming rate (Belkin 2009) to the IPCC-2007 global average SST warming rate of 0.133±0.047°C/decade (Trenberth et al. 2006).

Primary Productivity

No large scale consistent pattern of either increase or decrease in primary productivity was observed. Of the 64 LMEs examined, only four 9-year trends were significant (P<.05) (Figure 4). Primary productivity declined in the Bay of Bengal, and increased in the Hudson Bay, Humboldt Current and Red Sea LMEs). The general declining trend in primary productivity with ocean warming reported by Behrenfeld (2006) was limited to the Bay of Bengal LMEs. No consistent trend among the LMEs was observed (Table 2). However, as previously reported (Chassot et al. 2007; Nixon et al. 1986; Ware and Thomson 2005) fisheries biomass yields did increase with increasing levels of primary productivity (P<.001) in all 63 LMEs, and for LMEs in each of the warming clusters (Figure 5A and 5B).

Table 2. Test results of primary productivity regression analysis for 9 years of mean annual Sea WiFS Primary Productivity (PP) data; +*P<0.05

LME	PP
Bay of Bengal	- *
Hudson Bay	+ *
Humboldt Current	+ *
Red Sea	+ *

Fisheries biomass yield trends

The effects of warming on global fisheries biomass yields were non-uniform in relation to any persistent global pattern of increasing or decreasing yields. The relationship between change in LME yield and SST change was not significant; the slight suggestion of a trend in the regression, was influenced by the data for the Humbolt LME (Figure 6). Partitioning of the results into LMEs with increasing trends in fisheries biomass yields, and those with declining trends divided the trends into two groups. Increasing yields were observed in 31 (49.2%) and decreasing trends in 32 (50.8%) of LMEs. Differences

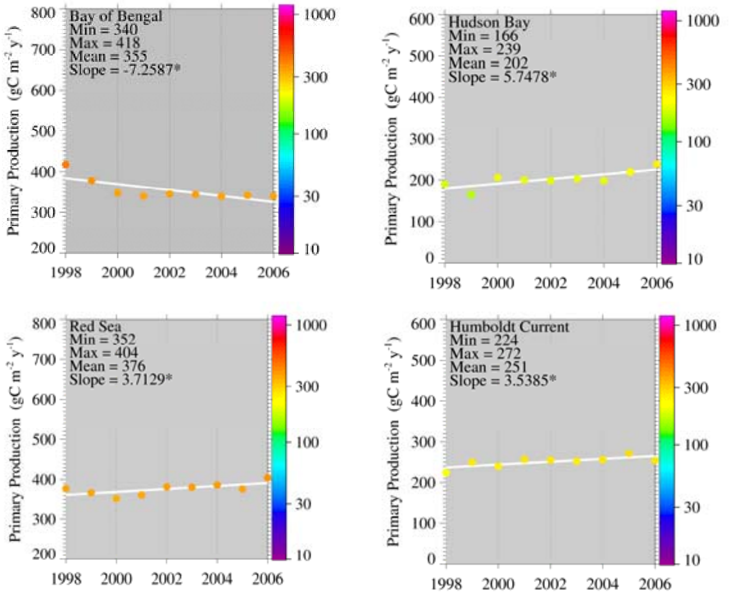


Figure 4. Primary productivity trends (1998-2006): Bay of Bengal, Hudson Bay, Humboldt Current and Red Sea.

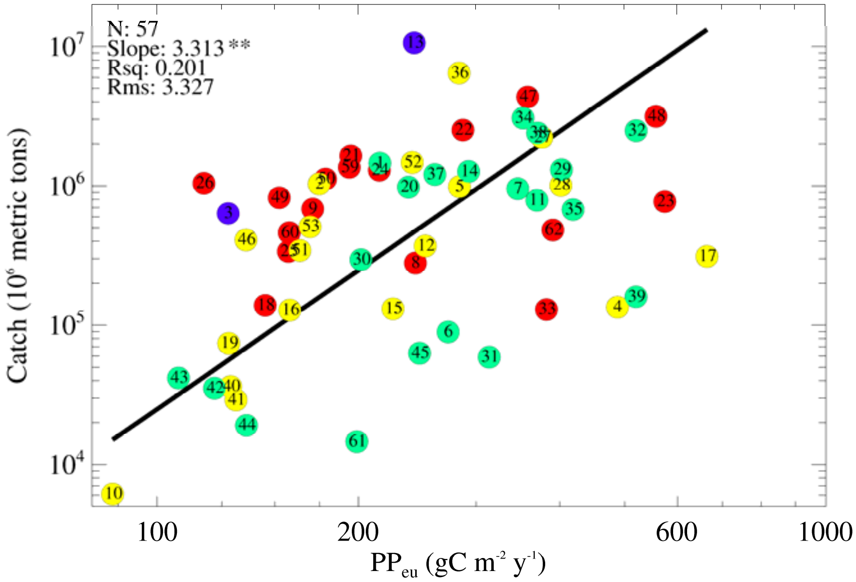


Figure 5A. Positive correlation of 5-yr. mean annual fisheries biomass yield with 9-yr. mean annual primary production in fast warming (red), moderately warming (yellow) and slower warming (green) LMEs. The two blue circles represent cooling LMEs. P<0.001.

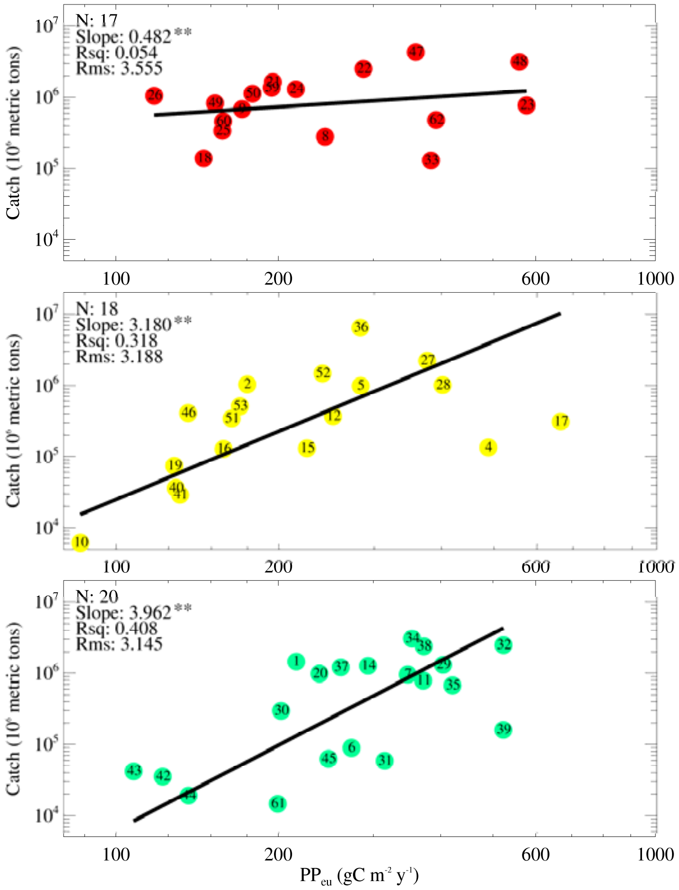


Figure 5A. P<0.001

Figure 5B. Comparison of 5-yr mean annual fisheries biomass yield with 9-yr mean annual primary production in fast warming (red), moderately warming (yellow) and slower warming (green) LMEs.

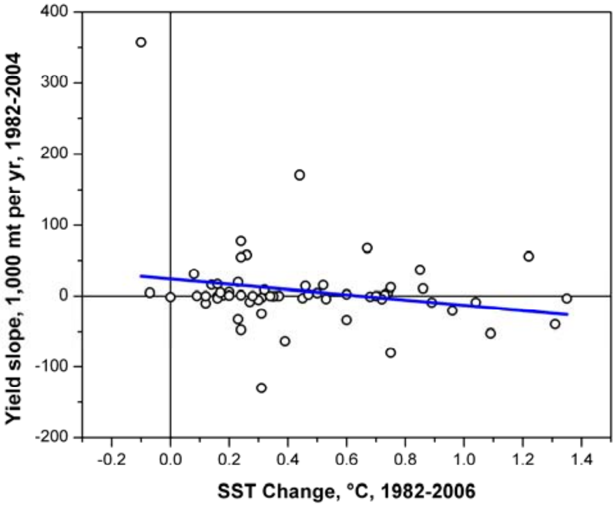


Figure 6. The relationship (shown with blue trend line) between LME yield trend slope and net SST change was not significant; the slight suggestion of a trend in the regression, was influenced by the data for the Humbolt LME.

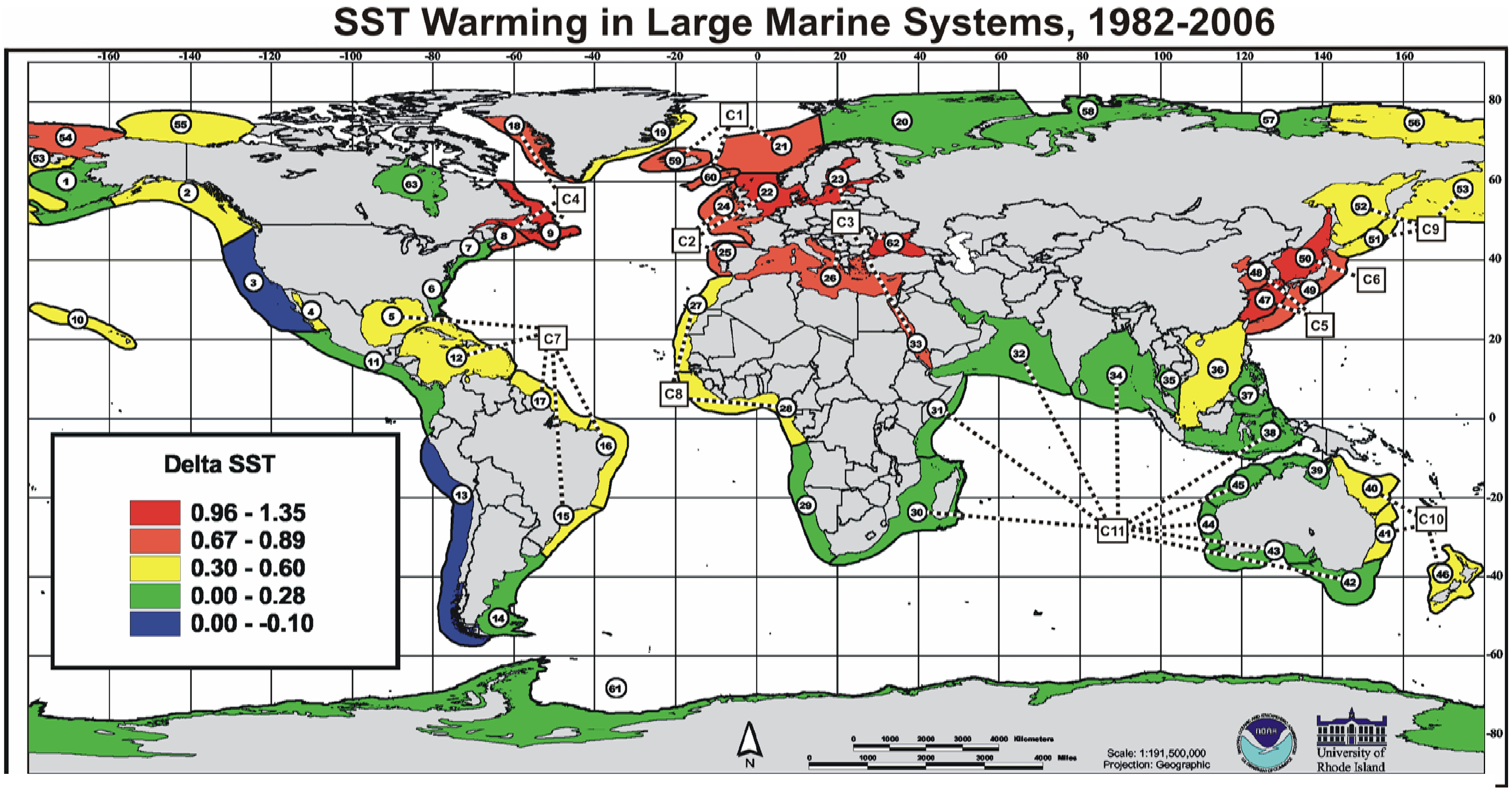


Figure 7. Warming Clusters of LMEs in Relation to SSTs, 1982-2006:

FAST WARMING:

C1 Northern European Cluster; **C2** Southern European; **C3** Semi-Enclosed European Seas; **C4** of the NW Atlantic; **C5** Fast Warming East Asian LMEs; **C6** Kuroshio Current and Sea of Japan/East Sea LMEs.

MODERATE WARMING:

C7 Western Atlantic LMEs; **C8** Eastern Atlantic LMEs; **C9** NW Pacific; **C10** SW Pacific.   Several **Non-Clustered, Moderate Warming LMEs** are moderate warming: NE Australia, Insular Pacific Hawaiian, Gulf of Alaska, Gulf of California; South China Sea, East Greenland Shelf;

SLOW WARMING:

C11 Indian Ocean and Adjacent Waters.

Non-clustered, Slow Warming LMEs include the U.S. Northeast Shelf, the U.S. Southeast Shelf, the Barents Sea, East Bering Sea; Patagonian Shelf, Benguela Current and Pacific Central American Coastal LMEs.

were similar in Fast Warming (8 increasing, 10 decreasing) and Moderate Warming LMEs (10 increasing, 8 decreasing). In the Slower Warming LMEs, most (14) were undergoing increasing biomass yields and 6 were in a decreasing condition (Table 3**).** Linear warming trends from 1982 to 2006 for each LME were distributed in distinct global clusters, (i) the Fast Warming LME clusters were in the Northeast Atlantic, African and Southeast Asian waters; (ii) the Moderate Warming LMEs were clustered in the Atlantic and North Pacific waters; and (iii) the Slow Warming LME clusters were located principally in the Indian Ocean, and also in locations around the margins of the Atlantic and Pacific Oceans (Figure 7). Comparisons of fisheries biomass yield trends for eleven LME warming clusters were examined.

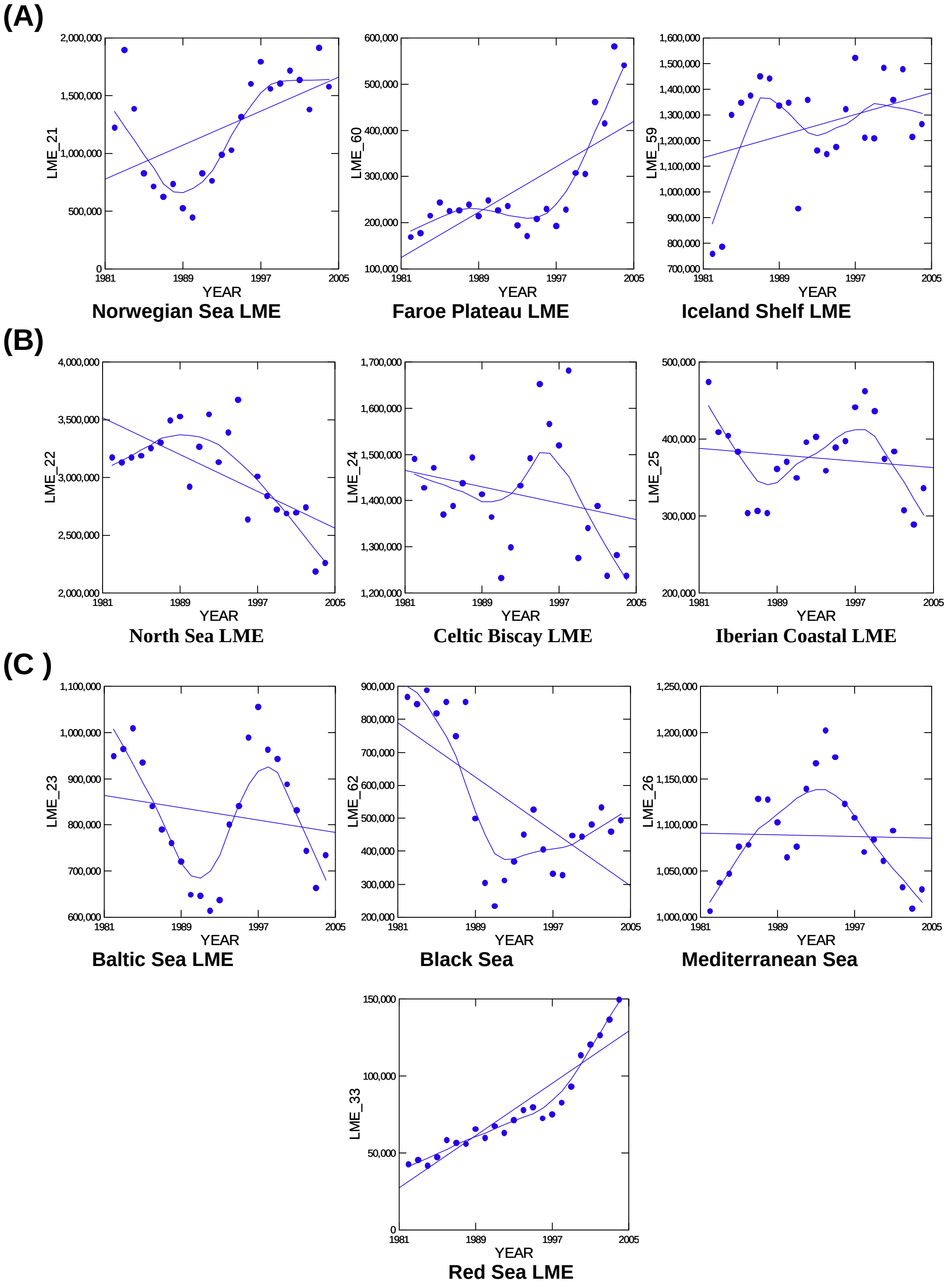
Table 3. Fisheries biomass trends in LMEs adjacent to developing and developed countries.

Fisheries biomass trend	**Status of adjacent countries**	**Fisheries biomass in million metric tons**	**Percentage of total**
Increasing fisheries (20 LMEs)	Developing countries	32.0	49%
Decreasing fisheries (9 LMEs)	Developing countries	6.2	9%
Increasing fisheries (11 LMEs)	Developed countries	4.4	6%
Decreasing fisheries (15 LMEs)	Developed countries	11.0	17%
California Current, Humboldt Current, and 7 Arctic LMEs (9 LMEs)		11.4	19%
Total fisheries biomass	All categories	65.0	100%

Comparative fisheries biomass yields in relation to warming: Fast warming European LMEs

In the **Norwegian Sea, Faroe Plateau, and Iceland Shelf,** the fisheries biomass yield is increasing. These three LMEs account for 3.4 million tons, or 5% of the world biomass catch, (Figure 8A). This cluster of LMEs is influenced from bottom-up forcing of increasing zooplankton abundance and warming hydrographic conditions in the northern areas of the North Atlantic, where stocks of herring, blue whiting and capelin are benefiting from an expanding prey field of zooplankton (Beaugrand and Ibanez 2004; Beaugrand et al. 2002) supporting growth and recruitment of these three species. The warming trend in the Norwegian Sea driving the increase in biomass of herring, capelin and blue whiting yields has been reported by (Skjoldal and Saetre 2004). On the Faroe Plateau LME, Gaard et al. (2002) indicate that the increasing shelf production of plankton is linked to the increased production of fish and fisheries in the ecosystem. Astthorsson and Vilhjálmsson (2002) have shown that variations of zooplankton in Icelandic waters are greatly influenced by large scale climatic factors and that warm Atlantic water inflows favor zooplankton that supports larger populations of capelin that serve as important prey of cod. The productivity and fisheries of all three LMEs are benefiting from the increasing strength of the sub-Polar gyre bringing warmed waters to the LMEs of the region generally in the northern northeast Atlantic and contributing to decreasing production and fisheries yields in the relatively warmer southern waters of the northeast Atlantic (Richardson and Schoeman 2004).

In southern Europe three LMEs, the **North Sea, Celtic Biscay, and Iberian Coastal LMEs** in fast warming clusters are experiencing declines in biomass trends representing 4.1 mmt (6.4%) of the mean annual global biomass yield (Figure 8B). It has been



Norwegian Sea LME
Faroe Plateau LME
Iceland Shelf LME
North Sea LME
Celtic Biscay LME
Iberian Coastal LME
Baltic Sea LME
Black Sea
Mediterranean Sea
Red Sea LME

Figure 8. Fisheries biomass yield trends (metric tons) in fast warming clusters A. Norwegian, Faroe Plateau and Iceland Shelf LMEs (C1) B. North Sea, Celtic Biscay and Iberian Coastal LMEs (C2) and C. Baltic Sea, Black Sea, Mediterranean Sea and Red Sea (C3) LMEs

reported that zooplankton abundance levels in the three LMEs are in decline, reducing the prey field for zooplanktivores (Beaugrand et al. 2002; Valdés and Lavin 2002; Valdés et al. 2007). Although we did not detect any significant decline in primary productivity in the three LMEs, the declining phytoplankton level in the region (Richardson and Schoeman 2004) is consistent with the declines in primary productivity in warming ocean waters reported by Behrenfeld (2006). The fisheries biomass yields of 80% of the targeted species are in an overexploited or fully exploited condition (Table 4), suggesting that the observed decline in biomass yield of pelagic species is related to both heavy exploitation and warming.

The three semi-enclosed European LMEs, the **Mediterranean, the Black Sea, and the Baltic Sea,** and the adjacent area of the **Red Sea** **(**Figure 8C**)**, are surrounded by terrestrial areas and are fast warming, with heavy fishing as a dominant feature. The four LMEs contribute 2.4 mmt (3.7%) of the mean annual global biomass yield. In three European LMEs, the fisheries biomass trend is decreasing, while in the Red Sea it is increasing. In the case of the **Black Sea**, the fisheries biomass is severely depleted, with 85% of fisheries stocks overexploited due to heavy fishing and a trophic cascade (Daskalov 2003). In the Baltic Sea, Red Sea and Mediterranean Sea LMEs, 78% of the stocks are in a fully exploited condition. Mixed species dominate in the **Red Sea,** where 88% of the species fished are fully exploited and 10% are overexploited (Table 4). It appears that heavy exploitation is the dominant driver of the biomass trends observed in all four LMEs.

Comparative fisheries biomass yields (in metric tons) in the fast warming clusters of the Northwest Atlantic (C4) LMEs and the Asian (C5, C6) LMEs

The three LMEs in this region contribute 1.1 mmt (1.7%) to the global biomass yield. In two LMEs of the Northwest Atlantic, the downward trends in fisheries yield have been attributed to the cod collapse in the **Newfoundland-Labrador Shelf** (Rice 2002), and to the cod collapse and collapse of other demersal fisheries in the **Scotian Shelf** LME from excessive fishing mortality (Choi et al. 2004; Frank et al. 2005). In the **West Greenland Shelf LME,** where the cod stock has collapsed from excessive fishing mortality, there is a recent increase in the landings of shrimp and other species (Aquarone and Adams 2008b) (Figure 9A).

Biomass yields of the fast warming LMEs of East Asian Seas

The 7.5 million metric tons (mmt) biomass yields of the **Yellow Sea and East China Sea LMEs** constitute 11% of the global yield. In both LMEs, yields are increasing (Figure 9B). The principal driver of the increase is food security to accommodate the needs of the People’s Republic of China and Korea (Tang 2003; Tang 2006; Tang and Jin 1999; Zhang and Kim 1999). Biomass yields are dominated by heavily fished “mixed” species. Seventy percent or more of the species constituting the yields are fully exploited or overexploited (Table 3), suggesting that the principal driver of increased biomass yields is full exploitation rather than global warming.

The fast warming **Kuroshio Current and Sea of Japan/East Sea LMEs** show declining fisheries trends (Figure 9B). They contribute 1.9 mmt (2.9%) to the global marine fisheries yield. For these two LMEs, exploitation levels are high with 90% of the species in a fully exploited to overexploited condition (Table 4). The fisheries are also subjected to periodic oceanographic regime shifts affecting the abundance of biomass yields (Chavez et al. 2003). Among the fast warming East Asian Seas LMEs, no analysis has been conducted for the ice-covered **Chukchi Sea LME**, as the data is limited and of questionable value.

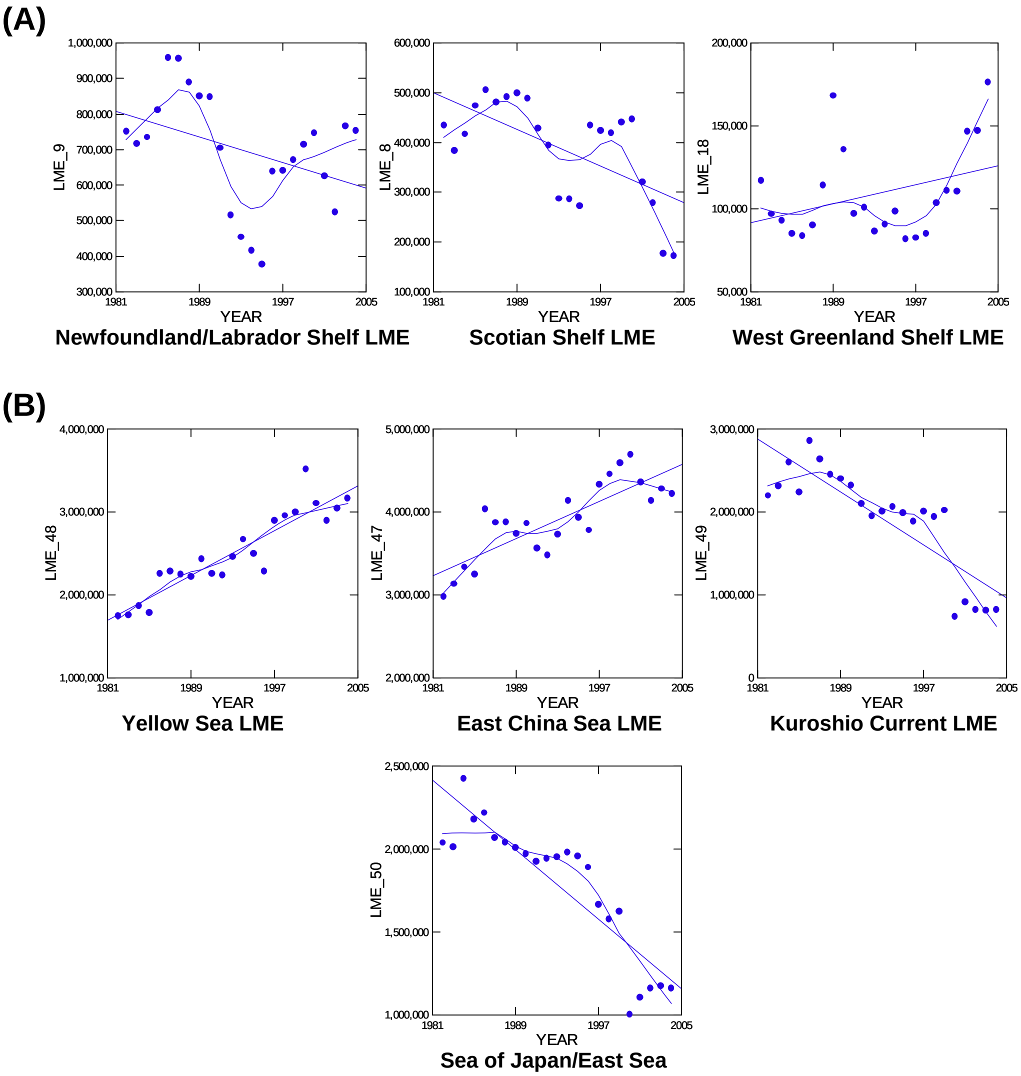


Figure 9. Comparative fisheries biomass yields (in metric tons) in the fast warming clusters of the (A) Northwest Atlantic (C4) LMEs and the(B) Asian (C5, C6) LMEs

Comparative Fisheries Biomass Yields (in metric tons) in Moderate Warming Western Atlantic LMEs (C7), Eastern Atlantic (C8) LMEs, and LMEs of the Asian Northwest Pacific region

A large cluster of moderately warming LMEs can be found in the Trade Winds region of the Atlantic Ocean. This is an important cluster of LMEs contributing 5.1 mmt (7.9%) to the mean annual global biomass yield. Five LMEs are clustered in the Western Atlantic, and two in the Eastern Atlantic. In the West Atlantic Ocean, the **Gulf of Mexico LME** fisheries biomass yields are decreasing, while in the **Caribbean, North Brazil, East Brazil, and South Brazil Shelf LMEs** fisheries biomass yields are increasing (Figure 10A).

The fisheries biomass yield trends in the Atlantic Ocean region appear to be driven principally by heavy exploitation rather than climate warming. The Caribbean, North Brazil, and East Brazil Shelf LMEs are in a fully exploited and over-exploited fisheries condition equal to or greater than 88% of the stocks. In the South Brazil Shelf, 60% of fisheries are fully exploited or overexploited (Table 4). The East Brazil Shelf and South Brazil Shelf LMEs are dominated by small pelagics and/or “mixed species”

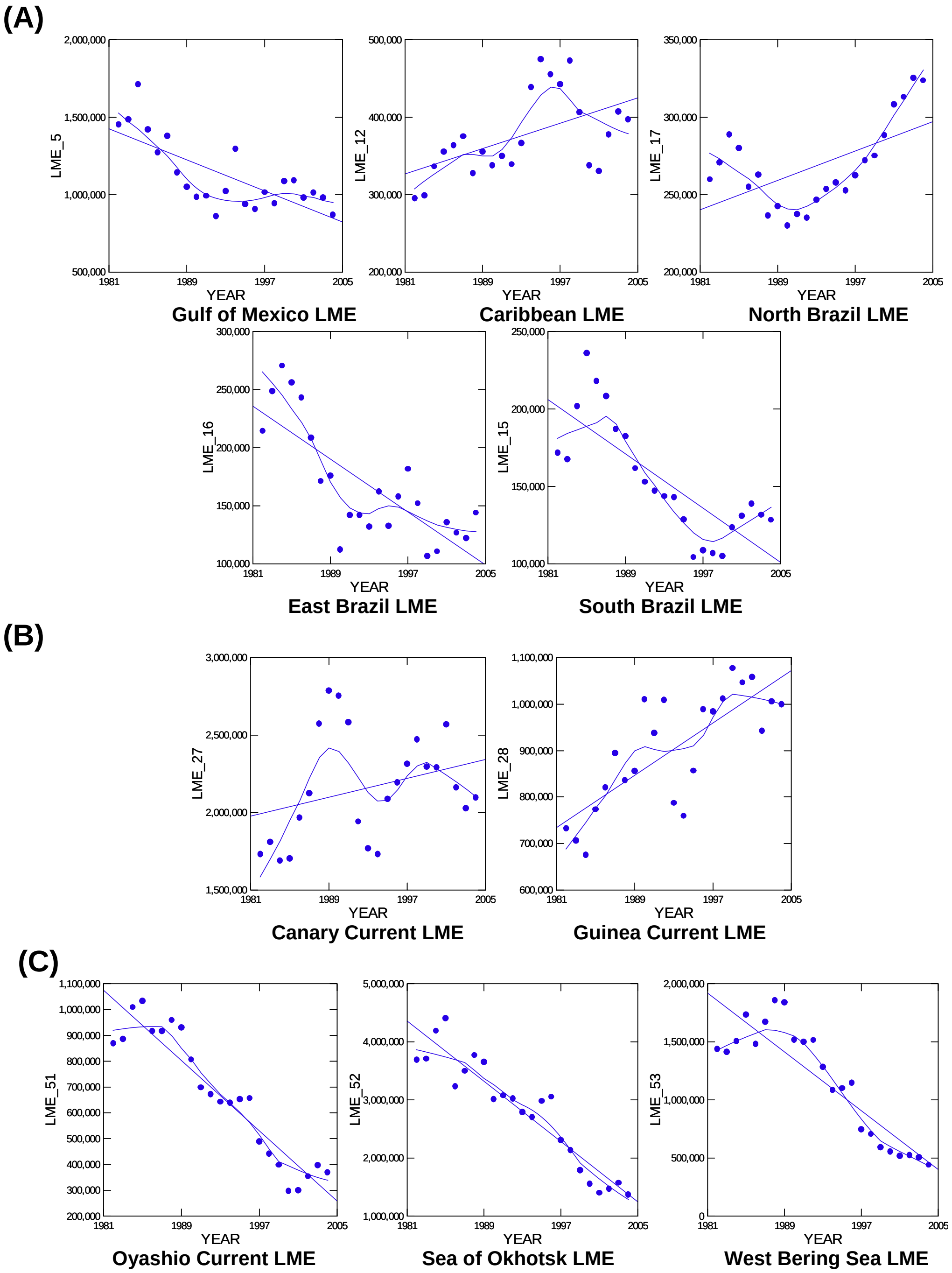


Figure 10. Comparative Fisheries Biomass Yields (in metric tons) in Moderate Warming (A) Western Atlantic LMEs (C7), (B) Eastern Atlantic (C8) and (C) Pacific LMEs

The two LMEs of the Eastern Atlantic are important sources of food security to the over 300 million people of West African countries adjacent to the LMEs. The **Canary Current and the Guinea Current** are showing increasing trends in biomass yield with “mixed species” dominant (Heileman 2008) (Figure 10 B&C. The fisheries stocks in both LMEs are at risk. Oceanographic perturbations are also a source of significant variability in biomass yields in the Guinea Current (Hardman-Mountford and McGlade 2002; Koranteng and McGlade 2002) and in the waters of the Canary Current LME (Roy and Cury 2003)(www.thegef.org, IW Project 1909).

Three LMEs, the **Sea of Okhotsk,** the **Oyashio Current,** and the **West Bering Sea**, contribute 2.3 mmt (3.5%) to the mean annual global biomass yield. They are in a condition where 78% of the fisheries stocks are overexploited (Table 4). The **Oyashio Current** and the **West Bering Sea LMEs** show decreasing trends in fisheries yields (Figure 10C. In the Sea of **Okhotsk**, the biomass yields are dominated by targeted table fish including pollock and cod. The increasing yield trend in the **Sea of Okhotsk LME** is related principally to a high level of overexploitation (Shuntov et al. 1999).

Comparative Fisheries biomass yields in Moderately Warming Southwest Pacific LMEs (C10) and other Non-clustered, Moderately Warming LMEs

The three moderately warming LMEs, two on the east coast of Australia **(Northeast and East Central Australia LMEs)** and the **New Zealand Shelf LME,** contribute 0.4 mmt (0.7%) to the mean annual global biomass yield. Biomass yields are decreasing in the Australian LMEs, whereas they are increasing in the New Zealand Shelf LME (Figure 11) under the present condition of full exploitation (Table 4). Whether their conditions are the result of top down or bottom up forcing is not clear. However, Individual Transferable Quota (ITQ) management to promote the recovery and sustainability of high priority fisheries stocks is in place. Stewardship agencies in Australia and New Zealand have implemented management actions for the recovery and sustainability of the overexploited species.

Six moderately warming LMEs occur in separate locations. Taken together they contribute 7.7 mmt (11.8%) to the mean annual global biomass yields. In the **Pacific,** landings are too low in the moderately warming **Insular Pacific Hawaiian LME** to draw any conclusion on biomass yield. In the moderate warming **Gulf of Alaska LME**, the overall 25-yr. fisheries biomass trend is decreasing. However, this LME shows evidence of a relatively recent upturn in yield, attributed to increases in biomass of Alaska Pollock and Pacific salmon populations in response to climate warming (Overland et al. 2005).

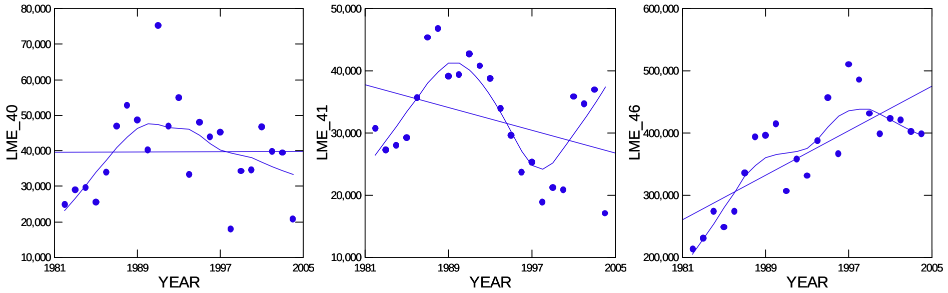
The biomass of the moderately warming **Gulf of California LME** is in a declining trend (Figure 11). The dominant biomass yield in this LME is from small pelagics and “mixed species,” suggestive of top down fishing as the principal driver of the decline. The **South China Sea** fisheries biomass yields are increasing. The dominant biomass yield of the LME is of “mixed species” and the level of exploitation is high with 83% fully exploited and 13% overexploited (Table 3). In this case, high population demand for protein by the adjacent countries contributes to drive the biomass yield upward.

The **Arctic** region’s **Beaufort Sea LME**, landings data are unavailable. The moderate warming **East Greenland Shelf** fisheries biomass yields are increasing with capelin, redfish and shrimp dominant; following the earlier collapse of cod and other demersal species. The role of global warming in relation to cause and effect of increasing yields is not known.

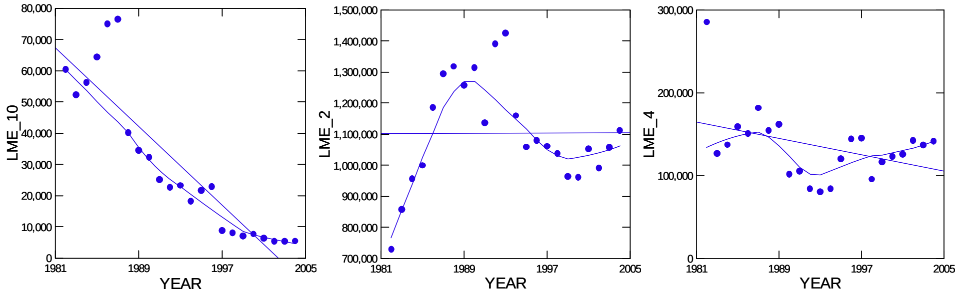
Table 4. LMEs, rates of warming, 5-yr. mean fisheries biomass yields, adjacent to developing or developed countries, status of stocks exploitation

FAST WARMING LMEs	**Adjacent countries developing**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
East China Sea LME	developing	increasing	4,339,890	77% fully exploited, 21% overxploited
Red Sea LME	developing	increasing	129,206	88% fully exploited, 10% overexploited
Yellow Sea LME	developing	increasing	3,147,211	70% fully exploited, 18% overexploited
FAST WARMING LMEs	**Adjacent countries developing**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Mediterranean Sea LME	developing	decreasing	1,045,214	78% fully exploited, 22% overexploited
Baltic Sea LME	developing	decreasing	771,911	88% fully exploited, 12% overexploited
Black Sea LME	developing	decreasing	481,699	0% fully exploited, 85% overexploited
MODERATELY WARMING LMEs	**Adjacent countries developing**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
North Brazil Shelf LME	developing	increasing	311,848	70% fully exploited, 29% overexploited
Canary Current LME	developing	increasing	2,229,215	72% fully exploited, 6% overexploited
Caribbean Sea LME	developing	increasing	370,231	40% fully exploited, 58% overexploited
Guinea Current LME	developing	increasing	1,010,453	71% fully exploited, 24% overexploited
East Brazil Shelf LME	developing	increasing	127,969	40% fully exploited, 48% overexploited
South Brazil Shelf LME	developing	increasing	130,669	20% fully exploited, 40% overexploited
Sea of Okhotsk LME	developing	increasing	1,472,394	10% fully exploited, 78% overexploited
South China Sea LME	developing	increasing	6,454,043	83% fully exploited, 13% overexploited
MODERATELY WARMING LMEs	**Adjacent countries developing**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Gulf of Mexico LME	developing	decreasing	987,865	36% fully exploited, 60%overexploited
West Bering Sea LME	developing	decreasing	508,804	1% fully exploited, 79% overexploited
Gulf of California LME	developing	decreasing	134,297	45% fully exploited, 48% overexploited
SLOWER WARMING LMEs	**Adjacent countries developing**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Arabian Sea LME	developing	increasing	2,486,227	84% fully exploited, 11% overexploited
Bay of Bengal LME	developing	increasing	3,062,147	83% fully exploited, 15% overexploited
Indonesian Sea LME	developing	increasing	2,392,818	88% fully exploited, 12% overexploited
Gulf of Thailand	developing	increasing	676,304	37% fully exploited, 50% overexploited
Sulu Celebes LME	developing	increasing	1,207,946	82% fully exploited, 17% overexploited
Agulhas Current LME	developing	increasing	295,364	30% fully exploited, 32% overexploited
Somali Current LME	developing	increasing	58,961	45% fully exploited, 50% overexploited
Pacific Central American LME	developing	increasing	788,191	42% fully exploited, 18% overexploited
Patagonian Shelf LME	developing	increasing	1,269,644	30% fully exploited, 69%overexploited
SLOWER WARMING LMEs	**Adjacent to developing countries**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Antarctic LME	developing	decreasing	14,553	0----------0---------- 0
Barents Sea LME	developing	decreasing	980,781	0% fully exploited, 60% over exploited
Benguela Current LME	developing	decreasing	1,307,649	50% fully exploited, 8% overexploited
FAST WARMING LMEs	**Adjacent countries developed**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Norwegian Sea LME	developed	increasing	1,643,808	2% fully exploited, 23% overexploited
Iceland Shelf LME	developed	increasing	1,359,767	0% fully exploited, 80% overexploited
Faroe Plateau LME	developed	increasing	460,686	83% fully exploited, 10% overexploited
West Greenland Shelf LME	developed	increasing	138,369	90% fully exploited, 0% overexploited

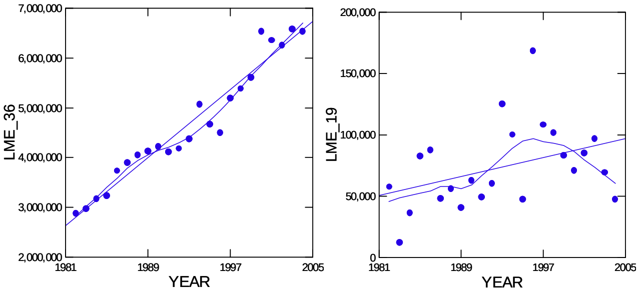
FAST WARMING, declines in fisheries biomass yields	adjacent countries developed	decreasing fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
North Sea	developed	decreasing	2,513,263	19% fully exploited, 63% overexploited
Newfoundland/Labrador Shelf	developed	decreasing	683,480	55% fully exploited, 10% overexploited
Scotian Shelf	developed	decreasing	279,470	29% fully exploited, 55% overexploited
Kuroshio Current	developed	decreasing	823,035	48% fully exploited, 42% overexploited
Sea of Japan/East Sea	developed	decreasing	1,121,826	45% fully exploited, 49% overexploited
Celtic-Biscay Shelf	developed	decreasing	1,296,762	65% fully exploited, 30% overexploited
Iberian Coastal	developed	decreasing	338,049	30% fully exploited, 61% overexploited
MODERATE WARMING LMEs	**Adjacent countries developed**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
New Zealand Shelf LME	developed	increasing	408,913	77% fully exploited, 21% overexploited
East Greenland Shelf LME	developed	increasing	73,932	6% fully exploited, 23% overexploited
MODERATE WARMING LMEs	**Adjacent countries developed**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited, collapsed
Oyashio Current LME	developed	decreasing	343,734	08% fully exploited, 85% overexploited
Insular Pacific Hawaiian	developed	decreasing	6,121	01% fully exploited, 54% overexploited
Gulf of Alaska	developed	decreasing	1,035,005	80% fully exploited, 18%overexploited
East Central Australian	developed	decreasing	29,095	18% fully exploited, 64% overexploited
Northeast Australian Shelf/ Great Barrier Reef	developed	decreasing	36,310	46% fully exploited, 30% overexploited
SLOWER WARMING LMEs	**Adjacent countries developed**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
North Australian Shelf	developed	Increasing	159,572	78% fully exploited, 18% overexploited
Northwest Australian Shelf	developed	Increasing	62,842	59% fully exploited, 18% overexploited
West Central Australian Shelf	developed	increasing	19,079	75% fully exploited, 10% overexploited
Southeast Australian Shelf	developed	increasing	35,339	50% fully exploited, 40% overexploited
Southwest Australia Shelf	developed	increasing	41,844	51% fully exploited, 27% overexploited
SLOWER WARMING LMEs	**Adjacent countries developed**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
East Bering Sea	developed	decreasing	1,454,881	62% fully exploited, 28% overexploited
U.S. Northeast Shelf	developed	decreasing	955,948	33% fully exploited, 45% overexploited
U.S. Southeast Shelf	developed	decreasing	89,216	54% fully exploited, 26% overexploited
Arctic LMEs yields are too low for trend analysis				
Chukchi			0	
East Siberian			0	
Beaufort Sea			8	
Hudson Bay			50	
Kara Sea			295	
Laptev Sea			0	
Arctic Ocean			242,913	
2 upwelling LMEs, cooling, adjacent to developed countries				
Humboldt Current LME			10,617,103	
California Current LME			634,669	



NE Australia LME **East Central Australia LME** **New Zealand Shelf**



Insular Pacific Hawaiian LME **Gulf of Alaska LME** **Gulf of California**

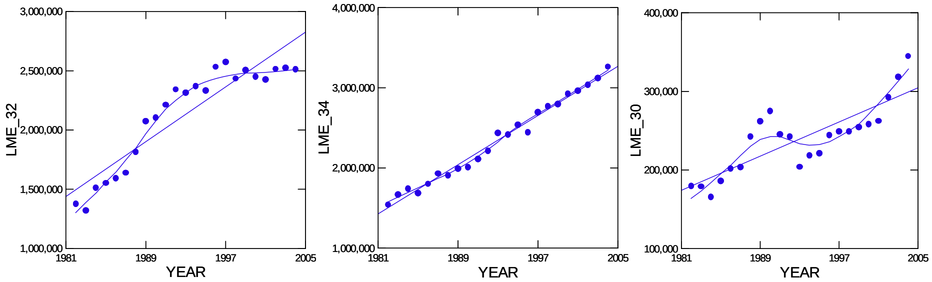


South China Sea LME **East Greenland Shelf LME**

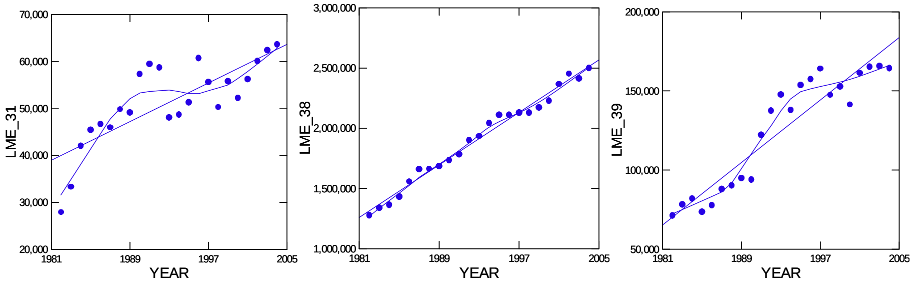
Figure 11. Comparative Fisheries Biomass Yields (in metric tons) in Moderately Warming Southwest Pacific LMEs (C10) and other Moderately Warming LMEs

Comparative Fisheries Biomass Yields in Slow Warming Indian Ocean and Adjacent LMEs (C11)

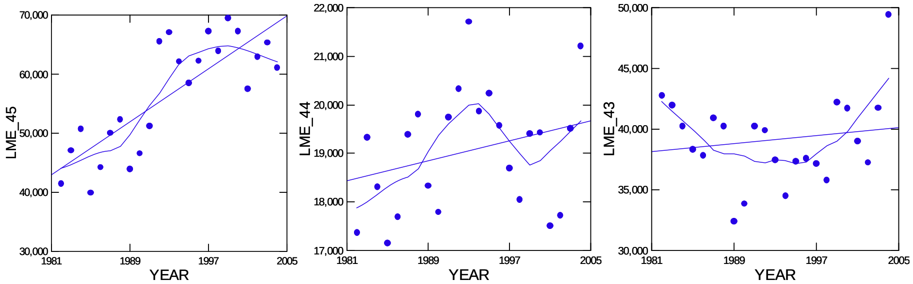
The 10 LMEs of the Indian Ocean, **Arabian Sea, Bay of Bengal, Agulhas Current, Somali Current, Indonesian Sea, North Australia, Northwest Australia, West Central Australia, Southwest Australia and Southeast Australia LMEs** are in the slow range of climate warming and their biomass trends are all increasing. This group of LMEs contributes 8.6 million metric tons, or 13.2% of the global biomass yield. The slow warming is consistent with the IPCC forecast of slow but steady warming of the Indian Ocean in response to climate change (IPCC 2007). While biomass yields are increasing, the landings adjacent to developing countries are composed primarily of mixed species and small pelagics (Heileman 2008) and the stocks are predominantly fully exploited and/or overexploited (Table 3), suggesting that top down fishing is the predominant influence on the condition of biomass yield. In the adjacent Southwest Pacific waters, the slow warming Sulu-Celebes and Gulf of Thailand LMEs contribute 1.8 mmt (2.8%) to the mean annual global biomass yield. The consistent pattern of increasing yields of the Indian Ocean LMEs adjacent to developing countries is driven principally by the demand for fish protein and food security (Ahmad et al. 1998; Dwivedi and Choubey 1998). In the case of the 5 LMEs adjacent to Australia, the national and provincial stewardship agencies are promoting stock recovery and sustainable management through ITQs. The fisheries stocks in the LMEs adjacent to developing countries are under national pressure to further continue to expand the fisheries to provide food security for the quarter of the world's population inhabiting the region. Given the demands on fisheries for food security for the developing countries bordering the Indian Ocean, there is a need to control biomass yields and sustain the fisheries of the bordering African and Asian LMEs.



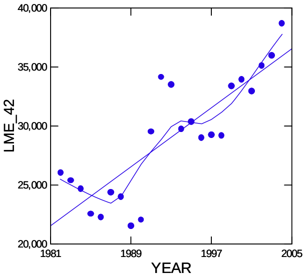
Arabian Sea LME **Bay of Bengal** **Agulhas Current LME**



Somali Current LME **Indonesian Sea LME** **North Australia LME**



Northwest Australia LME **West-Central Australia** **Southwest Australia LME**



Southeast Australia LME

Figure 12. Comparative Fisheries Biomass Yields (in metric tons) in Slow Warming Indian Ocean and Adjacent LMEs (C11)

The biomass yields of other slow warming LMEs of the Northwest Atlantic and the United States East Coast, Barents Sea, East Bering Sea, Patagonian Shelf, Benguela Current, and Pacific Central American Coastal LMEs

There is slow warming taking place in the Northeast US Shelf and in the Southeast US Shelf. The LMEs contribute 1.0 mmt (1.6%) to the mean annual global marine biomass yield. For both LMEs, the declines are attributed principally to overfishing (NMFS 2006) For these two LMEs and the Gulf of Mexico, the Gulf of Alaska, the East Bering Sea, Chukchi Sea, Beaufort Sea, Insular Pacific Hawaiian Islands, and the Caribbean, the United States has underway a fisheries stock rebuilding program for increasing the spawning stock biomass of overfished species(NMFS 2007).

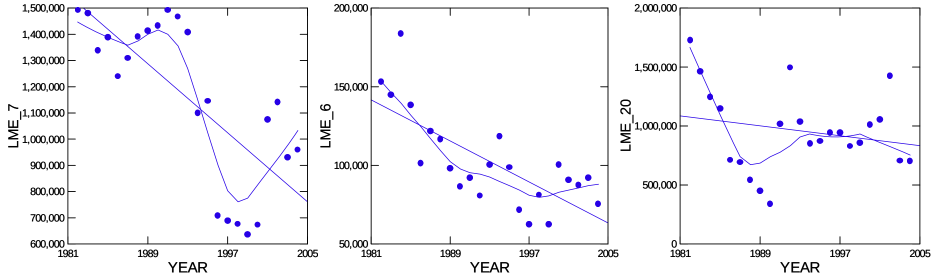
Biomass yields of the slow warming LMEs of the Arctic region

For several of the slow warming LMEs bordering the Arctic including the Laptev Sea, Kara Sea, East Siberian Sea and Hudson Bay, biomass yield data is at present incomplete and is not included in the trend analyses. In the case of the **Barents Sea LME**, there is a decreasing biomass trend attributed to the over-exploited condition of many fish stocks inhabiting the LME (Table 4)(Figure 13). During the present warming condition, variability in ice cover has an important influence on biomass yields (Matishov et al. 2003)

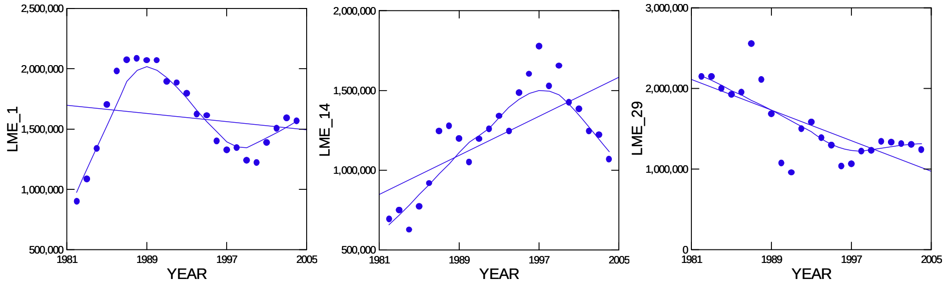
Biomass yields of other LMEs

Four widely separated LMEs, the **East Bering Sea**, the **Patagonian Shelf**, **Benguela Current,** and **Pacific Central American LMEs** are located in slow warming waters (Figure 13). Together they contribute 3.3 mmt (5.1%) to the mean annual global biomass yield. In the North Pacific Ocean, the slow warming East Bering Sea has an overall decline in fisheries biomass yield. However, in recent years there has been an upturn in yield, attributed to climate warming and increases in biomass of Alaska Pollock and Pacific Salmon populations (Overland et al. 2005). In the Southwest Atlantic Ocean Patagonian Shelf LME, increasing biomass yields are reflective of a very high level of fisheries exploitation, overshadowing any climate change effects, where 30% of fisheries are fully exploited, and 69% are overexploited (Table 4). The increasing biomass trends of the Pacific Central American Coastal LME are the result of high levels of exploitation (Table 4) driven principally by the need for fish protein and food security of the adjacent developing countries and secondarily by oceanographic regime shifts (Bakun et al. 1999).

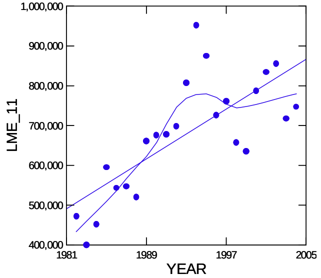
The biomass yields of the Benguela Current (BCLME), southwest African coast are in a declining trend (Figure 13). The living resources of the BCLME have been stressed by both heavy exploitation and environmental perturbations during the past 25 years (van der Lingen et al. 2006) The southwestward movement of sardines (Sardinella) populations from the coastal areas off Namibia to southeastern South Africa has been attributed to recent warming. The southerly migration has disrupted the Namibian fisheries. A further southerly movement of sardines and anchovies from the vicinity of island colonies of African penguins off South Africa led to a decrease in availability of small pelagic fish prey of penguins resulting in a 40% penguin population decline (Koenig 2007).



U.S. Northeast shelf LME **U.S. Southeast Shelf LME** **Barents Sea LME**



East Bering Sea LME **Patagonian Shelf LME** **Benguela Current LME**



Pacific Central American LME

Figure 13. Comparative Fisheries Biomass Yields (in metric tons) in <u>Slow Warming LMEs</u> of the United States East Coast, Barents Sea, East Bering Sea, Patagonian Shelf, Benguela Current and Pacific Central American Coastal LMEs

Discussion

Emergent trends

From the analysis, we conclude that in four LME cases the warming clusters of LMEs are influencing 7.5 mmt or 11.3% of the world's fisheries biomass yields. The first and clearest case for an emergent effect of global warming on LME fishery yields is in the increasing biomass yields of the fast warming temperature clusters affecting 3.4 mmt (5.0%) of global yields for the Iceland Shelf, Norwegian Sea, and Faroe Plateau LMEs in the northern Northeast Atlantic. Warming in this region has exceeded levels expected from entering the warm phase of the Atlantic Multi-decadal Oscillation (Trenberth and Shea 2006). The increase in zooplankton is related to warming waters in the northern areas of the Northeast Atlantic (Beaugrand et al. 2002) leading to improved feeding conditions of three zooplanktiverous species that are increasing in biomass yields. Herring, blue whiting, and capelin yields are increasing in the Iceland Shelf and Norwegian Sea LMEs, and blue whiting yields are increasing in the Faroe Plateau LME.

The second case is in the contrasting declines in biomass yields of the fast warming cluster of more southern Northeast Atlantic waters including the North Sea, the Celtic-

Biscay Shelf, and Iberian Coastal LME where declines in warm water plankton (Valdés et al. 2007) and northward movement of fish (Perry et al. 2005) are a negative influence on 4.1 mmt (6.3%) of the mean annual global biomass yields. Recent investigations have found that SST warming in the northeast Atlantic is accompanied by increasing zooplankton abundance in cooler more northerly areas, and decreasing phytoplankton and zooplankton abundance in the more southerly warmer regions of the northeast Atlantic in the vicinity of the North Sea, Celtic-Biscay Shelf and Iberian Coastal LMEs (Richardson and Schoeman 2004). Due to tight trophic coupling fisheries are adversely affected by shifts in distribution, reduction in prey and reductions in primary productivity generated by strong thermocline stratification inhibiting nutrient mixing (Behrenfeld et al. 2006).

In the third case, recent moderate warming of the Gulf of Alaska, and slow warming of the East Bering Sea are supporting increasing levels of zooplankton production and recent increasing biomass yields of Alaska Pollock and Pacific Salmon (Grebmeier et al. 2006; Hunt et al. 2002; Overland et al. 2005).

The biomass yields of the fourth case are more problematic. Biomass yields of all 10 LMEs (8.6 mmt) (13.2%) around the western and central margin of the **Indian Ocean** are increasing (Figure 12). The increasing yields of the five LMEs adjacent to developing countries, the Agulhas Current, Somali Current, Arabian Sea, Bay of Bengal and Indonesian Sea are dominated by mixed species and small pelagic species, driven by the fish protein and food security needs of nearly one quarter of the world's population inhabiting the bordering countries of Africa and Asia (Heileman and Mistafa 2008). The overexploited condition of most species is at present masking any gains in biomass yield that may be attributed to the slow and steady warming of waters predicted for the Indian Ocean by the IPCC (2007) and observed during the present study. In contrast, the slow warming five Australian LMEs on the eastern margin of the Indian Ocean are driven principally by economic considerations and are closely monitored by governmental stewardship agencies that practice an adaptive management system of Individual Transferable Quotas (Aquarone and Adams 2008a). Taken together, the 8.6 mmt mean annual biomass yield of the Indian Ocean LMEs are critical for food security of the heavily populated adjacent countries. In this region there is a need to exercise a precautionary approach (FAO 1995) to recover and sustain the fisheries in the LMEs of east Africa and Asia, in the slow warming clusters.

Precautionary Cap and Sustain Action

From a global perspective 38.2 mmt or 58% of the mean annual 2001-2006 biomass yields are being produced in 29 LMEs adjacent to developing countries (Table 3). This vital global resource is at risk from serious overexploitation (Table 4). Given the importance for sustaining 58% of the world's marine fisheries biomass yield, it would be prudent for the GEF supported LME assessment and management projects to immediately cap the total biomass yield at the annual 5-year mean (2000-2004) as a precautionary measure and move toward adoption of more sustainable fisheries management practices.

The management strategies for protecting the 26.8 mmt or 42% of global marine biomass yields in LMEs adjacent to the more developed countries (Table 3) have had variable results ranging from highly successful fisheries biomass yield recovery and sustainability actions for stocks in LMEs adjacent to Australia, New Zealand, the United States, Norway, and Iceland to the less successful efforts of the European Union and LMEs under EU jurisdiction in the Northeast Atlantic (Gray and Hatchard 2003). An ecosystem-based cap and sustain adaptive management strategy for groundfish based on an annual overall total allowable catch level and agreed upon TACs for key species is proving successful in the management of the moderately warming waters of the Gulf of Alaska LME and slow warming East Bering Sea LME Alaska Pollock and Pacific Salmon stocks, providing evidence that cap and sustain strategies can serve to protect fisheries biomass yields (NPFMC 2002; Witherell et al. 2000).

In LMEs where primary productivity, zooplankton production and other ecosystem services are not seriously impaired, exploited, overexploited and collapsed stocks as defined by Pauly and Pitcher (2000) can be recovered where the principal driver is excessive fishing mortality and the global warming rates are moderate or slow. The principal pelagic and groundfish stocks in the slow warming US Northeast Shelf ecosystem have been targeted for rebuilding from the depleted state of the 1960s and 1970s by the New England Fisheries Management Council and the Mid Atlantic Fisheries Management Council. In collaboration with NOAA-Fisheries and the results of productivity and fisheries multi-decadal assessment surveys it was concluded that the principal driver of the declining trend in biomass yield was overfishing. Reductions in foreign fishing effort in the 1980s resulted in the recovery of herring and mackerel stocks.

Further reductions in US fishing effort since 1994 initiated recovery of spawning stock biomass of haddock, yellowtail flounder and sea scallops. Similar fish stock rebuilding efforts are underway in all 10 of the LMEs in the US coastal waters (NMFS 2007).

From our analysis, it appears that the emerging increasing trends in biomass yields can be expected to continue in fast warming LMEs of the northern North Atlantic (Iceland Shelf, Faroe Plateau, Norwegian Sea) and the moderate and slow warming LMEs of the northeast Pacific (Gulf of Alaska, East Bering Sea and the U.S. Northeast Shelf). The countries bordering these LMEs (U.S., Norway, Faroes Islands) have in place sufficiently advanced ecosystem-based capacity to support adaptive assessment and management regimes for maintaining sustainable levels of fishery biomass yields.

In the absence of the capacity for conducting annual assessments for a large number of marine fish species in many developing countries, and in recognition of the uncertainties of effects of climate warming, in the observed slow warming and increasing fisheries biomass yields of LMEs adjacent to east Africa and south Asia along the margins of the Indian Ocean, it would be prudent for the bordering countries to implement precautionary actions to protect present and future fishery yields with a cap and sustain strategy aimed at supporting long term food security and economic development needs.

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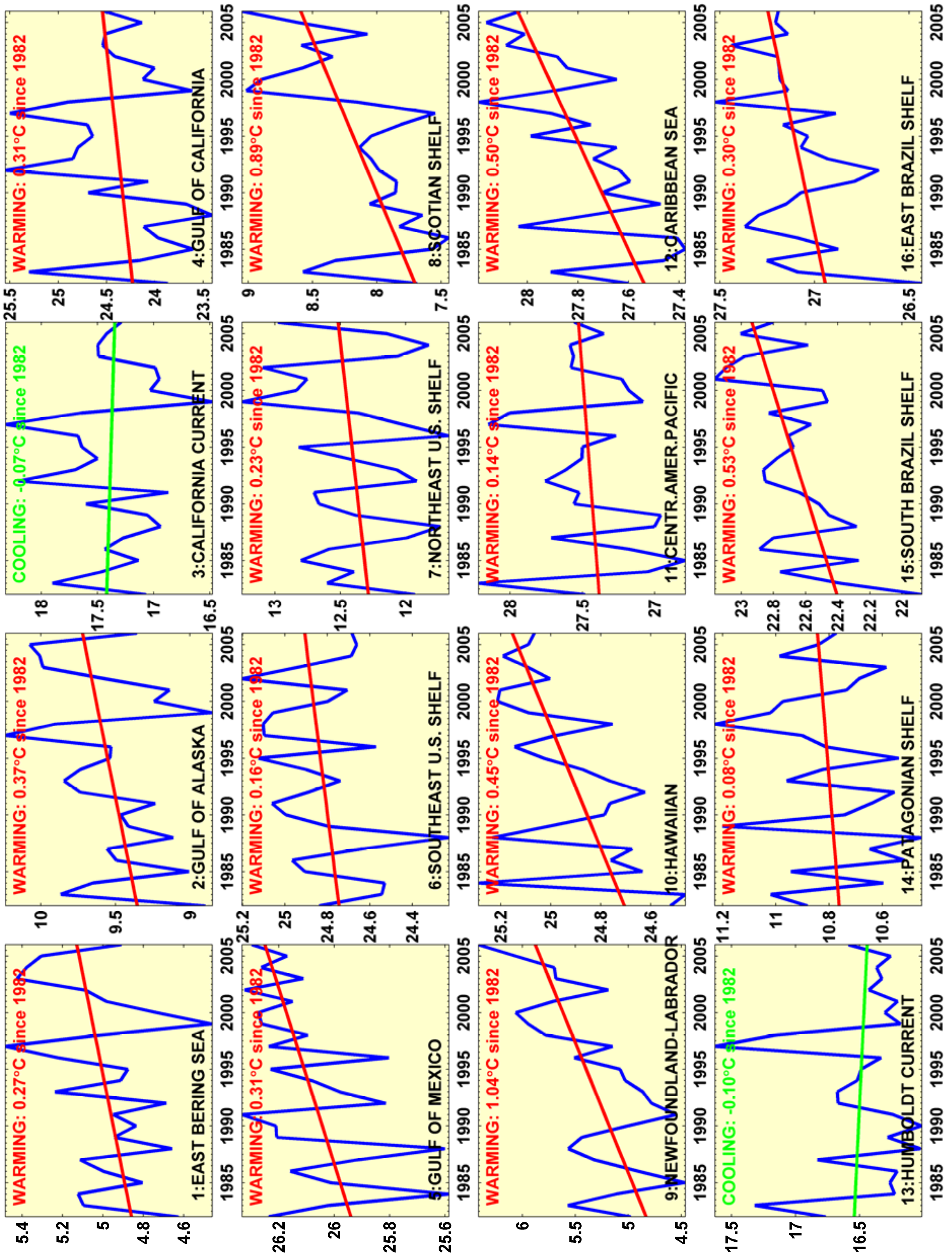
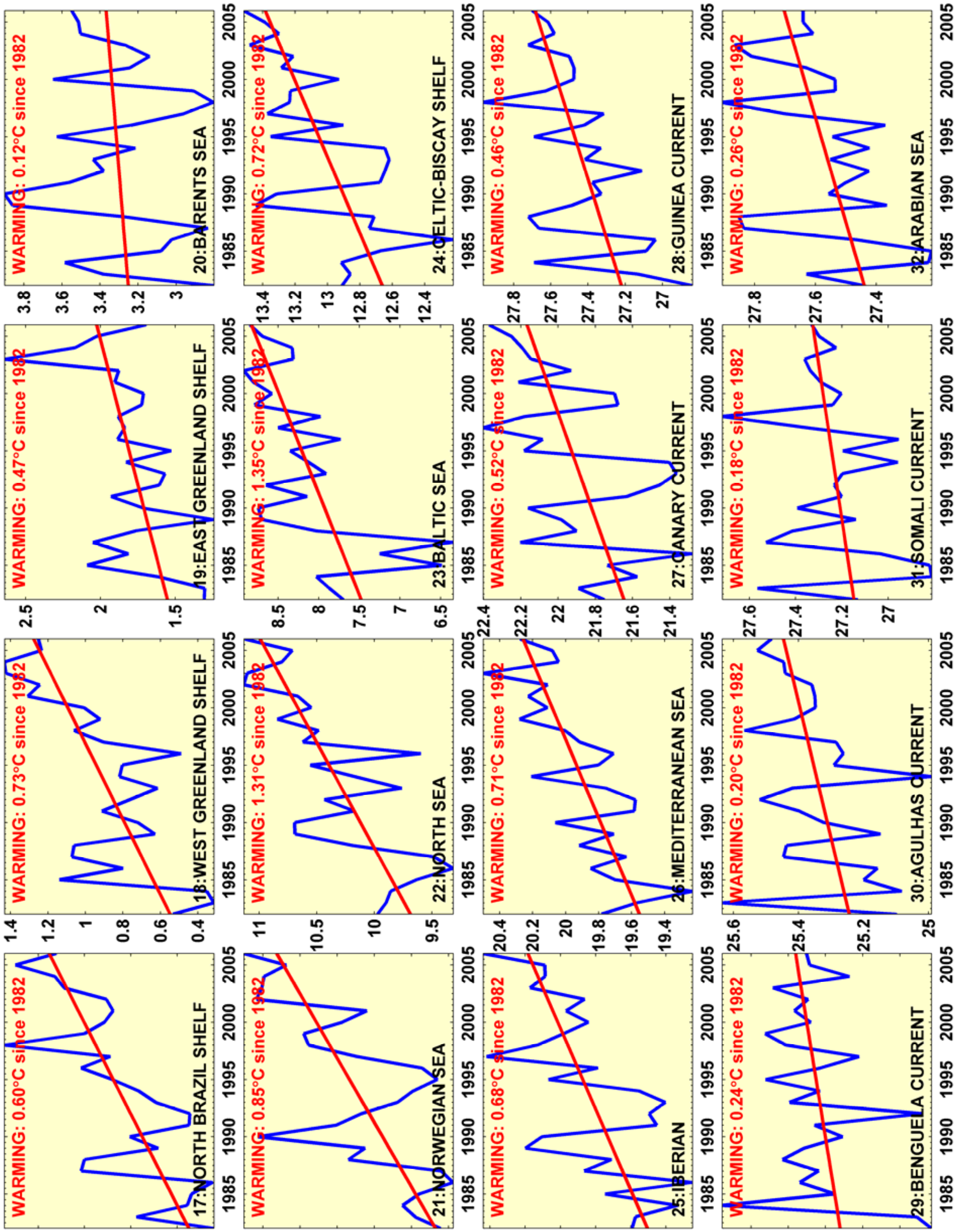
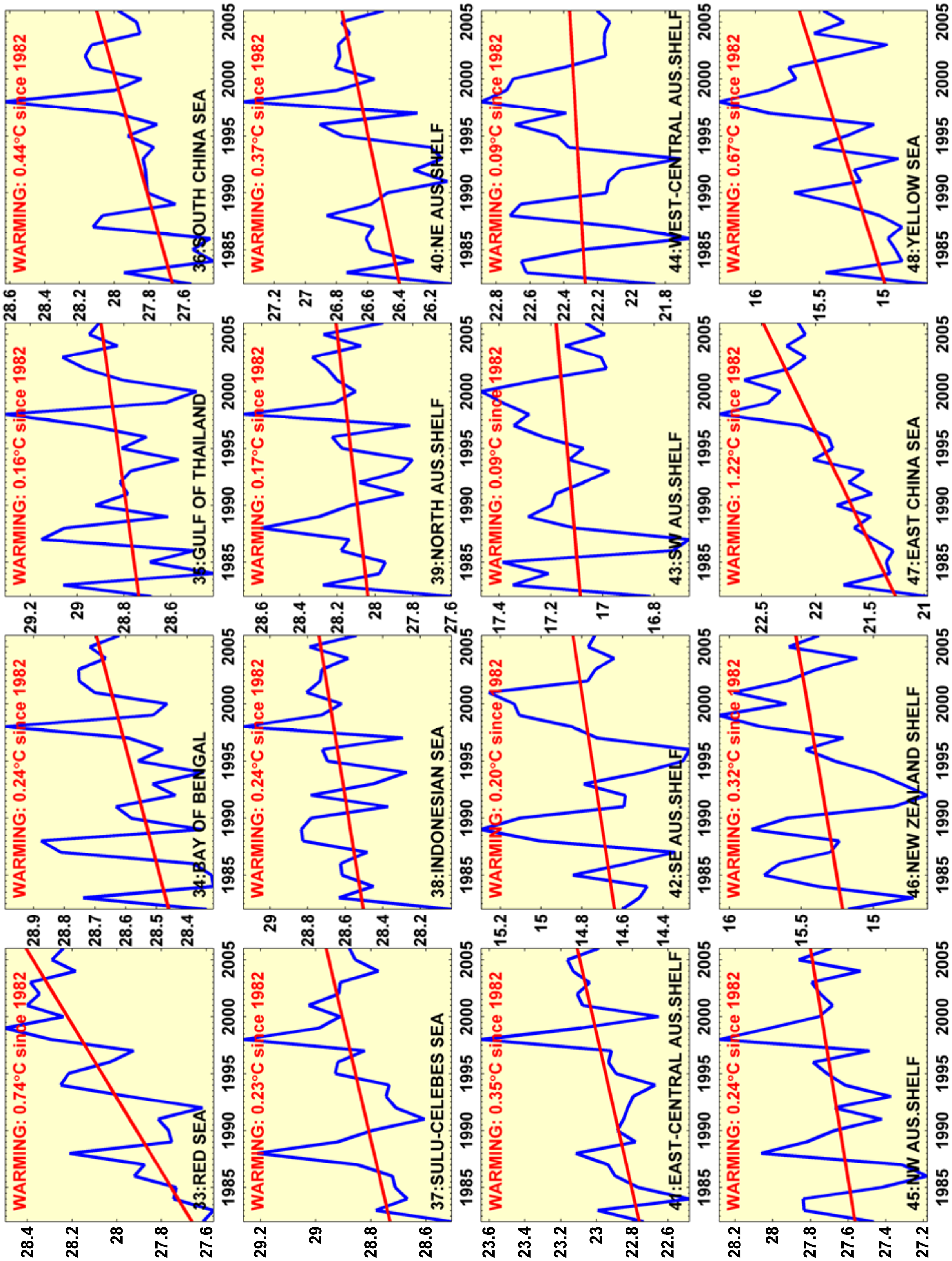
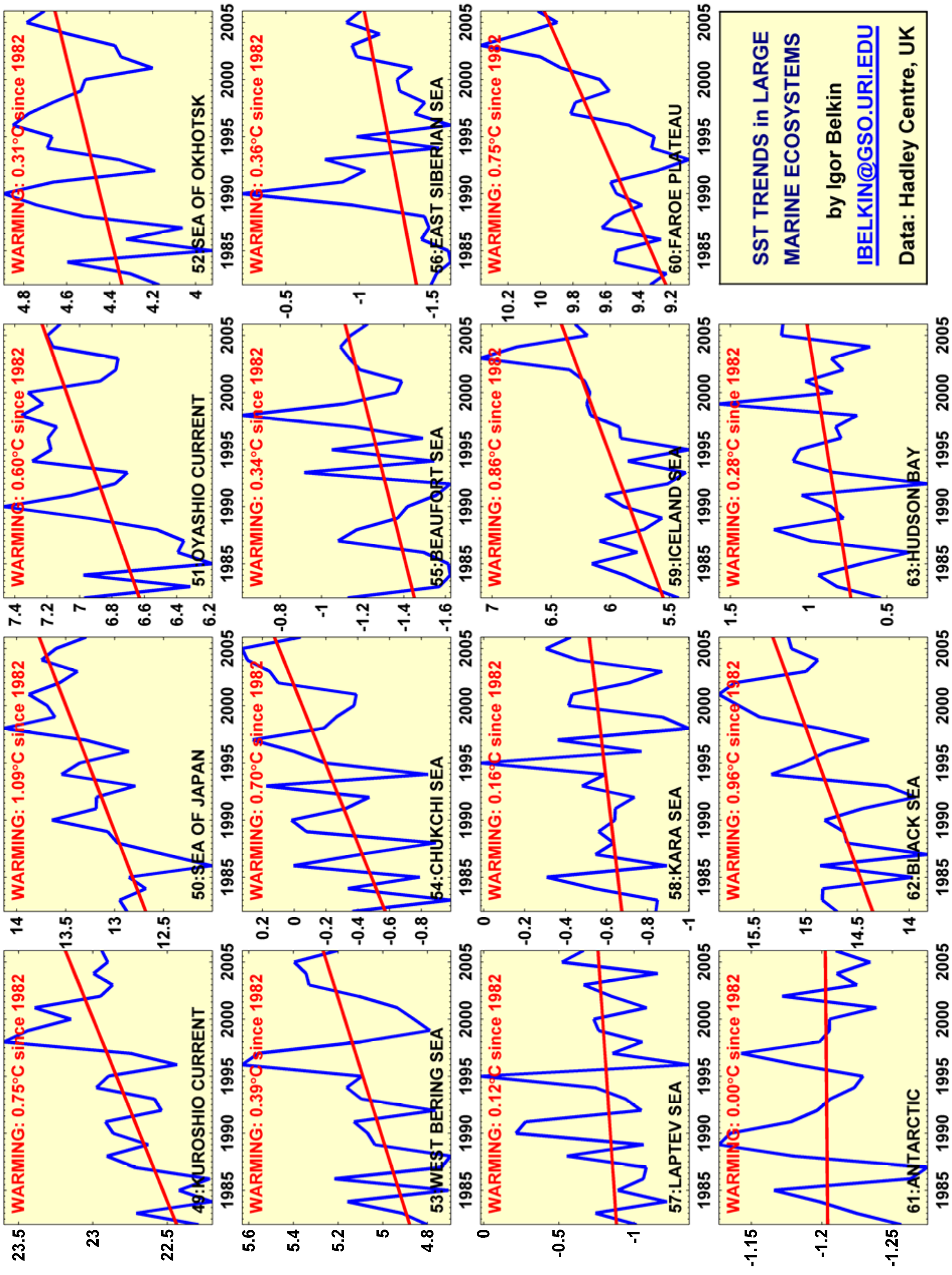
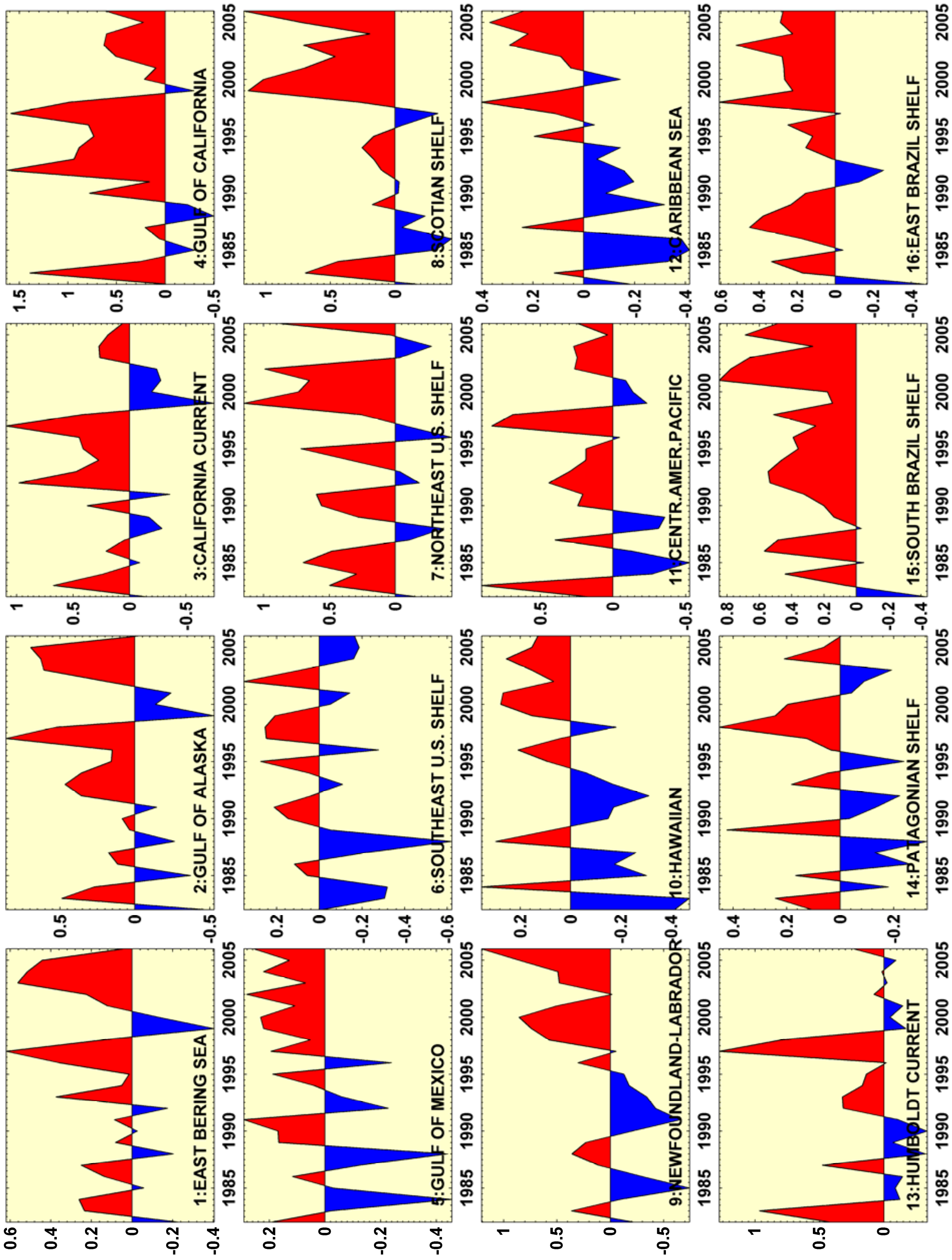
APPENDIX 1. Mean annual SST for all LMEs and SST anomalies, 1982-2006.

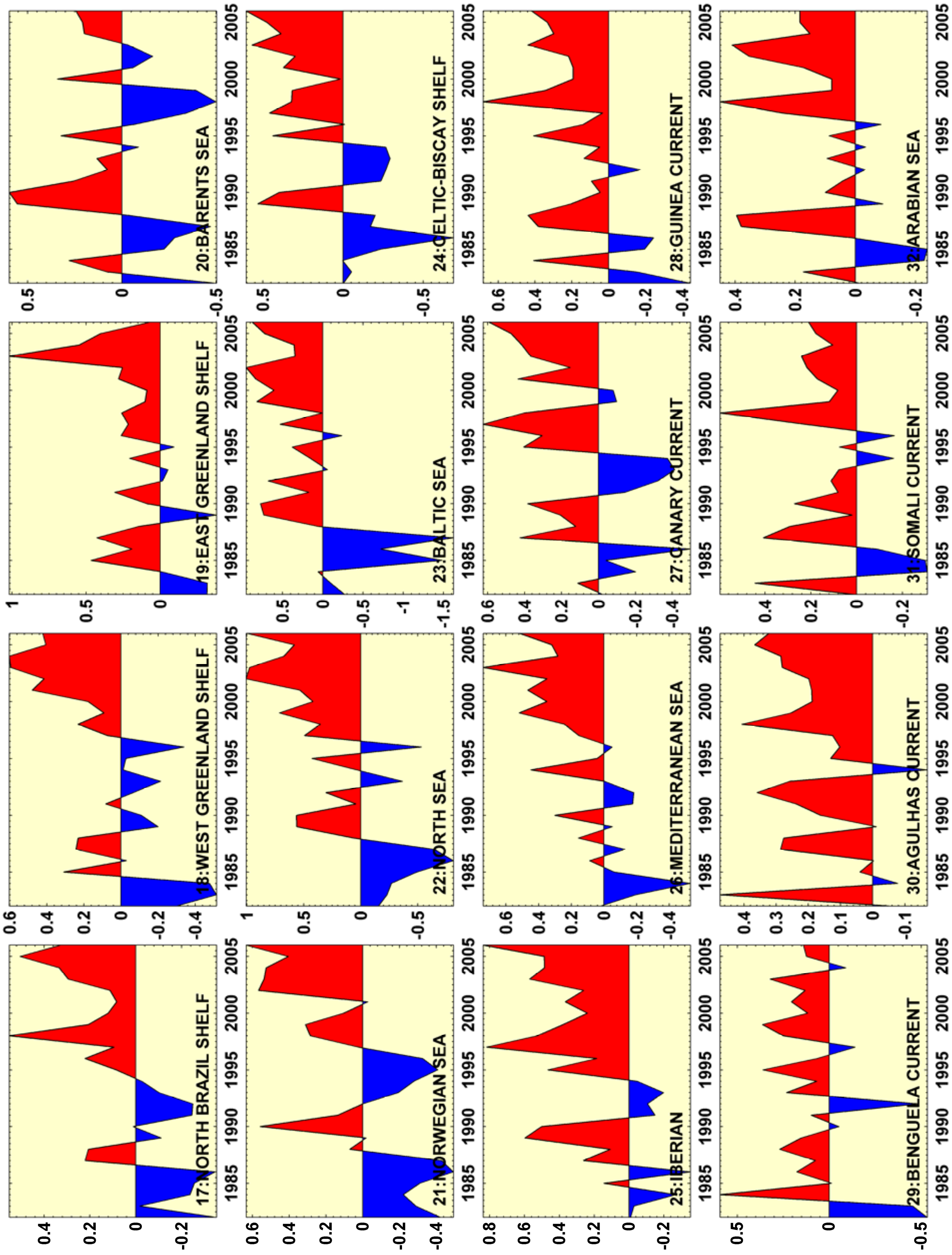


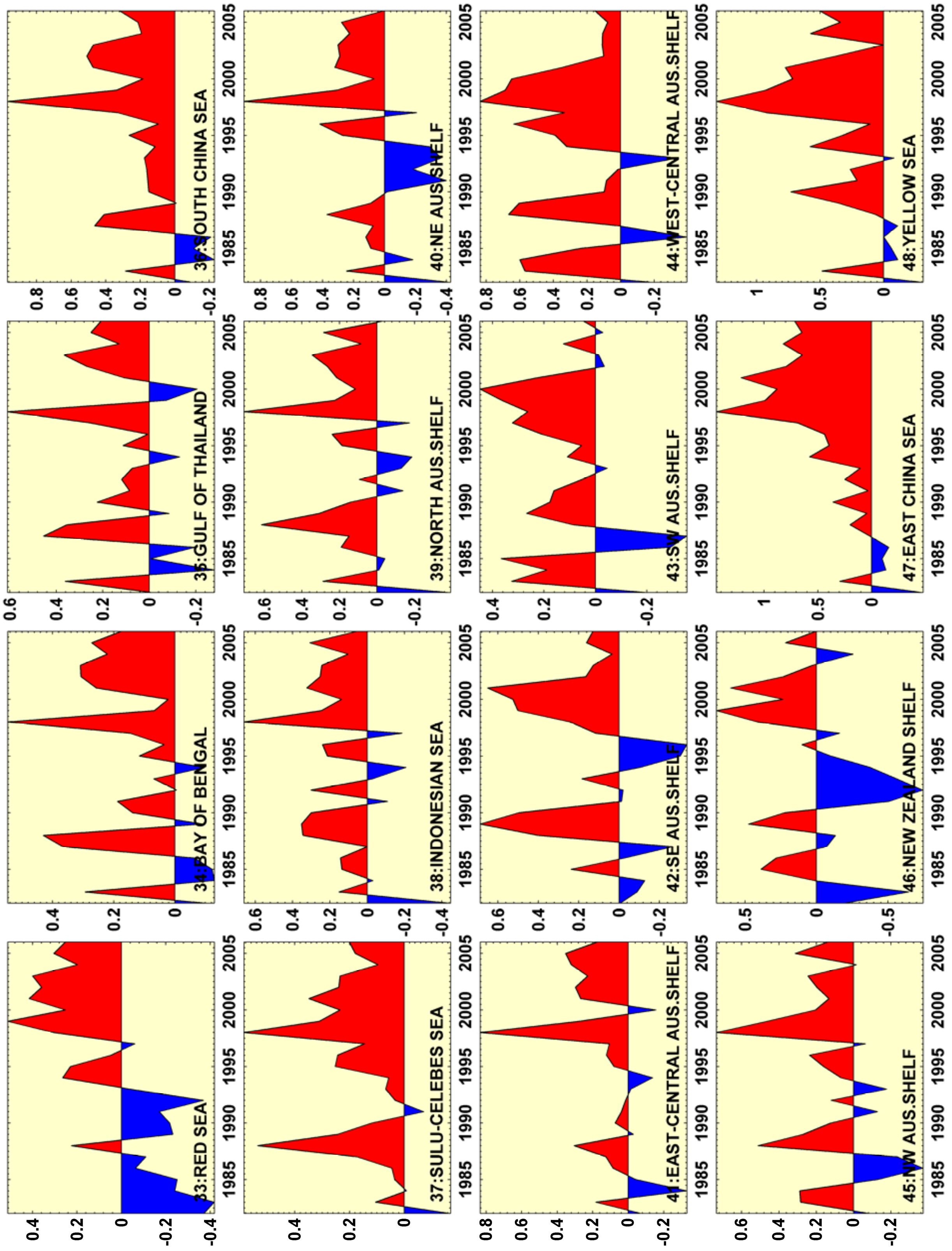

17:NORTH BRAZIL SHELF
WARMING: 0.60°C since 1982
28.2
28
27.8
27.6
18:WEST GREENLAND SHELF
WARMING: 0.73°C since 1982
1.4
1.2
1
0.8
0.6
0.4
19:EAST GREENLAND SHELF
WARMING: 0.47°C since 1982
2.5
2
1.5
20:BARENTS SEA
WARMING: 0.12°C since 1982
3.8
3.6
3.4
3.2
3
21:NORWEGIAN SEA
WARMING: 0.85°C since 1982
9
8.8
8.6
8.4
8.2
8
22:NORTH SEA
WARMING: 1.31°C since 1982
11
10.5
10
9.5
23:BALTIC SEA
WARMING: 1.35°C since 1982
8.5
8
7.5
7
6.5
24:CELTIC-BISCAY SHELF
WARMING: 0.72°C since 1982
13.4
13.2
13
12.8
12.6
12.4
25:IBERIAN
WARMING: 0.68°C since 1982
17.4
17.2
17
16.8
16.6
16.4
26:MEDITERRANEAN SEA
WARMING: 0.71°C since 1982
20.4
20.2
20
19.8
19.6
19.4
27:CANARY CURRENT
WARMING: 0.52°C since 1982
22.4
22.2
22
21.8
21.6
21.4
28:GUINEA CURRENT
WARMING: 0.46°C since 1982
27.8
27.6
27.4
27.2
27
29:BENGUELA CURRENT
WARMING: 0.24°C since 1982
21
20.8
20.6
20.4
20.2
30:AGULHAS CURRENT
WARMING: 0.20°C since 1982
25.6
25.4
25.2
25
31:SOMALI CURRENT
WARMING: 0.18°C since 1982
27.6
27.4
27.2
27
32:ARABIAN SEA
WARMING: 0.26°C since 1982
27.8
27.6
27.4
1985
1990
1995
2000
2005

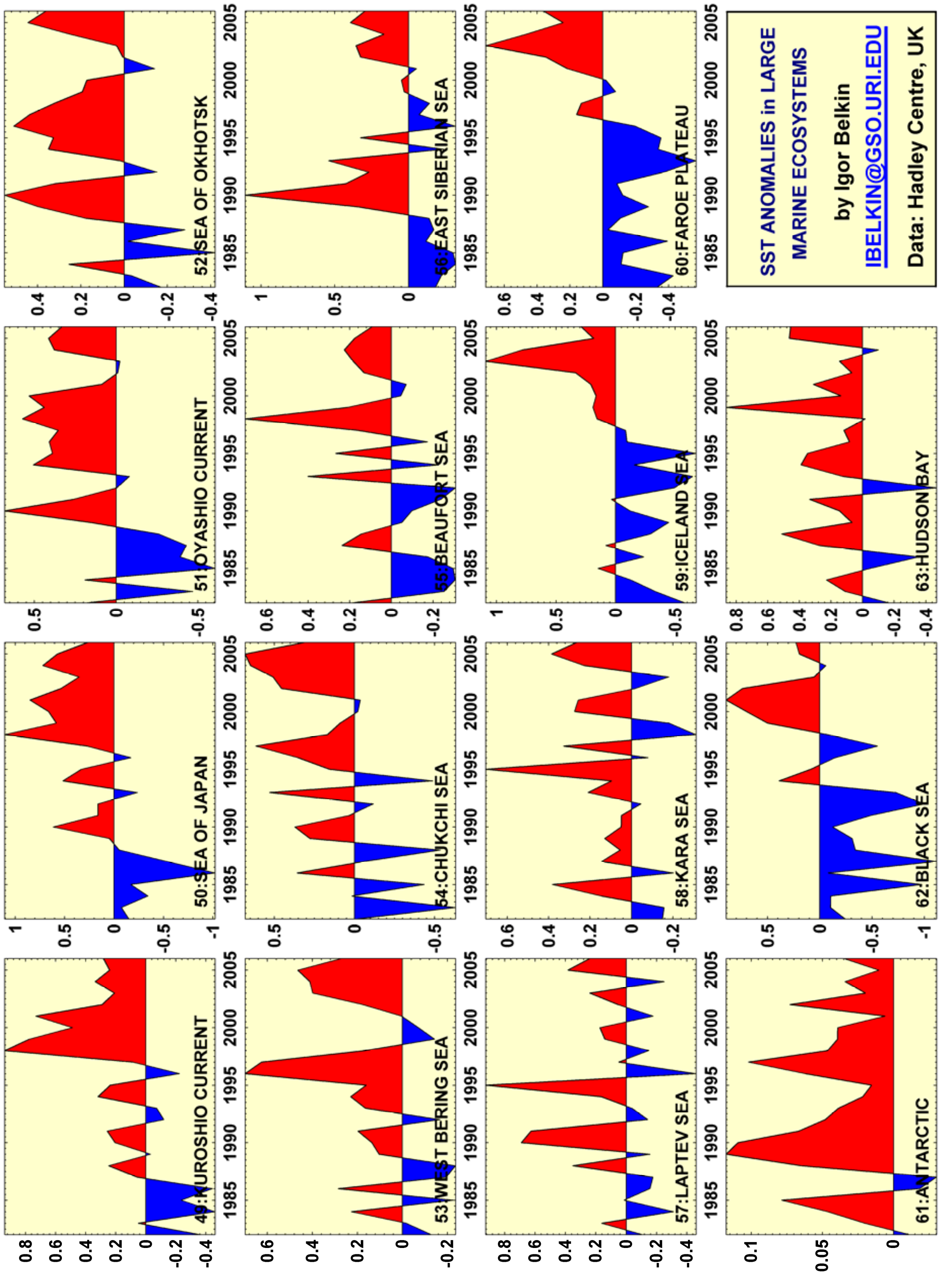

WARMING: 0.74°C since 1982
33:RED SEA
WARMING: 0.24°C since 1982
34:BAY OF BENGAL
WARMING: 0.16°C since 1982
35:GULF OF THAILAND
WARMING: 0.44°C since 1982
36:SOUTH CHINA SEA
WARMING: 0.23°C since 1982
37:SULU-CELEBES SEA
WARMING: 0.24°C since 1982
38:INDONESIAN SEA
WARMING: 0.17°C since 1982
39:NORTH AUS.SHELF
WARMING: 0.37°C since 1982
40:NE AUS.SHELF
WARMING: 0.35°C since 1982
41:EAST-CENTRAL AUS.SHELF
WARMING: 0.20°C since 1982
42:SE AUS.SHELF
WARMING: 0.09°C since 1982
43:SW AUS.SHELF
WARMING: 0.09°C since 1982
44:WEST-CENTRAL AUS.SHELF
WARMING: 0.24°C since 1982
45:NW AUS.SHELF
WARMING: 0.32°C since 1982
46:NEW ZEALAND SHELF
WARMING: 1.22°C since 1982
47:EAST CHINA SEA
WARMING: 0.67°C since 1982
48:YELLOW SEA
1985
1990
1995
2000
2005


49:KUROSHIO CURRENT
WARMING: 0.75°C since 1982
50:SEA OF JAPAN
WARMING: 1.09°C since 1982
51:OYASHIO CURRENT
WARMING: 0.60°C since 1982
52:SEA OF OKHOTSK
WARMING: 0.31°C since 1982
53:WEST BERING SEA
WARMING: 0.39°C since 1982
54:CHUKCHI SEA
WARMING: 0.70°C since 1982
55:BEAUFORT SEA
WARMING: 0.34°C since 1982
56:EAST SIBERIAN SEA
WARMING: 0.36°C since 1982
57:LAPTEV SEA
WARMING: 0.12°C since 1982
58:KARA SEA
WARMING: 0.16°C since 1982
59:ICELAND SEA
WARMING: 0.86°C since 1982
60:FAROE PLATEAU
WARMING: 0.75°C since 1982
61:ANTARCTIC
WARMING: 0.00°C since 1982
62:BLACK SEA
WARMING: 0.96°C since 1982
63:HUDSON BAY
WARMING: 0.28°C since 1982
1985
1990
1995
2000
2005
SST TRENDS in LARGE
MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK

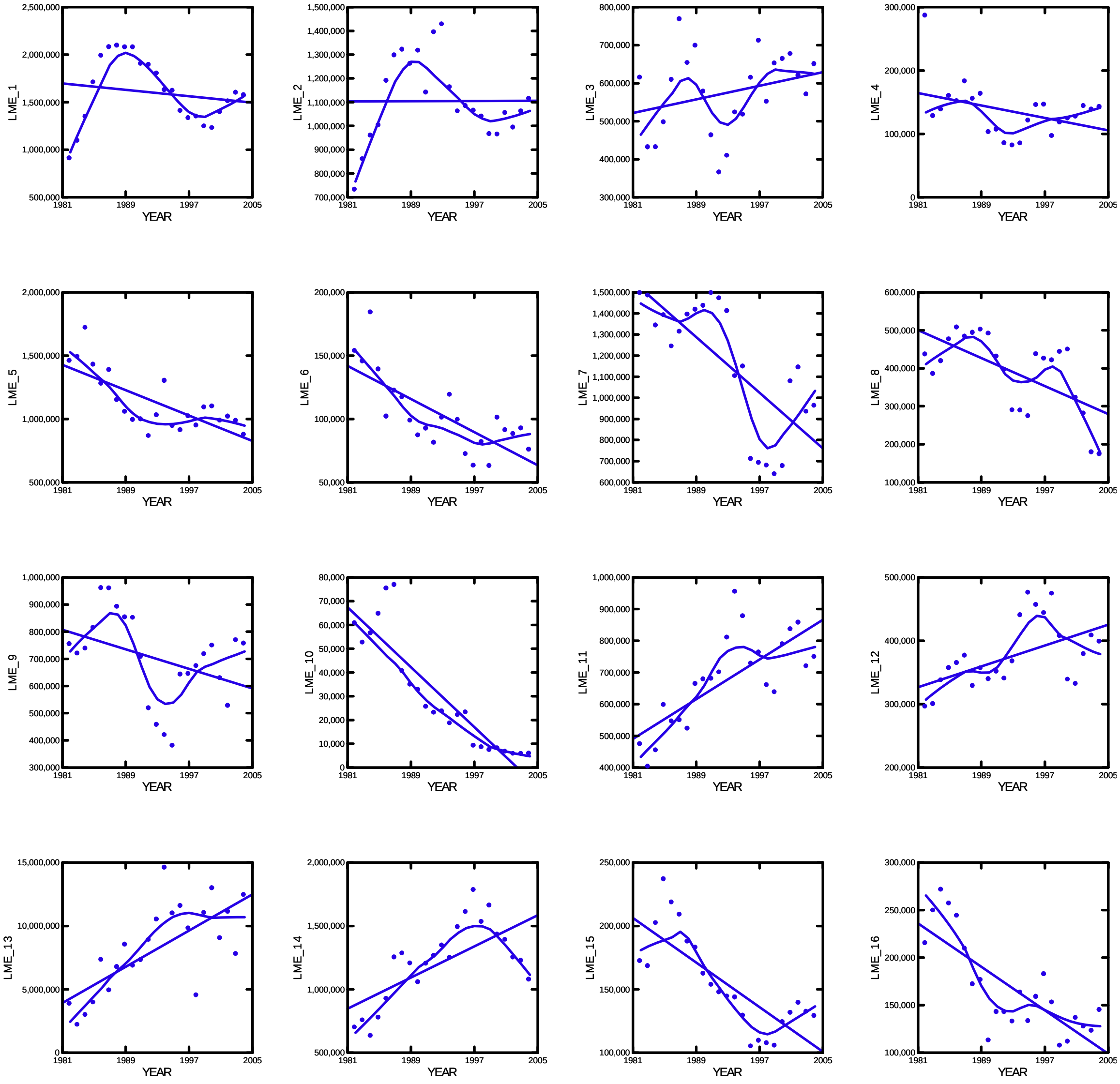

1:EAST BERING SEA
2:GULF OF ALASKA
3:CALIFORNIA CURRENT
4:GULF OF CALIFORNIA
5:GULF OF MEXICO
6:SOUTHEAST U.S. SHELF
7:NORTHEAST U.S. SHELF
8:SCOTIAN SHELF
9:NEWFOUNDLAND-LABRADOR
10:HAWAIIAN
11:CENTR.AMER.PACIFIC
12:CARIBBEAN SEA
13:HUMBOLDT CURRENT
14:PATAGONIAN SHELF
15:SOUTH BRAZIL SHELF
16:EAST BRAZIL SHELF
1985
1990
1995
2000
2005

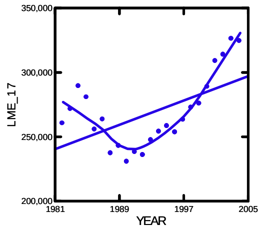

17:NORTH BRAZIL SHELF
18:WEST GREENLAND SHELF
19:EAST GREENLAND SHELF
20:BARENTS SEA
21:NORWEGIAN SEA
22:NORTH SEA
23:BALTIC SEA
24:CELTIC-BISCAY SHELF
25:IBERIAN
26:MEDITERRANEAN SEA
27:CANARY CURRENT
28:GUINEA CURRENT
29:BENGUELA CURRENT
30:AGULHAS CURRENT
31:SOMALI CURRENT
32:ARABIAN SEA
1985
1990
1995
2000
2005

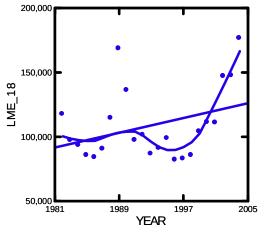

33:RED SEA
34:BAY OF BENGAL
35:GULF OF THAILAND
36:SOUTH CHINA SEA
37:SULU-CELEBES SEA
38:INDONESIAN SEA
39:NORTH AUS.SHELF
40:NE AUS.SHELF
41:EAST-CENTRAL AUS.SHELF
42:SE AUS.SHELF
43:SW AUS.SHELF
44:WEST-CENTRAL AUS.SHELF
45:NW AUS.SHELF
46:NEW ZEALAND SHELF
47:EAST CHINA SEA
48:YELLOW SEA
1985
1990
1995
2000
2005

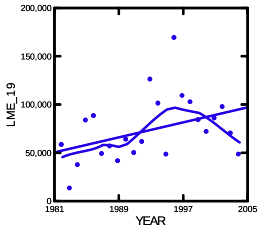

49:KUROSHIO CURRENT
50:SEA OF JAPAN
51:OYASHIO CURRENT
52:SEA OF OKHOTSK
53:WEST BERING SEA
54:CHUKCHI SEA
55:BEAUFORT SEA
56:EAST SIBERIAN SEA
57:LAPTEV SEA
58:KARA SEA
59:ICELAND SEA
60:FAROE PLATEAU
61:ANTARCTIC
62:BLACK SEA
63:HUDSON BAY
1985
1990
1995
2000
2005
SST ANOMALIES in LARGE
MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK

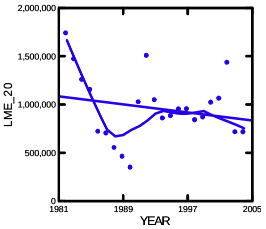
APPENDIX 2. Fishery biomass yields by year for Large Marine Ecosystems, linear regression lines cover the period 1982-2004, smoothing curves are LOWESS smoothers at tension=0.5. LME numbers correspond to the LME numbers in Figure 1, p.42 (this volume).




350,000
300,000
250,000
200,000
LME_17
1981
1989
1997
2005
YEAR


200,000
150,000
100,000
50,000
LME_18
1981
1989
1997
2005
YEAR


200,000
150,000
100,000
50,000
0
LME_19
1981
1989
1997
2005
YEAR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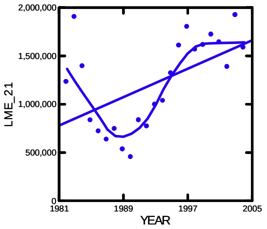
1,000,000
500,000
0
LME_20
1981
1989
1997
2005
YEAR


2,000,000
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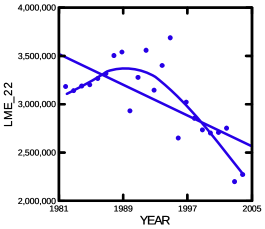
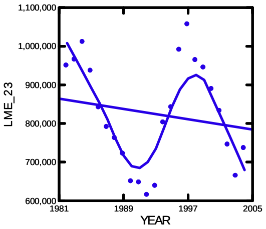
1,000,000
500,000
0
LME_21
1981
1989
1997
2005
YEAR


4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
LME_22
1981
1989
1997
2005
YEAR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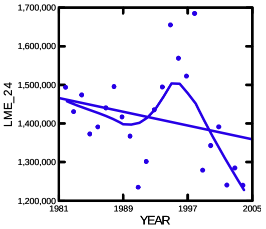
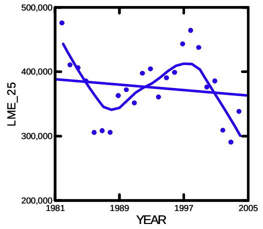
1,000,000
900,000
800,000
700,000
600,000
LME_23
1981
1989
1997
2005
YEAR


1,700,000
1,600,000
1,500,000
1,400,000
1,300,000
1,200,000
LME_24
1981
1989
1997
2005
YEAR


500,000
400,000
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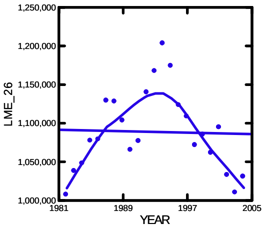
LME_25
1981
1989
1997
2005
YEAR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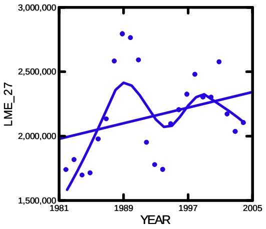
1,100,000
1,050,000
1,000,000
LME_26
1981
1989
1997
2005
YEAR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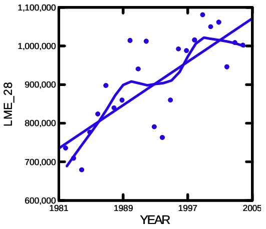
LME_27
1981
1989
1997
2005
YEAR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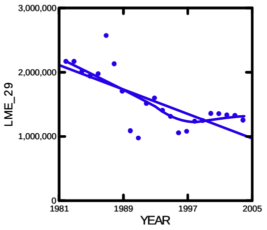
LME_28
1981
1989
1997
2005
YEAR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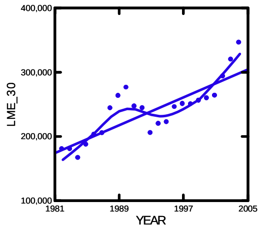
0
LME_29
1981
1989
1997
2005
YEAR


400,000
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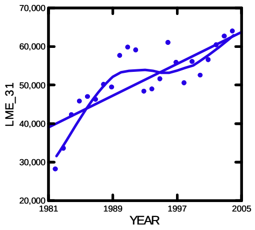
LME_30
1981
1989
1997
2005
YEAR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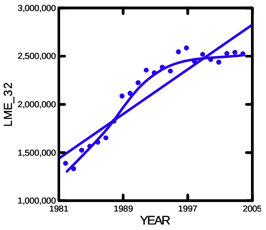
LME_31
1981
1989
1997
2005
YEAR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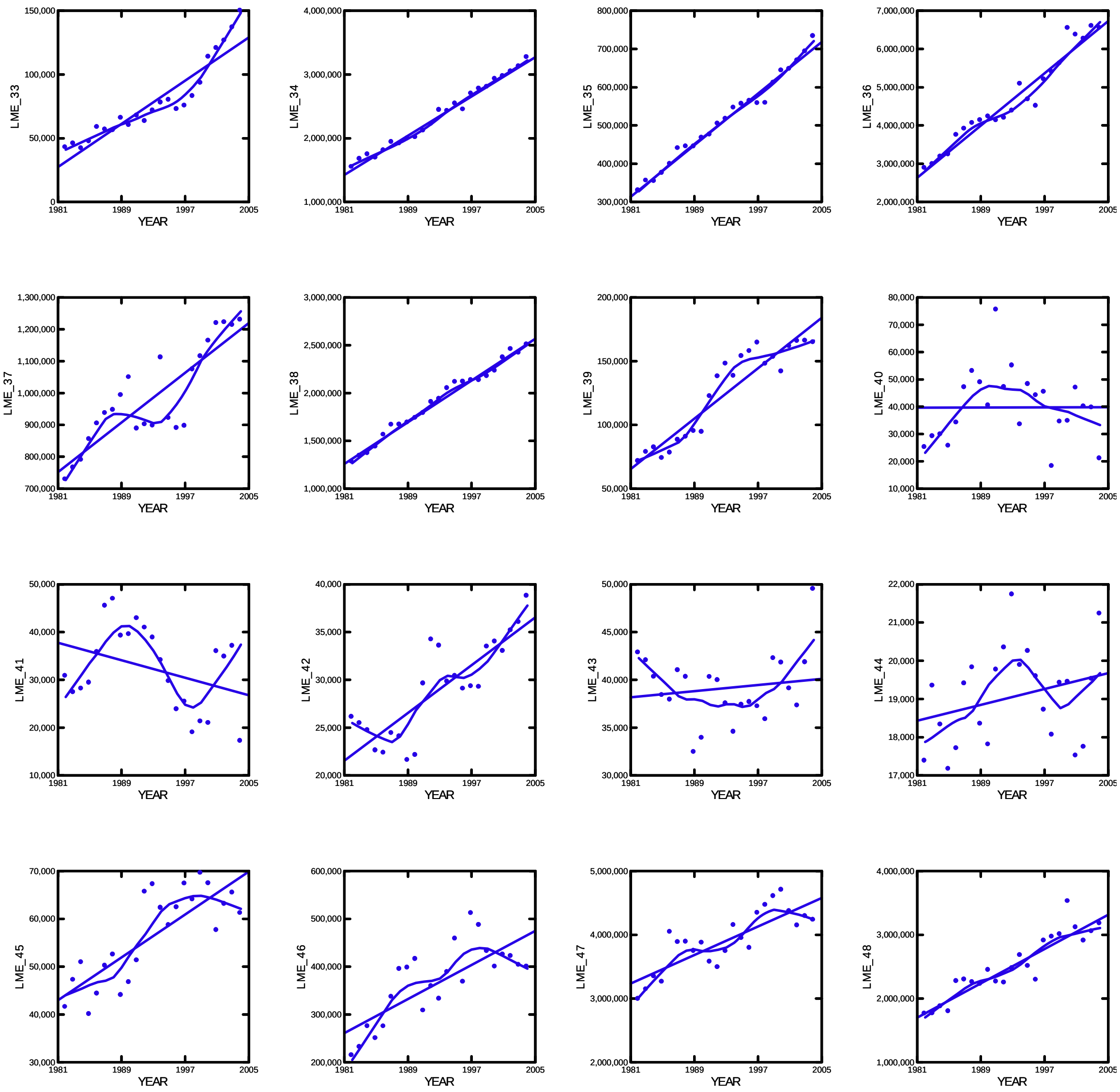
1,500,000
1,000,000
LME_32
1981
1989
1997
2005
YEAR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50,000
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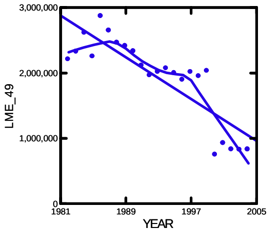
LME_34
4,000,000
3,000,000
2,000,000
1,000,000
LME_35
800,000
700,000
600,000
500,000
400,000
300,000
LME_36
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
LME_37
1,300,000
1,200,000
1,100,000
1,000,000
900,000
800,000
700,000
LME_38
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
LME_39
200,000
150,000
100,000
50,000
LME_40
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
LME_41
50,000
40,000
30,000
20,000
10,000
LME_42
40,000
35,000
30,000
25,000
20,000
LME_43
50,000
45,000
40,000
35,000
30,000
LME_44
22,000
21,000
20,000
19,000
18,000
17,000
LME_45
70,000
60,000
50,000
40,000
30,000
LME_46
600,000
500,000
400,000
300,000
200,000
LME_47
5,000,000
4,000,000
3,000,000
2,000,000
LME_48
4,000,000
3,000,000
2,000,000
1,000,000
1981
1989
1997
2005
YEAR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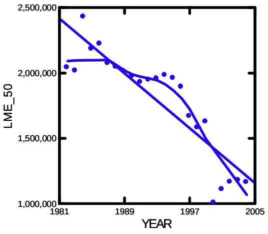
1989
1997
2005
YEAR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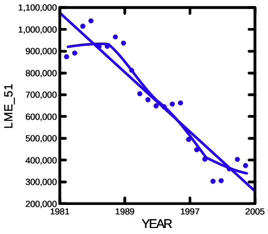
1981
1989
1997
2005
YEAR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700,000
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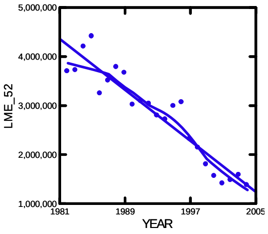
300,000
200,000
1981
1989
1997
2005
YEAR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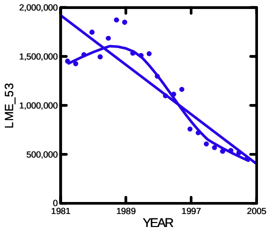
1989
1997
2005
YEAR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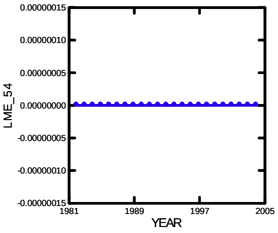
1981
1989
1997
2005
YEAR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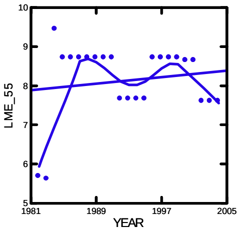
1989
1997
2005
YEAR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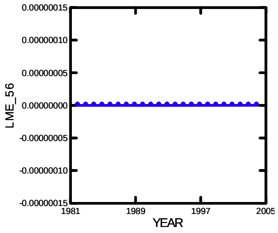
10
9
8
7
6
5
1981
1989
1997
2005
YEAR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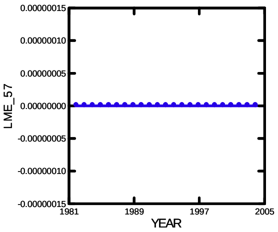
-0.00000010
-0.00000015
1981
1989
1997
2005
YEAR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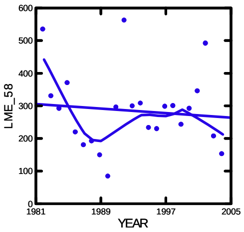
1989
1997
2005
YEAR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500
400
300
200
100
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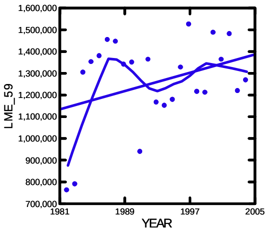
1981
1989
1997
2005
YEAR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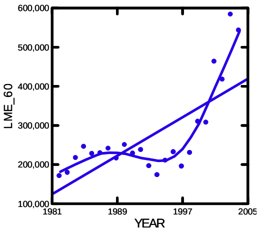
1981
1989
1997
2005
YEAR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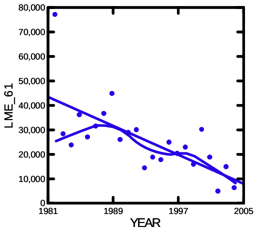
1981
1989
1997
2005
YEAR


LME_61
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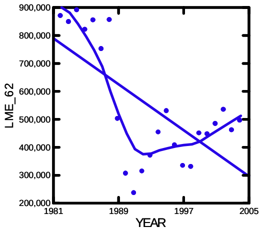
1981
1989
1997
2005
YEAR


LME_62
900,000
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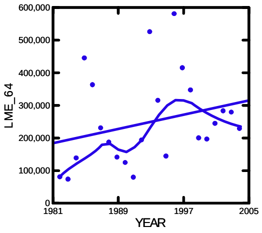
700,000
600,000
500,000
400,000
300,000
200,000
1981
1989
1997
2005
YEAR


LME_64
600,000
500,000
400,000
300,000
200,000
100,000
0
1981
1989
1997
2005
YEAR

Land-based Nutrient Loading to LMEs: A Global Watershed Perspective on Magnitudes and Sources

Sybil P. Seitzinger and Rosalynn Y. Lee

Abstract

Land-based nutrient (nitrogen and phosphorus) inputs to coastal systems around the world have markedly increased due primarily to the production of food and energy to support the growing population of over 6 billion people. The resulting nutrient enrichment has contributed to coastal eutrophication, degradation of water quality and coastal habitats, and increases in hypoxic waters, among other effects. There is a critical need to understand the quantitative links between anthropogenic activities in watersheds, nutrient inputs to coastal systems, and coastal ecosystem effects. As a first step in the process to gain a global perspective on the problem, a spatially explicit global watershed model (NEWS) was used to relate human activities and natural processes in watersheds to nutrient inputs to LMEs, with a focus on nitrogen.

Many LMEs are currently hotspots of nitrogen loading in both developed and developing countries. A clear understanding of the relative contribution of different nutrient sources within an LME is needed to support development of effective policies. In 73% of LMEs, anthropogenic sources account for over half of the dissolved inorganic nitrogen (DIN) exported by rivers to the coast. In most of these, agricultural activities (fertilizer use and wastes from livestock) are the dominant source of DIN loading, although atmospheric deposition and, in a few LMEs, sewage can also be important.

Over the next 50 years, human population, agricultural production, and energy production are predicted to increase especially rapidly in many developing regions of the world. Regions of particular note are in southern and eastern Asia, western Africa, and Latin America. Unless substantial technological innovations and management changes are implemented, this will lead to further increases in nutrient inputs to LME coastal waters with associated water quality and ecosystem degradation. An approach is needed such as that being developed in GEF-sponsored LMEs programs where all stakeholders – including scientists, policy makers and private sector leaders – work together to develop a better understanding of the issues and to identify and implement workable solutions.

Introduction of the Problem

Human activities related to food and energy production have greatly increased the amount of nutrient pollution entering the coastal environment from land-based sources (Howarth et al. 1996; Seitzinger and Kroeze 1998; Galloway et al. 2004; Green et al. 2004). Small amounts of nutrient enrichment can have beneficial impacts to some coastal waters and marine ecosystems by increasing primary production which can have potentially positive impacts on higher trophic levels. However, a high degree of nitrogen and phosphorus enrichment, causing eutrophication of coastal and even inland waters, tends towards detrimental effects including degradation of fisheries habitats. The negative effects of eutrophication begin with nutrient uptake by primary producers that can result in blooms of phytoplankton, macroalgae, and nuisance/toxic algae. When phytoplankton blooms die and sink, decomposition of the biomass consumes and may deplete dissolved oxygen in the bottom water resulting in hypoxic or “dead zones.” There are many other effects of nutrient over-enrichment including increased water turbidity, loss of habitat (e.g., seagrasses), decreases in coastal biodiversity and distribution of species, increase in frequency and severity of harmful and nuisance algal blooms, and coral reef degradation, among others (National Research Council 2000; Diaz et al. 2001; Rabalais 2002).

Nutrient over-enrichment and associated coastal ecosystem effects are occurring in many areas throughout the world and a number of recent assessments have begun to document their regional and global distribution. The European Outlook reported that in 2000, more than 55% of ecosystems were endangered by eutrophication. This includes the notable hypoxic/anoxic zones in the Baltic Sea, Black Sea and Adriatic Sea, among many others. In the USA, a recent assessment of over 140 coastal systems by the National Oceanic and Atmospheric Administration found that in 2004 50% of the assessed estuaries had a high chlorophyll a (phytoplankton) rating and 65% of the assessed estuaries were moderately to highly eutrophic (Bricker et al. 2007). In a recent literature review by the World Resources Institute (Selman et al. 2008), 375 eutrophic and hypoxic coastal systems were identified around the world, including many areas in developing countries.

The need to address nutrient over-enrichment as a priority threat to coastal waters and Large Marine Ecosystems (LMEs) has been recognized at national and global levels. The Global Plan of Action for the Protection of the Marine Environment from Land-based Activities (GPA), which was adopted by 108 Governments and the European Commission in 1995, recognized the need for global, regional and national action to address nutrients impacting the coastal and marine environment. Continued widespread government support to address nutrients has been noted in both the Montreal and Beijing Declarations. In 2002, the World Summit on Sustainable Development convened in Johannesburg identified substantial reductions in land-based sources of pollution by 2006 as one of their 4 marine targets. Over 60 countries have developed national policies or national action plans to address coastal nutrient-enrichment within the context of sustainable development of coastal areas and their associated watersheds.

Over the next 50 years, human population, agricultural production, and energy production are predicted to increase especially rapidly in many developing regions of the world (Hassan et al. 2005). Unless substantial technological innovations and management changes are implemented, this will lead to further increases in nutrient (nitrogen and phosphorus) inputs to the coastal zone with associated water quality and ecosystem degradation. In order to optimize use of land for food and energy production while at the same time minimizing degradation of coastal habitats, there is a critical need to understand the quantitative links between land-based activities in watersheds, nutrient inputs to coastal systems, and coastal ecosystem effects.

In this chapter we primarily address the links between land-based activities in watersheds and nutrient inputs to coastal systems around the world. Here we use a global watershed model (NEWS) to examine the patterns of nutrient loading and source attribution at global and regional scales and then apply the model at the scale of large marine ecosystems (LMEs) (Sherman & Duda 1999). Within all LMEs, 80% of the world's marine capture fisheries occur (Sherman 2008) which emphasizes the importance of cross political-boundary management of these international marine ecosystem units, as in the Global International Waters Assessment (GIWA; UNEP 2006). Various aspects including ecosystem productivity, fish and fisheries, pollution and ecosystem health, socioeconomic conditions, and governance, have been examined for many individual LMEs, but limited assessments across all LMEs have been made with a primarily fisheries emphasis (e.g., Sea Around Us Project 2007). In individual LMEs, few estimates of nutrient loading have been made, and only in the Baltic Sea LME has source apportionment been investigated (HELCOM 2004, 2002). At the end of the chapter we return to coastal ecosystem effects.

A Watershed Perspective

Rivers are a central link in the chain of nutrient transfer from watersheds to coastal.systems. Nutrient inputs to watersheds include natural (biological N_2-fixation, weathering of rock releasing phosphate) as well as many anthropogenic sources. At the global scale, anthropogenic nitrogen inputs to watersheds are now greater than natural inputs (Galloway et al. 2004). Anthropogenic nutrient inputs are primarily related to food and energy production to support the over 6 billion people on Earth with major sources including fertilizer, livestock production, sewage, and atmospheric nitrate deposition resulting from NOx emissions from fossil fuel combustion.

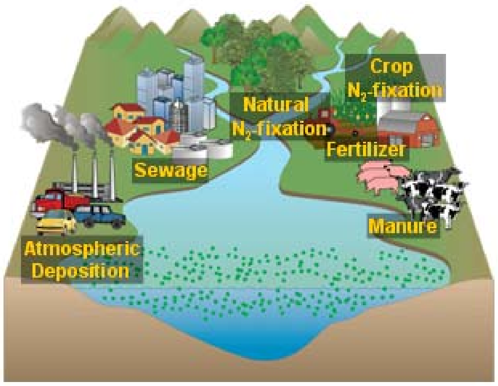


Figure 1. Watershed schematic of nitrogen inputs and transport to coastal systems. Symbols for diagram courtesy of the Integration and Application Network (ian.umces.edu/symbols), University of Maryland Center for Environmental Science.

Uneven spatial distribution of human population, agriculture, and energy production leads to spatial differences in the anthropogenic alterations of nutrient inputs to coastal ecosystems (Howarth et al. 1996; Seitzinger and Kroeze 1998; Green et al. 2004; Seitzinger et al. 2005). While many site-specific studies have documented river transport of nutrients (nitrogen (N), phosphorus (P), carbon (C) and silica (Si)) to coastal systems, there are many more rivers for which there are no measurements; sustained monitoring of temporal changes in exports is rarer still. A mechanism is needed to develop a comprehensive and quantitative global view of nutrient sources, controlling factors and nutrient loading to coastal systems around the world under current conditions, as well as to be able to look at past conditions and plausible future scenarios.

A Global Watershed Nutrient Export Model (NEWS)

In order to provide regional and global perspectives on changing nutrient transport to coastal systems throughout the world, an international workgroup (Global NEWS – Nutrient Export from WaterSheds; http://www.marine.rutgers.edu/globalnews) has developed a spatially explicit global watershed model that relates human activities and natural processes in watersheds to nutrient inputs to coastal systems throughout the world (Beusen et al. 2005; Dumont et al. 2005; Harrison et al. 2005a and b; Seitzinger et al. 2005). Global NEWS is an interdisciplinary workgroup of UNESCO's Intergovernmental Oceanographic Commission (IOC) focused on understanding the relationship between human activity and coastal nutrient enrichment.

In addition to current predictions, the NEWS model is also being used to hindcast and forecast changes in nutrient, carbon and water inputs to coastal systems under a range of scenarios. In this chapter we briefly describe the NEWS model and then present results for mid-1990's conditions at both global scales and as specifically applied to LME regions.

NEWS Model Basics. The NEWS model is a multi-element, multi-form, spatially explicit global model of nutrient (N, P, and C) export from watersheds by rivers (Table 1). The model output is the annual export at the mouth of the river (essentially zero salinity). The NEWS model was calibrated and validated with measured export near the river mouth from rivers representing a broad range of basins sizes, climates, and land-uses. Over 5000 watersheds are included in the model with the river network and water discharge defined by STN-30 (Fekete et al. 2000; Vörösmarty et al. 2000a and b). The input databases are at the scale of 0.5^o latitude by 0.5^o longitude.

***Table 1.* Nutrient forms modeled in Global NEWS. DIC and DSi sub-models (in italics) are currently in development.**

	Dissolved		Particulate
	Inorganic	Organic	
N	DIN	DON	PN
P	DIP	DOP	PP
C	*DIC*	DOC	POC
Si	*DSi*		

Whereas previous efforts have generally been limited to a single element or form, the Global NEWS model is unique in that it can be used to predict magnitudes and sources of multiple bio-active elements (C, N, and P) and forms (dissolved/particulate, organic/inorganic). It is important to know coastal nutrient loading of multiple elements because different elements and elemental ratios can have different ecosystem effects. The various forms of the nutrients (dissolved inorganic and organic and particulate forms) also have different bioreactivities. For example, the dissolved inorganic nitrogen (DIN) pool is generally considered to be bio-available, while only a portion of river transported dissolved organic nitrogen (DON) is readily available for uptake by micro-organisms, including bacteria and some phytoplankton (Bronk, 2002; Seitzinger et al., 2002a). However, DON can be an important N source and it is implicated in the formation of some coastal harmful algal blooms (Paerl, 1988; Berg et al., 1997 and 2003; Granéli et al., 1999; Glibert et al., 2005a and b). Particulate and dissolved species can also have very different impacts on receiving ecosystems.

The NEWS model predicts riverine nutrient export (by form) as a function of point and non-point nutrient sources in the watershed, hydrological and physical factors, and removal within the river system (Figure 2) (Beusen et al. 2005; Dumont et al. 2005; Harrison et al. 2005a and b; Seitzinger et al. 2005). A further feature of the model is that it can be used to estimate the relative contribution of each watershed source to export at the river mouth. The NEWS model builds on an earlier model of dissolved inorganic N (DIN) export (Seitzinger and Kroeze 1998).

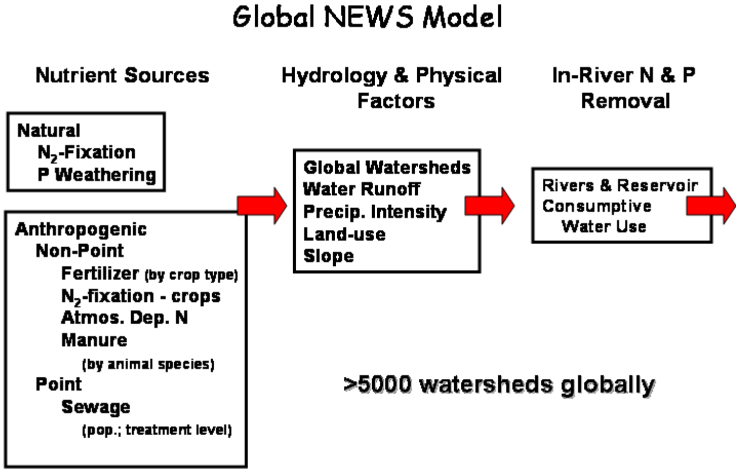


Figure 2. Schematic of some of the major inputs and controlling factors in the Global NEWS watershed river export model.

There is considerable detail in the input databases and model parameterizations that reflect food and energy production and climate (Figure 2). For example, crop type is important in determining fertilizer use, the amount of manure produced is a function of animal type (e.g., cows, camels, chickens, goats, etc.), nutrient loading from sewage depends not only on the number of people in a watershed but also on their connectivity to a sewage system and level of sewage treatment, atmospheric nitrate deposition is related to fossil fuel combustion. A number of hydrological and physical factors are important in transferring nutrients from soils to the river, with water runoff being important for all elements and forms. Once in the river, N and P can be removed by biological and physical processes during river transport within the river channels, in reservoirs, and through water removal for irrigation (consumptive water use).

NEWS Model Output: The NEWS model has provided the first spatially distributed global view of N, P and C export by world rivers to coastal systems. At the global scale rivers currently deliver about 65 Tg N and 11 Tg P per year according to NEWS model predictions (Tg = tera gram = 10^{12} g) (Figure 3). For nitrogen, DIN and particulate N (PN) each account for approximately 40% of the total N input, with DON comprising about 20%. This contrasts with P, where particulate P (PP) accounts for almost 90% of total P inputs. However, while DIP and dissolved organic P (DOP) each contribute only about 10% of total P, both of these forms are very bioreactive and thus may have a disproportionate impact relative to PP on coastal systems.

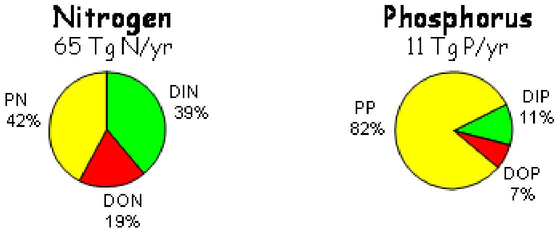


Figure 3. Global N and P river export to coastal systems by nutrient form based on the NEWS model (Dumont et al. 2005; Harrison et al. 2005a).

There is large spatial variation around the world in river nutrient export, including different patterns for the different nutrient forms (DIN, DON and PN) (Figure 4). Using N yield (kg N per km^2 watershed per year that is exported to the river mouth), DIN yield shows considerable variation at regional and continental scales, as well as among adjacent watersheds. As might be expected based on past measurements of river nutrient export, the NEWS model predicts relatively high watershed yields in the eastern USA, the Mississippi basin, and much of western Europe. Of particular note, however, are also the high DIN yields from developing regions including much of southern and eastern Asia, Central America and small coastal watersheds in western Africa.

The large spatial variation in N yield reflects the variable magnitudes of the different nutrient sources and controlling factors among watersheds. This underscores the importance of the need for a clear understanding of the nutrient sources and controls within LMEs at many scales in order to develop effective policies and implementation strategies to control coastal nutrient loading.

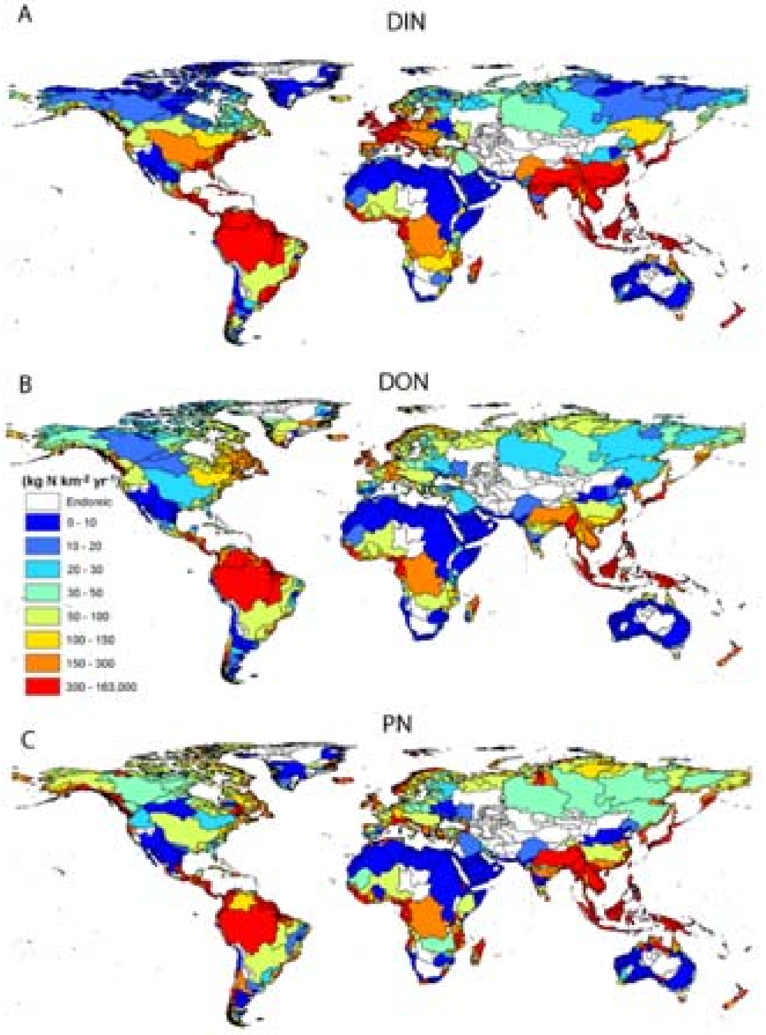


Figure 4. NEWS-model-predicted A) DIN, B) DON, and C) PN yield (kg N km-2 yr-1) to coastal systems from basins globally. Model output replotted from Harrison et al., 2005b, Dumont et al 2005, and Beusen et al. 2005.

N and P differ markedly in the relative contribution of different nutrient sources to river nutrient export (Seitzinger et al. 2005). At the global scale, natural sources account for about 40% of DIN and DIP river export (biological N_2-fixation and rock weathering, respectively) (Figure 5). Anthropogenic sources for DIN export are dominated by agriculture (fertilizer and manure) in contrast to DIP where sewage accounts for ~60% of river export. This difference in major sources, illustrates the need for different strategies to reduce nitrogen or phosphorus loading to coastal systems.

Of course there is considerable variation in the relative contribution of nutrient sources at continental, regional and watersheds scales, and this must be known and taken into consideration when developing nutrient reduction strategies. At the continental scale, for example, in South America livestock production (manure) is by far the largest anthropogenic N source contributing to river DIN loading to coastal systems (Figure 6). This contrasts with Asia where fertilizer use is about twice as great as livestock production in contributing to river DIN loading.

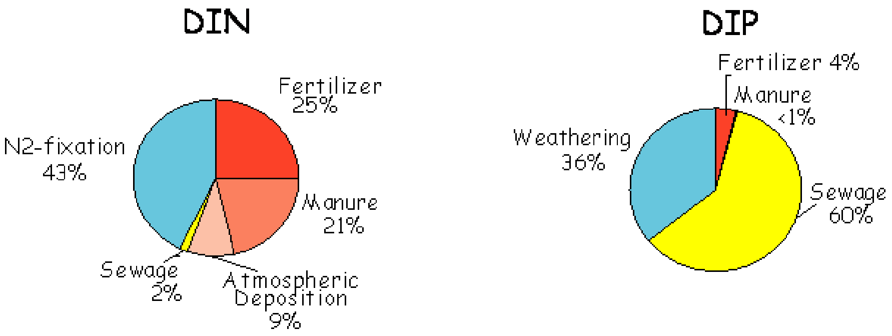


Figure 5. Contribution of different sources to DIN and DIP river export globally.

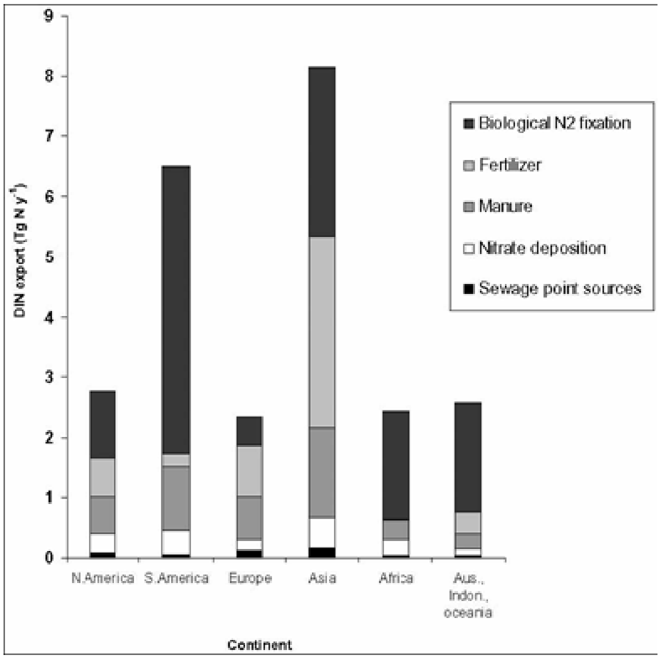


Figure 6. Contribution of N sources in watersheds to model predicted DIN river export to the coastal zone of each continent. (Figure from Dumont et al. 2005)

NEWS Model Application to LMEs

Land-based pollution of coastal waters in LMEs can have sources in multiple countries often located upstream at a considerable distance from the coastal zone. The release of nutrients into rivers can cross national borders and create environmental, social and economic impacts along the way - until reaching the coastal zone, which may be in a different country. Thus an LME transboundary approach is essential for identifying watershed nutrient sources and coastal nutrient loading to support policy development and implementation in LMEs that will reduce current and future coastal eutrophication.

Few estimates of nutrient loading have been made in individual LMEs, and only in the Baltic Sea LME has source apportionment been investigated (HELCOM 2004, 2002). As a first step in bridging the gap between land-based activities and LME waters, we examined the relative magnitudes and distribution of DIN loading from watersheds to LMEs globally. We focused on N because it is often the most limiting nutrient in coastal waters and thus important in controlling coastal eutrophication. DIN is often the most abundant and bioavilable form of nitrogen, and therefore contributes significantly to coastal eutrophication.

Watershed DIN export to rivers predicted by the NEWS model described above was compiled for each of the 64 LMEs (2002 delineation; Duda & Sherman 2002) except for the Antarctic (LME 61) where database information was limited. Total DIN load to each LME was aggregated from all watersheds with coastlines along that LME for point sources and only those watersheds with discharge to that LME for diffuse sources. This work was part of the GEF Medium-Sized Project: Promoting Ecosystem-based Approaches to Fisheries Conservation and LMEs (Component 3: Seitzinger and Lee 2007).

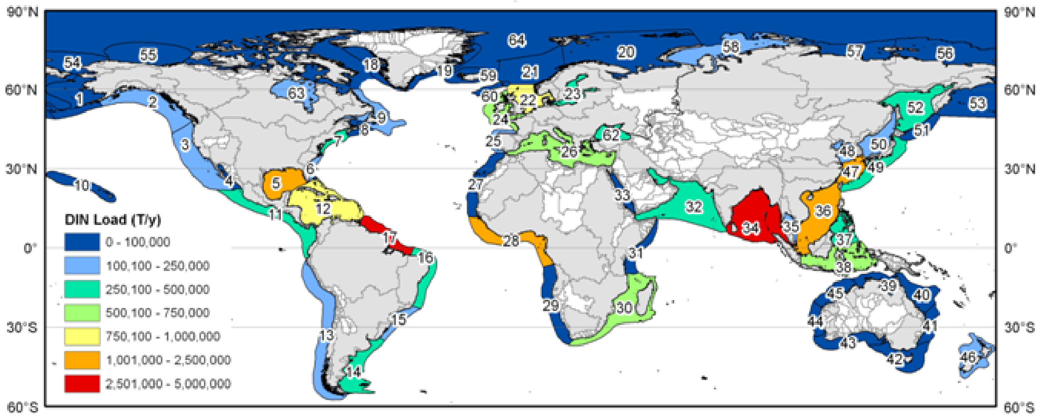


Figure 7. DIN inputs to LMEs from land-based sources predicted by the NEWS DIN model. Watersheds discharging to LMEs are grey; watersheds with zero coastal discharge are white. Units: Tons N/y. See Table 2 for LME identification. (Figure from Lee and Seitzinger submitted).

Table 2. LMEs identified by name and number (see Fig. 7 and 8)

LME #	LME name
1	East Bering Sea
2	Gulf of Alaska
3	California Current
4	Gulf of California
5	Gulf of Mexico
6	Southeast U.S. Continental Shelf
7	Northeast U.S. Continental Shelf
8	Scotian Shelf
9	Newfoundland-Labrador Shelf
10	Insular Pacific-Hawaiian
11	Pacific Central-American Coastal
12	Caribbean Sea
13	Humboldt Current
14	Patagonian Shelf
15	South Brazil Shelf
16	East Brazil Shelf
17	North Brazil Shelf
18	West Greenland Shelf
19	East Greenland Shelf
20	Barents Sea
21	Norwegian Sea
22	North Sea
23	Baltic Sea
24	Celtic-Biscay Shelf
25	Iberian Coastal
26	Mediterranean Sea
27	Canary Current
28	Guinea Current
29	Benguela Current
30	Agulhas Current
31	Somali Coastal Current
32	Arabian Sea

LME #	LME name
33	Red Sea
34	Bay of Bengal
35	Gulf of Thailand
36	South China Sea
37	Sulu-Celebes Sea
38	Indonesian Sea
39	North Australian Shelf
40	Northeast Australian Shelf-Great Barrier Reef
41	East-Central Australian Shelf
42	Southeast Australian Shelf
43	Southwest Australian Shelf
44	West-Central Australian Shelf
45	Northwest Australian Shelf
46	New Zealand Shelf
47	East China Sea
48	Yellow Sea
49	Kuroshio Current
50	Sea of Japan
51	Oyashio Current
52	Okhotsk Sea
53	West Bering Sea
54	Chukchi Sea
55	Beaufort Sea
56	East Siberian Sea
57	Laptev Sea
58	Kara Sea
59	Iceland Shelf
60	Faroe Plateau
61	Antarctic (not included in this analysis)
62	Black Sea
63	Hudson Bay
64	Arctic Ocean

DIN export from watersheds to LMEs varies globally across a large range of magnitudes (Figure 7). The smallest loads are exported to many polar and Australian LMEs, while the largest loads are exported to northern tropical and subtropical LMEs. Of particular note are the large loads exported to the Gulf of Mexico, South China Sea, East China Sea, and North Sea LMEs in which high anthropogenic activity occurs in their watersheds. The Carribean Sea, Mediterranean Sea and Indonesian Sea LMEs, among others, also receive substantial DIN loads.

The NEWS model also predicts substantial DIN export from the North Brazil Shelf LME which has relatively low anthropogenic activity in its watersheds. Further investigation is underway to evaluate the NEWS model for these large and relatively pristine tropical river basins. The high DIN load may reflect a number of factors including the large role that high water runoff from tropical rivers plays in the export of DIN, high biological N_2-fixation, low denitrification, and model uncertainty.

Identification of Land-based Nutrient Sources to LMEs. DIN loading to each LME was attributed to diffuse and point sources including natural biological N_2-fixation, agricultural biological N_2-fixation, fertilizer, manure, atmospheric deposition and sewage. Dominant sources of DIN to LMEs were also identified which may be useful for the management of land-based nutrient loading to LMEs.

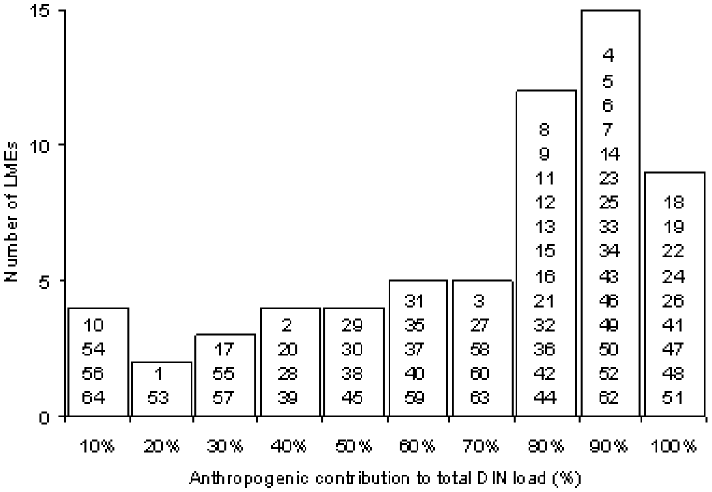


Figure 8. Histogram of anthropogenic contribution to total DIN load to LMEs. LME numbers are shown in each bar. See Table 2 for LME identification.

Land-based sources of DIN include natural sources (biological N_2-fixation in natural landscapes) and anthropogenic activities. In watersheds draining to LMEs, anthropogenic activities contribute to over half of the total DIN load in 73% of LMEs (Figure 8). These anthropogenic DIN dominant LMEs are distributed across most continents, except sub-Saharan Africa and most polar regions. Some of the highest proportions (> 90%) of anthropogenic DIN loads are to European LMEs, such as the North Sea and Mediterranean LMEs, and East Asian LMEs, such as the Yellow Sea and East China Sea LMEs.

Agriculture is a major source of the anthropogenic DIN export to LMEs (Lee and Seitzinger submitted). In 91% of the LMEs with agriculture occurring in their related watersheds, over half their anthropogenic export is due to agricultural sources such as agricultural biological fixation, manure, and fertilizer. Attribution of agricultural DIN export to these three sources reveals the predominance of fertilizer and manure over agricultural biological fixation. For example, LMEs with the largest agricultural loads have less than 20% of the total DIN load due to biological fixation and over 50% due to either fertilizer (e.g., in many northern temperate and Southeast Asian LMEs such as the Bay of Bengal, East China Sea and South China Sea LMEs), to manure (e.g., in most Central and South American LMEs such as the Caribbean and North Brazil Shelf LMEs) or to a combination of both (e.g., in the North Sea and Celtic-Biscay Shelf LMEs) due to local agricultural practices. There is no agricultural export to most polar LMEs.

Atmospheric deposition is important in regions where there are few other land-based inputs (e.g., in polar regions such as the West and East Greenland Shelf LMEs), where fossil fuel combustion from development is extreme (e.g., in the North- and Southeast U.S. Continental Shelf LMEs), or where extensive landscape burning occurs (e.g., in the Guinea Current LME which is fed by savannah fires in Western Central African watersheds; Barbosa et al. 1999). Sewage is an important source of DIN to only a few LMEs (as a primary source to the Kuroshio Current, Red Sea, West-Central Australian Shelf, and Faroe Plateau LMEs), while agricultural fixation plays an even lesser role as a primary source to only the Southwest Australian Shelf LME and a secondary source to the Benguela Current, North Australian Shelf, and West-Central Australian Shelf LMEs.

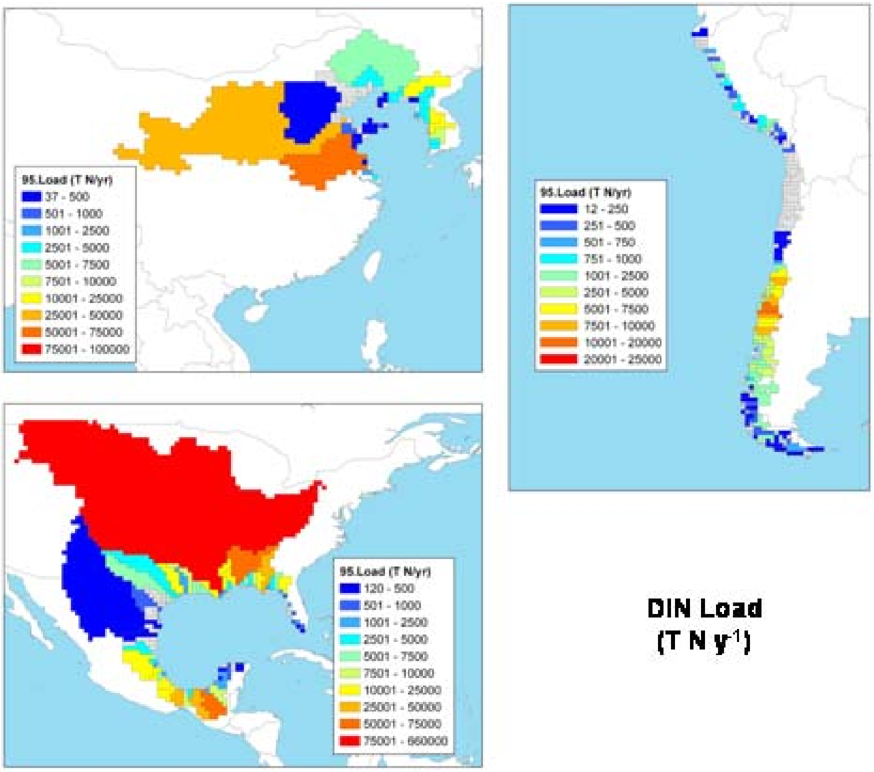


Figure 9. DIN export predicted by the NEWS DIN model from watersheds within the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs. Units: Tons N/yr.

The variability in watershed DIN export and source attribution within individual LMEs exhibits comparably large differences as with across LMEs. Examples from different world regions including Asia, South America and the US-Latin America are presented below. Among the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs, the DIN load from individual watersheds ranges over several orders of magnitude across both small and large watersheds (Figure 9). For example, similarly sized watersheds in both the Yellow Sea and Humboldt Current LMEs exhibit both the largest and smallest magnitudes of watershed DIN export. In contrast, the Mississippi watershed is the largest watershed contributing to the Gulf of Mexico LME and also exports the largest load of DIN to the Gulf of Mexico.

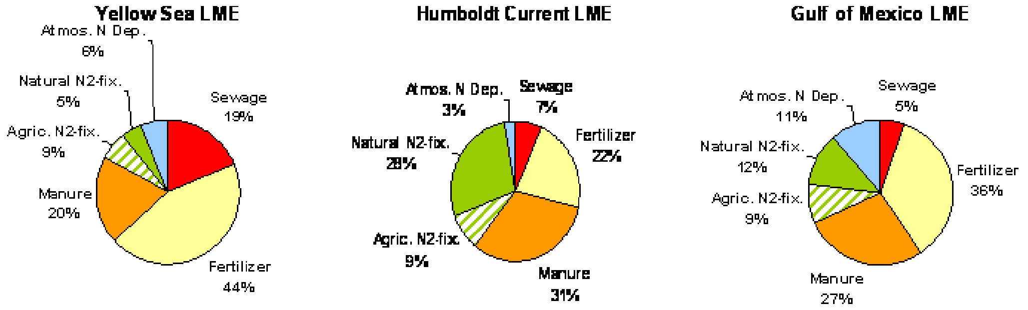


Figure 10. Source attribution of DIN export predicted by the NEWS DIN model to the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs. Units: Tons N/yr.

The relative importance of different watershed sources of DIN to LME loading also varies, e.g., among the Yellow Sea, Humboldt Current and Gulf of Mexico LMEs (Figure 10). Agricultural sources dominate the DIN export in all of these LMEs, but fertilizer contributes the most to export to the Yellow Sea and Gulf of Mexico LMEs while manure is relatively more important than fertilizer to the Humboldt Current LME. In the Yellow Sea LME, sewage is also a significant source (19%) to DIN export, while less so to the Humboldt Current and Gulf of Mexico LMEs. Nitrogen fixation occurring in natural landscapes is a significant source (28%) to the DIN export to only the Humboldt Current LME. Atmospheric deposition is a lesser source of DIN export to all three example LMEs, but contributes, relatively, the largest percentage (11%) to the Gulf of Mexico LME. The identification of dominant sources of DIN and their relative contribution at the individual LME level is essential for developing effective nutrient management strategies on an ecosystem level.

Implications of Future Conditions in LME Watersheds

At the global scale, river nitrogen export to coastal systems is estimated to have approximately doubled between 1860 and 1990, due to anthropogenic activities on land (Galloway et al., 2004). Over the next 50 years the human population is predicted to increase markedly in certain world regions, notably Southern and Eastern Asia, South America, and Africa (United Nations, 1996). Growing food to feed the expanding world population will require increased use of nitrogen and phosphorus fertilizers (Alcamo et al., 1994; Bouwman et al., 1995; Bouwman, 1997). Increased industrialization, with the associated combustion of fossil fuels and NOx production, is predicted to increase atmospheric deposition of N (Dentener et al., 2006; IPCC, 2001). Thus, unless substantial technological innovations and management changes are implemented, increasing food production and industrialization will undoubtedly lead to increased export of N to coastal ecosystems (Galloway et al. 2004), with resultant water quality degradation.

Based on a business-as-usual (BAU) scenario, inorganic N export to coastal systems is predicted to increase 3-fold by the year 2050 (relative to 1990) from Africa and South

America (Figure 11) (Kroeze and Seitzinger, 1998; Seitzinger et al., 2002b). Substantial increases are predicted for Europe (primarily eastern Europe) and North America. Alarmingly large absolute increases are predicted for eastern and southern Asia; almost half of the total global increased N export is predicted for those regions alone.

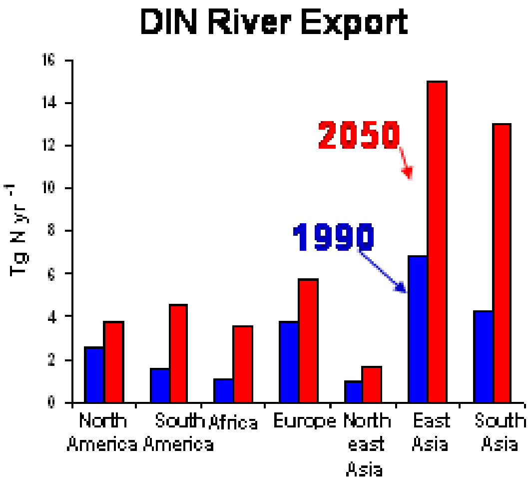
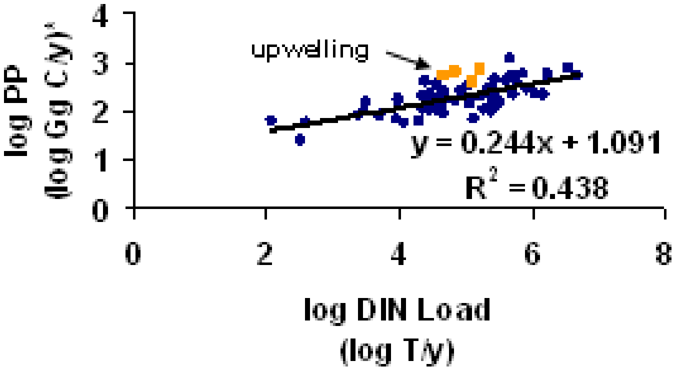


Figure 11. Predicted DIN export to coastal systems in 1990 and 2050 under a business-as-usual (BAU) scenario. Modified from Kroeze and Seitzinger (1998).

The above scenario for 2050 was based on projections made from early 1990 trajectories and using a relatively simple DIN model (Seitzinger and Kroeze 1998). The NEWS model has more parameters and more detail behind the inputs (e.g., fertilizer use by crop type, level of sewage treatment, etc.) (Figure 2) thus facilitating more advanced scenario development and analyses. For example, it is now possible to explore the effects of a range of development strategies, effects of climate change, production of biofuels, increase in dams for hydropower, and consumptive water use (irrigation) on coastal nutrient loading. Using the NEWS model, we are currently analyzing a range of alternative scenarios for the years 2030 and 2050 based on the Millennium Ecosystem Assessment (www.millenniumassessment.org) to provide insights into how changes in technological, social, economic, policy and ecological considerations could alter future nutrient export to coastal systems around the world (Seitzinger et al. in prep.).

Coastal Ecosystem Effects

As noted at the beginning of this chapter, nutrient over-enrichment can lead to a wide range of coastal ecosystem effects. The most direct response of coastal ecosystems to increased nutrient loading is an increase in biomass (e.g., chlorophyll a) of primary producers or primary production rates (Nixon 1995). How might land-based DIN loading be affecting primary production in LMEs? As a preliminary examination, we compared land-based DIN loads predicted by the NEWS model to LME primary production (modeled SeaWiFS data; Sea Around Us Project 2007) (Figure 12). This analysis suggests that land-based DIN export supports a significant portion of primary production at the level of an entire LME. In areas with upwelling, nutrient-rich bottom waters support high rates of photosynthetic production. This is reflected in the generally higher primary productivity than predicted by the regression solely with land-based DIN inputs in LMEs characterized by upwelling (the Guinea Current, Arabian Sea, Pacific Central-American, Humboldt Current, California Current, Gulf of Alaska, Benguela Current, Canary Current, Northwest Australian, and Southwest Australian LMEs).



* Sea Around Us Project

Figure 12. Phytoplankton production vs. DIN load to the 63 LMEs. Orange points are LMEs in upwelling regions. Phytoplankton production rates are from the Sea Around Us Project; DIN loads are from the NEWS model (Dumont et al. 2005). Figure from Lee and Seitzinger submitted.

The above analysis compares land-based N loading to average primary production for waters in the entire LME. In the near shore areas of LMEs, land-based N loading likely supports a much higher proportion of primary production than suggested by the overall relationship in Figure 12 and should be investigated. The additional effects of high nutrient loading to estuaries and near shore waters in LMEs on hypoxia, biodiversity, toxic and nuisance algal blooms, habitat quality, and fisheries yields also warrants further analysis.

Future Needs

We are beginning to make significant advances in understanding the relationship between human activities in watersheds and coastal nutrient loading at a range of scales (e.g., watershed, LME, and global) as illustrated by the application of the NEWS model. However, this is only a start. For example, to date the LME, regional, and global analyses have relied on input databases at the scale of 0.5 ^{o} latitude x 0.5^{o} longitude. The use of higher spatial resolution input databases based on local knowledge from specific LME regions could significantly improve the model predictions. Similarly, additional data for model validation is need. Development of scenarios based on local projections of population, agricultural production, biofuels, dam construction, and climate change, among others could provide information of use to policy makers.

Development of nutrient reduction policies and effective mitigation strategies also requires widely applicable, quantitative relationships between nutrient loading and coastal ecosystem effects. While there is considerable information on nutrient sources and coastal impacts, this information is often much dispersed and has not yet been compiled into a consistent database so that nutrient sources in specific LMEs can be linked to impacts in their associated coastal system. This is a critical next step in order for a toolbox to be developed so that effective policy measures can be formulated and measures taken, and for the outcomes of those policies and measures to be evaluated.

Many technical and political options are available to reduce fertilizer use, decrease nutrient runoff from livestock waste, decrease NOx emissions from fossil fuel burning, and enhance sewage treatment. The fact that many of these tools have not yet been implemented on a significant scale suggests that additional technological options and new policy approaches are needed. In addition, policy approaches to address non-point source pollution are often nonexistent or very limited. To ensure that the science used to develop these technologies and polices is sound and complete, existing data on nutrient sources, mobilisation, distribution, and effects need to be assessed. An approach is needed such as that being developed in GEF-sponsored LME programs and as promoted by the International Nitrogen Initiative (INI: INitrogen.org) where all stakeholders – including scientists, policy makers and private sector leaders – work together to develop a better understanding of the issues and to identify and implement workable solutions.

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LMEs and REGIONAL SEAS

I WEST AND CENTRAL AFRICA

I-1 Benguela Current LME

S. Heileman and M. J. O'Toole

The boundaries of the Benguela Current LME extend from the Agulhas Current to 27° E longitude, and to the northern boundary of Angola. It encompasses the Exclusive Economic Zones (EEZs) of Angola and Namibia, and part of the EEZ of South Africa, with an area of 1.5 million km^2 of which 0.59% is protected, and contains 0.06% of the world's sea mounts (Sea Around Us 2007). One of its unique features is that it is bounded in the north and south by two warm water systems, the Angola Current and Agulhas Current, respectively. These boundaries are highly dynamic and the neighbouring warmer waters directly influence the ecosystem as a whole as well as its living resources. A strong wind-driven coastal upwelling system, with the principal upwelling centre located off Lüderitz (27°S, southern Namibia), dominates this LME. The system is complex and highly variable, showing seasonal, interannual, and decadal variability as well as periodical regime shifts in local fish populations (Shannon & O'Toole 1998, 1999, 2003). The Benguela Current LME has a temperate climate, and plays an important role in global climate and ocean processes (GEF/UNDP/UNOPS/NOAA 1999). Its major estuaries and river systems include the Kwanza and Cunene Rivers. Books, book chapters, articles and reports on this LME include Crawford *et al*. (1989), Palomares and Pauly (2004), O'Toole et al. (2001), Shannon & O'Toole (2003), Shannon *et al*. (2006) and UNEP (2005).

I. Productivity

The Benguela Current LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}). The distinctive bathymetry, hydrography, chemistry and trophodynamics of the Benguela Current LME make it one of the most productive marine areas of the world. The plankton has been generally regarded as a diatom-dominated system, but this perception is to some extent an artefact of past sampling (Shannon & O'Toole 1998). Copepods, which are numerically the most abundant and diverse zooplankton group, play an important role in the trophodynamics of this LME since they are the principal food of sardines, anchovies, and other pelagic fish including the larval and juvenile stages of both fish and squid. The high level of primary productivity supports an important global reservoir of biodiversity and biomass of fish, seabirds, crustaceans, and marine mammals. Favourable conditions exist for a high production of small pelagic fishes such as sardines, anchovies, and round herrings. The LME's estuaries provide nursery areas for a number of fish stocks that are shared among the bordering countries, while both the estuaries and coastal lagoons provide critical feeding grounds for migratory birds.

The LME's considerable climatic and environmental variability is the primary driving force of biomass change in the Benguela Current LME (Sherman 2003, Shannon *et al*. 2006). Harmful Algal Blooms (HABs) regularly occur, and have been associated with fish mortalities as a result of oxygen depletion in the water during and after major blooms (Shannon & O'Toole 1998). Satellite images show frequent and widespread eruptions of toxic hydrogen sulphide off the coast of Namibia (Weeks *et al*. 2004). Eruptions often seem to be coincident with either increased intensity of wind-driven coastal upwelling or the passage of a low-pressure weather cell. In 2001, nine major hydrogen sulphide eruptions occurred, with the largest covering 22,000 km^2 of ocean. Their relevance to the fishery resources, including lobsters, is likely to be high. For example, a widespread depletion of oxygen is blamed for the deaths of two billion young hake in 1993 (Hamukuaya *et al.* 1998, Weeks *et al*. 2004).

Since 1995, efforts have been underway in the BENEFIT and Benguela Current LME project (see Governance) to better understand this highly variable and complex system of physical, chemical, and biological interactions and processes (Shannon *et al*. 2006). Systematic surveys have been conducted to assess oceanographic conditions using both shipboard sensors and satellite remote sensors for temperature, chlorophyll, nutrients, and primary productivity.

Oceanic fronts (after Belkin et al. 2009): The coastal upwelling zone off South Africa extends from Cape of Good Hope (34.5°S) north to 13°S and consists of the two major areas, the northern and southern Benguela upwelling frontal zones (UFZ) separated by the so-called Lüderitz line (LL) at 28°S, where the shelf's width is at a minimum (Shannon 1985, Shillington 1998) (Figure I-1.1). The northern UFZ is year-round, whereas the southern UFZ is seasonal). A peculiar double front is observed within the southern UFZ, between 28°S-32°S, with the inshore front close to the coast (a few tens of km) and the offshore front over the shelf break (150-200 km off the coast). This double-front pattern can be explained by the conceptual model put forth by Barange and Pillar (1992). A vast frontal zone develops seasonally off the Angolan coast. This zone consists of numerous fronts; most fronts extend ESE-WNW; the entire zone seems to protrude seaward from the Angolan coast north of 20°S (Belkin et al. 2009). This zone is likely related to the Angola-Benguela Front (ABF) (Shannon *et al*. 1987, Meeuwis & Lutjeharms 1990).

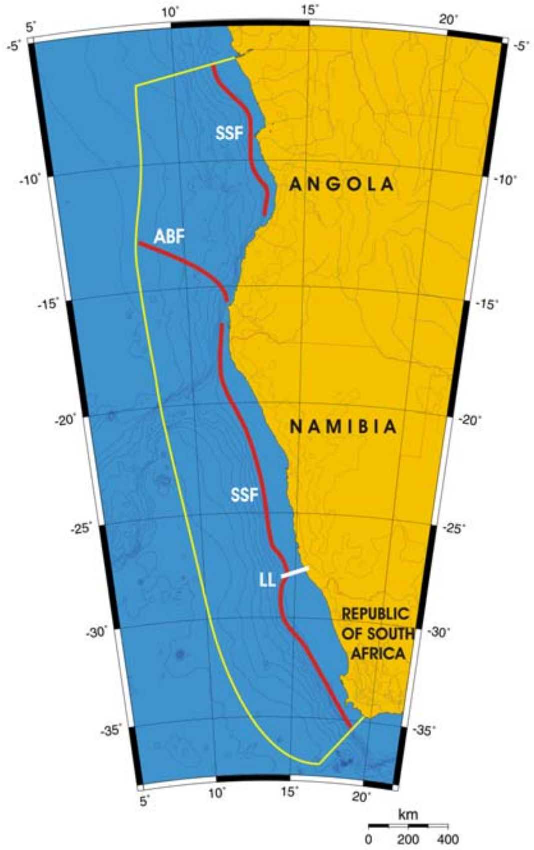

Figure I-1.1. Fronts of the Benguela Current. ABF, Angola-Benguela Front; LL, Lüderitz Line; SSF, Shelf-Slope Front. Yellow line, LME boundary. (Belkin et al. 2009)

Benguela Current SST (after Belkin 2009)
Linear SST trend since 1957: 0.26°C.
Linear SST trend since 1982: 0.24°C.

The Benguela Current's thermal history was punctuated by warm and cold events associated with Benguela El Niños and La Niñas, Atlantic counterparts of the Pacific El Niños and La Niñas. Fidel and O'Toole, in a presentation made at the 2nd Global Conference on Large marine Ecosystems in Qingdao, distinguished five major Benguela El Niños over the last 50 years. The most pronounced warming of >1.2°C occurred after the all-time minimum of 1958 and took 5 years to peak in 1963. Other warm events peaked in 1973 and 1984, alternated with cold events of 1982 and 1992. Clearly, decadal variability in the Benguela Current was strong through the last warm event of 1984. After that, the Benguela Current experienced a shift to a new, warm regime, in which decadal variability is subdued. Some researchers also note the 1995 warm event, although this maximum is not conspicuous from Hadley SST data. The post-1982 warming of the Benguela Current LME was spatially non-uniform: whereas SST in some areas of northern Benguela (between 12-26°S) increased by 0.6 to 0.8°C, the inshore shelf area of southern Benguela experienced a slight cooling (Fidel and O'Toole, 2007, after Pierre Florenchie, University of Cape Town, personal communication).

The thermal history of this LME bears limited commonality with either the Guinea Current LME (its northern neighbor) or to the Agulhas Current LME (its southern neighbor). This is not at all surprising since these three LMEs are oceanographically disconnected. Indeed, the Agulhas Current retroflects southwest of Cape Agulhas and therefore does not feed the Benguela Current, save possibly for small occasional alongshore leakages. In the north, the Angola-Benguela Front (ABF) blocks any direct along-shelf connection between two neighbors, the Benguela Current LME and Guinea Current LME.

Correlation analysis suggests different responses to environmental forcing in the northern, central, and southern parts of the Benguela Current region (Jury and Courtney, 1995). For example, the lower correlation in the southern Benguela between SST and local winds suggests that SST variability here is often driven by advection, likely by the Agulhas Current and its extension. The higher correlation in the central Benguela between SST and local winds indicates that SST variability here is largely driven by local upwelling.

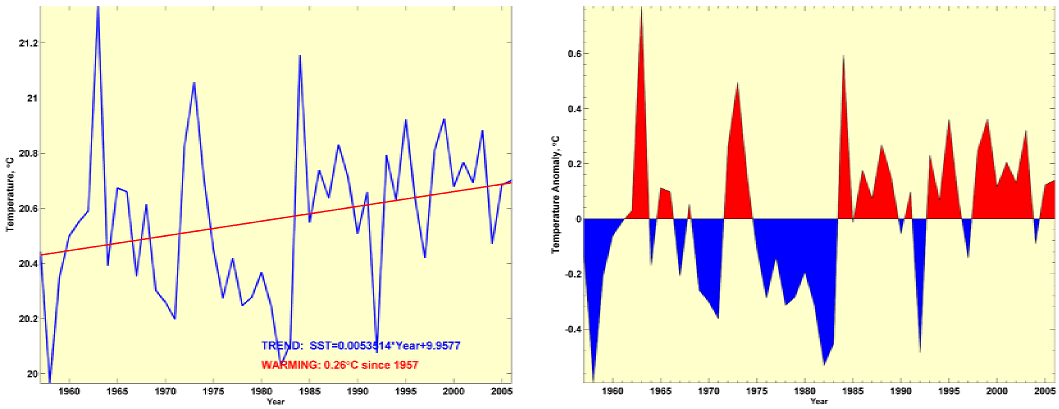

Figure I-1.2. Benguela Current LME mean annual SST (left) and annual SST anomalies (right), 1957 – 2006, based on Hadley climatology (after Belkin 2009).

Benguela Current Trends in Chlorophyll a and Primary Productivity: The Benguela Current LME is a Class I, highly productive ecosystem (>300 $gCm^{-2}y^{-1}$).

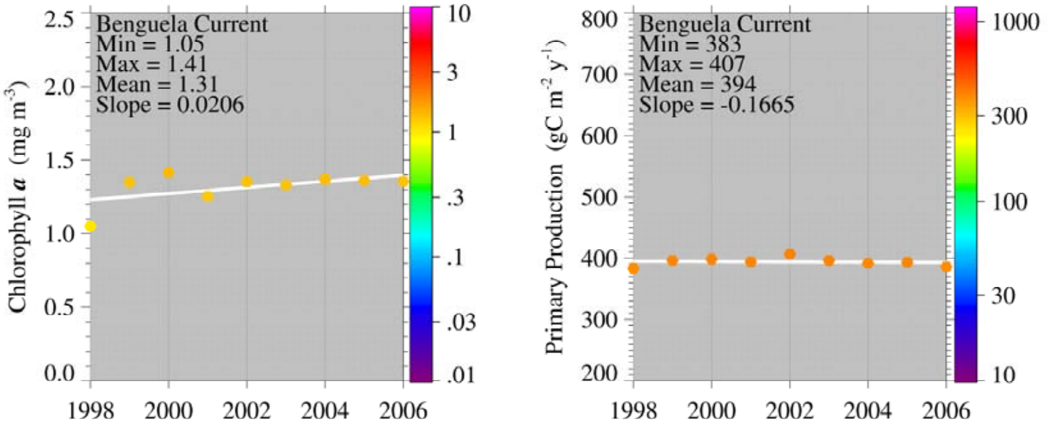

Figure I-1.3. Benguela Current LME trends in chlorophyll *a* (left) and primary productivity (right) 1998-2006; values are color coded to the right hand ordinate. Courtesy of J. O'Reilly and K. Hyde. Sources discussed p.15 this volume.

II. Fish and Fisheries

The Benguela Current LME is very rich in pelagic and demersal fish. Most of the LME's major fisheries resources are shared between the bordering countries or migrate across national jurisdictional zones, and include sardine (*Sardinops sagax*), anchovy (*Engraulis capensis*), hake (*Merluccius capensis* and *M*. *paradoxus*), horse mackerel (*Trachurus trachurus* and *T*. *trecae*), sardinella (*Sardinella* spp.), and rock lobster (*Jasus lalandii*). Artisanal, commercial (industrial) and recreational fisheries are all of significance in the LME, with artisanal fisheries being particularly important for Angola. Total reported landings of the LME increased steadily from 1950 to a peak of about 3 million tonnes in 1978 (Figure I-1.4). In the subsequent years, however, the landings show a general decline, down to about 1.1 million tonnes in 2004. The trend in the value of the reported landings closely resembles that of the reported landings, peaking at just under 3 billion US$ (in 2000 real US$) in 1978 (Figure I-1.5).

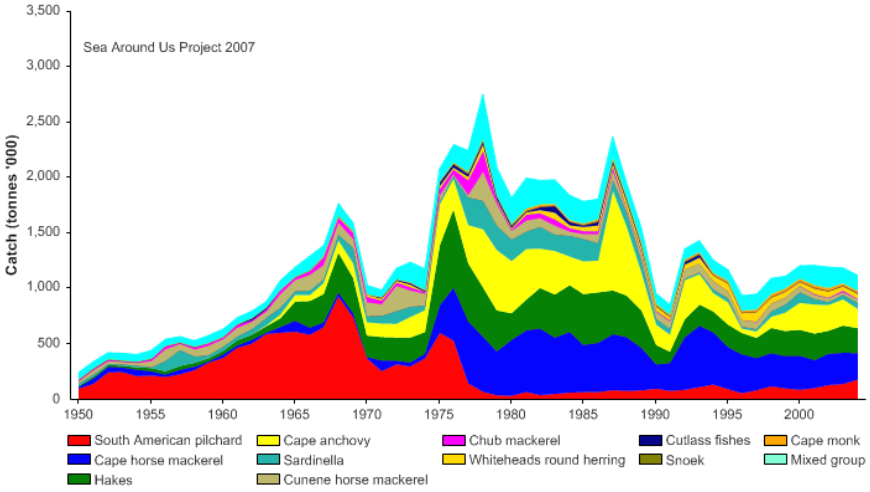

Figure I-1.4. Total reported landings in the Benguela Current LME by species (Sea Around Us 2007).

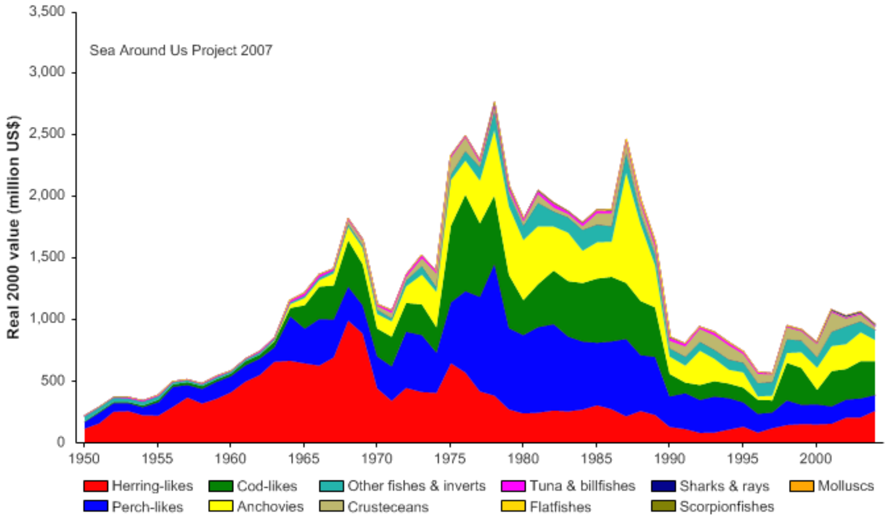

Figure I-1.5. Value of reported landings in the Benguela Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached one third of the observed primary production by the mid 1970s, but has since declined to half that level (Figure I-1.6). Although there were large numbers of foreign fleets operating in the LME in the 1970s and 1980s, since the early 1990s, Namibia and South Africa have the largest ecological footprints in the region.

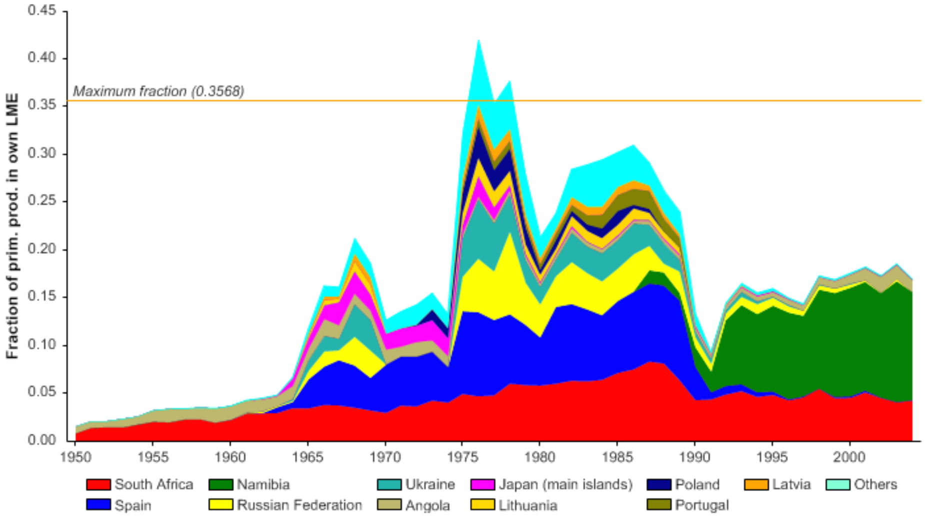

Figure I-1.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Benguela Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Since the mid 1970s, the mean trophic level of the reported landings (i.e, the MTI, Pauly & Watson 2005) has been relatively stable in this LME, (Figure I-1.7 top), but as the amount of catch (tonnage) has declined over the same period, the FiB index shows a rapid decline (Figure I-1.7 bottom).

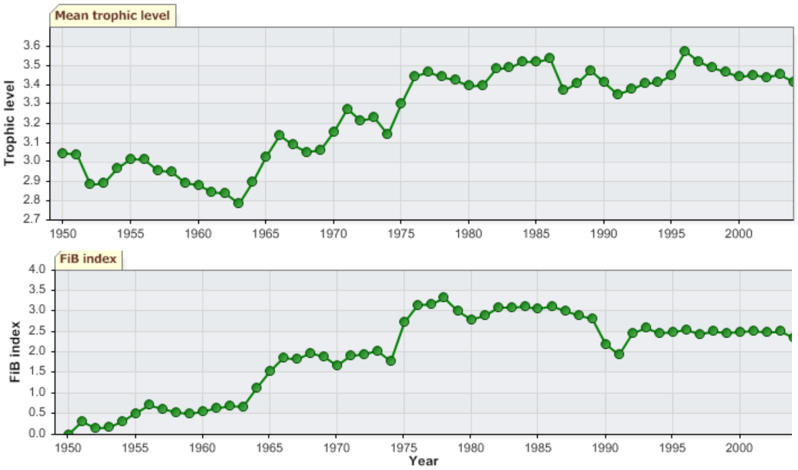

Figure I-1.7. Trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Benguela Current LME (Sea Around Us 2007).

This decline of the FiB index is particularly strong off Namibia (Willemse and Pauly 2004), where the ecosystem has been greatly modified, with jellyfish now dominating the food web (Lynam *et al.* 2006). This is a case of 'fishing down marine food webs' (Pauly *et al.* 1998), but one in which the species that replaced the exploited species are presently not targeted by fisheries.

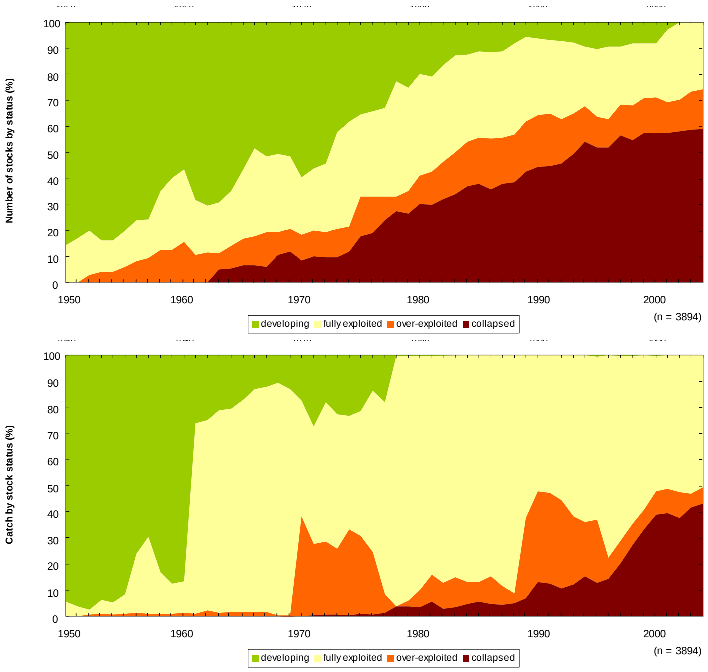

Figure I-1.8. Stock-Catch Status Plots for the Benguela Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.* this vol. for definitions).

The Stock-Catch Status Plots indicate that about 60% of commercially exploited stocks in the LME has collapsed, with another 10% overexploited (Figure I-1.8 top), with fully-exploited stocks contributing 50% of the catch (Figure I-1.8, bottom). However, fully exploited stocks, while accounting for less than 30% of the stocks, provide over 50% of the reported landings (Figure I-1.8).

Major changes in the key harvested species have occurred in the last century (Hampton *et al*. 1999, Shannon & O'Toole 2003). While environmental variability has been a contributing factor, some of these changes were undoubtedly the consequence of overexploitation (FAO 2003, Sherman 2003). The decline in these fisheries is caused, in part, by excessive fishing effort and overcapacity of fleets, excess processing capacity, catching of under-sized fish, and inadequate fisheries management (GEF/UNDP/UNOPS/NOAA 1999). As a result, the fisheries in the LME have experienced years of catches well below the maximum or optimal sustainable yields, with dramatic declines in stock sizes and catch per unit effort.

Decline in commercial fish stocks and non-optimal fishing of living resources is now a major transboundary problem in the LME (GEF/UNDP/UNOPS/NOAA 1999). In all three countries bordering the LME, major fisheries resources have undergone significant changes in annual catch (Hampton *et al*. 1999, Tapscott 1999) and this is also true for exploitation of invertebrate resources. For example, rock lobster catches have declined dramatically since the early 1960s, particularly off Namibia, where catches are now well below their 1960s peak. Assessments of the South African rock lobster resource have shown it to be seriously depleted, and estimates of recruitment in recent decades are only about 35% of its pre-exploitation condition (Hampton *et al*. 1999). The abalone stock has also been declining since 1996 (Tarr *et al*. 2000) and the stock is considered to be on the brink of collapse as a result of illegal fishing (Tarr 2000) and an ecological shift in abundance (Tarr *et al*. 1996).

Some of the major stock fluctuations have undoubtedly been influenced by the large-scale environmental perturbations that occur periodically in the system (Shannon & O'Toole 1998, Shannon *et al*. 2006). System-wide changes in abundance of species and species shifts (e.g., sardine and anchovy) are well-documented in this LME (e.g., Hampton *et al*. 1999, Shannon & O'Toole 2003). Fluctuations in abundance of the LME's fish stocks have also been detected through acoustic surveys for pelagic species such as sardines and anchovies (Barange *et al*. 1999, Hampton *et al*. 1999), and trawl surveys for demersal species (Hampton *et al*. 1999). The geographic displacement of stocks (e.g., *Sardinella aurita* and *S*. *maderensis* in Angola into Gabon) is also a common phenomenon with alongshore migration of fish populations across national boundaries in the Benguela Current LME having important implications for resource management. Global warming and associated phenomena are also expected to influence the LME's upwelling system, with potentially significant impact on the local food webs and the entire ecosystem, including fish recruitment and fisheries production.

Fluctuations in fish stocks can also have effects on top predators such as seabirds and seals (Crawford 1999, Crawford *et al*. 1992). For example, the distribution of Cape gannets, Cape cormorants, and African penguins has changed over the past three decades in response to changes in the distribution and relative abundance of sardine and anchovy (Crawford 1998). The high mortality and breeding failure of Cape fur seal colonies in Namibia in 1994 and 1995 can be attributed to low food availability resulting from low sardine abundance, a consequence of the catastrophic environmental variability and anomalous low oxygen events (O'Toole 1996).

Despite the vast scale of the fisheries in the LME, bycatch is not a major problem, and is taken mostly in the large pelagic and demersal fisheries. Discarding is controlled by strict regulations as well as by observers in some fisheries (e.g., Patagonian toothfish) but by self-policing where the bycatch is used as a luxury product. In the demersal trawl fishery of South Africa, 10% of the total catch is discarded (Walmsley-Hart *et al*. 2000). Both South African and Angolan purse seine fisheries yield bycatch rates between 10-20% of the total catch (Crawford *et al*. 1987).

The status of the fisheries is problematic, as the countries develop and implement national and regional fisheries policies and management programmes (GEF/ UNDP/ UNOPS/ NOAA 2002). Furthermore, some stocks show signs of response to environmental variability, e.g., recently correlated with a movement of sardines from Namibian waters to the south and southwest coasts toward the Agulhas Bank (van der Lingen *et al*. 2006). Sardine stocks in South Africa showed signs of recovery from the mid-1990s as a result of careful control of bycatch of juveniles, and the introduction of an operational management procedure which focused on rebuilding sardine stocks while optimally utilising the anchovy. However, recent stock assessment surveys of sardines around the Cape indicate a decline to very low levels compared with the mid 1990s.

III. Pollution and Ecosystem Health

Pollution: Virtually the entire coastline of the Benguela Current LME is exposed to the open ocean and experiences a relatively high degree of wave action. Strong wave action and currents tend to rapidly dissipate any pollution reaching the marine environment. Pollution is not a serious problem in the open marine areas of most of the LME, and is mostly evident in localised areas or hotspots such as ports and enclosed lagoons in all three countries. Poorly planned coastal developments, inadequate waste management, chronic oil pollution, inappropriate agricultural practices, contaminated stormwater run-off, as well as industrial and sewage wastewater discharges are among the factors that contribute to the deterioration of coastal and marine environments in the LME (UNEP 2005, Taljaard et al. 2006). Levels of pollution, with the exception of hotspots, are considered moderate (UNEP 2005). With poor urban infrastructure, there is a very real danger that a rapidly expanding urban population will pose a serious pollution threat, as untreated sewage is discharged into the sea in increasing volumes. HABs have been identified as a major transboundary problem, and their frequency of occurrence, spatial extent, and duration appear to be increasing (GEF/UNDP/UNOPS/NOAA 1999). Although HABs occur naturally in all three bordering countries (Tapscott 1999), several factors, including nutrient loading from anthropogenic activities (e.g., discharge of untreated sewage), can promote their incidence and spread. Toxins produced by HABs have led to mortalities of fish, shellfish, and humans, as well as anoxia in inshore waters that can cause mass mortality of marine organisms (GEF/UNDP/UNOPS/NOAA 1999).

Diamond mining operations impact negatively on the marine environment. Certain mining activities are conducted close to national boundaries (e.g., diamond mining near the Orange River mouth on both sides of the border between South Africa and Namibia), across which negative consequences may be transmitted. Diamond mining is also thought to affect marine living resources. For instance, although the dramatic decrease in Namibian rock lobster catches in the 1990s may be attributed to large scale environmental perturbations, it is evident that stock abundance might have also been influenced by marine diamond mining (Tapscott 1999). While mining is the primary cause of increased suspended solids in the marine areas, poor agricultural practices also contribute to this problem, particularly in estuaries, lagoons, and sheltered bays. Marine litter from land and shipping poses a serious growing problem throughout the LME, with significant transboundary consequences (GEF/UNDP/UNOPS/NOAA 1999). Oil and gas exploration and production are considered to pose a major threat, particularly off Angola, with oil spills sometimes causing severe local pollution which impacts artisanal fisheries. A substantial volume of oil is transported through the region, and poses a significant risk of contamination to coastal environments, damage to shared and straddling fish stocks, and to coastal infrastructure (GEF/UNDP/UNOPS/NOAA 1999).

Habitat and community modification: Four estuaries and five coastal lagoons in the Benguela Current LME are considered to be of transboundary significance. Several lagoons have been designated as Ramsar sites. Species that are endemic to only one or two estuarine systems within the LME are also present. The rare estuaries represent the only sheltered marine habitat in the LME, and are important both for biodiversity and as a focus of coastal development.

Habitat and community modification was assessed as severe in the Benguela Current LME (UNEP 2005). The TDA produced by the GEF-supported Benguela Current Large Marine Ecosystem (BCLME) Project has identified habitat destruction and alteration, including modification of the seabed and coastal zone, and degradation of coastscapes, as a transboundary problem in this LME (GEF/UNDP/UNOPS/NOAA 1999). Nevertheless, compared to other parts of the world, these effects are minor in the Benguela Current LME.

Modification of the few estuarine systems was found to be severe in the Benguela Current LME (UNEP 2005). There is some loss of rocky and sandy foreshores in the region due to port construction, seawalls, resort development, and coastal diamond mining particularly in South Africa and Namibia, and some sand mining in Angola. The invasion of a significant stretch of coastline by the alien mussel (*Mytilus galloprovincialis*) has drastically altered community structure and functional group composition on the shore. Exploitation of some species in the kelp beds and mangroves has led to changes in community structure within these habitats.

The potential impacts of sea level rise on the coastal areas of the Benguela Current LME include increased coastal erosion and inundation of coastal areas. Available evidence suggests that variability and extremes in rainfall pattern are increasing in the south, particularly in the drier western parts (Tyson 1986, Mason *et al*. 1999). The resulting projected changes in stream flow are likely to have serious consequences for the estuaries.

Pollution, particularly microbiological, chemical and solid waste as well as eutrophication, is expected to become worse in the future, if poorly planned urbanization and economic development in the coastal areas of this LME continue (UNEP 2005). Habitat modification and loss are also expected to become worse if current practices continue, increasing the concern over the cumulative future effects on the health of this ecosystem.

IV. Socioeconomic Conditions

A large part of the population of the countries bordering the Benguela Current LME lives in urban areas, many of which are situated near the coast. The LME and its resources are of considerable socioeconomic importance to the bordering countries. For example, the production of oil and gas off the coast is the most important economic activity in Angola, contributing 90% of the total Gross Domestic Product (GDP). The fisheries sector is an important source of revenue, food, and employment in the three countries. Traditionally, fisheries have contributed significantly to the livelihoods of coastal communities. In Angola, this sector currently rates third after oil and diamond mining, and is estimated to provide half of the animal protein consumed in the country. Fishing contributes 9% to Namibia's GDP (SADC 2003), with annual fisheries exports worth over 225 million US$. Although the fisheries sector plays a small part in South Africa's economy, contributing about 1% to GDP (FAO 2006), it makes a significant contribution to the regional economy of the Western Cape, which is the centre for the industrial fisheries. In some coastal areas of South Africa, this sector is the dominant employer.

Fisheries constitute an important contribution to national revenue, employment, and food security in the bordering countries. These include a variable and uncertain job market, loss of national revenue, loss of food security, erosion of sustainable livelihoods, missed opportunities through underutilisation and wastage, and loss of competitive edge on global markets (GEF/UNDP/UNOPS/NOAA 1999). Unpredictable fisheries yields have sometimes resulted in closure of fish processing plants. Conflicts between subsistence, artisanal, commercial, and recreational fisheries also arise when resources become scarce. Subsistence fisheries depletion may adversely affect the diet and consequently the health of those dependent on fisheries. In many coastal settlements fishing is the only source of livelihood for the poorer segments of the population. Reduced fisheries resources also lead to migration of human populations from rural coastal areas to cities, resulting in expansion of urban poverty. Regime shifts as well as factors possibly related to climate change may displace fish stocks, contributing to socio-economic difficulties and threats to breeding populations of endemic species, e.g. African penguin.

V. Governance

The Benguela Current LME is located within the UNEP Regional Seas for the West and Central Africa Region, which was forged in the early 1980s. The West and Central African Action Plan for the Protection and Development of the Marine Environment and Coastal Areas of the West and Central African Region, the Abidjan Convention for Co-operation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region (Abidjan Convention) and associated Protocol Concerning Co-operation in Combating Pollution in Cases of Emergency were adopted by the Governments of the region in 1981. Projects on contingency planning, pollution, coastal erosion, environmental impact assessment, environmental legislation and marine mammals soon followed. A Conference of Plenipotentiaries, which met in Dakar, Senegal, in 1991, adopted the Regional Convention on Fisheries Cooperation among African States bordering the Atlantic Ocean (Dakar Convention), to which Angola has acceded.

There is a strong need for harmonising legal and policy objectives and for developing common strategies for resource surveys, as well as investment in sustainable ecosystem management in the Benguela Current LME. In 1997 a major regional cooperative initiative (BENEFIT: BENguela-Environment-Fisheries-Interaction and Training Programme) was launched jointly by Angola, Namibia, and South Africa, together with foreign partners (Norway and Germany) to enhance science capacity required for the optimal and sustainable utilization of living resources of the Benguela Current LME. This programme has been remarkably successful in developing cooperation among the three countries and in helping to strengthen marine scientific capacity in the region. A GEF grant and in-kind support of 38 million US$ to Angola, Namibia and South Africa, the three countries participating in the Benguela Current LME assessment and management project, will allow for significant additional support for initiating time-series measurement of selected indicators of the ecosystem’s productivity, fish and fisheries, pollution and ecosystem health, and socioeconomics.

In March 2000, this regional cooperation was further enhanced with the initiation of the implementation phase of the Benguela Current LME Programme (www.bclme.org), to assist Angola, Namibia, and South Africa to assess and manage the marine resources of the LME in an integrated and sustainable manner. This programme, which is funded in part by the GEF and the 3 participating countries, chiefly addresses transboundary problems in three key areas of activity: the sustainable management and utilisation of living resources; the assessment of environmental variability, ecosystem impacts and improvement of predictability; and maintenance of ecosystem health and management of pollution. Through this project, the Transboundary Diagnostic Analysis (TDA) and Strategic Action Plan (SAP) were used to review the existing knowledge on the status of, and to identify the threats to the Benguela Current LME. One of the main goals of the BCLME Programme was the creation of the Benguela Current Commission. This process was formalised through the signing of an Interim Agreement by the three countries on 29 August 2006 in Cape Town. This transitional management entity, which will last for four years, will be the precursor of the fully-fledged Benguela Current Commission whose function and responsibilities will be to implement an ecosystem approach to ocean governance in the Benguela region. This will include annual stock assessments of key economic species, annual ecosystem reports, the provision of advice on harvesting resource levels and other matters related to sustainable resource use, particularly fisheries and the management of the Benguela Current LME as a whole.

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I-2 Guinea Current LME

S. Heileman

The geographical boundaries of the Guinea Current LME extend from the intense upwelling area of the Guinea Current in the north, to the northern seasonal limit of the Benguela Current in the south. While the northern border of the Guinea Current is distinct, but with seasonal fluctuations, its southern boundary is less well-defined, and is formed by the South Equatorial Current (Binet & Marchal 1993). Sixteen countries border the LME - Angola, Benin, Cameroon, Congo, Democratic Republic of the Congo, Côte d'Ivoire, Gabon, Ghana, Equatorial Guinea, Guinea, Guinea-Bissau, Liberia, Nigeria, São Tomé and Principe, Sierra Leone and Togo. The tropical climate of the region is influenced by the northward and southward movements of the Inter-Tropical Convergence Zone (ITCZ) associated with the southwest monsoon and the Northeast Trade Winds. This LME covers an area of about 2 million km^2, of which 0.33% is protected, and includes 0.15% of the world's sea mounts and 0.20% of the world's coral reefs (Sea Around Us 2007). Twelve major estuaries and river systems (including the Cameroon, Lagos Lagoon, Volta, Niger-Benoue, Sanaga, Ogooue, and Congo rivers) form an extensive network of catchment basins enter this LME, which has the largest continental shelf in West Africa, although it should be noted that the West Africa's shelf is relatively narrow compared with many other shelves of the World Ocean. A volume on this LME was edited by McGlade *et al*. (2002), while another (Chavance *et al*. 2004) contains numerous accounts on this system. Other articles and reports include Binet & Marchal (1993), UNEP (2004) and Ukwe & Ibe (2006).

I. Productivity

The Guinea Current LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}). The Guinea Current LME is characterised by seasonal upwelling off the coasts of Ghana and Côte d'Ivoire, with intense upwelling from July to September weakening from about January to March (Roy 1995). Seasonal upwelling drives the biological productivity of this LME, which includes some of the most productive coastal and offshore waters in the world. The cold, nutrient-rich water of the upwelling system is subject to strong seasonal and inter-annual changes (Demarcq & Aman 2002, Hardman-Mountford & McGlade 2002), linked to the migration of the ITCZ. The LME is subject to long-term variability induced by climatic changes (Binet & Marchal 1993). Changes in meteorological and oceanographic conditions such as a reduction of rainfall, an acceleration of winds, an alteration of current patterns, and changes in nearshore biophysical processes might have significant consequences for biological productivity (Koranteng 2001). The coastal habitats and marine catchment basins also play an important role in maintaining the LME's productivity (Entsua-Mensah 2002).

Oceanic fronts (Belkin et al. 2009): Fronts in the Guinea Current occur mainly off its northern coast, in winter and summer (Figure I-2.1). The winter front appears to be the easternmost extension of the coastal Guinea Current that penetrates the Gulf; the front fully develops in January-February, reaching 5°E by March. The summer front emerges largely off Cape Three Points (2°W), usually in July-September, the upwelling season in the Gulf, and sometimes extends up to 200 km from the coast. Wind-induced upwelling develops east of Cape Palmas (7.5°W) and Cape Three Points owing to the coast's orientation relative to the prevailing winds. Current-induced upwelling and wave propagation also contribute to the observed variability in the Gulf (Ajao & Houghton 1998).

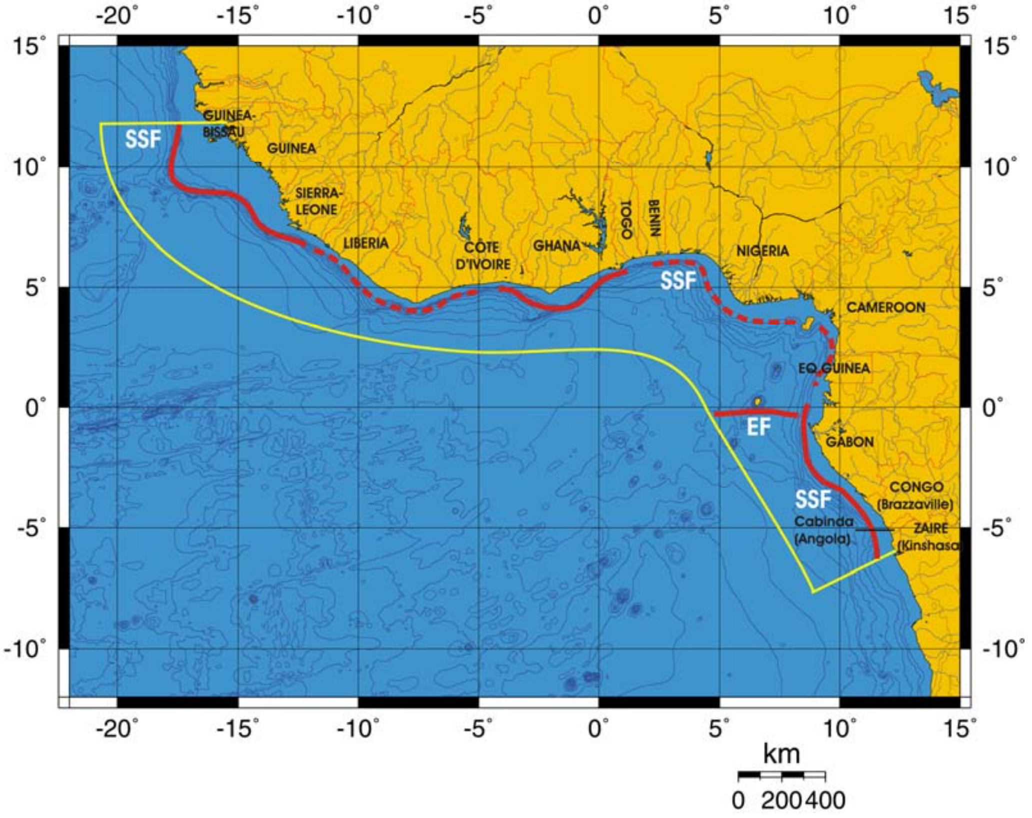

Figure I-2.1. Fronts of the Guinea Current LME. EF, Equatorial Front; SSF, Shelf-Slope Front (solid line, well-defined path; dashed line, most probable location). Yellow line, LME boundary. After Belkin (2009).

Guinea Current LME SST (after Belkin 2009)
Linear SST trend since 1957: 0.58°C.
Linear SST trend since 1982: 0.46°C.

The thermal history of the Guinea Current (Figure 1-2.2) included (1) a relatively stable period until the all-time minimum of 1976; (2) warming until the present at a rate of ~1°C in 30 years. Interannual variability of this LME is rather small, with year-to-year variations of about 0.5°C. The only conspicuous event, the minimum of 1976, cannot be linked to a similar cold event of 1972 in the two adjacent LMEs (Canary Current, Benguela Current) because of the 4-year time lag between the two events, which seems too long for oceanic advective transport of cold anomalies from one LME to another. The only plausible explanation invokes a cold offshore anomaly, probably localized within the equatorial band. Indeed, the North Brazil Shelf LME located on the western end of the equatorial zone saw the all-time SST minimum in 1976, the same year as the all-time minimum in the Guinea Current LME. Since the equatorial zone offers a fast-track conduit for oceanic anomalies, it remains to be seen from high-resolution data if both minima were truly synchronous – hence caused by large-scale (ocean-wide) forcing – or whether this cold anomaly propagated along the equator from one LME to another across the Atlantic Ocean.

The above results are consistent with an analysis of AVHRR SST data from 1982-1991 (Hardman and McGlade, 2002). The latter study has found 1982-1986 and 1987-1990 to be cool and warm periods respectively, with 1984 being exceptionally warm. As can be seen from Hadley data, 1984 was exceeded first by 1988 and then by 1998, when SST reached the all-time maximum probably linked to El-Niño. The SST variability mirrors the upwelling intensity, with strong upwelling in 1982-83, and weak upwelling in 1984 and 1987-1990 (Hardman and McGlade, 2002).

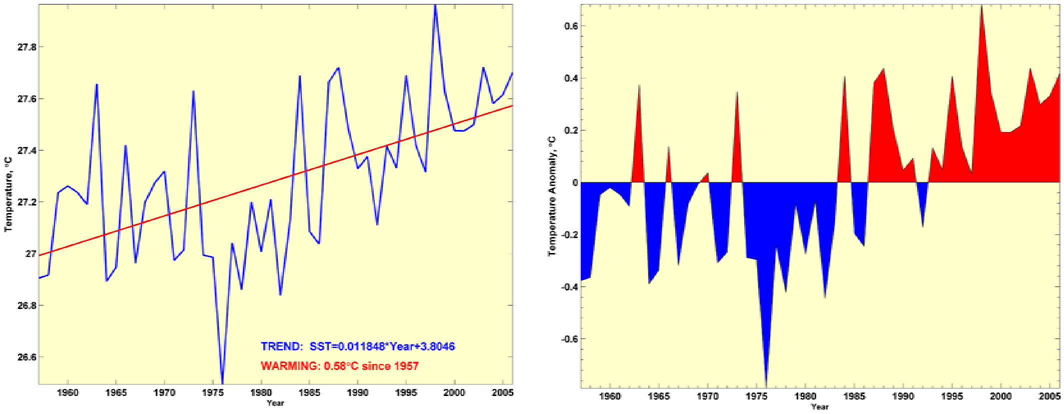

Figure I-2.2 Guinea Current LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Guinea Current Trends in Chlorophyll and Primary Productivity: The Guinea Current LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}).

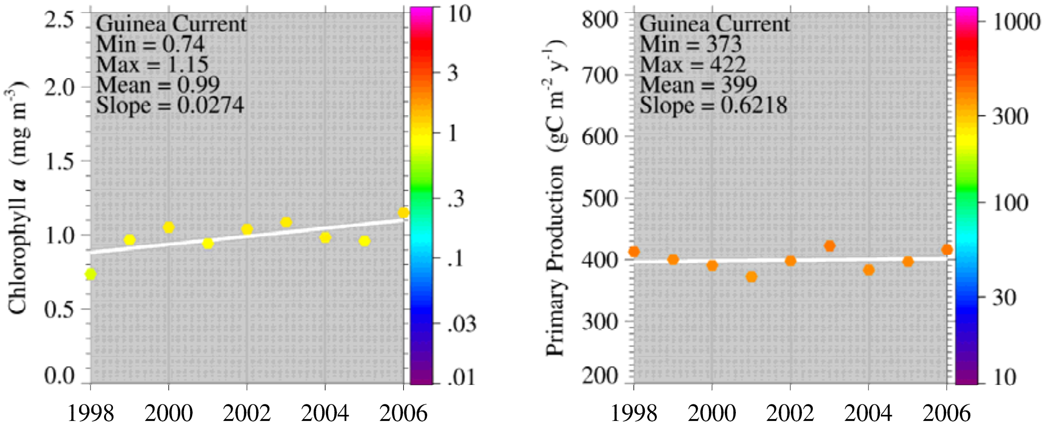

Figure I-2.3 Guinea Current LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Guinea Current LME is rich in living marine resources. These include locally important resident stocks supporting artisanal fisheries, as well as transboundary straddling and migratory stocks that have attracted large commercial offshore foreign fishing fleets. Exploited species include small pelagic fishes (e.g., *Sardinella aurita*, *Engraulis encrasicolus*, *Caranx* spp.), large migratory pelagic fishes such as tuna (*Katsuwonus pelamis*, *Thunnus albacares* and *T*. *obesus*) and billfishes (e.g., *Istiophorus albicans*, *Xiphias gladius*), crustaceans (e.g., *Penaeus notialis*, *Panulirus regius*), molluscs (e.g., *Sepia officinalis hierredda*), and demersal fish (e.g., *Pseudotolithus senegalensis*, *P*. *typus*, *Lutjanus fulgens*) (Mensah & Quaatey 2002). Several fishery resource surveys have been conducted in the LME (Koranteng 1998, Mensah & Quaatey 2002), with the Guinean Trawling Survey conducted in 1963-1964 having been the first large-scale survey in West African waters (Williams 1968). Data from this survey have recently been recovered (Zeller *et al.* 2005).

Total reported landings show a series of peaks and troughs, although there has been an overall trend of a steady increase from 1950 to the early 1990, followed by fluctuations with a peak at just over 900,000 tonnes (Figure I-2.4). Due to the poor species breakdown in the official landings statistics, a large proportion of the landings falls in the category named ‘mixed groups’. The trend in the value of the reported landings increased to a peak of around US$ 1 billion (in 2000 US dollars) in 1991 and thereafter declined considerably until the mid 1990s, before recovering to just over US $800 million (Figure I-2.5). Nigeria and Ghana account for about half of the reported landings in this LME, while European Union countries such as Spain and France, as well as Japan, are among the foreign countries fishing in the LME in recent times. Since the 1960s, high fishing pressure by foreign and local industrial fleets has placed the fisheries in the LME at risk (Bonfil *et al.*1998; Kacynski & Fluharty 2002).

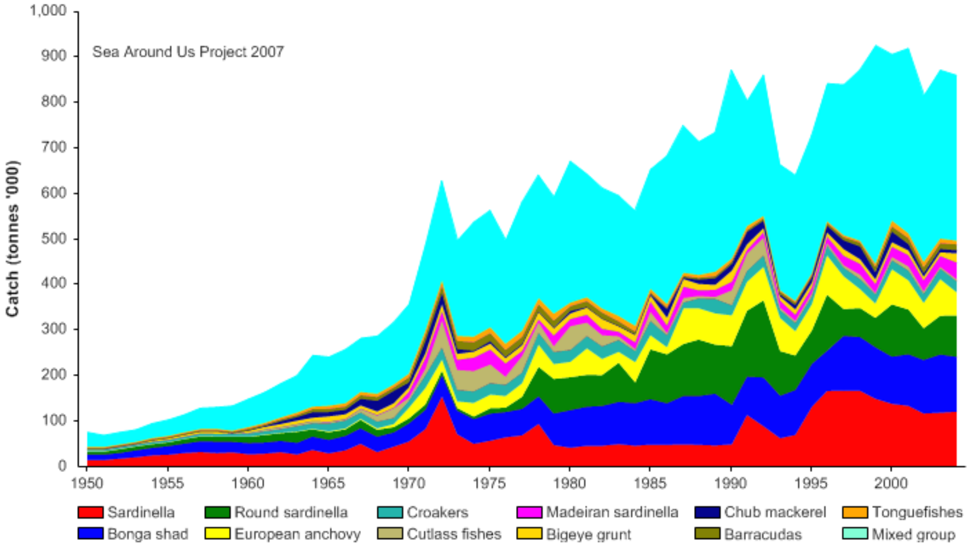

Figure I-2.4. Total reported landings in the Guinea Current LME by species (Sea Around Us 2007).

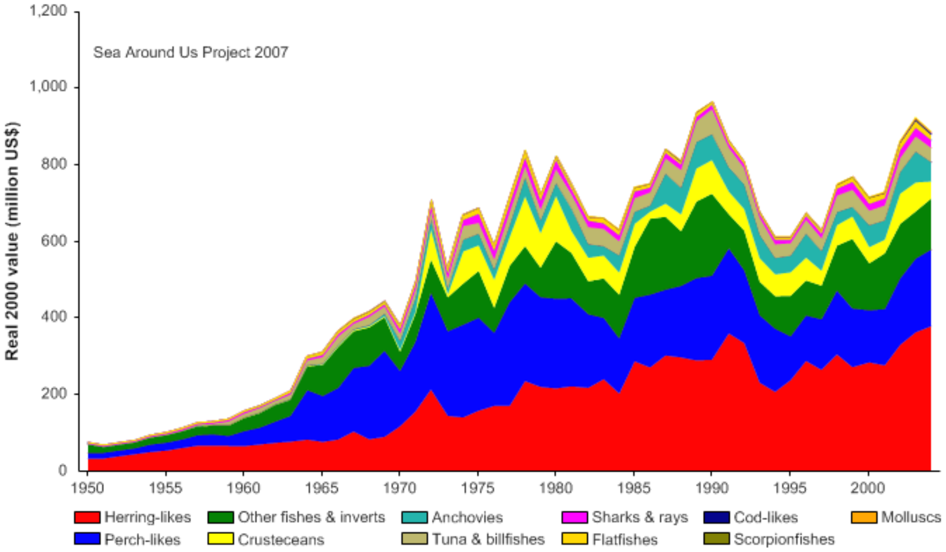

Figure I-2.5. Value of reported landings in the Guinea Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached 9% of the observed primary production in the early 1990s and has fluctuated between 6 to 9% (Figure I-2.6). Nigeria and Ghana account for the two largest ecological footprints in the LME.

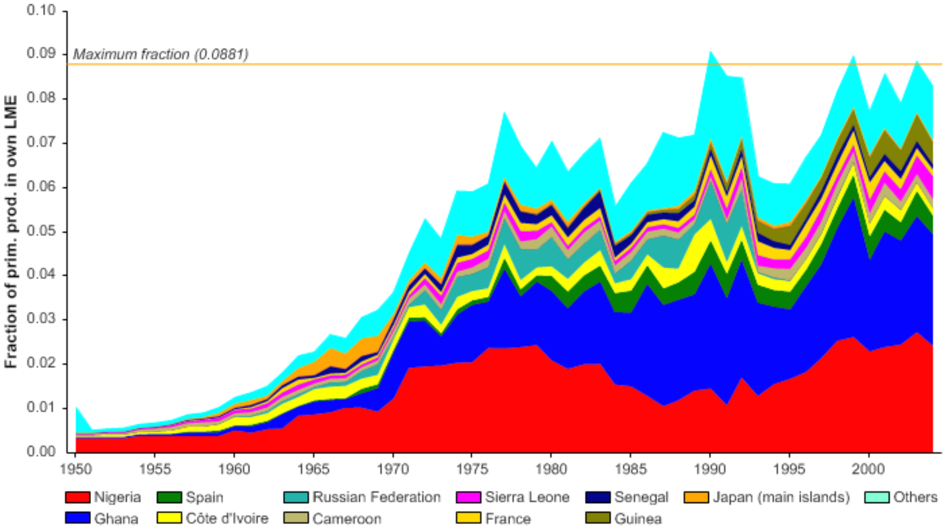

Figure I-2.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Guinea Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Since the mid 1970s, the mean trophic level of the reported landings (i.e., MTI; Pauly & Watson 2005) has declined (Figure I-2.7 top), an indication of a 'fishing down' of the local food webs (Pauly *et al*. 1998). The FiB index, on the other hand, has remained stable

(Figure I-2.7 bottom), suggesting that the increase in the reported landings over this period has compensated for the decline in the MTI (Pauly & Watson 2005).

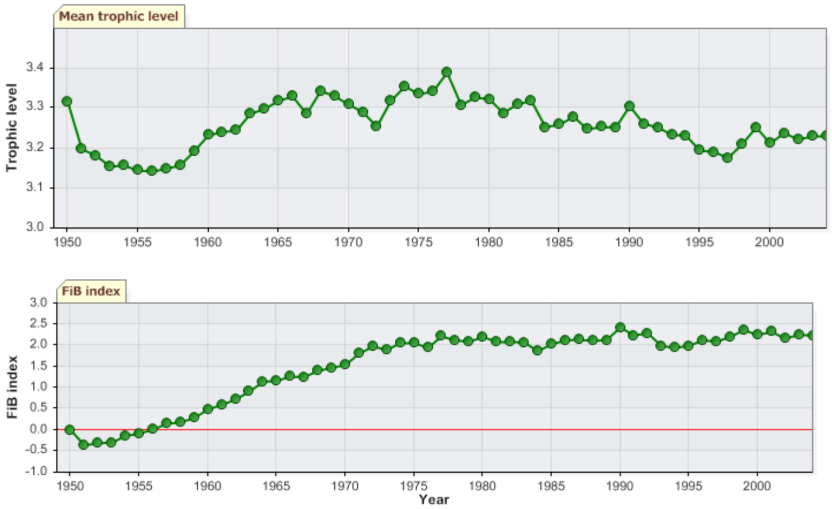

Figure I-2.7. Trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Guinea Current LME (Sea Around Us 2007).

The Stock-Catch Status Plots show that fisheries on collapsed stocks are rapidly increasing in numbers (Figure I-2.8, top). However, the catch is still overwhelmingly supplied by stocks in the fully exploited category (Figure I-2.8, bottom), which account for just under 30% of the stocks.

While some fish stocks such as skipjack tuna, small pelagic fish in the northern areas of the Gulf of Guinea, and offshore demersal fish and cephalopods are underexploited (Mensah & Quaatey 2002), the level of exploitation was found to be significant in this LME (UNEP 2004). The Guinea Current LME TDA (see Governance) has identified the decline in fish stocks and unsustainable fishing as a major transboundary problem (UNIDO/ UNDP/ UNEP/ GEF/ NOAA 2003) and reviews of the status of the LME's fisheries resources indicate that several fish stocks are either overexploited or close to being fully exploited (Ajayi 1994, Mensah & Quaatey 2002). These include small pelagics and shrimps in the western and central Gulf of Guinea and coastal demersal resources throughout the LME. There is also evidence of depletion of straddling and highly migratory fisheries stocks, with heavy exploitation of yellow-fin and big-eye tunas (Mensah & Quaatey 2002). Overexploitation has resulted in declining stock biomass and catch per unit effort (CPUE), particularly for inshore demersal species, and this decline has been attributed to trawlers operating in inshore areas (Koranteng 2002, Koranteng & Pauly 2004).

The use of small-sized mesh, especially in trawl, purse and beach seine nets is a widespread problem, especially in the central part of the region. This practice leads to excessive bycatch, but because these catches, mainly of juvenile fishes, are generally utilised, they are discarded only in a few fisheries (e.g., the shrimp fishery). Other destructive fishing practices such as the use of explosives and chemicals are also common in the inshore areas (e.g., see Vakily 1993).

There are indications that overexploitation has altered the ecosystem as a whole, with impacts at all levels, including top predators. Species diversity and average size of the most important fish species have declined as a result of overexploitation (Koranteng 2002, FAO 2003). Strong patterns of fish variability in the LME are thought to be related to strong interactions between species or communities, as well as to environmental forcing (Cury & Roy 2002). The influence of environmental variability on fish stock abundance and distribution in the LME has been demonstrated, for example, by Williams (1968), Koranteng *et al*. (1996), and Roy *et al*. (2002). Several oceanographic features that influence fish recruitment have also been identified (Hardman-Mountford & McGlade 2002). For instance, the abundance and distribution of small pelagic fish species are controlled mainly by the intensity of the seasonal coastal upwelling, which also determines the period of the main fishing season (Bard & Koranteng 1995).

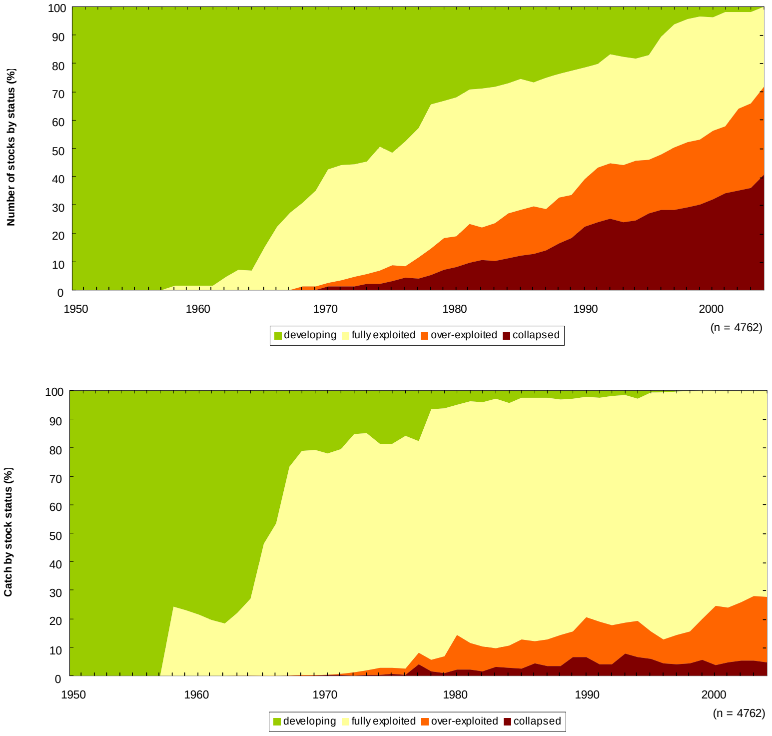

Figure I-2.8. Stock-Catch Status Plots for the Guinea Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.*, this vol. for definitions).

The most significant changes in species abundance are reflected in sardinella (*Sardinella aurita*) and triggerfish (*Balistes capriscus*). The sardinella fishery experienced a collapse in 1973, and was followed by a vast increase in the abundance of triggerfish between 1973 and 1988. The decline of the triggerfish after 1989 was followed by an increase of the sardinella to unprecedented levels during the 1990s (Binet & Marchal 1993, Cury & Roy 2002). Koranteng & McGlade (2002) attributed the almost complete disappearance of the triggerfish after the late 1980s to environmental changes and an upwelling intensification off Ghana and Côte d'Ivoire. The highly variable environment of the Guinea Current LME contributes to uncertainty regarding the status of fisheries stocks and yields which is likely to increase considering the impact of global climate change (UNIDO/UNDP/ UNEP/ GEF/ NOAA 2003). Therefore, environmental variability must be considered in the sustainable use and management of the region’s fisheries resources. Cooperation among the countries bordering this LME in the management of the fisheries resources would help to improve the fisheries situation in the future.

III. Pollution and Ecosystem Health

Pollution: LMEs have experienced various stresses as a result of the intensification of human activities. The coastal and marine environments of the Guinea Current are seriously polluted in the vicinity of large cities (Scheren & Ibe 2002). An assessment of the state of the environment with respect to the GPA land-based sources of pollution in this region is given by Gordon & Ibe (2006). More than 60% of existing industries are concentrated in the coastal areas and an estimated 47% of the population lives within 200 km of the coast. Pollution from land-based sources is particularly important, and together with sea-based sources, has contributed to a deterioration of water quality in the bordering countries. The TDA has identified the deterioration of water quality from land and sea-based activities as one of the four broad environmental problems in the LME (UNIDO/UNDP/UNEP/GEF/NOAA 2003). Overall, pollution was assessed as moderate, but more serious in coastal hotspots associated with the larger coastal cities (UNEP 2004). Despite being mainly localised, pollution also has transboundary impacts in this LME through the transport of contaminants by wind and water currents along the coast.

Sewage is one of the main sources of coastal pollution in the LME (UNEP 1999) and arises from generally poor treatment facilities and widespread release of untreated sewage into coastal areas (Scheren & Ibe 2002). Microbiological pollution is localised around coastal cities and remains a problem in terms of human health. Organic pollution from domestic, industrial and agricultural wastes has resulted in eutrophication and oxygen depletion in some coastal areas (Awosika & Ibe 1998, Scheren & Ibe 2002). While the incidence of eutrophication is not widespread and tends to be episodic, there are instances of continuous and persistent causes of eutrophication in large coastal water bodies (e.g., the Ebrié Lagoon in Abidjan). The increasing occurrence of HABs is of concern to the bordering countries (Ibe & Sherman 2002). Pollution from solid waste originating from domestic and industrial sources and offshore activities is severe across the entire region, with the enormous bulk of solid waste produced daily being a serious threat. Pollution from suspended solids is moderate along the coast, and arises mainly from soil loss from farms and deforested areas. Although much of the silt is trapped in dams and reservoirs, this has caused extensive siltation of coastal water bodies.

Chemical pollution is serious in coastal hotspots. Some chemical contaminants enter the aquatic environment through the use of pesticides, agro-chemicals including persistent organic pollutants (POPs) and as industrial effluents. Large quantities of residues (e.g., phosphate, mercury, zinc) from mining operations are discharged into coastal waters. Oil production is an important activity in some of the countries, especially Nigeria, and most of these countries have important refineries on the coast, only a few of which have proper effluent treatment plants. Moreover, the LME’s coastline lies to the east and downwind of the main oil transport route from the Middle East to Europe. Pollution from spills is significant, and arises mainly from oil spills from production points, loading and discharge points and from shipping lanes. Significant point sources of marine pollution have been detected around coastal petroleum mining and processing areas, releasing large quantities of oil, grease and other hydrocarbon compounds into the coastal waters of the Niger delta and off Angola, Cameroon, Congo and Gabon. It is estimated that about 4 million tonnes of waste oil are discharged annually into the LME from the Niger Delta sub-region (UNIDO/ UNDP/ UNEP/ GEF/ NOAA 2003). Much of the oil found on beaches originates from spills or tank washing discharged from tankers in the region’s ports (Portmann *et al*.1989). Because of the wind and ocean current patterns in the

Guinea Current LME, any oil spill from the offshore or shore-based petroleum activities could easily become a regional problem.

Habitat and community modification: The Guinea Current LME is interspersed with diverse coastal habitats such as lagoons, bays, estuaries and mangrove swamps. Besides being important reservoirs of biological diversity, these habitats provide spawning and breeding grounds for many fish, including transboundary species and shellfish in the region, and therefore are the basis for the regenerative capacity of the region's fisheries (Ukwe *et al*. 2001). Both anthropogenic activities and natural processes threaten these habitats. Although this is mainly localised, there are transboundary impacts related to migratory and straddling fish stocks that may use these habitats as spawning and nursery grounds.

It is estimated that 30% of habitat modification has been caused by natural processes, including erosion and sedimentation due to wave action and strong littoral transport. Coastal erosion is the most prevalent coastal hazard in the LME. Human activities, on the other hand, are thought to be largely responsible for habitat modification in this LME (UNEP 1999). Habitat and biodiversity loss due to hydrocarbon exploration and exploitation is significant. Many coastal wetlands have been reclaimed for residential and commercial purposes, with accompanying loss of wetland flora and fauna. The introduction of exotic species is also recognised as a transboundary problem (UNIDO/UNDP/UNEP/GEF/NOAA 2003).

Mangroves and estuaries have suffered the most losses, followed by sandy foreshores and lagoons. The LME has large expanses of mangrove forests (the mangrove system of the Niger Delta is the third largest in the world). However, these mangrove forests are under pressure from over-cutting, conversion into agricultural farms or saltpans, erosion, salinity changes, and other anthropogenic impacts (e.g., pollution). About 60% of Guinea's original mangroves and nearly 70% of the original mangrove vegetation of Liberia is estimated to be lost (Macintosh & Ashton 2002). The grass *Paspalum vaginatum* is replacing the original mangrove vegetation in these countries. In other areas the extent of mangrove destruction is: 45% in the Lake Nokoue area (Benin), 33% in the Niger delta (Nigeria), 28% in the Warri Estuary (Cameroon) and 60% in Côte d'Ivoire. Dam construction has led to reduction of freshwater and sediment discharge in the lower estuarine reaches of the rivers and altered the extent of intrusion of the estuarine salt wedge inland. This has important ecological effects on the flora and fauna of the coastal habitats.

Climate change is expected to also lead to habitat modification and loss. The IPCC (2001) has reported that Africa is highly vulnerable to climate change and sea level rise. Studies conducted in Nigeria estimated that over 1,800 km^2, or 2% of Nigeria's coastal zone, and about 3.68 million people would be at risk from a 1 m rise in sea level (Awosika *et al*. 1992). Moreover, Nigeria could lose over 3,000 km^2 of coastal land from floods and coastal erosion by the end of the 21st Century. Sea level rise would result in modification or loss of flora, fauna and biodiversity in flooded lands and coastal habitats, particularly in brackish waters (Ibe & Ojo 1994).

The LME is an important reservoir of marine biological biodiversity and has natural resources of global significance. Green, leatherback, hawksbill, loggerhead and olive ridley turtles are found in the LME. The LME is also inhabited by marine mammals (whales, dolphins, and manatees), among which are the Atlantic humpback dolphin and the African manatee, both of which appear on the IUCN Red List of endangered species (IUCN 2002). The humpbacked dolphin is classified as highly endangered and the

African manatee as vulnerable under the Convention on International Trade of Endangered Species (CITES).

IV. Socioeconomic Conditions

The 16 countries bordering the Guinea Current LME have an estimated total population of 300 million. At the present rate of population growth, this is expected to double in 20-25 years. Approximately 47% of the people live within 200 km of the coast (GIS analysis based on ORNL 2003). Rapid expansion of coastal populations with areas of high population densities has resulted from high population growth rates and movements between rural and urban areas (UNEP 1999). In addition, many of the region's poor are crowded in the coastal areas for subsistence activities such as fishing, farming, sand and salt mining and production of charcoal.

The Guinea Current LME and its natural resources represent a source of economic and food security for the bordering countries. In addition to being of major importance for food security in this region, fisheries also provide employment for thousands of people and are a substantial source of foreign exchange for countries such as Angola, Côte d'Ivoire, Ghana, and Guinea. A large proportion of the population could potentially be affected by overexploitation of fisheries (UNEP 2004). A reduction in the size and quality of the fish catch has widespread socioeconomic impacts, since more than 500,000 men and women along the coast from Mauritania to Cameroon are employed in the artisanal fishery (Bortei-Doku Aryeetey 2002). In Ghana, the national fish requirement has been estimated at 794,000 tonnes for a population of about 17.9 million, but fisheries production in 1998 achieved only 57% of the required volume (Akrofi 2002).

Over the past three decades, there has been evidence of reduced economic returns, loss of employment and user conflicts between artisanal and large commercial trawlers for access to the fishery resources (ACOPS/UNEP 1998). Côte d'Ivoire reported losses of about US$80 million in 1998 due to decreased fishing activities. This loss was attributed to the degradation of the coastal zone and its resources (GEFMSP/ACOPS/UNESCO 2001). The overexploitation of transboundary and migratory fish by offshore foreign fleets is having a detrimental effect on artisanal fishermen as well as on those coastal communities that depend on the near-shore fisheries resource for food. Local communities are at risk if artisanal fishing cannot proceed. This becomes particularly serious in the context of exploding demographics in the coastal areas and the fact that most of the fish catch is exported out of the region where all the countries, except Gabon, were classified by the FAO as Low Income Food Deficit Countries in 1998 (FAO 2002).

The socioeconomic impacts of pollution and habitat degradation include loss of recreational resources, pollution of food sources, decline in living coastal resources, and subsequent loss of subsistence livelihoods and reduction in food security and economic activity. In addition, increased pressure on governments to produce alternative livelihoods, and political instability at local or national levels may also arise. Coastline erosion also causes some concern because of the threat to coastal settlements, tourist infrastructure, agricultural and recreational areas, harbour and navigation structures, and oil producing and export handling facilities. The costs of coastal protection and habitat restoration can be high. For example, the restoration of the Korle Lagoon in Ghana has cost the government nearly US$65 million (Government of Ghana 2000). Public health risks from the presence of sewage pathogens and HABs are of concern. The cost of treatment of water-borne diseases is significant. For example, the Korle Lagoon Ecological Restoration Project (Government of Ghana 2000) estimated the cost of treatment to range from US$10 to US$50 per person, depending on the duration and intensity of the disease.

V. Governance

The countries bordering the Guinea Current LME participate in numerous bodies that work together on various aspects of coastal degradation and protection of living marine resources. The LME comes under the UNEP Regional Seas Programme for the West and Central Africa Region (see the Benguela Current LME for more information). They have adopted several international environmental conventions and agreements, among which is the Abidjan Convention and the Dakar Convention.

Mechanisms to provide regional collaboration on transboundary issues in the form of a regional coordination unit, and regionally agreed environmental quality standards and monitoring protocols and methods have been limited. These and other environmental issues are being addressed through joint projects. The GEF-supported Guinea Current Large Marine Ecosystem Project (Ibe & Sherman 2002, Ukwe *et al*. 2006) is an ecosystem-based effort to assist countries adjacent to the Guinea Current LME to achieve environmental and resource sustainability by shifting from short-term sector-driven management objectives to a longer-term perspective and from managing commodities to sustaining the production potential for ecosystem-wide goods and services (www.chez.com/gefgclme/). The pilot phase of this project (Water Pollution Control and Biodiversity Conservation in the Gulf of Guinea Large Marine Ecosystem) involved Côte d'Ivoire, Ghana, Togo, Benin, Nigeria and Cameroon, and ended in November, 1999. In 1998, the Ministerial Committee of this pilot project signed the Accra Declaration on Environmentally Sustainable Development of the Guinea Current LME, as an expression of their common political will for the sustainable development of marine and coastal areas of the Gulf of Guinea.

The second phase of this project 'Combating Living Resource Depletion and Coastal Area Degradation in the Guinea Current LME through Ecosystem-based Regional Actions', has extended the pilot phase to include 10 additional countries (Angola, Congo Brazzaville, Congo-Kinshasa, Equatorial Guinea, Gabon, Guinea, Guinea-Bissau, Liberia, São Tomé and Príncipe, and Sierra Leone). This phase includes the preparation of a TDA and a SAP. A project goal is to build capacity of the countries to work jointly and in concert with other nations, regions and with GEF projects in West Africa to define and address priority transboundary environmental issues within the framework of their existing responsibilities under the Abidjan Convention and the UNEP Regional Seas Programme. The Ministers of Environment of Angola, Benin, Cameroon, Congo, Côte d'Ivoire, Democratic Republic of Congo, Equatorial Guinea, Gabon, Ghana, Guinea, Guinea Bissau, Liberia, Nigeria, Sao Tome and Principe, Sierra Leone and Togo, gathered in Abuja, Nigeria, 21 – 22 September, 2006 on the occasion of the First Meeting of Ministers responsible for the implementation of the Guinea Current Large Marine Ecosystem (GCLME) Project; the Ministers signed the Abuja Declaration on 22 September, establishing the framework for an Interim Guinea Current Commission. The Interim Commission was brought into force on 22 September 2006 in Abuja, Nigeria, and is presently operating from Accra, Ghana. The focus of the Interim Commission is on achieving sustainable development through integration of environmental concerns in planning,accounting and budgeting, building capacity through multi-sector participation, management of transboundary water bodies and living resources of land, forests and biodiversity conservation, and development of information and data exchanges.

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I-3 Canary Current LME

S. Heileman and M. Tandstad

The Canary Current LME is a major upwelling region off the coast of northwest Africa, bordered by Morocco, Mauritania, Senegal, Guinea-Bissau, the Canary Islands (Spain), Gambia, Cape Verde and Western Sahara (a disputed, non-self governing territory). It is strongly influenced by the Canary Current, which flows along the African coast from north to south between 30° N – 10° N and offshore to 20° W (Barton 1998). The surface waters of the Canary Current are relatively cool as a result of the entrainment of upwelled water from the coast as it flows southwards (Mittelstaedt 1991). Several drainage systems in this region flow only seasonally because of the high seasonal variation in rainfall, e.g., the Senegal and Gambia Rivers. The LME has an area of about 1.1 million km^2, of which 0.77% is protected, and contains 0.12% of the world's sea mounts and 0.01% of the world's coral reefs (Sea Around Us 2007). There are 7 major estuaries and river systems draining into the LME including the Casamance, Senegal and Gambia. Books, book chapters and reports pertaining to the LME include Bas (1993), Prescott (1993), Roy & Cury (2003), Chavance *et al.* (2004) and UNEP (2005).

I. Productivity

The Canary Current LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}). Hydrographic and climatic conditions play a major role in driving the dynamics of this LME, which shows seasonal and longer-term variations (Bas 1993, Roy & Cury 2003). Climatic variability is the primary driving force, with intensive fishing being the secondary driving force, of biomass changes in the LME (FAO 2003, Sherman 2003). The biomass of small pelagic fish species is clearly influenced by the LME's oceanographic conditions (Bas 1993). A cyclonic gyre in the west acts to accumulate plankton from the north. The massive nutrient-rich upwelling stimulates, although with fluctuating intensity, seasonal bursts of primary productivity, then progressively of zooplankton and small pelagic fishes, other opportunistic feeders and predators, including mackerel, tuna and marine mammals in the pelagic zones. The normal community of zooplankton is composed of copepods, but mysid shrimps are also very important in this LME (Bas 1993). Inhabited by a large number of endemic and migrant species, the Canary Current LME is a unique ecosystem of global significance.

Oceanic fronts (after Belkin et al., 2009): Persistent northerly winds along the coast of Northwest Africa cause a year-round coastal upwelling. The upwelled water is drawn offshore by the Canary Current and also by current jets formed farther south, protruding transversally several hundred km offshore (Barton 1998, Barton *et al*. 1998). These processes create a large number of surface-intensified fronts that develop seasonally, synchronised with coastal upwelling (Figure I-3.1). The upwelling zone expands in winter and shrinks in summer and fall. It also migrates meridionally as the season progresses. The zone begins its southern advance in October and reaches its maximum southward extent (5°N) in January-March, then retreats northward, reaching 15°N in late summer.

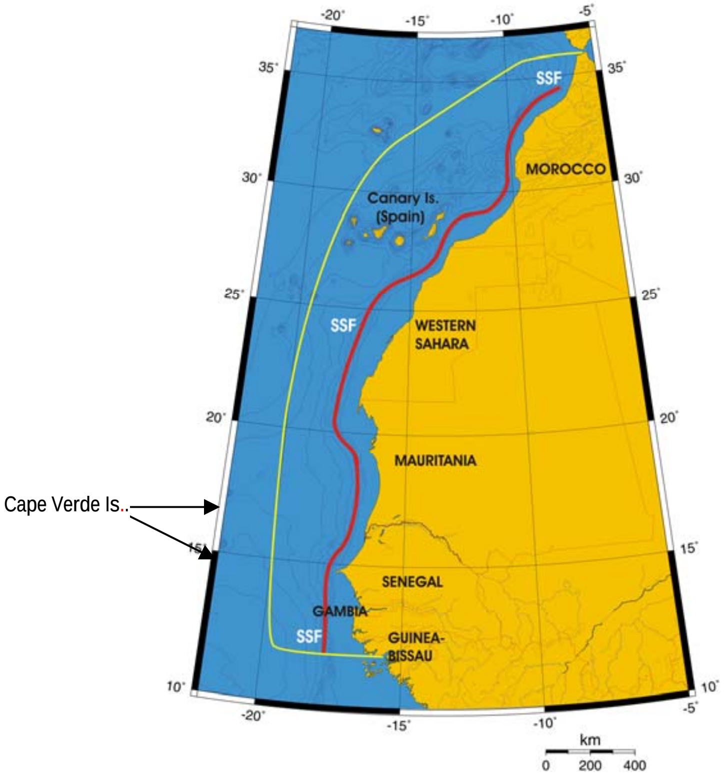

Figure I-3.1 Fronts of the Canary Current LME. SSF, Shelf-Slope Front. Yellow line, LME boundary. After Belkin et al.(2009).

Canary Current SST (after Belkin, 2009)
Linear SST trend since 1957: 0.48°C.
Linear SST trend since 1982: 0.52°C.

The moderate-rate warming since 1957 was interrupted by reversals (Figure 1-3.2). The most significant cold spell occurred after the warm event of 1969 and lasted a decade. The near-all-time maximum of 1969 was concurrent with the all-time maximum in the Caribbean Sea LME. This simultaneity likely was not coincidental since both LMEs are strongly affected – and connected – by trade winds blowing westward across the North Atlantic. The synchronism of both maxima across the North Atlantic, over a 5,000-km distance, strongly suggests a dominant role of atmospheric teleconnection, albeit westward advection by trade wind currents could also have played a role.

The Canary Current is one of four major areas of coastal upwelling in the World Ocean. Global warming is thought to increase the strength of equatorward winds, and hence to increase the upwelling intensity, leading to cooling in major upwelling areas. While the California Current LME and Humboldt Current LME indeed cooled over the last 25 years, the Canary Current actually warmed, as did the Benguela Current LME. This result is especially striking since the 20th century intensification of coastal upwelling off Northwest Africa is well documented (McGregor et al., 2007). The ongoing warming in the Mauritanian waters area is shown to have been beneficial for round sardinella (*Sardinella aurita*), which thrives after upwelling intensification in spring followed by retention of upwelled water – and primary production enhancement - over shelf in summer (Zeeberg et al., 2008).

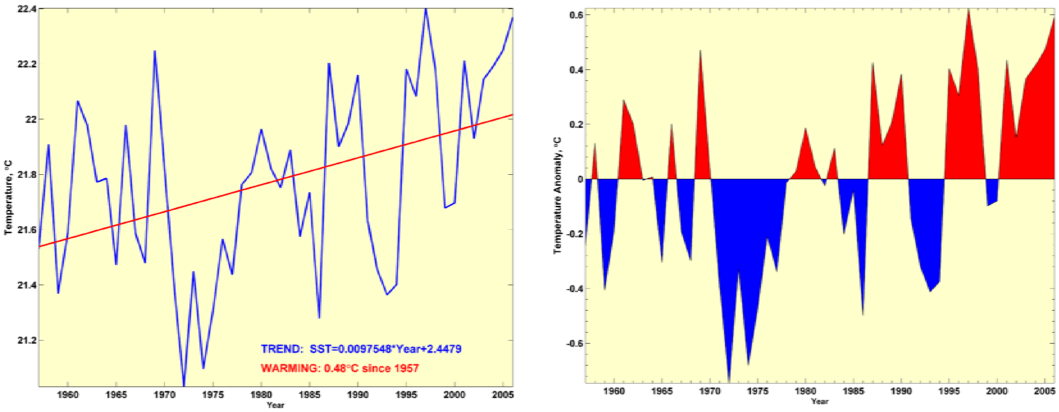

Figure 1-3.2 Canary Current LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology, (after Belkin, 2009).

Canary Current Trends in Chlorophyll and Primary Productivity: The Canary Current LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}).

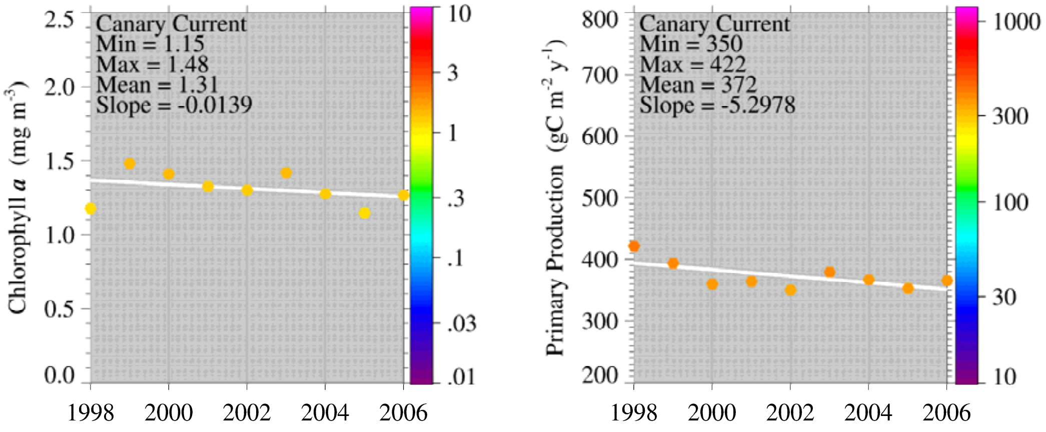

Figure I-3.3. Canary Current LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Canary Current LME is rich in fisheries resources among which are the small pelagic fish such as sardine (*Sardina pilchardus*), sardinella (*Sardinella aurita*, *S. maderensis*), anchovy (*Engraulis encrasicolus*), chub mackerel (*Scomber japonicus*) and horse mackerel (Trachurus spp.) constitute more than 60% of the catch in the LME. Other species caught in the LME include tuna (e.g., *Katsuwonus pelamis*), coastal migratory pelagic finfish, hakes (*Merluccius merluccius*, *M. senegalensis* and *M. poli*), a wide range of demersal finfish including *Pagellus bellotti*, Pseudotolithus sp., *Dentex canariensis*, *Galeoides decadactylus* and *Brachydeuterus auritus*, cephalpods (*Octopus vulgaris*, Sepia spp., and *Loligo vulgaris*) and shrimps (*Parapenaeus longirostris* and *Penaeus notialis*). Most of these species are transboundary or migratory, with the distribution of tunas often extending beyond the bordering countries' EEZs into international waters. Fishing activities in the LME have increased over the last three decades. In addition to small national fleets, the EEZs of Mauritania, Senegal, Gambia and Guinea Bissau all accommodate large distant water fleets from the European Union and Asia (FAO 2005a).

Total reported landings in the LME increased steadily to about 2.4 million tonnes in 1976, followed by a series of large fluctuations between 1.5 and 2.5 million tonnes (Figure I-3.4). The fluctuations in the total landings are also reflected in their value, which varies between US$1.5 billion and just under US$3 billion (in 2000 US dollars; Figure I-3.5). In recent years, however, both total reported landings and especially their value have undergone a noticeable decline.

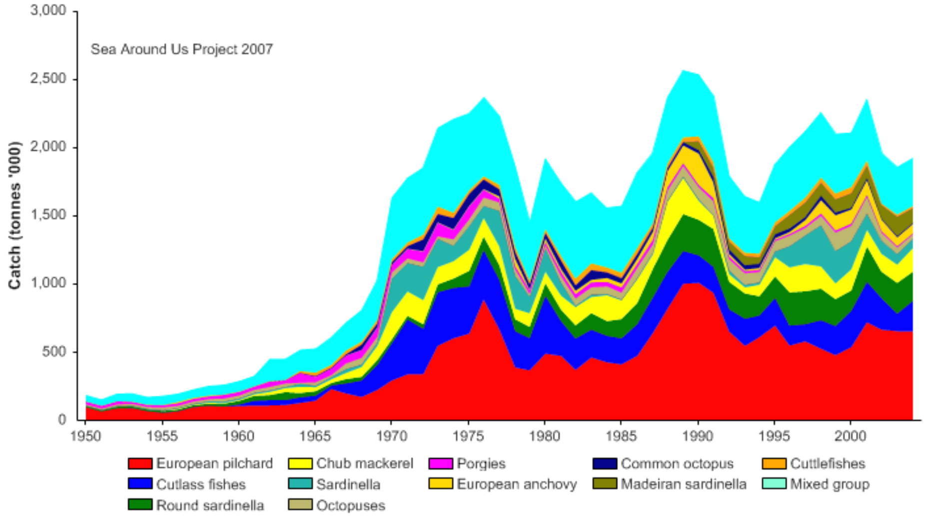

Figure I-3.4. Total reported landings in the Canary Current LME by species (Sea Around Us 2007).

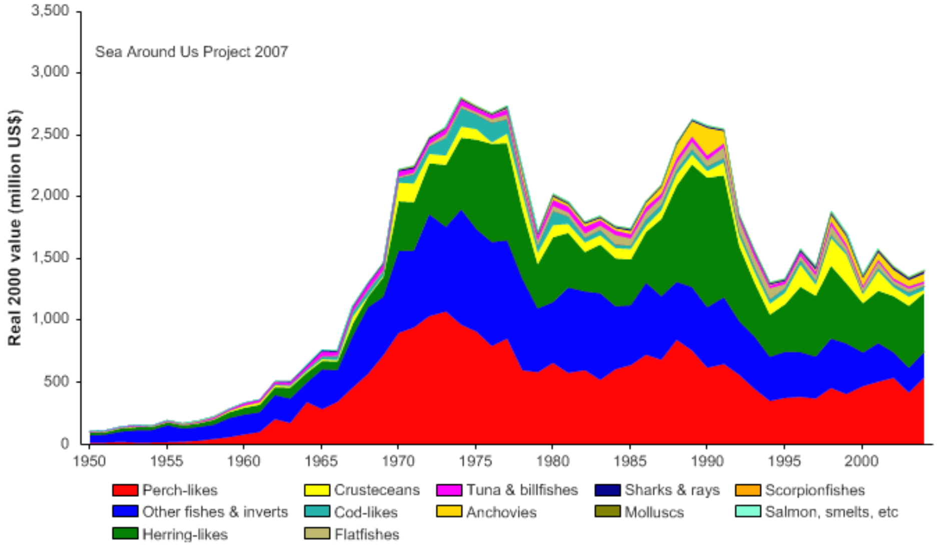

Figure I-3.5. Value of reported landings in the Canary Current LME by commercial groups (Sea Around Us 2007)

From the late 1960s to early 1990s, distant-water fleets from members of the former USSR, Spain and others countries accounted for most of the landings from the LME (Bonfil *et al.* 1998). In 1992, reported landings from the former USSR ceased, and the bulk of the landings were reported by the now independent countries of the former USSR. Substantial foreign fishing continues, notably off Mauritania (Gascuel 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landing in the LME reached 25% of the observed primary production in the early 1970s, but has since fluctuated to about 15% (Figure I-3.6). Spain, Morocco and Senegal are currently the countries with the largest ecological footprints in this LME, although the Soviet Union's republics (Russian Federation, Ukraine, Lithuania, Latvia, and Estonia) also accounted for large footprints in the 1970s and 1980s.

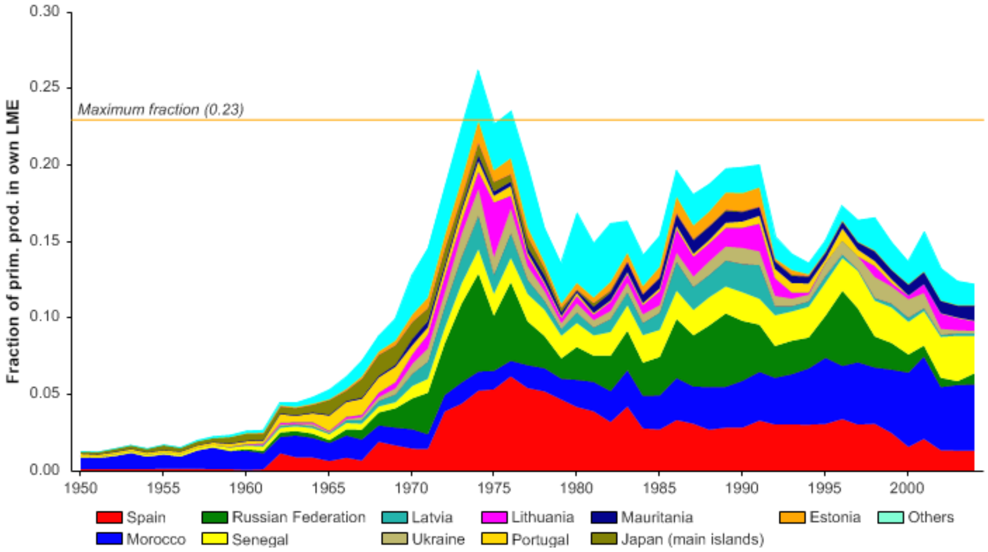

Figure I-3.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Canary Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has declined since the mid 1970 (Figure I-3.7 top), an indication of a 'fishing down' of the food web (Pauly *et al*. 1998). The FiB index indicates a possible slight decline during this period (Figure I-3.7 bottom), suggesting a situation in which catches that should increase when trophic levels decrease, are in fact decreasing (Pauly & Watson 2005).

The Stock-Catch Status Plots show that about 40% of exploited stocks can be considered collapsed, and another 40% are overexploited in the LME (Figure I-3.8, top). Still, over 70% of the catch originates from stocks that are classified as 'fully exploited' (Figure I-3.8, bottom).

Thus, overexploitation is of major concern in the bordering countries (UNEP 2005) of the Canary Current LME. Many fish stocks are being fished at or beyond maximum sustainable yield (MSY) levels in Senegal, Mauritania, Morocco and Gambia, and in some countries such as Morocco, Senegal and Gambia, demersal production over the past decade has been near and even above the MSY level (FAO 2005a). With the exception of Cape Verde, the intensification of fishing activities in the region has had a

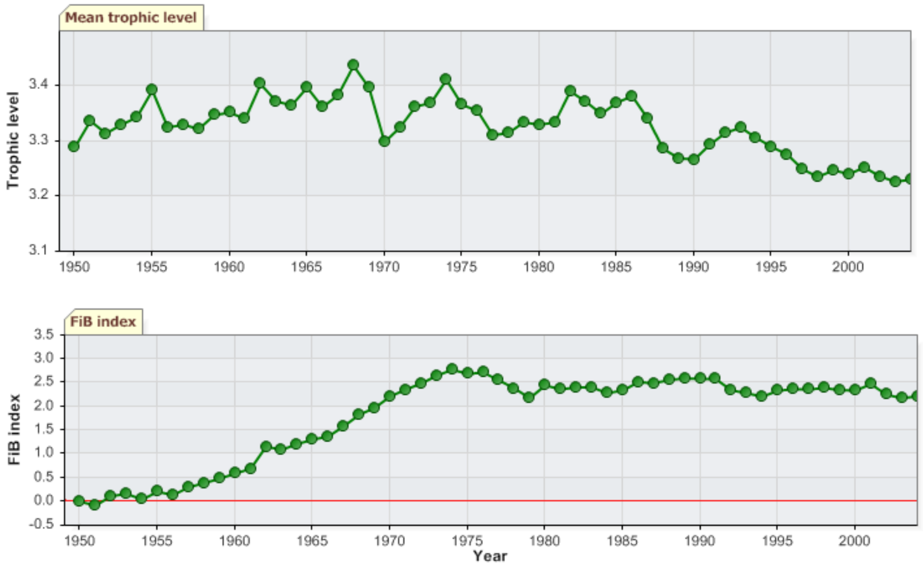

Figure I-3.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Canary Current LME (Sea Around Us 2007).

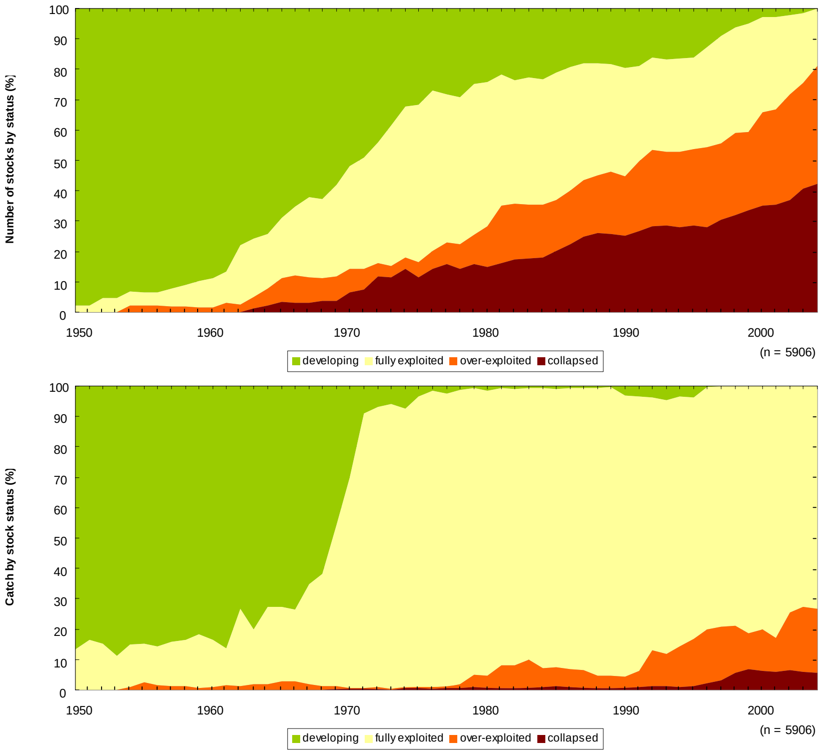

Figure I-3.8. Stock-Catch Status Plots for the Canary Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

drastic impact on the pelagic resources, which have undergone a strong decline in productivity (Fonseca 2000). High fishing pressure has also led to the marked decline in the catch of the demersal finfish fishery accompanied by the opportunist expansion of fisheries targeting octopus (Bas 1993, European Commission 2005). Bycatch and discards were assessed as moderate, and can be attributed to the use of small-meshed nets, especially in the artisanal fishery (UNEP 2005), although high discard rates were observed in the Spanish cephalopod trawl fishery in Morocco (Balgueiras 1997). Cephalopod trawlers fishing in Mauritania and Senegal were also found to discard 72% and 60-75% of their total catch, respectively, while the Senegalese mixed fleet targeting finfish and shrimps in shallow waters had a discard rate of 67%. Pech et al. (2001) explore the difficulties in fitting a model of flexible multifleet–multispecies fisheries to Senegalese artisanal fishery data.

Fish stocks in the LME are also expected to be influenced by global warming and the consequent rise in sea surface temperatures. Upwelling intensity and sea surface temperatures are strongly linked, and are believed to affect both the spatial distribution and abundance of fish in the LME (Cury & Roy 1991, Roy & Cury 2003). For example, periods of high sardine abundance appear to be associated with the ENSO variability (Roy & Cury 2003). Positive values of the Southern Oscillation Index are also associated with enhanced upwelling and coincide with higher catch rates (Roy & Reason 2001). The impact of climate on fish stock abundance and distribution must be taken into consideration in the development of fisheries management programmes in this LME.

III. Pollution and Ecosystem Health

***Pollution**:* Pollution is a major concern in localised hotspots, especially in emerging coastal mega-cities that are primary centres of industrial development and high population densities (UNEP 2005). There is strong evidence of serious localised degradation in the coastal environment of this and adjacent LMEs (Gordon & Ibe 2006). Eutrophication and the decay of organic matter create anoxia and subsequent fish mortality particularly in areas around major cities, bays and ports. Most countries in the Canary Current LME have environmental laws related to industrial, toxic, hazardous and medical wastes. However, enforcement of these regulations is inadequate, and pollution from these sources is evident in localised areas, especially near expanding coastal cities like Dakar (pop. 2,500,000 in 2007) in Senegal and Dar-el-Beida (Casablanca: pop. 3,900,000 in 2007) and Rabat (pop. 1,810,000 in 2007) in Morocco.

Some common features across the countries of the Canary Current LME are desertification, overgrazing on fragile rangelands, cultivation of crops on steep slopes (Cape Verde) and soil erosion. The resulting run-off and increased turbidity in the major rivers leads to increased turbidity in coastal waters throughout the LME. Domestic and industrial solid waste management and disposal are of concern in the bordering countries, and efforts are being made to address the problem. Spills around oil refineries are a chronic source of localised water column contamination. There is some evidence of minor spills of hazardous materials, but this is limited to harbours and fishing ports (UNEP 2002)

Habitat and community modification: Industrial development in the coastal zone of the Canary Current LME, as well as migration of people from inland rural areas to the coastal industrial centres, have led to increasing threats of coastal degradation and moderate habitat modification in this LME (UNEP 2005). Over the last 2 - 4 decades, marshes, swamps and mangroves have been degraded and lost through natural factors such as drought, but more significantly, through human activities such as unsustainable agricultural practices, urbanisation, mining and other industries, natural resources exploitation, and modification of rivers that has reduced water supply to wetlands and marine areas.

Approximately 30% of the surface area of wetland habitats has been permanently destroyed. Those that have not been destroyed are being modified largely because of continuing human activities. In some coastal lagoons there is a progressive decline of certain endemic algae species such as *Psidona oceanica*, due to the spread of *Caulerpa prolifera*. The replacement of mangroves by 'tannes', with a complete disappearance of mangroves, is evident in some areas. The construction of dams across certain tributaries of, for example, the Gambia and Senegal Rivers, has resulted in the die-back of extensive areas of mangrove forests. Significant quantities of sand from coastal erosion also contribute to mangrove death, by preventing the influx of sea water into mangrove areas. In addition, data indicate the extension of aquatic plants in estuaries and bays, particularly due to flow alteration and reduction (UNEP 2002). Ongoing and planned initiatives aimed at the control of pollution and the conservation of important habitats of the Canary Current LME (see Governance) are expected to lead to an improvement in the health of this LME (UNEP 2005).

IV. Socioeconomic Conditions

The total population of the countries bordering the Canary Current LME is about 58 million, of which an estimated 70% are directly reliant on the LME for their livelihoods. More than 60% of the population lives in the coastal areas where most cities and industrial infrastructure are located (UNEP 2002). These coastal populations are engaged mostly in marine fisheries, agriculture and tourism activities. The backbone of the countries' economy is based on agriculture and fisheries, with a very weak industrial sector contribution to GDP.

Fisheries provide livelihoods, fish protein supplies and revenue for the bordering countries, several of which are classified as Low-Income Food-Deficit Countries (FAO 2005b). These countries do not necessarily benefit from increased fish supplies or increased government revenue when foreign fleets access their waters (Kaczynski & Fluharty 2002). Much of the catch of the foreign fleets is exported or shipped directly out of the region, while compensation for access is often low compared to the value of the catch.

Overfishing has severe socioeconomic consequences in this LME, and includes reduction in national incomes, loss in fishing industries, reduction of food supply, loss of employment and increase in the cost of maritime surveillance as well as reduction of biological diversity. Loss of employment (which may be as high as 80% in Senegal) translates to impoverishment and suffering of people, among them being vulnerable groups such as women, children and the elderly. Overfishing also leads to conflicts among different user groups for dwindling resources. Depleted fisheries resources accentuate protein deficiency particularly in small children, leading to diseases such as kwashiorkor. This situation is aggravated mostly in rural areas where livestock is under severe threat from droughts. Management of the fisheries of the Canary Current LME to ensure sustainability is therefore of prime concern to all the bordering countries.

The economic sectors affected by pollution and habitat modification and loss are agriculture, fisheries, and tourism. Impacts on fisheries as well as the agriculture sectors can have severe economic ripples since they make a significant contribution to the overall national product (more than 30% of GDP in the region). Socioeconomic impacts include those of overfishing, as described above, as well as loss of tourism and recreational amenities. Migration of people (occasionally transboundary) including conflicts over resources could also arise. Loss of or modification of wetlands also results in shortage of firewood that is vital to the majority of households in rural areas. Pollution around densely populated coastal cities such as Dakar is a major cause of losses in the tourism industry in Senegal. In addition, pollution of coastal waters presents significant public health risks, through contaminated bathing beaches and consumption of contaminated fishery products. Loss and degradation of habitats also compromise the quality of water as wetlands generally act as sinks for pollutants from land-based activities. This in turn aggravates public health problems.

V. Governance

Several regional and sub-regional institutions and programmes are operating in the Canary Current LME region, including the UNEP Regional Seas Programme for the West and Central Africa Region (see the Benguela Current LME for more information), the Gambia River Development Authority, the Senegal River Development Authority and the Sub-Regional Fisheries Commission. The Ministerial Conference on Fisheries Cooperation among African States Bordering the Atlantic Ocean and the Fishery Committee for the Eastern Central Atlantic bring together all the states sharing the basins and coastal areas to ensure the proper use and management of their resources. Most of the bordering countries are signatories to various international environmental conventions, including the Abidjan Convention and Dakar Convention. Cape Verde, Guinea, Morocco and Senegal are members of the International Commission for the Conservation of Atlantic Tunas and have formally agreed to the subsequent Protocols of 1992 and 1997. All the Canary Current LME countries, except Mauritania and Morocco, are members of the Economic Community of West African States.

The coordinated management of this LME is a challenge (Prescott 1993). The historically fragmented nature of coastal and marine resource management is a legacy of the colonial past as well as of the political situation in these countries. There are regionally incompatible laws and there is a paucity of environmental regulations. The preparatory phase of the project ‘Protection of the Canary Current Large Marine Ecosystem’ has been finalised and a full scale project developed. The long-term environmental goal of the CCLME program is to “reverse the degradation of the Canary Current Large Marine Ecosystem caused by over-fishing, habitat modification and changes in water quality by adoption of an ecosystem-based management approach” and the CCLME project objective is to “enable the countries of the Canary Current Large Marine Ecosystem to address priority trans-boundary concerns on declining fisheries, associated biodiversity and water quality through governance reforms, investments and management programs.” A Preliminary TDA has confirmed the focus of regional concern on depleted fisheries and on habitat, associated biodiversity and water quality critical to fisheries.

The project will assist the seven participating countries to meet the sustainable fisheries target of WSSD including contribution to implementation of the Environment Action Plan under NEPAD. Close linkages are to be developed with GEF projects for the river basins draining into the LME and the neighbouring GEF International Waters projects on the Guinea Current and the Benguela Current LMEs. Consistent with other GEF LME projects, a TDA and SAP will be prepared for the Canary Current LME.

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II EASTERN AFRICA

II-4 Agulhas Current LME
II-5 Somali Coastal Current LME

II-4 Agulhas Current LME

S. Heileman, J. R. E. Lutjeharms and L. E. P. Scott

The Agulhas Current LME is located in the southwestern Indian Ocean, encompassing the continental shelves and coastal waters of mainland states Mozambique and eastern South Africa, as well as the archipelagos of the Comoros, the Seychelles, Mauritius and La Reunion (France). At the centre of the LME is Madagascar, the world's fourth largest island, with an extensive coastline of more than 5000km (McKenna and Allen 2005). The dominant large-scale oceanographic feature of the LME is the Agulhas Current, a swift, warm western boundary current that forms part of the anticyclonic gyre of the South Indian Ocean (Lutjeharms 2006a). This LME is influenced by mixed climate conditions, with the upper layers being composed of both tropical and sub-tropical surface waters (Beckley 1998). Large parts of the system are characterised by high levels of mesoscale variability, particularly in the Mozambique Channel and south of Madagascar. About 1.5% and 0.3% of the world's coral reefs and sea mounts, respectively, occur in this LME, which covers an area of about 2.6 million km², 0.64% of which is protected (Sea Around Us 2007). The coastal zones of both mainland and island states are characterised by a high faunal and floral diversity. At least 12 of the 38 marine and coastal habitats recognised as distinct by UNEP are found in every country of the LME, with Mozambique having 87% of habitat types (Kamukala and Payet 2001). Most of the Western Indian Ocean Islands exhibit a high level of endemism, with Madagascar classified as the country having the most endemic species in Africa, and the 6th most endemic species for a country, worldwide (UNEP 1999). The major mainland estuaries and river systems in this LME include the Mangoki and Zambezi, and provide considerable freshwater and sediment input into the coastal zones, particularly during seasonal tropical cyclone events..

I. Productivity

Lutjeharms (2006b) has provided descriptions of the oceanography and hydrology of the coastal oceans off southeastern Africa and their influence on biological productivity and biota.

The Agulhas Current LME is a moderately productive ecosystem (150-300 $gCm^{-2}year^{-1}$). It is a dynamic region of nutrient cycling, localised upwelling and associated fisheries potential (Bakun *et al*. 1998, Lutjeharms 2006b). For instance, the region directly to the east of Madagascar has been shown to have a seasonal, deep-sea phytoplankton bloom (Longhurst, 2001) for which the causes are still being debated. Furthermore, episodic upwelling of colder water on the shoreward edge of the Agulhas Current has been shown to create a favourable environment for pelagic clupeoid fishes (Beckley 1998). Such localised, intermittent upwelling has also been observed at specific offsets in the coastline in the Mozambique Channel and at the southeastern tip of Madagascar (Lutjeharms 2006a). An upwelling cell observed at Angoche in Mozambique had the highest chlorophyll density in the Mozambique Channel; off Madagascar the chlorophyll is concentrated in a subsurface maximum. The ecosystem impact of these marked upwelling cells remains unknown due to very few observations. The Agulhas Current furthermore plays an important role in the southward dispersal of early life history stages of tropical fish species.

The movement of water in the Mozambique Channel is, by contrast, dominated by eddies. Intense anticyclonic eddies are formed at the narrows of the Channel and move steadily southward. Cyclonic eddies are formed south of Madagascar and may in turn move equatorward on the eastern side of the Mozambique Channel. These eddies seem to have disparate effects on the local ecosystems. It has been noted (Weimerskirch, 2004) that top marine predators feed preferentially at the edges of the anticyclones. It has also been noted in satellite remote sensing of ocean colour (e.g. Quartly and Srokosz 2004) that passing eddies may draw out more productive water from adjacent shelf regions into the deep ocean. The contribution these different processes make to the general productivity of the region is as yet not known. The primary flow of near-bottom water in the western Indian Ocean is South-East through the discordance zone in the Southwest Indian Ridge, via the Crozet Basin, northwards into the Madagascar basin, then into the shallower Mascarene basin, through the Amirante trench to the Somali basin (Schmitz 1996).

The LME is considered a distinct biogeographic province of the Indo-West Pacific, with high levels of biodiversity and regional endemism in coastal habitats. Inhabiting the LME are at least 20 species of cetaceans, five species of marine turtles, numerous seabirds, as well as an important remnant population of the threatened dugong. The LME is also home to the CITES-listed coelacanth (*Latimeria chalumnae*), which belongs to a group of primitive fish earlier believed to be extinct.

Ocean currents: The greater Agulhas Current system may be considered to consist of five generic parts: a source region, the northern Agulhas Current, the southern Agulhas Current, the Agulhas retroflection and the Agulhas Return Current, each of which has a different influence on the marine ecosystem (Figure II-4.1).

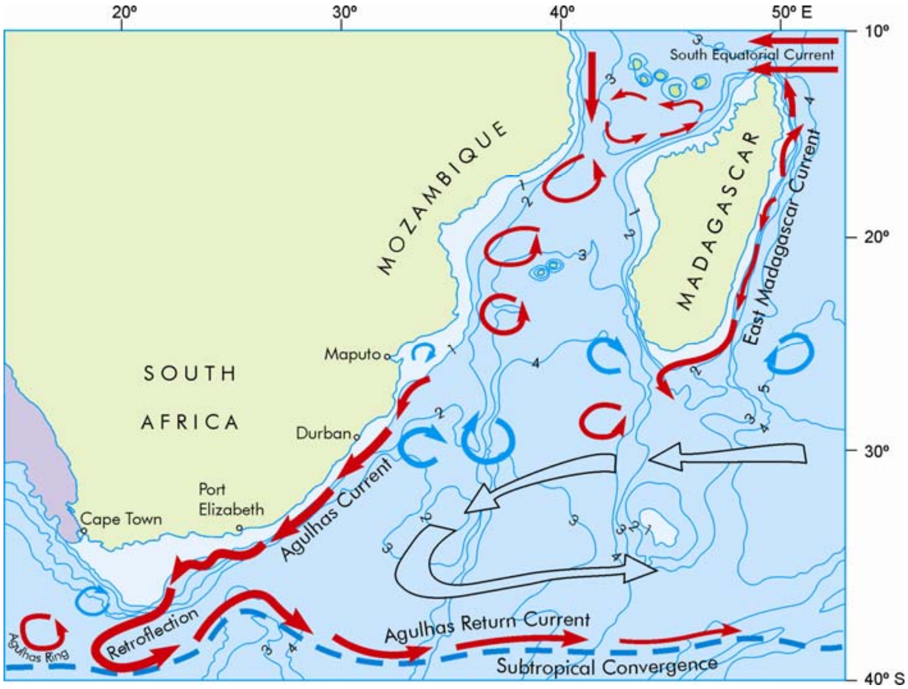

Figure II-4.1a. A simplified depiction of the circulation and currents of the greater Agulhas system. Red arrows denote anticyclonic motion; blue arrows cyclonic motion or eddies, and a broken, blue line gives the average location of the Subtropical Convergence. Open arrows denote inferred general motion of the Southwest Indian subgyre. Depth is given in kilometre. All the generic components of the current system are shown, including the source currents of the Agulhas Current, its outflows as well as the northern and southern Agulhas Current themselves, located to either side of Port Elizabeth (after Ansorge and Lutjeharms 2007).

The Agulhas Current has three recognised sources, in order of volume flux: recirculation in a Southwest Indian Ocean subgyre, contributions by the southern branch of the East Madagascar Current and the flow through the Mozambique Channel (Stramma and Lutjeharms 1997). The recirculation gyre is found west of 70º E. Its waters are largely oligotrophic, but its circulation may play a decisive role in the lifecycle of leatherback sea turtles. The second source from the east of Madagascar is usually in the form of eddies consisting of warm tropical surface water. These eddies are formed at the southern termination of the East Madagascar Current and can be both cyclonic and anticyclonic. The smallest contribution to the flux of the Agulhas Current comes from the Mozambique Channel by the aforementioned eddies. The contribution to the volume flux of the Current by these eddies may be small, but their impact on downstream behaviour is substantial.

The northern Agulhas Current flows along the east coast of South Africa following the shelf edge very closely. At irregular occasions this stability is interrupted by a single meander, the Natal Pulse, that is believed to be triggered by the impact of a Mozambique eddy (Schouten et al. 2002). The downstream passing of this meander causes a reversal in the shelf currents and may contribute to the upstream dispersal of biota. At two locations the Current passes form a narrow shelf to a wider shelf: at Cape St Lucia just upstream of Durban and at the eastern edge of the Agulhas Bank (vide Figure II-4.2). At both these locations there is a distinct upwelling cell with enhanced primary productivity. These cells may have a decisive influence on the ecosystems of the shelf segments of which they form part.

The southern Agulhas Current has very different flow behaviour. When the Agulhas Current moves past the eastern side of the wider Agulhas Bank, it starts meandering quite extensively to either side (Lutjeharms 2006a). In this process shear edge eddies and warm plumes are formed on its shoreward side. On passing the southern tip of the Bank such warm plumes may move equatorward along the eastern edge of the Bank or may be turned back by lee eddies formed here (Lutjeharms et al. 2007, vide Figure II-4.1). This motion is crucial to the fisheries in the BCLME since the larvae of pelagic fish that spawn on the Bank may be carried to the west coast upwelling region or be removed to the deep sea, depending on the direction of the flow at its western edge.

Having passed the most southern tip of Africa, the Agulhas Current retroflects. The Agulhas Current Retroflection is very unstable and the retroflection loop occludes at irregular intervals, creating large Agulhas Rings that drift off into the South Atlantic Ocean carrying with them Indo-Pacific species. The major part of the volume flux from the Retroflection is however eastward in the Agulhas Return Current. This current is either juxtapositioned or flows parallel to the Subtropical Convergence that is recognised for its high levels of primary production (e.g. Allanson *et al.* 1981). This primary production takes place as intermittent events of limited duration (Llido *et al.* 2005), an unusual behaviour to which the local, endemic biota have to be adjusted. Although this frontal system is one of the most intense in the world ocean, the currents mentioned above generate their own fronts.

Oceanic fronts (Belkin 2009): The Agulhas Current Front (ACF) for instance is the inshore boundary of the Agulhas Current (Figure II-4.1). This front is very deep and is observed year-round. Also included in this LME are average fronts related to the movement of the abovementioned Mozambique eddies. The East Madagascar Current Front (EMCF) is most clearly observed off southeastern Madagascar, and off the northern tip of Madagascar, where the Glorioso Islands Front (GIF) protrudes northwestward from the Glorioso Islands at 11°30'S, 47°20'E. The latter was only described in the literature with the advent of satellite remote sensing, and was discovered during a global survey of oceanic fronts (Belkin *et al*. 2008). However, these fronts are based on the mean circulation and some may be very intermittent or ephemeral.

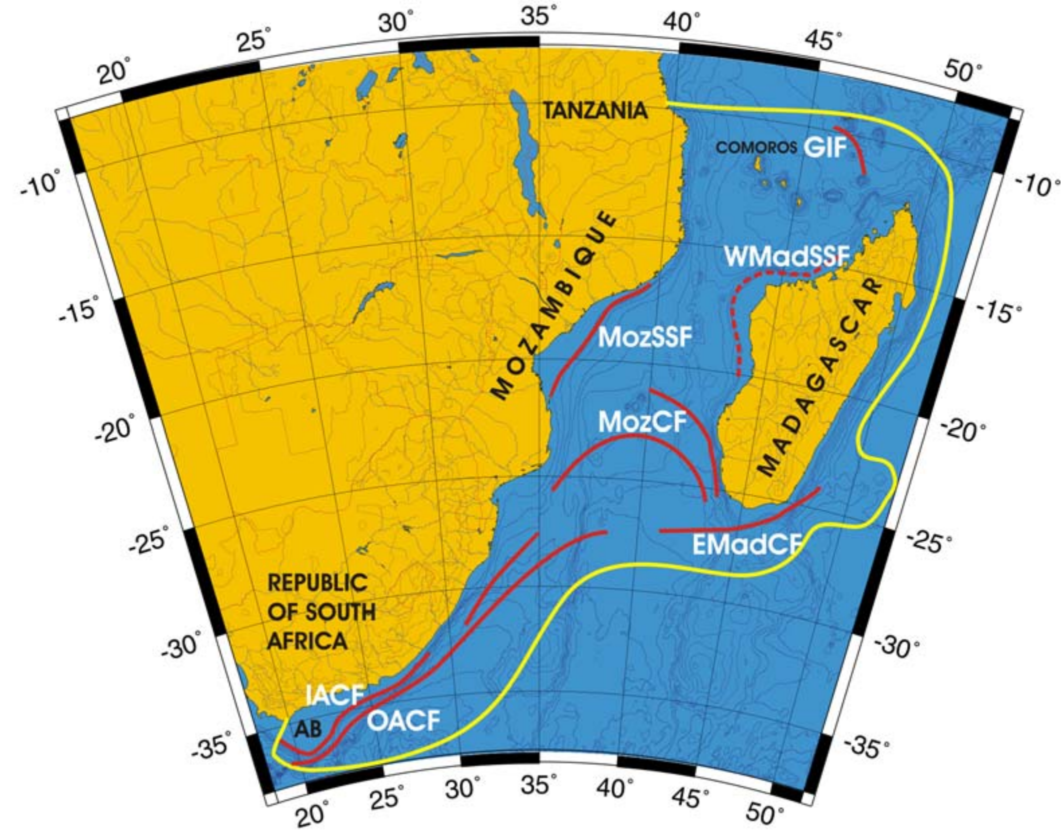

Figure II-4.1b. Fronts of the Agulhas Current LME. AB, Agulhas Bank; ACF, Agulhas Current Front; EMadCF, East Madagascar Current Front; GIF, Glorioso Islands Front; IACF, Inshore Agulhas Current Front; MozCF, Mozambique Channel fronts; MozSSF, Mozambique Shelf-Slope Front; OACF, Offshore Agulhas Current Front; WMadSSF, West Madagascar Shelf-Slope Front (most probable location). Yellow line, LME boundary. After Belkin (2009).

Agulhas Current SST (after Belkin 2009)
Linear SST trend since 1957: 0.68°C
Linear SST trend since 1982: 0.20°C

Over the past decades the sea surface temperatures (SST) of the Agulhas Current LME have undergone some significant changes. A linear SST trend since 1957 has been an increase of 0.68°C and 0.20°C since 1982 (Figure II-4.2). The Agulhas Current's long-term warming was punctuated by relatively small-scale cold/warm events with a magnitude of about 0.5°C. A substantial synchronism between increases in SST in the Somali and Agulhas LMEs has been observed. For example, the all-time minima of 1964-1965 occurred during the same years in the Somali and Agulhas LMEs, as well as the all-time maximum of 1983 in the Agulhas Current and the near-all-time maximum in 1983 in the Somali Current. The post-1982 warming of the Agulhas Current was spatially non-uniform: the Agulhas Current Retroflection SST increased by up to 1.0°C, while SST in some inshore shelf areas of the Agulhas Bank decreased (Fidel and O'Toole 2007, after Pierre Florenchie, University of Cape Town, personal communication).

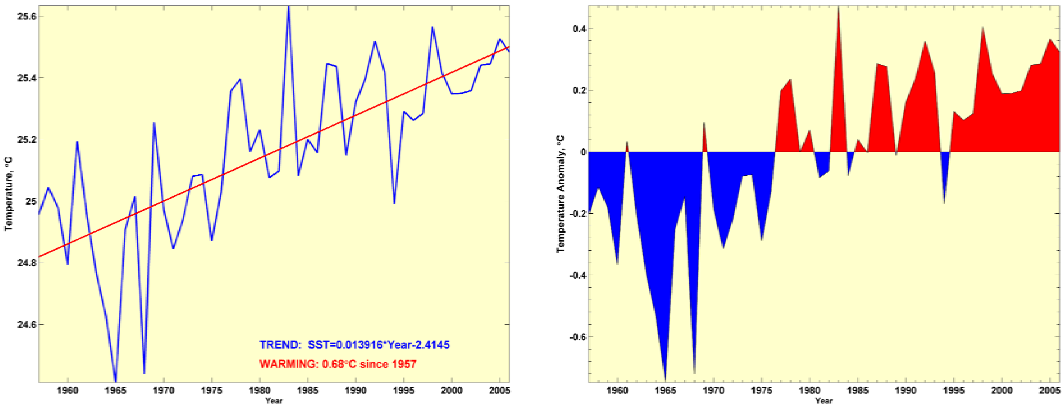

Figure II-4.2 Agulhas Current LME mean annual SST (left) and SST anomalies (right), 1957-2006. After Belkin (2009).

Agulhas Current LME Trends in Chlorophyll and Primary Productivity: The Agulhas Current LME is a moderately productive ecosystem (150-300 gCm^{-2}year^{-1}).

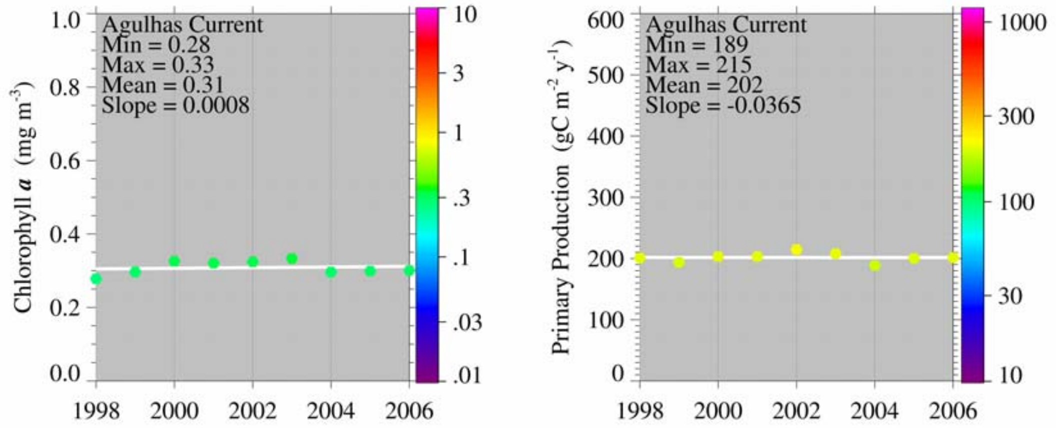

Figure II-4.3. Agulhas Current LME trends in chlorophyll a (left) and primary productivity (right) 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Total reported landings in this LME peaked at just under 600,000 tonnes in 1974 with a record landings of Cape anchovy and South American pilchard (Figure II-4.4). However, with the collapse of these fisheries in the mid 1970s, the reported landings were diminished down to 180,000 tonnes and have remained at this low level for some time, Some signs of growth can be seen in recent years, particularly in the landings of South American pilchard, and total landings have reached 270,000 tonnes in 2004. The trend in the value of the reported landings has mirrored that of the tonnage, and as shown in Figure II-4.5, it peaked at just over 700 million US$ (in 2000 real US$) in 1973 (Sea around us 2007).

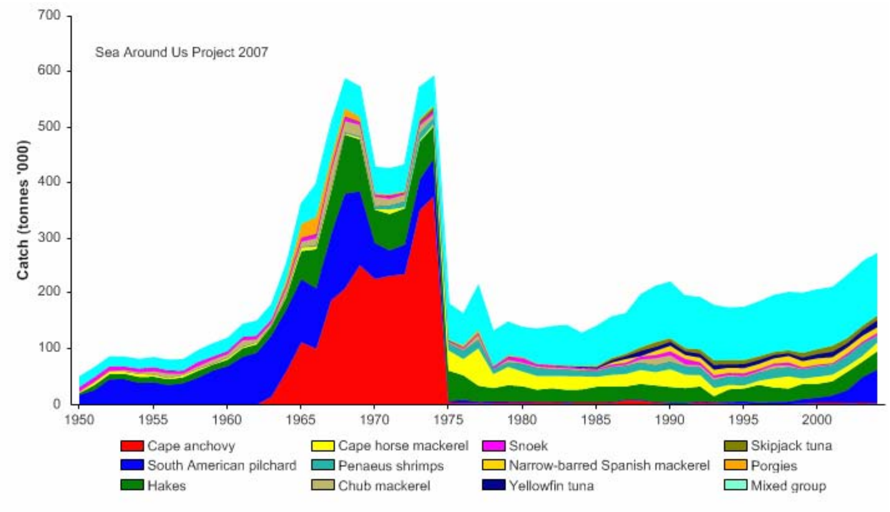

Figure II-4.4. Total reported landings in the Agulhas Current LME by species (Sea Around us 2007).

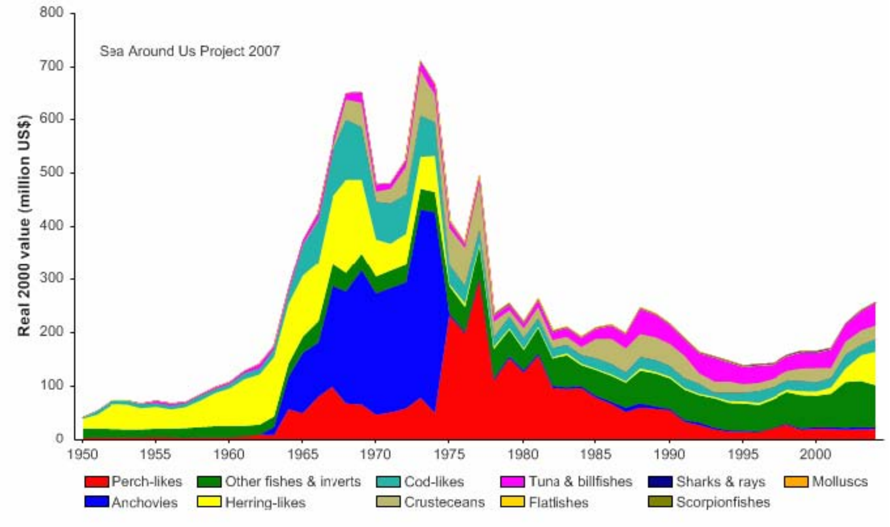

Figure II-4.5. Value of reported landings in the Agulhas Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR, Pauly & Christensen 1995) to sustain the reported landings in the LME reached close to 8% of the observed primary production in 1968, when the highest level of reported landings was recorded (Figure II-4.6). With the collapse of the Cape anchovy and South American pilchard fisheries in the mid 1970s, the PPR declined to around 2%. In the 1980s, however, it returned to about 5% (Sea Around Us 2007). South Africa and Madagascar account for the largest ecological footprints in the LME, though in the 1960s and the early 1970s, foreign fleets accounted for the majority of the footprint.

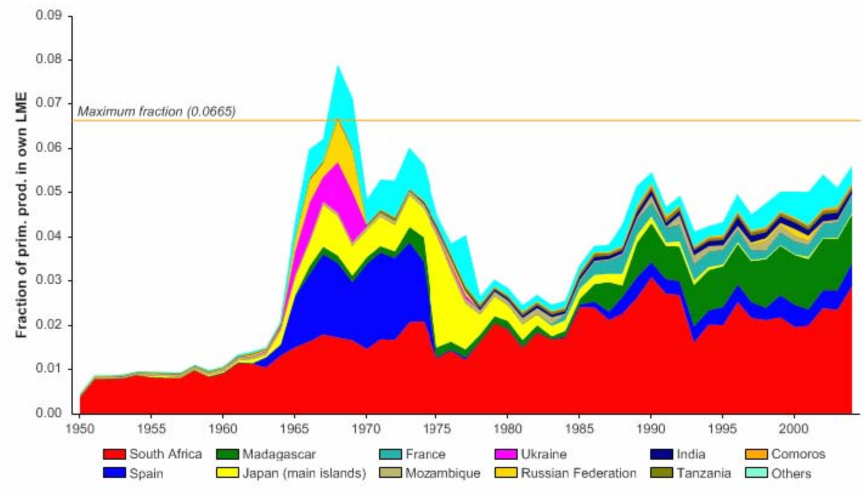

Figure II-4.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Agulhas Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The sharp increase in the mean trophic level of the fisheries catch (i.e., the MTI; Pauly & Watson 2005) observed in the mid-1970s reflects the collapse of the pilchard and anchovy fisheries, two species with low trophic levels (Figure II-4.7 top).

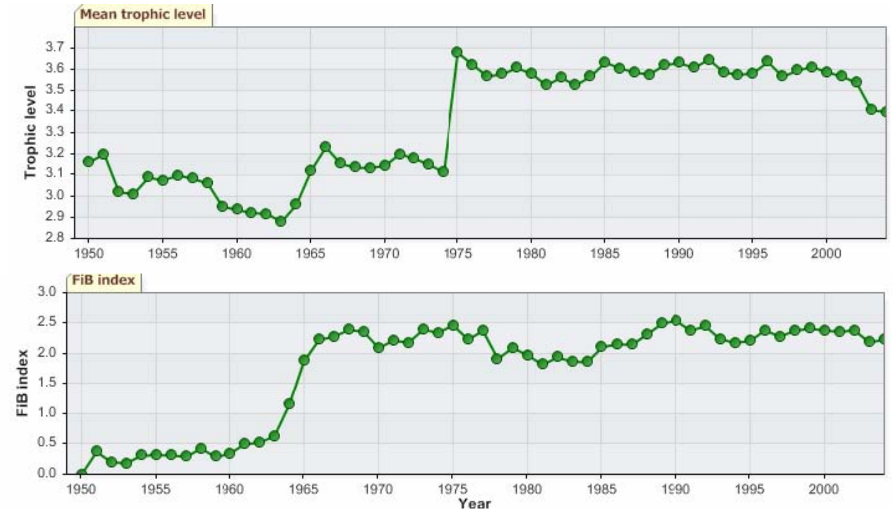

Figure II-4.7. Marine trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Agulhas Current LME (Sea Around Us 2007).

Although the MTI has declined over the last few years, likely due to the increased pilchard landings, there is no observable decline indicative of a 'fishing down' of the food web (Pauly *et al*. 1998) in the LME. Over the same period, the FiB index showed at best a minor decline (Figure II-4.7 bottom), suggesting that the increasing catches over this period may not sufficiently compensate for the decline in the MTI (Pauly & Watson 2005).

The Stock-Catch Status Plots show that the number of collapsed stocks is higher than that of overexploited or fully exploited stocks (Figure II-4.8, top), while the three groups contribute equally to the catch biomass (Figure II-4.8, bottom).

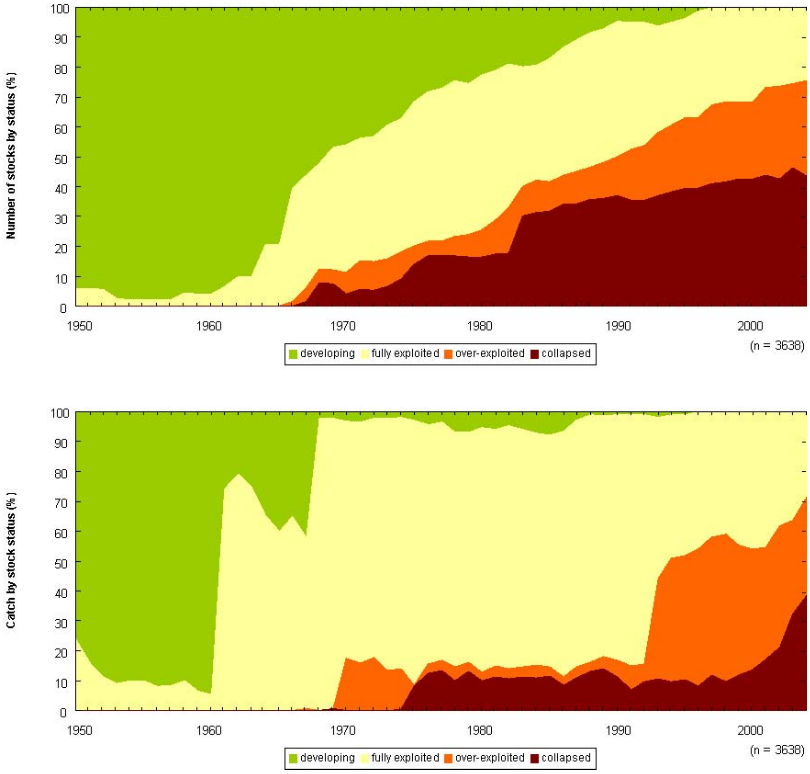

Figure II-4.8. Stock-Catch Status Plot for the Agulhas Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Although some marine fisheries resources in the region have been sustainably fished (Pauly 1992; Cochrane *et al*. 1997), most show signs of overexploitation. Invertebrate resources such as shellfish have been severely impacted by subsistence fishing (Griffiths & Branch 1997, Barnes *et al*. 1998). Overexploitation of many reef fishes in the region is also prevalent. For example, recent stock assessments indicate that spawning stock levels of some species of the seabreams (Sparidae) and kobs (Sciaenidae) have been reduced to less than 25% of their pre-exploitation levels in South Africa (Mann 2000). Fish and shellfish stocks in Madagascar and the Seychelles are also believed to be fully fished or overexploited (UNEP 1999). As a consequence of the depletion of inshore stocks, fleets have had to seek new fishing grounds or move further out to sea (PRE/COI 1998). Valuable tuna stocks in the Agulhas Current LME, which are heavily exploited by foreign vessels, also show signs of overexploitation. Following a record tuna catch in the Indian Ocean in 2003 (about 100,000 tonnes greater than the sustainable limit), the Indian Ocean Tuna Commission expressed concern about depletion of tuna stocks in this region.

Highly efficient, non-selective fishing methods being used in the region have resulted in greater numbers and variety of fish being caught. Trawling is becoming increasingly common, with resulting destruction of benthic habitats and increased mortality rates for juvenile fish. This is of particular concern in the shrimp fishing grounds such as Sofala and Tugela Banks which are subjected to intensive trawling.

Other destructive fishing practices include the use of dynamite, poisons and purse-seines, which are of concern especially around island areas. As a consequence of these destructive methods, fish stocks and biodiversity are declining in the LME, with several species now facing potential economic extinction. Reduced catch rates and decrease in mean sizes of fish caught are evident in the landings (UNEP 2002). In addition, catching of non-target endangered marine species, such as turtles, dolphins and dugongs are also cause for great concern. Fisheries bycatch is severe in both Mozambique and South African fisheries.

Overall, overexploitation, excessive bycatch and discards, and destructive fishing practices appear to be severe in the Agulhas Current LME (UNEP 2006). This will continue to threaten fisheries sustainability and food security of the bordering countries. The situation, however, is expected to improve with the implementation of new approaches to the management of the LME's fisheries resources (see Governance).

III. Pollution and Ecosystem Health

Pollution: While pollution in the Agulhas Current LME was found to be moderate and not to pose a regional threat, the inadequate treatment of wastes results in severe localised problems near cities and industrialised areas in all the countries. Marine pollution originates from both land- and sea-based sources and activities (Nguta 1998, Ruwa 2006). Among them are growing coastal populations and increasing tourism, for which sewage treatment facilities are inadequate. As a result, raw sewage is often discharged directly into rivers or the sea, leading to eutrophication in localised areas. In addition, untreated effluents from fish processing plants, abattoirs and chemical and manufacturing industries are frequently discharged into the sea, causing varying degrees of pollution in some localities.

Severe localised pollution is caused by dumping of domestic and industrial solid wastes in government-approved sites on the coast, but with little or no environmental regulation in place. Leachates from dump sites flow into coastal areas, especially during the rainy season, further degrading coastal habitats. Plastics constitute an increasing proportion of coastal and marine litter, and pose a serious threat to protected species such as marine turtles, dugongs, whales and dolphins (UNEP 2002).

The intensive use of agro-chemicals such as dichlorodiphenyltrichloroethane (DDT), dieldrin and toxophene is common throughout the region, with potential transboundary consequences. Use of fertilisers is also common and has caused localised occurrences of eutrophication and HABs (PRE/COI 1998). Poor farming practices and deforestation in the coastal and hinterland areas result in excessive siltation in the coastal and marine environments, smothering seagrass beds and coral reefs.

Marine-based pollution in this LME stems from oil tanker traffic, exploitation of the seabed, construction, dredging and ocean dumping (Nguta 1998). Oil pollution caused by oil tanker traffic, discharge of waste oil in rivers, frequent oil spills in harbours and other maritime activities, is a major problem in some coastal areas. About 450 million tonnes of hydrocarbon products are transported annually through the Mozambique Channel, posing a high potential risk of oil spills (Salm 1996). The prevailing southeasterly Trade Winds make the Mozambican coast most vulnerable, as demonstrated by the Katina-P oil spill in 1992 near Maputo Bay (Massinga & Hutton 1997).

Pollution of the coastal zone poses a direct threat to human health through the consumption of contaminated seafood or swimming in contaminated waters. Throughout the region, pollution has impacted the ecosystem in far less obvious but more significant ways by reducing the abundance and variety of fish available for local consumption, indirectly leading to overexploitation of the remaining stocks of certain species and subsequent collapse of coral reef ecosystems (UNEP 1999). Polluted coastal areas and loss of charismatic species such as whales also reduce revenues from tourism.

Habitat and community modification: The productivity of coastal waters is highly dependent on the health of mangroves, coral reefs, estuaries and seagrass beds, as well as the quality of run-off from land. Estuaries play a significant role in providing food and shelter for juvenile organisms in the high energy marine environment of the LME. Some of these organisms, particularly shared and migratory fish stocks, are of transboundary importance. Modification of coastal habitats such as mangroves, coral reefs and seagrass beds is moderate but widespread and is a major threat to sustainable use of resources and development in the coastal zone. Coral reefs are under increasing pressure from urbanisation, tourism, dredging and extraction of coral and shells, limestone mining and destructive fishing methods including dynamite fishing. These activities are also depleting the buffer zone provided by coral reefs, making the shores more exposed to wave action, storm surges and inundation (UNEP 2002). The coral reefs of the islands have been severely degraded or even lost in several areas (Bryant *et al*. 1998, PRE/COI 1998). Some coral reefs of Seychelles have been classified as being under the highest threat and risk of degradation (Bryant *et al*. 1998).

The most important immediate cause of mangrove loss is unsustainable harvesting, particularly for firewood, construction, and production of charcoal around the main cities. Other causes of mangrove loss include the clearing of mangrove for salt production, human settlements, urban development, mariculture ponds and sand mining.

There has been considerable modification of coastal habitats by beach erosion as a result of coastal construction, beach replenishment schemes, coastal mining and dredging in harbours. Poor management of catchment basins has led to reduced freshwater inflow and degradation of estuaries, which are also under threat from excessive siltation and other anthropogenic factors. The water quality in about 20% of South Africa’s estuaries in this LME has been described as poor or very poor (Harrison *et al*. 2000). Seagrass beds have also been smothered by sediments, resulting in loss of shelter, food and nursery grounds for valuable fish, shellfish, dugong and turtles (UNEP 1999). Mining of titanium and zirconium, as well as other mining-related activities, have adverse environmental impacts on sand dune systems, wetlands and estuaries. As already discussed, pollution in the coastal zone has severe localised impacts and also contributes to habitat degradation and loss.

Global climate change is expected to have grave impacts on the marine and coastal environments of the Agulhas Current LME and their living resources. The most notable impact of climate change has been widespread bleaching of corals in the Indian Ocean Islands. In 1998, a 1°C temperature rise, induced by El Niño, caused the bleaching and death of up to 90% of the region’s corals (Obura *et al*. 2000); in many instances, this loss was irreversible.

Increasing economic development, growing urbanisation, and unsustainable use of the natural resources in the coastal areas will continue to threaten the health of the LME. Furthermore, the impacts of habitat modification and loss on the economy and people of the coastal areas will be magnified by global climate change. Appropriate measures based on sound scientific knowledge are urgently required to address the deterioration in ecosystem health which will otherwise severely undermine the economic stability of the region (Kamukala and Payet 2001) .

IV. Socioeconomic Conditions

Coastal cities, commercial ports and industrial centres are rapidly developing in the Agulhas Current LME. The coastal population of Mozambique has been estimated at about 6.5 million (about 40% of the total population), while the coastal population of eastern South Africa is estimated at about 7 million. The total population of the Western Indian Ocean islands was about 17 million in 1998 and is expected to exceed 43 million by 2050 (UN Population Division 1998).

The economy of the bordering countries is reliant on agriculture, forestry, wildlife, fisheries, tourism and exploitation of minerals. Island states share the characteristics of economies dependent on imports and high levels of unemployment (Gossling, 2006).

International tourism makes a significant contribution to GDP, especially in South Africa and the Indian Ocean islands. For example, in the Seychelles, tourism contributes 15% to GDP, up to 75% of foreign exchange earnings and employs 20% of the labour force (Republic of Seychelles 1997, UNDP 1997). Tourism has grown exponentially in the past 15 years, in some countries by an order of magnitude. While providing some clear economic benefit through employment generation, foreign exchange earnings, the promotion of the development of infrastructure and the protection of cultural heritage, a lack of integrated planning has exacerbated negative impacts. These include the overuse of fresh water, overfishing, damage to coral reefs, land use transformation, clearing of mangroves, increased pollution and lack of benefit to local communities (Gossling 2006).

Marine fisheries are a significant source of foreign exchange, employment, and protein in most countries. In Mozambique, the industrial and semi-industrial fleets generate about 40% of foreign currency income (Schleyer *et al.* 1999). In the Seychelles, fish and fish products account for 95% of domestic exports and are the second highest foreign exchange earner after tourism (UNDP 1997). In some of the countries, fish often represents the primary source of animal protein available to the local populations.

The socioeconomic impacts of habitat modification are significant, considering that a large number of people are dependent on these resources and that they make a valuable contribution to the economies of the countries adjacent to the LME (Massinga & Hutton 1997, UNEP 1999, 2002). Destruction of these critical habitats results in loss of shelter, food and nursery grounds for commercially important fish, shellfish, turtle and dugong (UNEP 1999). The subsequent reduction in recruitment of shrimp and fish as well as reduced catches in subsistence and industrial fisheries will threaten food security, employment and national income.

Sea level rise and associated impacts such as flooding and erosion will result in disruption of infrastructure and economic activities including loss of employment, income and food source. Other economic costs of sea level rise are associated with beach replenishment schemes, dredging and coastal protection to prevent beach erosion. The islands in particular will suffer significant economic losses in the tourist industry due to loss of beach and reef-based activities (IPCC 1995).

V. Governance

The lack of knowledge on the environment is a severe limiting factor for environmental governance in the Agulhas Current region. An exhaustive review by Lutjeharms (2006a) shows that we have a dearth of information and data, compared to that available for other similar regions. The gaps in knowledge must be addressed in order to identify critical concerns about fisheries, productivity and ecosystem health, as well as developing ameliorating measures. Governance in the Agulhas Current region is also constrained by regionally incompatible laws and a paucity of environmental regulations.

This LME is located within the UNEP Eastern Africa Regional Seas. All the countries have ratified the Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region (Nairobi Convention) with its Protocols on Protected Areas and Wild Fauna and Flora, and on Co-operation in Combating Marine Pollution in cases of Emergency. Regional organisations involved in the management of coastal and marine resources in the West Indian Ocean are the Western Indian Ocean Fishery Sub-Commission, the Inter-governmental Oceanographic Commission's Regional Committee for the Cooperative Investigation of the North and Central Western Indian Ocean and the Indian Ocean Commission.

The GEF supported Agulhas and Somali Current Large Marine Ecosystems (ASCLME) Project is part of a multi-project, multi-agency Programme to institutionalize cooperative and adaptive management of the Agulhas and Somali LMEs. A phased approach is planned that progressively builds the knowledge base and strengthens technical and management capabilities at the regional scale to address transboundary environmental concerns within the LMEs, builds political will to undertake threat abatement activities and leverages finances proportionate to management needs. In addition to the ASCLME Project, the Programme includes two parallel projects, one that addresses land-based sources of pollution and coastal degradation (WIO-LaB, implemented by UNEP); and one that builds knowledge for the purposes of managing industrial fisheries (SWIOFP, implemented by the World Bank).

The activities within the ASCLMEs Project are focused on filling the significant coastal and offshore data and information gaps for these LMEs by capturing essential information relating to the dynamic ocean-atmosphere interface and other interactions that define the LMEs, along with critical data on artisanal fisheries, larval transport and nursery areas along the coast. The overall objective of this excercise will be to deliver two Transboundary Diagnostic Analyses (TDAs), and two Strategic Action Programmes (SAPs); one for the Agulhas Current LME, and the other for the Somali Current LME. The parallel UNEP and World Bank Projects will also feed pertinent information into the TDAs/SAPs formulation process, and identify policy, legal and institutional reforms and needed investments to address transboundary priorities. Collectively, the projects build foundational capacities at regional scale for management of the LMEs.

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II-5 Somali Coastal Current LME

S. Heileman and L. E. P. Scott

The Somali Coastal Current LME extends from the Comoro Islands and the northern tip of Madagascar in the south to the Horn of Africa in the north (Alexander 1998, Okemwa 1998). It is bordered by Somalia, Kenya and Tanzania. Early descriptions of the circulation patterns of the system related to the monsoons and oceanography are given by Newell (1957) and Johnson *et al*. (1982). Weather and ocean currents in the Somali Current LME are strongly influenced by the two distinct monsoon seasons. The prevailing winds during the monsoons are a particularly important influencing factor on water circulation (affecting the distribution of nutrients and marine organisms as well as biological processes), changing wave action, and affecting a wide range of human activities (Richmond 2002). From November to March, the prevailing trade wind is from the North-East, but more north-westerly in direction to the South of the Equator. From June to September, the stronger South-West monsoon wind prevails. South of the Equator, this wind is more south-easterly in direction (Newell 1957, Okemwa 1998, Richmond 2002). This LME's unique bathymetry results from major submarine tectonic features of the Indian Ocean, including the mid-Indian Ridge, the Owen Fracture Zone and the Carlsberg Ridge (Okemwa 1998). Covering an area of about 840,710 km^2, of which 0.86% is protected, the LME contains about 0.98% of the world's coral reefs and 0.01% of the world's sea mounts (Sea Around Us 2007). A volume edited by Sherman *et al*. (1998) on the Indian Ocean LMEs contains several articles on this LME.

I. Productivity

The Somali Current LME is a highly productive ecosystem (>300 gCm^{-2}year^{-1}). During the Southwest Monsoon, upwelling off Somalia becomes one of the most intense coastal upwelling systems in the world (Baars *et al*. 1998, Bakun *et al*. 1998). However, the mean phytoplankton density and productivity are lower than expected, possibly due to the dilution of the upwelling effects over a large area because of the strong winds and the high speed of the Somali Current (Baars *et al*. 1998). Productivity has been noted during some SW Monsoon seasons (in 1987, for example) to be highest two hundred kilometres offshore; likely due to the dynamics of the offshore eddy which enhances productivity, rather than any consequence of coastal upwelling (Hitchcock and Olson 1992). Euphausids make up about 25% of total zooplankton biomass while copepods make up most of the remainder (Okemwa 1998). Within the upwelling zone, the dominant zooplankton species include the large copepods *Calanoides carinatus* and *Eucalanus elongatus*, as well as several species of smaller copepods. Most taxa, with the exception of *C*. *carinatus*, persist throughout the Northeast Monsoon, during which primary productivity decreases but without a substantial decrease in the zooplankton stock (Baars *et al*. 1998).

The LME encompasses a rich diversity of coastal habitats including coral reefs, mangroves, seagrass beds and estuaries that play an important role in its overall health and productivity (Okemwa 1998, WWF 2002). Several endangered marine turtle and whale species, as well as the dugong and the CITES-listed coelacanth, *Latimeria chalumnae*, occur in the LME.

***Oceanic fronts*:** (after Belkin et al. 2009) The Somali Current (Figure II-5.1) velocity and direction are linked to the monsoon that dominates the meteorological and hydrographic regime of the Indian Ocean. In summer, the prevailing winds from the southwest accelerate the along-shore Somali Current that flows north. North of the Equator, the

Somali Current is deflected eastward, thus resulting in the upwelling of cold, nutrient-rich waters along the Somali coast. These waters are separated by a sharp front from the warm and salty waters carried by the Somali Current. With the advent of the boreal winter monsoon, the wind field reverses and the prevailing winds from the North-East shut down the coastal upwelling, spin down the Somali Gyre and cause downwelling along the Somali coast (Belkin *et al*. 2009).

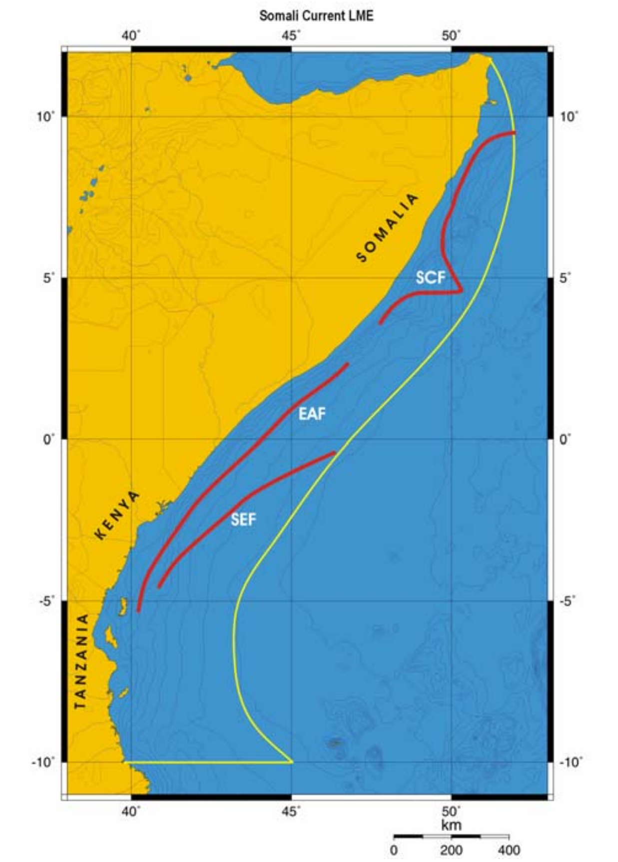

Figure II-5.1. Fronts of the Somali Coastal Current LME. SSF, Shelf-Slope Front. Yellow line, LME boundary. After Belkin et al. 2009).

Somali Coastal Current SST (after Belkin 2009)
Linear SST trend since 1957: 0.46°C
Linear SST trend since 1982: 0.18°C

The Somali Current has warmed slowly and steadily from 1957 to the present. On the southern end, the Somali Current cold/warm events likely affected the Agulhas Current LME through sporadic southbound leakages. On the northern end, the Somali LME has no LME neighbour and its connection to the Arabian Sea LME is tenuous at best. And yet, the all-time maximum of 1998 occurred simultaneously in both LMEs, which could have resulted from large-scale forcing since this maximum has been observed more or less synchronously around the entire Indian Ocean. The two most conspicuous warm events, of 1983 and 1998, are linked to the extremely low values of the Southern Ocean Oscillation (SOI) Index (Annamalai & Murtugudde 2004; Reynolds & Smith 1994).

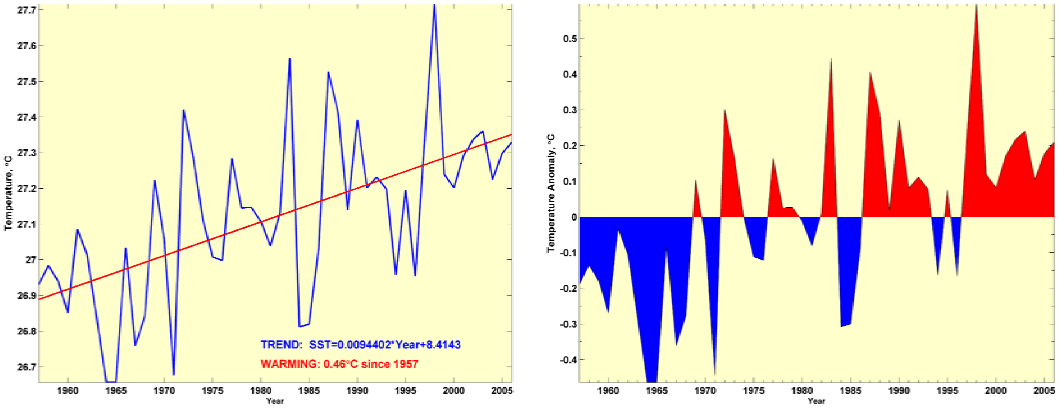

Figure II-4.2. Somali Current LME annual mean SST (left) and annual SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Somali Current LME Trends in Chlorophyll and Primary Productivity: The Somali Current LME is a highly productive ecosystem (>300 gCm^{-2}year^{-1}).

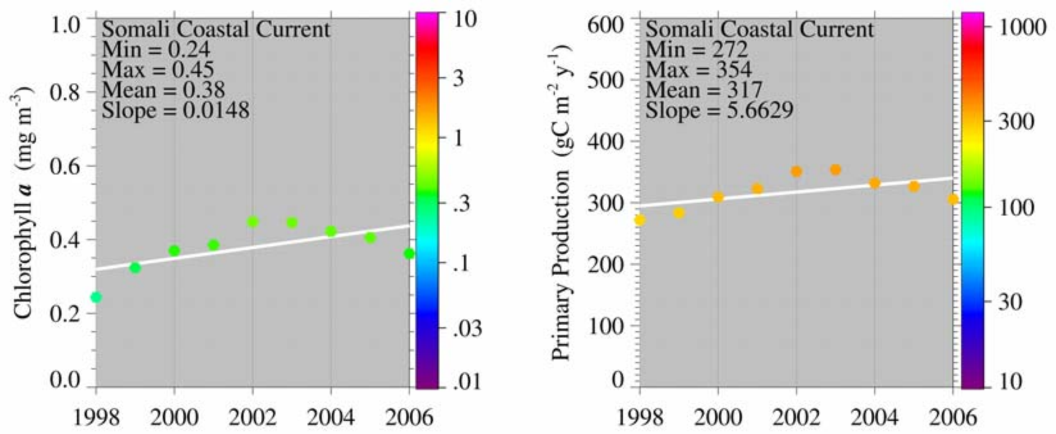

Figure II-4.3 Somali Current LME trends in chlorophyll *a* (left) and primary productivity (right) 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Over half of the reported landings in the Somali Coastal Current LME consists of the 'mixed group.' The LME contains a high level of subsistence and artisanal fisheries which are confined to its inshore areas, due to the ease of access and lack of appropriate expertise and technology to fish in offshore waters. In 1994 in Tanzania, more than 96 % of the total marine production was contributed by small-scale artisanal fishers, while in Kenya the value was 80%. In 1984 in Somalia, it was estimated that 90 000 – 100 000 people were directly or indirectly involved in the artisanal fishing industry. Fishing gears used include gillnets (drift and demersal), long lines, cast nets, traps and handlines (Marshall and Barnett 1997). There is no large fishery for small pelagic fish (Everett 1996) as there is in the Canary Current and Benguela Current LMEs. Oceanic fisheries in the LME are dominated by distant-water fishing fleets from Europe and East Asia.

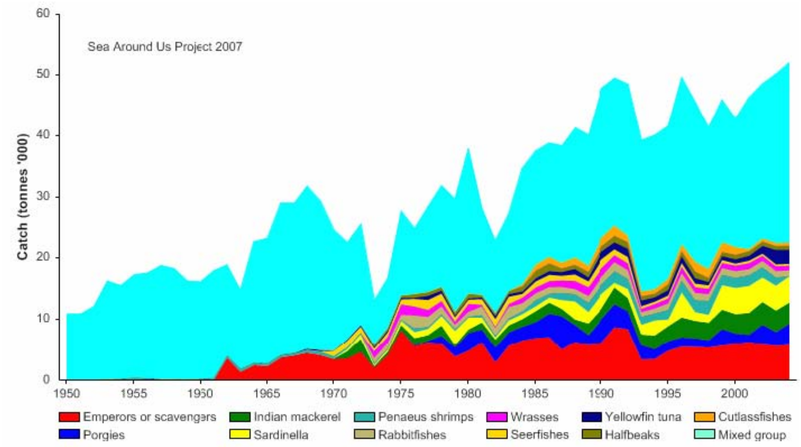

Figure II-5.4. Total reported landings in the Somali Coastal Current LME by species (Sea Around Us 2007).

Due to the poor quality of the available landings statistics in the region, a majority of the landings in the LME can only be classified as 'unidentified marine fish' (included in the 'mixed group in Figure II-5.4), making interpretation of the status of marine fisheries in the LME extremely difficult. Total reported landings in the LME showed a general increase over the reported period, but with marked fluctuations, recording 52,000 tonnes in 2004 (Figure II-5.4). The value of the reported landings peaked in the late 1970s at around 70 million US$ (in 2000 real US$), with recent years between 50-60 million US$ (Figure II-5.5).

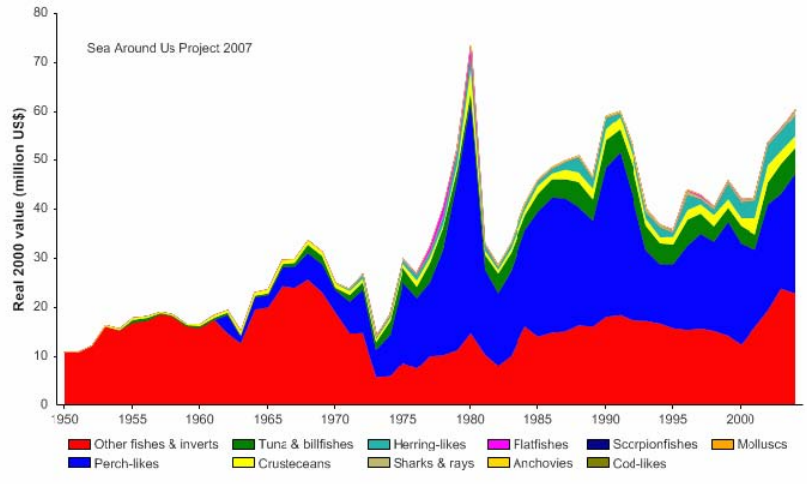

Figure II-5.5. Value of reported landings in the Somali Coastal Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME has increased over the years, reaching 2.5% in recent years (Figure II-5.6). Tanzania accounts for the largest ecological footprint in the region, though a number of foreign fleets can also be found to be operating in the LME.

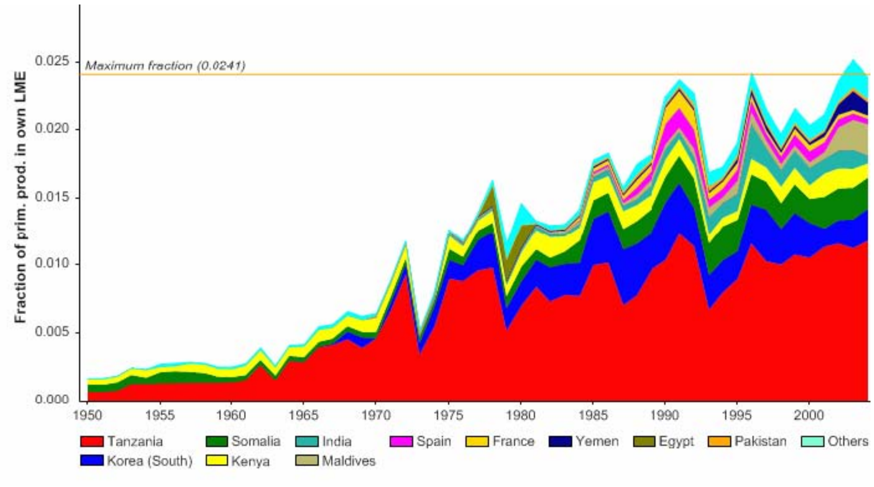

Figure II-5.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Somali Coastal Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Due the high proportion of unidentified catches in the underlying statistics, the mean trophic level (i.e., the MTI; Pauly & Watson 2005) and the FiB index of the reported landings estimated for this LME should not be viewed as good indicators of the state of its fisheries. The increase in the MTI from 1950 to the mid 1970 (Figure II-5.6 top) is likely a result of the improvement in the taxonomic details of the reported landings (see Figure II-5.4), while the increase in the FiB index (Figure II-5.6 bottom) seems to be informative, as it suggests the spatial expansion of fisheries in the region.

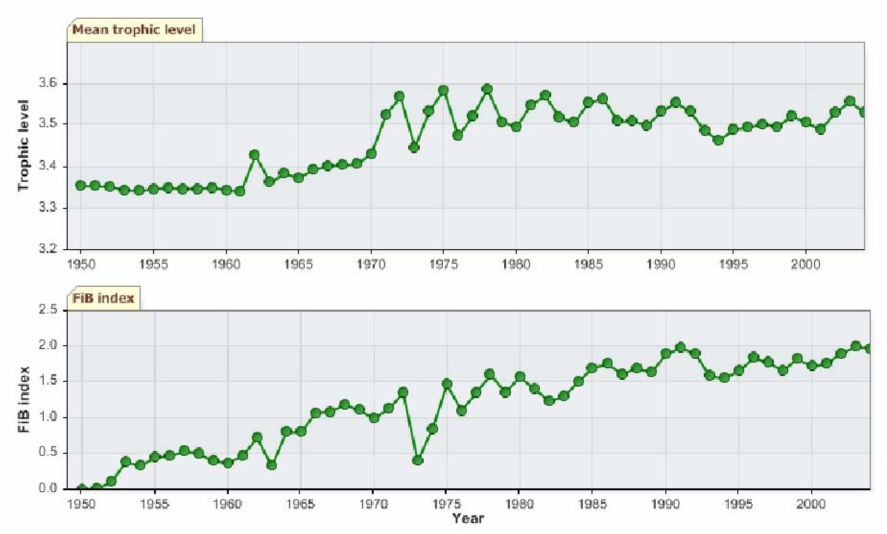

Figure II-5.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Somali Coastal Current LME (Sea Around Us 2007).

The Stock-Catch Status Plots show that local fisheries predominantly target stocks that are classified as 'overexploited' (Figure II-5.8, top) and that fully and overexploited stocks contribute a majority of the reported landings biomass (Figure II-5.8, bottom). Again, we must stress the high level of taxonomic uncertainty in the underlying statistics.

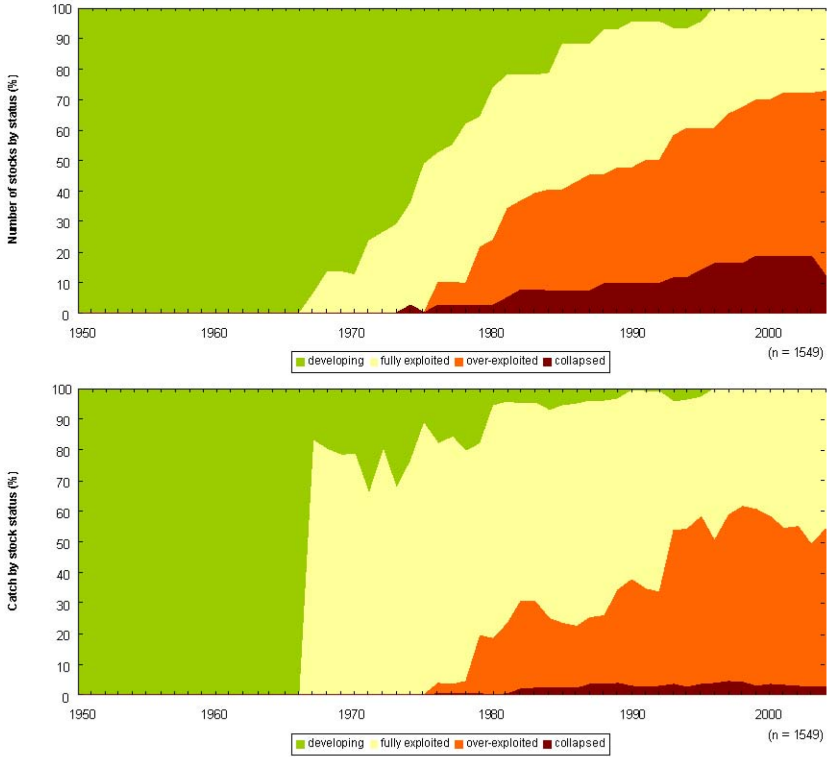

Figure II-5.8. Stock-Catch Status Plots for the Somali Coastal Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2003. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The fisheries of the Somali Coastal Current LME are heavily exploited, contrary to assumptions of huge unrealized potentials (Aden 2007), with indications of unsustainable exploitation documented in several areas (Kelleher & Everett 1997, Fielding & Mann 1999). Harvests of inshore resources are dwindling, including the giant mangrove mud-crab *Scylla serrata*, the mangrove oyster *Saccostrea cucullata*, lobsters (*Panulirus* sp.) and prawns *(Penaeus* sp.). The average size of lobsters caught has diminished, with most of the lobsters now caught before they have reached the age of maturity. Furthermore, berried females are often caught during the breeding season, when the fishery is not strictly managed (Fielding & Mann 1999). Shark populations are also on a rapid decline as a consequence of the harvest of shark fins by fishers from Yemen, Somalia, Djibouti and Sudan, despite such practice being banned in most cases (Pilcher & Alsuhaibany 2000). According to FAO (2000), most tuna stocks are fully exploited in all oceans, including the Western Indian Ocean and some are overexploited or severely depleted.

While there is no evidence to suggest that the offshore stocks of the LME are at risk of collapse, this may well be due to the absence of adequate observations, including the lack of reliable data on fishing effort, total catch, and bycatch. The problem of Illegal, Unregulated and Unreported (IUU) fishing is particularly acute in Somalia, largely as a result of civil wars and the lack of a functioning government for the last decade (Gelchu & Pauly 2007). The status of the LME's fish stocks is not known with any certainty and a need exists for stock assessments and enactment of appropriate management measures.

Destructive fishing practices also pose a threat to coastal fisheries and coral reefs. In areas around coral reefs, unsustainable exploitation is related to increasing fishing effort and the use of destructive gear (McClanahan 1996, Obura et al. 2000). The use of dynamite, pull seine nets, poisons and selective fishing on certain species and juveniles are widespread in the region (UNEP 2002). Offshore trawling grounds, especially those targeting prawns, are showing signs of overexploitation with excessive bycatch and discards. A significant fraction of shrimp bycatch is composed of juvenile fish and on average, only 32% of the bycatch is retained, with a discard rate of up to 1.8 tonnes per trawler per day (KMFRI 2003). Purse seines yield a high bycatch of cetaceans and shark gill nets also catch non-target species such as turtles, dugong, dolphins and whales (Pilcher & Alsuhaibany 2000, Van der Elst & Salm 1998). The bycatch of shark gill nets in Somalia also includes sawfish (Pristis microdon and P. pectinata), which are of global concern as they have been overexploited worldwide (IUCN 1997). Somalia may be one of the last refuges for these vulnerable elasmobranchs (Van der Elst & Salm 1998).

Problems of unsustainable exploitation are expected to persist in the future due to a lack of or inadequate capacity for effective management and surveillance, including failures in addressing illegal fishing and conducting stock assessments, and inadequate knowledge and information. The most important knowledge gaps that currently preclude optimal management of transboundary living resources are identified in the Somali Coastal Current LME TDA (GEF 2003). For the overexploited inshore resources, an approach that reduces fishing pressure, while promoting fisheries restoration and sustainable exploitation practices is indispensable. Sustainable exploitation of the offshore resources in the LME is of great interest for the countries of the region and there is an urgent need for fisheries surveys in order to determine the potential for development of these fisheries. However, efforts are being directed at developing the fisheries for small pelagic and mesopelagic fish (Okemwa 1998).

II. Pollution and Ecosystem Health

Pollution: The coastal areas of the Somali Coastal Current LME are under increasing pressure from land and sea-based sources of pollution, including agrochemical, industrial and municipal wastes as well as sea-based petroleum wastes, which cause varying degrees of localised pollution (Nguta 1998, Okemwa 1998, UNEP 2002, Ruwa 2006). Pollution is generally moderate in this LME (UNEP 2006), although estuaries and urban areas located along the coastline are pollution hot spots (UNEP 2001, Van der Elst & Salm 1998).

Most of the coastal municipalities do not have the capacity to handle the vast quantities of sewage and solid wastes generated daily. Raw sewage containing organic materials, nutrients, suspended solids, parasitic worms and benign and pathogenic bacteria and viruses is discharged into waterways and coastal areas (Okemwa 1998). High microbial levels are observed in areas near to sewage outfalls (Mwaguni 2000). Large quantities of wastes from fish processing plants, slaughterhouses and tanneries also contribute to pollution along the coast (Nguta 1998, Van der Elst & Salm 1998). Because of the lack of purification facilities, industrial pollution is severe and includes solid and liquid industrial wastes such as noxious oils, organic and inorganic chemicals (Nguta 1998, Okemwa 1998). Large volumes of solid wastes are dumped on the shores or disposed of in an unsatisfactory manner and are blown or washed out to sea where they pose a threat to wildlife and human health (UNEP 2002). In addition, seepage and leakages from coastal dump sites pose serious pollution problems, especially during the rainy season (Nguta 1998). These leakages are high in BOD and contain significant amounts of dissolved toxic metals and organic chemicals.

Fertilisers and pesticides are increasingly being manufactured and used in the region, with resulting increase in agricultural-based sources of pollution in coastal areas, from both land run off and direct discharge of wastes from fertiliser factories. The latter is a severe problem in the region (Okemwa 1998). Likewise, poor land use practices such as slash and burn agriculture, overgrazing and nomadic pastoralism as well as farming in river basins contribute to increased suspended solids that are ultimately deposited in the ocean. For example, about 16-21 million tonnes of sediments are deposited into the ocean annually from the two perennial rivers, Tana and Athi Rivers in Kenya (Kitheka 2002). Mining, urban development and dredging also contribute to increased sedimentation in coastal areas (Okemwa 1998). As a consequence, the coastal configuration, accretion and erosion patterns and associated ecosystems are changing. For example, the size of river deltas and estuaries is increasing, and beach as well as seafloor composition has been altered. Eutrophication is not yet a serious issue, although isolated pockets are found in sheltered bays, with threat of occurrence of HABS (Mwaguni 2000).

Maritime activities also contribute to pollution in the Somali Coastal Current LME, especially in harbours and along the coastline during the Southeast Monsoon. Oil and ballast water are the principal contaminants from shipping activities, with ballast waste water, waste oil, as well as sewage released directly into the sea (Okemwa 1998). Longshore currents and winds in the Western Indian Ocean are instrumental in the horizontal distribution of pollutants, particularly in bringing oil slicks and residues of degraded oil from the open sea to coastal waters (UNEP 2002). Beaches in this region are sometimes littered with tar balls, with deleterious effects on marine biota and humans (UNEP 2002). For instance, soluble PCBs from these products are toxic to marine life and also accumulate in the food chain. Plastic litter is a major concern at turtle beaches.

Habitat and community modification: The Somali Coastal Current LME contains a variety of habitats including coral reefs, mangrove forests, estuaries and seagrass beds that serve as shelter, breeding grounds and nurseries for several commercially important fish species as well as endangered species of animals such as marine turtles and dugong. These habitats also have high biodiversity. For example, the coral reefs of Somalia, which are still in good, often pristine condition, especially in Marine Protected Areas (MPA), are among the most biologically diverse in the entire Indian Ocean (Pilcher & Alsuhaibany 2000). Coral cover distribution is more abundant in the area between the Athi/Sabaki river estuary and Ruvuma river estuary, which has been described as the ‘Coral Coast’ by virtue of its rich coral assemblage (WWF 2002). These coastal habitats also protect the adjacent land from erosion and wave damage.

Coral reefs are impacted by several anthropogenic activities such as mining, pollution, exploitation of reef fishes and other organisms for food and ornamental trade, tourism and siltation. Many reefs outside of MPAs are overexploited and severely degraded (Spalding et al. 2001). High fishing effort and destructive fishing methods such as dynamiting not only cause overfishing in coral reefs but also lead to structural damage as well as changes in biodiversity, for instance, population explosions of sea-urchin (McClanahan 1996). Coral bleaching has had a significant impact on many of the LME’s coral reefs, especially during the 1998 El Niño (Muhando 2002). In Kenya, the surviving corals appeared to have recovered one year later, but severely damaged areas had still not been re-colonised. Another major threat to the marine habitats is increased sedimentation (Obura et al. 2000). Conversion of mangrove habitat for agricultural, industrial and residential uses and salt and lime production, as well as over-harvesting of mangrove wood for building, charcoal, firewood and trade purposes have caused deterioration of mangrove forests and their faunal communities. Destruction of mangrove forests is also leading to heavy offshore siltation and reduction in nutrients for offshore species with concomitant reduction in fish catches (Okemwa 1998).

Seagrass meadows are under threat from destructive fishing methods such as drag nets, pollution from various sources and siltation (Okemwa 1998). Estuaries are being modified through pollution, sedimentation and infilling. Damming of rivers for hydropower and irrigation (e.g., Tana River) and abstraction of water for irrigation (e.g., Athi-Sabaki Rivers) have various impacts on the coastal, estuarine and marine habitats through reduced inflow of freshwater and nutrients into the coastal zone (Raal & Barwell 1995). Degradation of beaches in the region by mining, litter, oil pollution, dredging, erosion and coastal development is also a major problem. This has affected endangered sea turtles that use undisturbed beaches as their sole nesting sites (Okemwa 1998). Coastal erosion is a major environmental concern along the East African coast and leads to shifting coastal features such as dunes, beaches and shoreline (UNEP 2002). Mitigation measures for coastal erosion have in some cases exacerbated the problem due to inadequate information and technical support (UNEP/GPA 2004)

Extreme droughts and floods linked with ENSO have been documented in the region in recent years (IPCC 2001, Kitheka & Ongwenyi 2002, UNEP 2001). These events induce strong responses in the LME, and have important effects on the distribution of fish stocks, as well as a potential negative impact on coastal habitats such as estuaries and mangroves in which inflow of freshwater is important for maintaining productivity. Sea level rise is also expected to have significant impacts in the Somali Coastal Current LME, since most of the low-lying coastal plains are only a few meters above the highest spring tide water level and therefore susceptible to sea water intrusion and flooding (Okemwa 1998).

Anthropogenic pressures from increasing human populations and unrestricted coastal development continue to threaten the health of the Somali Coastal Current LME. This is exacerbated by inadequate monitoring as well as insufficient data needed to characterise the impact of these pressures on natural resources. An immediate need towards improving the health of this LME and sustainable use of its coastal and marine resources is to fill the existing gaps in knowledge (GEF 2003).

III. Socioeconomic Conditions

The Somali Coastal Current LME region supports about 15 million people, more than half of whom live in coastal areas (Kelleher & Everett 1997, UNEP 2001). Following an increase in the 1980s, the population growth rate has recently shown a marked decline. There is a high rate of urbanisation in the region, with major coastal cities such as Mombasa and Dar es Salaam growing at a rate of 5% and 6.7% respectively (Hatziolos et al. 1996). Other population movements are conflict-driven, e.g., the movement of refugees. Poverty is particularly acute among various vulnerable groups such as households headed by the elderly and children. Furthermore, there is a general food deficit, particularly of protein, causing a high level of under-nourishment, especially in Somalia.

The main economic sectors are agriculture, fisheries, industry, manufacturing and services (the latter includes tourism and maritime transport). Coastal tourism is a significant industry, especially in Kenya which leads the region with some 940, 000 international arrivals in 1999 (Gossling 2006). Although the contribution of the industrial fisheries to GDP is small (0.04% for Kenya, 2% for Somalia, 2.7% for Tanzania), the artisanal fisheries are regarded as a significant source of employment and food. In Tanzania, more than 25% of the country accrues direct benefit from the coastal zone (Kamukala and Payet 2001), and the artisanal and traditional fisheries play a significant role in food security (Cunningham and Bodiguel 2005). The socioeconomic impact of overexploitation is severe in this LME and includes the loss of employment and reduction in the capacity of local communities to meet basic needs. Furthermore, the increase in the industrial fisheries has further reduced the resources available to artisanal fishers and considerable friction between the two groups has arisen as a result of the destruction of stationary artisanal fishing gear by industrial vessels (Okemwa 1998). Mariculture of seaweed, shrimps, finfish, sea-cucumbers and pearl oysters is a growing sector of the economy (Richmond 2002).

Degradation of the coastal zone poses a threat to economic returns and employment from activities such as fishing and tourism, through the loss of critical habitats and recreational areas. Economic costs of habitat modification and loss are associated with beach replenishment schemes, dredging and coastal protection to prevent beach erosion. Protected species such as marine turtles, dugongs, whales and dolphins are reportedly declining as a result of increasing levels of wastes, notably plastics (UNEP 2002). This could have a negative impact on tourism. Human health is also at risk from pollution through the consumption of contaminated sea food or through direct contact.

V. Governance:

Kenya and Tanzania have extensive legal and institutional frameworks to manage water resources. However, law enforcement is a major problem due to poor monitoring and surveillance systems. Somalia lacks specific laws and regulations to protect and preserve the marine environment, which has further been aggravated by the political situation and conflicts in this country. This LME comes under the UNEP Eastern Africa Regional Seas Programme. All three countries have ratified the Nairobi Convention. GEF is supporting three projects in this LME together with the Agulhas Current LME.

As described in section II-4 for the Agulhas Current LME, The Agulhas and Somali Current Large Marine Ecosystems (ASCLME) Project, currently underway, will seek to institutionalize cooperative and adaptive management of the Agulhas and Somali LMEs. A phased approach is planned that progressively builds the knowledge base and strengthens technical and management capabilities at the regional scale to address transboundary environmental concerns within the LMEs, builds political will to undertake threat abatement activities and leverages finances proportionate to management needs. In addition to the ASCLME Project, the Programme includes two parallel projects, one that addresses land-based sources of pollution and coastal degradation (WIO-LaB, implemented by UNEP); and one that builds knowledge for the purposes of managing industrial fisheries (SWIOFP, implemented by the World Bank).

The activities within the ASCLMEs Project are focused on filling the significant coastal and offshore data and information gaps for these LMEs by capturing essential information relating to the dynamic ocean-atmosphere interface and other interactions that define the LMEs, along with critical data on artisanal fisheries, larval transport and nursery areas along the coast. A Transboundary Diagnostic Analyses (TDA), and Strategic Action Programmes (SAP) will be developed for the Somali Current LME. The parallel UNEP and World Bank Projects will also feed pertinent information into the TDAs/SAPs formulation process, and identify policy, legal and institutional reforms and needed investments to address transboundary priorities.

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III Red Sea and Gulf of Aden

III-6 Red Sea LME

S. Heileman and N. Mistafa

The Red Sea LME is bordered by Djibouti, Egypt, Eritrea, Israel, Jordan, Saudi Arabia, Sudan and Yemen. It has a surface area of 458,620 km^2, of which 2.33% is protected and includes 3.8% of the world's coral reefs (Sea Around Us 2007). It is characterised by dense, salty water formed by net evaporation with rates up to 1.4 - 2.0 m yr^{-1} (Hastenrath & Lamb 1979) and deep convection in the northern sector resulting in the formation of a deep water mass flowing out into the Gulf of Aden underneath a layer of less saline inflowing water (Morcos 1970). A dominant phenomenon affecting the oceanography and meteorology of the region is the Arabian monsoon. In winter, northeast monsoon winds extend well into the Gulf of Aden and the southern Red Sea, causing a seasonal reversal in the winds over this entire region (Patzert 1974). The seasonal monsoon reversal and the local coastal configuration combine in summer to force a radically different circulation pattern composed of a thin surface outflow, an intermediate inflowing layer of Gulf of Aden thermocline water and a vastly reduced (often extinguished) outflowing deep layer (Patzert 1974). Within the basin itself, the general surface circulation is cyclonic (Longhurst 1998).

High evaporation and low precipitation maintain the Red Sea LME as one of the most saline water masses of the world oceans, with a mean surface salinity of 42.5 ppt and a mean temperature of 30° C during the summer (Sofianos *et al*. 2002). Three depressions greater than 2,000 m in depth occur in the axial trough of the LME. Here the water is heated by mineral-rich thermal vents (hot brine regions), reaching up to 62 °C (Scholten *et al*. 1998) and being enriched with various heavy metals such as manganese, iron, zinc, cadmium and copper. Book chapters and reports pertaining to the LME are by Baars *et al*. (1998), Getahun (1998) and UNEP (2005).

I. Productivity

The Red Sea LME, at >300 gCm^{-2}year^{-1}, can be considered a Class I, highly productive ecosystem. Baars *et al*. (1998) described the seasonal fluctuations in plankton biomass and productivity in the southern Red Sea, based on research cruise data. During spring and summer, the LME is oligotrophic, while in winter (northeast monsoon) productivity is higher in the upper layers of the southern Red Sea. During this monsoon period, diatom blooms occur and mesozooplankton biomass increases, attributed to the entrainment of nutrients from below the thermocline due to wind-induced mixing and winter cooling. The phytoplankton community is dominated by the dinoflagellate *Pyrocystis pseudonoctiluca, Ceratium carriense, C*. *trichocerus* and *C*. *massiliense* (Getahun 1998). Prominent blooms of *Oscillatoria erythraeum* are frequent in the open parts of the Red Sea LME (Longhurst 1998). The Red Sea is a net importer of zooplankton from the Indian Ocean, though many species do not survive the extreme conditions of this LME.

The phytoplankton, zooplankton and fish fauna bear more similarity to the Indian Ocean biota than to the Mediterranean Sea. Its complex reefs, together with extensive mangroves, seagrass and macro-algal beds form highly productive habitats for unique species assemblages. Endemism is very high, especially among reef fishes and invertebrates, the latter including a number of dinoflagellates and euphausiids (Roberts *et al*.1992, Getahun 1998). Several species of marine mammals, as well as turtles and seabirds also occur in the LME.

Oceanic fronts (after Belkin et al. 2009): The Red Sea LME has the highest temperatures and salinities observed in the World Ocean. The extremely high evaporation rate leads to formation of salinity fronts, on which temperature fronts tend to develop. Despite the relative uniformity of meteorological conditions over the Red Sea, fronts emerge owing to wind-induced upwelling, whose effect is accentuated by steep bathymetry and local orographic features. Three groups of fronts are distinguished north to south: (1) Egypt-Saudi Arabia Front (ESSF); (2) Sudan-Saudi Arabia fronts (SSAF); and (3) Eritrea-Yemen fronts (EYF) (Figure III-6.1). Although these fronts are poorly studied *in situ*, satellite observations hold promise given the largely cloud-free conditions over the Red Sea.

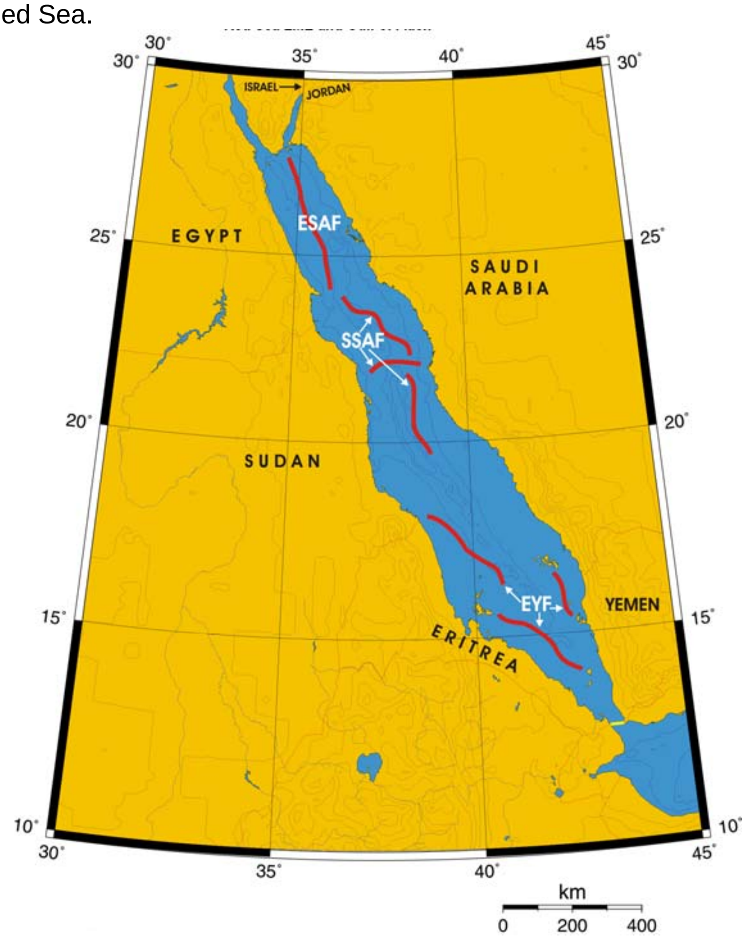

Figure III-6.1. Fronts of the Red Sea LME. ESSF, Egypt-Saudi Arabia Front; EYF, Eritrea-Yemen fronts; SSAF, Sudan-Saudi Arabia fronts. Yellow line, LME boundary (afterBelkin et al. 2009).

Red Sea LME SST (after Belkin 2009).
Linear SST trend since 1957: 0.29°C.
Linear SST trend since 1982: 0.74°C.

The long-term warming of the Red Sea is modulated by moderate-to-strong decadal variability while interannual variability is relatively small (Figure III-6.2). Since the Red Sea is almost completely land-locked, any correlations with other LMEs must have been caused by large-scale factors and teleconnections. The most pronounced warming event peaked in 1969 at >28.5°C. This mark has not been surpassed since, even in 1998-1999, during and after the strongest El-Niño of the last 50 years, when SST reached 28.5°C in 1999. The coolest event bottomed out in 1975 at <27.5°C, after which SST rose by 0.7-0.8°C in 31 years, a relatively fast rate. Even though SST slightly decreased after the peak of 1999, the present period can be considered as a warm one.

The Red Sea circulation features a series of eddies or sub-gyres that vary spatially and temporally depending mostly on wind forcing (Sofianos and Johns, 2007). The Red Sea response to wind forcing strongly depends on wind direction: Along-axis winds do not interact with the surrounding topography, whereas cross-axis winds interact with high, steep mountains surrounding the Red Sea, resulting in a highly structured wind field conducive to oceanic eddy formation (Clifford et al., 1997). Since oceanic eddies modulate SST, long-term variability of the Indian monsoon could strongly affect SST field in the Red Sea.

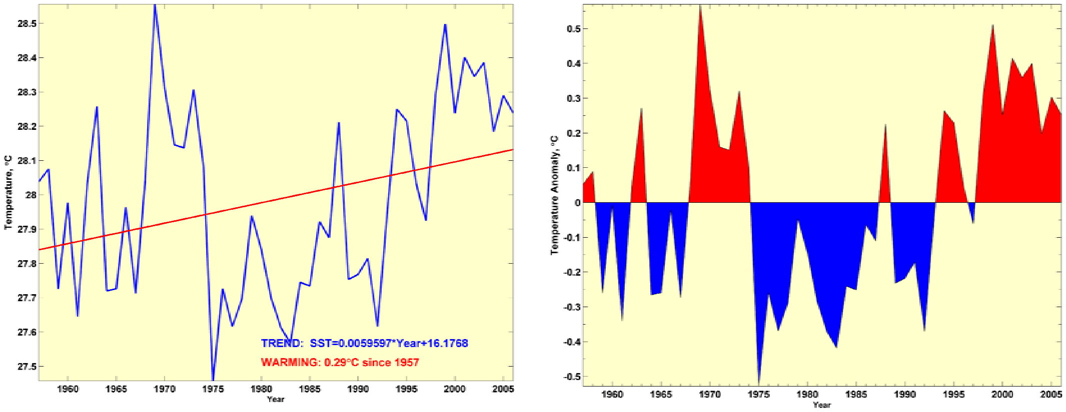

Figure III-6.2. Red Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology (after Belkin, 2009).

Red Sea LME Trends Chlorophyll and Primary Productivity: The Red Sea LME, at >300 gCm^{-2}year^{-1}, can be considered a Class I, highly productive ecosystem.

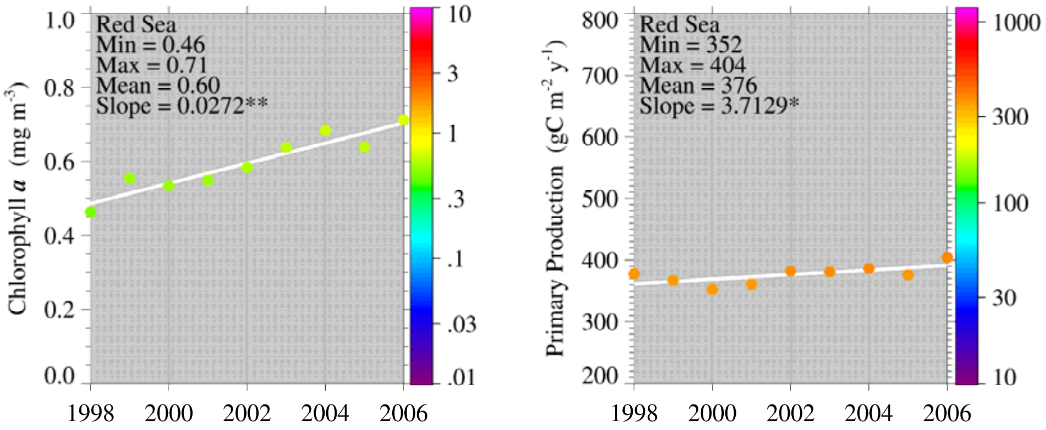

Figure III-6.3. Red Sea LME Trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

About 1,200 species of fish are known to occur in the Red Sea LME (Ormond & Edwards 1987). Marked differences occur in fish species richness, assemblage compositions and species abundance in different parts of the Red Sea, reflecting the heterogeneous nature of its environment (Sheppard *et al*. 1992). Fishing occurs mainly at the subsistence or artisanal levels, although commercial trawling and purse seining are also carried out in Egypt, Saudi Arabia and Yemen (FAO 2005).

Total reported landings from this LME have increased steadily, recording over 130,000 tonnes in 2004, most of it in the 'mixed group' (Figure III-6.4). The value of the reported landings has also increased to about US$130 million in 2004 (in 2000 US dollars; Figure III-6.5).

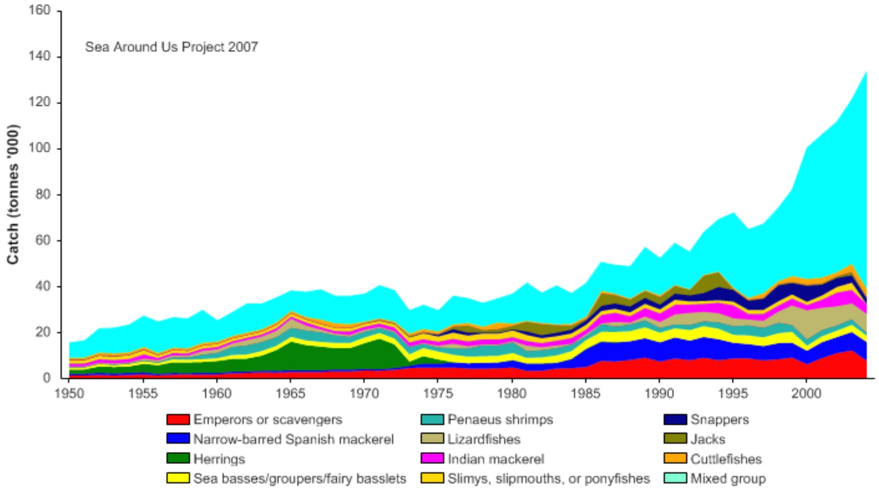

Figure III-6.4. Total reported landings in the Red Sea LME by species (Sea Around Us 2007).

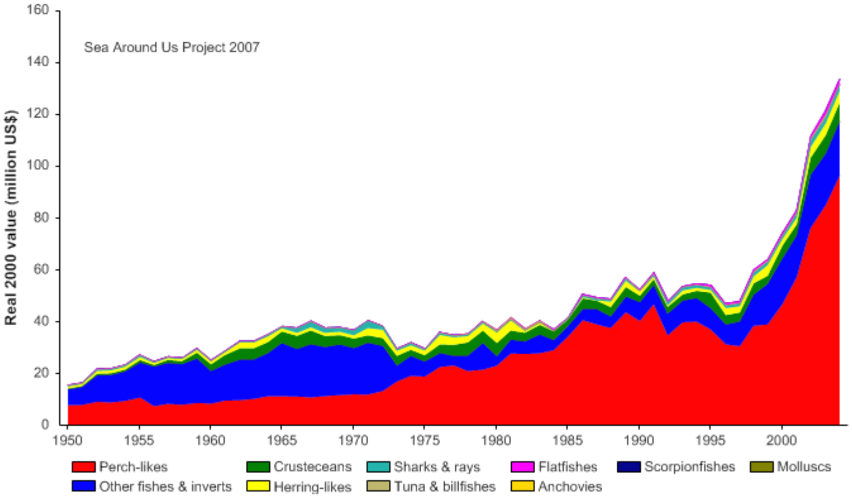

Figure III-6.5. Value of reported landings in the Red Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landing in this LME is increasing in recent years, but has yet to reach 10% of the observed primary production (Figure III-6-6). A large share of the ecological footprint in the region is accounted for by the countries bordering the LME, namely Yemen, Egypt and Saudi Arabia. The fisheries of the Red Sea LME are still expanding, and therefore, they show high and stable mean trophic levels (i.e., the MTI; Pauly & Watson 2005; Figure III-6.7 top), with a increase in the FiB index (Figure III-6.7 bottom).

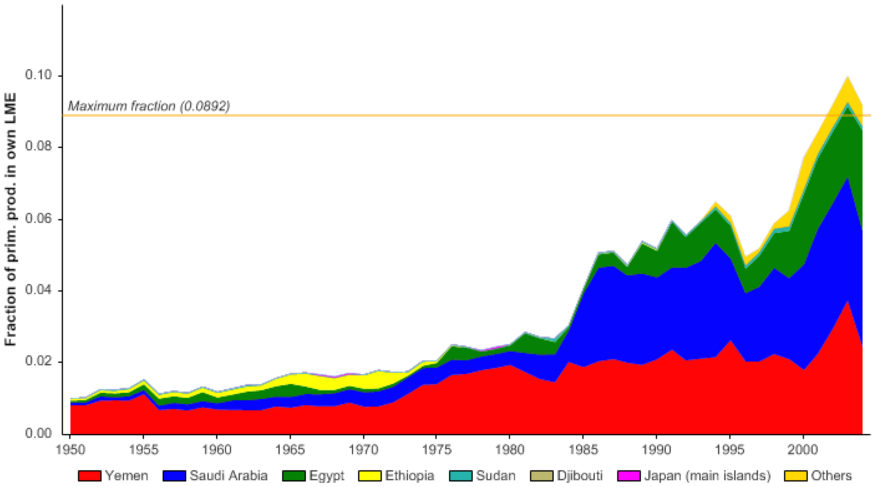

Figure III-6.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Red Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

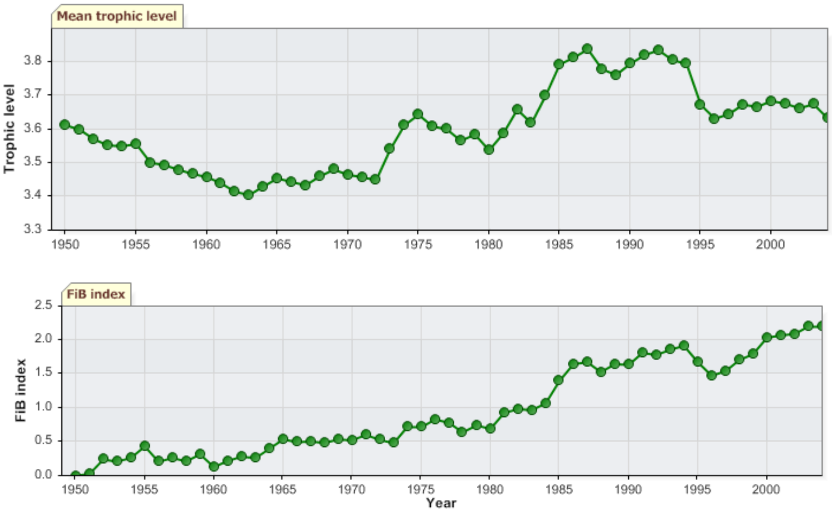

Figure III-6.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Red Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that although a few stocks have recently collapsed (Figure III-6.8, top), about 90% of the catch still originates from fully exploited stocks (Figure III-6.8, bottom).

Overexploitation, destruction of spawning, nursery and feeding grounds, and inadequate resource management and regulations, in conjunction with a lack of enforcement, are main barriers to the sustainable development of the LME's fisheries resources (PERSGA 1998). The absence of effective control and surveillance has also resulted in widespread illegal fishing and habitat destruction by both national and foreign vessels (PERSGA

2000). Ultimately, these factors may pose a serious threat to the LME's biological diversity and productivity.

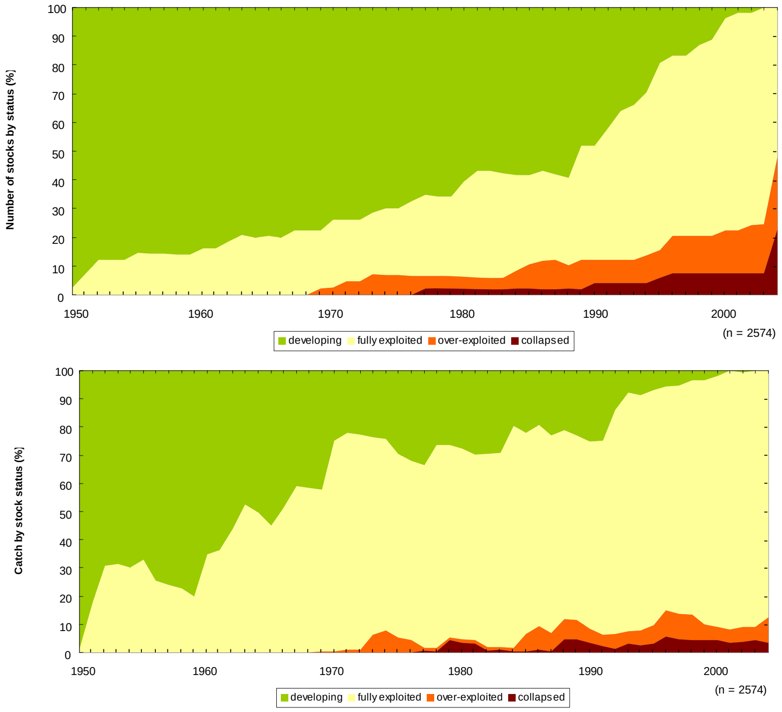

Figure III-6.8. Stock-Catch Status Plots for the Red Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The lack of stock assessments and incomplete fisheries statistics (see for example Tesfamichael & Pitcher 2007) causes major uncertainties in the status of the LME's fish stocks (PERSGA 1998). Reported declines in catches and in the average size of fish landed are indicators of overfishing (PERSGA 1998, 2000) and may illustrate the incomplete nature of the official reported landings data. With the exception of some small pelagic resources, most fish stocks are assumed to be fully exploited while others are overexploited (FAO 1997, PERSGA 1998). These include finfish and shark at the ecosystem scale and mollusc (*Strombus*), lobster and shrimp in the southern areas. Overexploitation of shark species is severe especially in Sudan, Djibouti and Yemen as a result of a large-scale illegal fishery for the East Asian shark fin market (PERSGA 1998, 2000).

Overall, prevalence of bycatch and discards and destructive fishing practices is considered to be limited (UNEP 2005). Where such fishing practices do occur, they involve the use of small meshed nets and dynamite fishing. These practices remove many reef herbivores, resulting in increased algal growth with reduced grazing pressure on algae (Pilcher & Abdi 2000). Trawl fisheries using very small meshes take a wide variety of small perciform fishes. Bycatch from net fishing also includes turtles, dugong and dolphins, which almost invariably, are discarded dead (PERSGA 1998). The fisheries resources of the Red Sea LME are also stressed by the destruction of coastal habitats resulting from uncontrolled land-filling and land-based pollution (see Pollution and Ecosystem Health).

III. Pollution and Ecosystem Health

Pollution: The slow water turnover times of six years for the surface layer and 200 years for the whole water body (Maillard & Soliman 1986, Sheppard *et al*. 1992), combined with its small size makes the Red Sea LME particularly vulnerable to pollution build-up, requiring careful consideration of any development activities in the coastal zone (Gerges 2002). The major sources of pollution in the LME are related to land-based activities as well as oil production and transportation. Pollution is severe in localised areas, including the Gulf of Aqaba (UNEP 2005).

Although its effects are usually limited to a small area around urban areas and large tourist developments (PERSGA 1998), sewage is a major source of coastal contamination throughout the LME (UNEP/PERSGA 1997). Because of rapid population growth and inadequate treatment and disposal facilities, poorly treated or untreated sewage is dumped in coastal areas. Sewage from ships also contributes to this problem at the regional scale (PERSGA 1998). The input of nutrient-rich sewage water also results in eutrophication of the coastal waters around some population centres, major ports and tourist facilities (Gerges 2002). Pollution from solid waste is a major problem in, although it is limited to small areas around urban centres, coastal villages, large tourist developments and major shipping lanes (PERSGA 1998, Gladstone *et al*. 1999).

Chemical pollution is limited to the vicinity of industrial zones and facilities (PERSGA 1998), which usually discharge their effluents directly into the sea. These industries include phosphate mines, desalination plants, chemical industrial installations and oil production and transportation facilities. Povelsen *et al*. (2003) identified a number of hotspots where the sediments were polluted by heavy metals (copper, mercury, lead, zinc) and hazardous organic pollutants such as polycyclic aromatic hydrocarbons ((PAH), aliphatic hydrocarbons, DDT, aldrin and dieldrin. The major sources of PAH and aliphatic hydrocarbons are oil production and transportation activities in the region.

Routine operational leaks and spills from oil and gas exploration and production in the Gulf of Suez and the northern and southern Red Sea LME have resulted in contamination of beaches and water by tar balls and oil slicks in localised areas throughout the LME (PERSGA 1998). Chronic oil pollution has already been observed in the immediate vicinity of some major Red Sea ports as a result of operations at oil terminals or discharges from power plants (Gerges 2002). Petroleum hydrocarbon levels are relatively high in the Gulf of Suez, with substantial oil and tar on the shores (Sheppard 2000). The risks of oil well blowouts, spills and other production accidents associated with the offshore oil industry in the northern Red Sea constitute another significant potential environmental threat to this LME (PERSGA 1998).

A major transboundary concern in the Red Sea LME is maritime pollution caused by international shipping. The Red Sea-Suez Canal is one of the world's busiest industrial shipping routes. About 25,000-30,000 ship transits occur annually in the Red Sea, mostly involving the transport of petrochemical products (Gladstone *et al*. 1999), including more than 100 million tonnes of oil (UNEP 2002a). As a consequence of the high volume of shipping traffic combined with insufficient tanker safety specifications and poor navigation aids, the potential for large oil spills and disasters at sea is high (PERSGA 1998). The discharge of ballast and bilge water and bunker oil spills are also a significant source of pollution, as a result of the lack of reception facilities at the region's ports.

Habitat and community modification: The Red Sea LME is globally renowned for its unique and attractive marine and coastal habitats with high species diversity. For example, the coral community of the Red Sea/Gulf of Aden is composed of more than 250 species of stony corals. This is the highest diversity in any part of the Indian Ocean (Pilcher & Alsuhaibany 2000). Of these, 6% are believed to be endemic (Sheppard & Sheppard 1991). These habitats are under variable anthropogenic pressures, especially adjacent to urban and industrial areas, port facilities, major shipping lanes and in the vicinity of coastal tourist developments (PERSGA 1998). The widespread destruction of coastal and marine habitats is a major transboundary concern in the region, with habitat and community modification considered severe in the Red Sea LME (PERSGA 1998).

Mangrove degradation is severe and widespread throughout the LME (PERSGA 1998). Urban and tourist development in coastal areas and extensive land filling have contributed to the decline of the region's mangroves (UNEP/PERSGA 1997). The combined effects of grazing by domesticated animals and cutting of mangroves for firewood, charcoal production and construction material have accelerated the degradation of mangroves near major human settlements (PERSGA/GEF 2004). This has been exacerbated by droughts that have forced nomads into the coastal areas, especially in Sudan (Gladstone *et al*. 1999). Mass mortality of mangrove trees appears to be a serious problem along the southern coasts of Yemen and Sudan, attributed to construction activities involving dredging and sediment dumping on the shore, diversion of tidal water and excessive sedimentation through the remobilisation of sand dunes. The recently emerging and growing shrimp farming industry also poses a serious threat to the region's mangroves (PERSGA/GEF 2004). Mangroves already exist near their upper limits of temperature and salinity tolerance in the Red Sea LME, which makes them very sensitive to disturbance (PERSGA 1998).

The status of Red Sea coral reefs is of concern. Recent declines have been reported in various locations (Pilcher & Alsuhaibany 2000, Hassan *et al*. 2002, PERSGA/GEF 2003). Major threats to the region's coral reefs include land filling and dredging for urban and tourism developments, sedimentation, destructive fishing methods, discharge of sewage and other pollutants and direct damage by tourists and boats in high-use areas (PERSGA 1998, PERSGA/GEF 2003). Anchor damage to corals and re-suspension of sediments and subsequent siltation caused by passing ships has also been implicated in the degradation of coral reefs in this LME.

Added to direct human impacts is coral bleaching, which caused extensive coral mortality, including near total mortality on several reefs in 1998 (Pilcher & Alsuhaibany 2000, Spalding *et al*. 2001). Several outbreaks of the crown-of-thorns starfish (COTS) (*Acanthaster planci*) and an increase in bio-eroding organisms such as the urchin *Diadema setosum* and the coral-eating gastropods *Drupella* and *Coralliophila* have also damaged coral reefs in some localised areas, for example, in Yemen and Djibouti (Hassan *et al*. 2002). A decline of 20-30% in coral cover, corresponding with COTS outbreaks, has been recorded at most sites surveyed in the Egyptian sector of the LME (Wilkinson 2000). Damage to seagrass beds and loss of associated species are moderate to severe in areas adjacent to urban and industrial developments (PERSGA 1998). This has been attributed to the release of untreated waste water from municipalities and aquaculture farms, coastal dredging and filling, as well as trawling, including illegal trawling by foreign vessels. Trawling impacts are particularly severe in the Gulf of Suez and the southern Red Sea LME.

Growing human populations, coastal urbanisation and tourist development as well as increasing oil and gas exploitation and transport in the region are expected to place increasing pressures on the health of the Red Sea LME (PERSGA 1998, Gladstone *et al*. 1999). Most of the environmental threats and impacts can be prevented by proper environmental planning and management, use of environmental assessments and through the enforcement of appropriate regulations, most of which are already in place (PERSGA 1998).

IV. Socioeconomic Conditions

The Red Sea LME is of major socioeconomic importance to the bordering countries. Much of the urban and industrial expansion, as well as the development of tourism has occurred in the coastal zone. The population along the shores of the LME and the Gulf of Aden has been estimated at five million (Hinrichsen 1990). Coastal urbanisation has been driven mainly by oil discoveries and industrialisation in or near the coastal zone and the associated new economic opportunities (UNEP 2002b). Accompanying the rapid expansion of urban centres has been the extensive desalination of seawater to meet the demands of the population and industry in some of the countries such as Saudi Arabia (UNEP/PERSGA 1997).

Oil production is by far the most important industry in several of the bordering countries. For example, Saudi Arabia has the largest reserves of petroleum in the world (26% of proven reserves), and ranks as the largest exporter of petroleum. In this country, the petroleum sector accounts for roughly 75% of budget revenues, 45% of GDP and 90% of export earnings. In the Red Sea LME as well as the Gulf of Aden, exploration, production, processing and transportation of more than half the world's proven oil reserves take place (PERSGA 1998). Most of the oil produced from both inland and offshore wells is exported, transforming the Red Sea LME into an oil tanker highway.

The value of the LME's biological resources to the prosperity of the region, particularly among the coastal populations, has long been recognised. The contribution of fisheries to GDP is relatively small (less than 1%), except in Yemen, where this sector accounts for 15% of GDP (FAO 2005). Nevertheless, fisheries, particularly artisanal fisheries, provide food and employment for thousands of the region's inhabitants. For example, in Yemen, more than 220,000 people depend on fishing as their principal source of income (FAO 2005). The fish resources of the Red Sea LME are regarded as an important source of domestic protein for coastal communities. Marine fisheries have potential for further development, for example, in Djibouti, where the potential contribution to GDP could rise substantially from 0.1% to around 5% (FAO 2005). However, realisation of that potential will depend on the continued upgrading of infrastructure and development of export markets.

Pollution and habitat degradation have negative impacts on the fisheries and tourism industries (UNEP 2005). Sewer outflows and runoff from farms and urban areas are also endangering human health. The high concentration of carcinogenic chrysene in fishes in Yemen is of concern. Based on the country's fish consumption, the daily intake of total carcinogens was calculated at 0.15 µg person^{-1}day^{-1} (DouAbul *et al*. 1997).

V. Governance

In their determination to strengthen participation in regional and international agreements, the nations bordering the Red Sea LME have signed or ratified a number of international conventions and adopted various other legal instruments. While they have approved many new environmental laws and standards in the last decade, implementation and enforcement remain generally poor (Pilcher & Alsuhaibany 2000).

The Regional Convention for the Conservation of the Environment of the Red Sea and Gulf of Aden (the Jeddah Convention) provides the legal framework for cooperation in marine environmental issues. This convention, which was adopted by the Regional

Conference of Plenipotentiaries, held in Jeddah, Saudi Arabia, in 1982, is supported by UNEP under its Regional Seas Programme. Also arising from the conference was the Action Plan for the Conservation of the Environment of the Red Sea and Gulf of Aden, as well as the Protocol Concerning Regional Cooperation in Combating Pollution by Oil and other Harmful Substances in Cases of Emergency. In addition, the Jeddah Conference adopted a Programme for the Environment of the Red Sea and Gulf of Aden (PERSGA), an official regional organisation responsible for the development and implementation of regional programmes for the protection and conservation of the marine environment of the Red Sea and Gulf of Aden. PERSGA was formally established in September 1996, with the signing of the Cairo Declaration by all cooperating parties to the Jeddah Convention. Major functions of PERSGA include the implementation of the Jeddah Convention, the Action Plan and the Protocol (PERSGA 2005).

PERSGA has prepared a Regional Action Plan for the Conservation of Coral Reefs in the Red Sea and Gulf of Aden, which was formulated from the Regional Action Plan for the Conservation of Coral Reefs in the Arabian Seas Region. The former provides a set of priority actions for the conservation and sustainable development of coral reefs in the Red Sea and Gulf of Aden. The Red Sea LME contains a number of MPAs (UNEP-WCMC 2005), and the formation of a regional network of MPAs has been proposed (PERSGA 2001). Annex 1 of the International Convention for the Prevention of Pollution from Ships (MARPOL) identifies the Red Sea as a special area in terms of the prevention of oil pollution from ships. GEF has supported the preparation of a SAP for the Red Sea and Gulf of Aden, which was led by PERSGA. The SAP identifies actions needed to protect the LME’s unique and fragile coral reefs, seagrass beds and mangroves. Implementation of the SAP is being supported by GEF through the project ‘Implementation of the Strategic Action Programme for the Red Sea and Gulf of Aden’. The long term objective of the project is to safeguard the coastal and marine environments of the Red Sea and Gulf of Aden and ensure sustainable use of its resources.

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IV MEDITERRANEAN SEA

IV-7 Mediterranean Sea LME

M.C. Aquarone, S. Adams and P. Mifsud

The Mediterranean Sea LME, located between Southwestern Europe and Northern Africa, is bordered by a large number of countries. It has a narrow continental shelf and covers a surface area of about 2.5 million km^2, of which 1.43% is protected, with 0.4% of the world's sea mounts (Sea Around Us 2007). A warm-temperate climate and several distinct biogeographical sub-units characterise this LME. For the origin and history of the Mediterranean and Adriatic Seas, see Bombace (1993). Book chapters and articles pertaining to this LME include Bombace (1993), Caddy (1993) and UNEP (1997). A new strategic partnership for the Mediterranean has been formed by the GEF, UNEP, and the World Bank to implement the Strategic Action Plan (SAP) agreed upon by the participating countries to reduce pollution impacts on environment and human health, to address pollution from land-based activities, reach sustainable fisheries, and protect coastal-marine biodiversity and communities (see www.medsp.org).

I. Productivity

Overall, the Mediterranean Sea LME is considered a Class III, low productivity ecosystem (<150 gCm^{-2}yr^{-1}). For an oceanographic overview of the Mediterranean Sea and its hydrographic inputs and primary production, see Caddy (1993). Temperature stratification can occur during extended periods of calm seas, high temperatures, and inflows of fresh water. This separates the warmer, less saline surface water from the deeper, colder and more saline water, resulting in autumnal algal blooms and extended hypoxia or anoxia. The LME presents a composite structure of environmental conditions, with local areas of upwelling, wind-driven currents, high water temperatures at least in some periods of the year, and nutrient inputs from rivers and human activities (see Caddy 1993). The major inflow into the Mediterranean is nutrient-poor, oxygenated Atlantic surface water through the Strait of Gibraltar, resulting in generally well-oxygenated bottom waters. Gyres and upwellings contribute to the Adriatic Sea's phytoplankton productivity. The highest levels of productivity occur along the coasts, near major cities and at estuaries, while the lowest levels occur in the southeastern Mediterranean (Darmouli 1988; Stergiou *et al.* 1997).

Oceanic Fronts (after Belkin et al. 2009): Western Mediterranean fronts include the North Balearic Front between France and Corsica, along 42^{o}N; gyre fronts of the western Alboran Sea; Almeria-Oran Front of the eastern Alboran Sea; Sardinia-Sicily Front; North Adriatic Front (winter); Albanian Upwelling Front (19^{o}E; fall and winter only); a zonal front south of Golfo di Taranto and Strait of Otranto; 395^{o}N; fall and winter) and Libyan Front (Figure IV-7.1).

Eastern Mediterranean fronts include the Mid-Mediterranean Jet Front, a permanent feature south of Crete, as well as some smaller fronts of local scale. Inter-annual variability of the Mediterranean fronts is very substantial, as shown by a comparison of the frontal map here with, for example, Philippe & Harang (1982). "Winter cooling, which extends deeper than the density-criterion mixed layer, is very brief so the pycnocline lies within the photic zone from March to November.

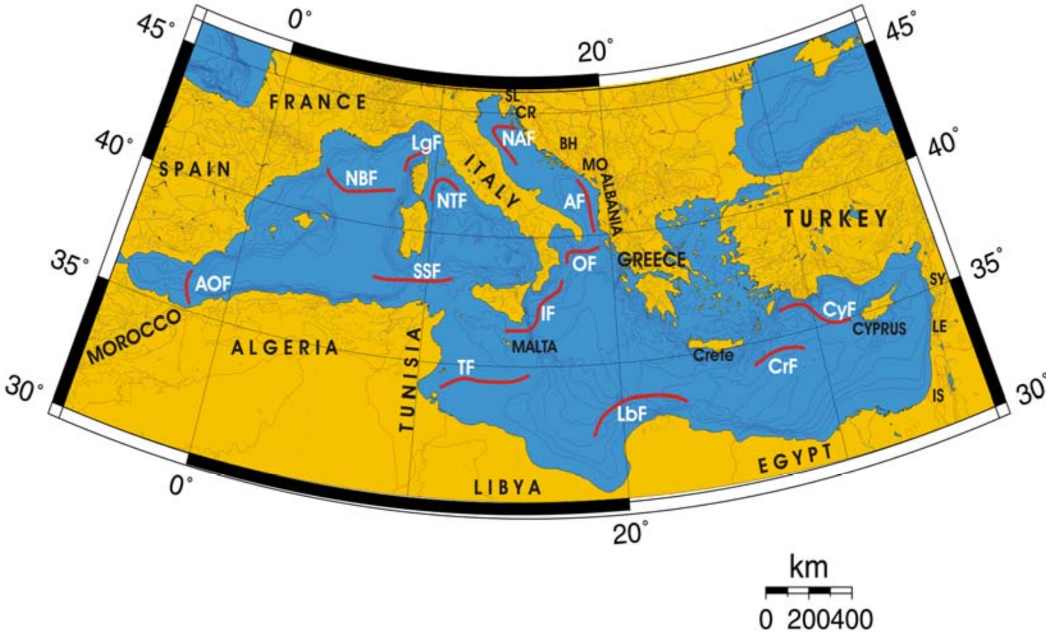

Figure IV-7.1. Fronts of the Mediterranean Sea LME. AF, Albanian Front; AOF, Almeria-Oran Front; CrF, Crete Front; CyF, Cyprus Front; LbF, Libyan Front; LgF, Ligurian Front; NAF, North Adriatic Front; NBF, North Balearic Front; NTF, North Tyrrhenian Front; OF, Otranto Front; SSF, Sardinia-Sicily Front; TF, Tunisian Front. Countries: BH, Bosnia-Herzegovina; CR, Croatia; IS, Israel; LE, Lebanon; MO, Montenegro; SL, Slovenia; SY, Syria. After Belkin et al. 2009).

The primary production rate is minimal in late summer, and increases when the mixed layer deepens in autumn. Chlorophyll accumulation is rapidly overtaken by loss in spring as herbivore consumption builds up to balance production" (Longhurst 1998). Belkin and O'Reilly (2008) have put forward an algorithm for oceanic front detection in chlorophyll and SST satellite imagery.

Mediterranean Sea SST (after Belkin 2009)
Linear SST trend since 1957: 0.43°C.
Linear SST trend since 1982: 0.71°C.

The thermal history of the Mediterranean Sea since 1957 has consisted of two major periods: (1) cooling until the all-time minimum in 1978; (2) warming until the present at a very fast rate of 1.2°C in 28 years. This rate is roughly consistent with the warming rate of 0.067°C per year based on satellite data from 1990-2006 (Del Rio Vera et al., 2006). High-resolution regional ocean models predict a 3°C SST rise in the Mediterranean Sea by 2100 (Somot et al., 2006), a rather conservative estimate given the current SST warming rate of approximately 0.5°C to 0.7°C per decade. The present warming was accentuated by the all-time maximum of 20.5°C in 2003, a result of an exceptional heat wave caused by a blocking anticyclone situated over Western Europe for >20 days in summer.

Most climate studies consider separately two major basins, Western and Eastern. Long-term variability of the Western Basin is linked to the North Atlantic Oscillation, whereas the Eastern Basin variability is linked to the Indian monsoon (CIESM, 2002). Lascaratos et al. (2002) used the COADS (Comprehensive Atmosphere-Ocean Data Set) data from 1945-1994 to study long-term variability of SST and atmospheric parameters over the Mediterranean Sea after removal of seasonal signal and quasi-biannual oscillation by a digital filter. Their SST time series is similar to ours, except for a different dating of the all-time minimum (1975 instead of 1978) likely caused by the digital filter. During the 15-year warming period of 1975-1990, they found SST increases of 0.8°C, 0.5°C and nearly zero in the Western Basin, Ionian and Levantine Seas respectively. The strong eastward diminishing trend is suggestive of eastward advection (Lascaratos et al., 2002). Alternatively, this trend reflects a diminishing influence of the North Atlantic toward east.

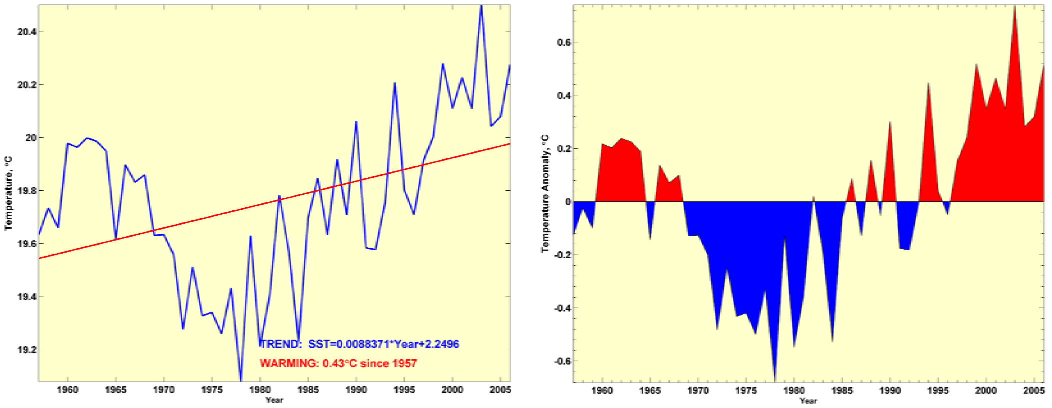

Figure IV-7.2. Mediterranean Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Mediterranean Sea LME Trends in Chlorophyll and Primary Productivity: Overall, the Mediterranean Sea LME is considered a Class III, low productivity ecosystem (<150 gCm^{-2}yr^{-1}), but that natural productivity is augmented by increased nutrient input from human induced activities.

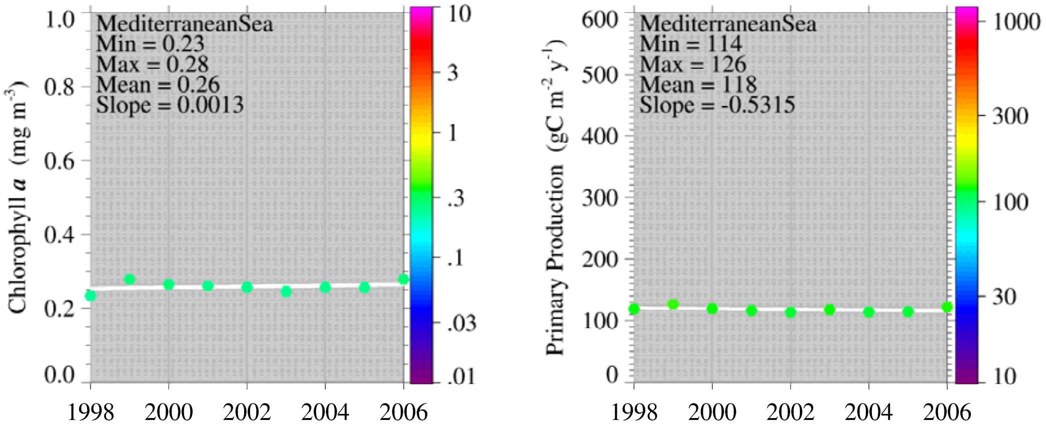

Figure IV-7.3. Mediterranean Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2007. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Mediterranean Sea LME is one of the most diverse and stable LMEs in terms of species groupings and their share in the total catch (Garibaldi and Limongelli 2003). For more information on primary production and fisheries, as well as a historical perspective on fisheries in the Mediterranean Sea, see Caddy (1993). For a study on ecology and fisheries in the Adriatic Sea, see Bombace (1993).

Total reported landings in the LME, consisting largely of clupeoids (pilchard, anchovy & sardinella), increased from 1950 to the mid 1980s, levelling off at around 900,000 tonnes in the 1990s, with landings over 1 million tonnes recorded in 1994 and 1995 (Figure IV-7.4). The value of the reported landings has peaked at about 2.4 billion US$ (in 2000 real US$) in 1988 (Figure IV-7.5).

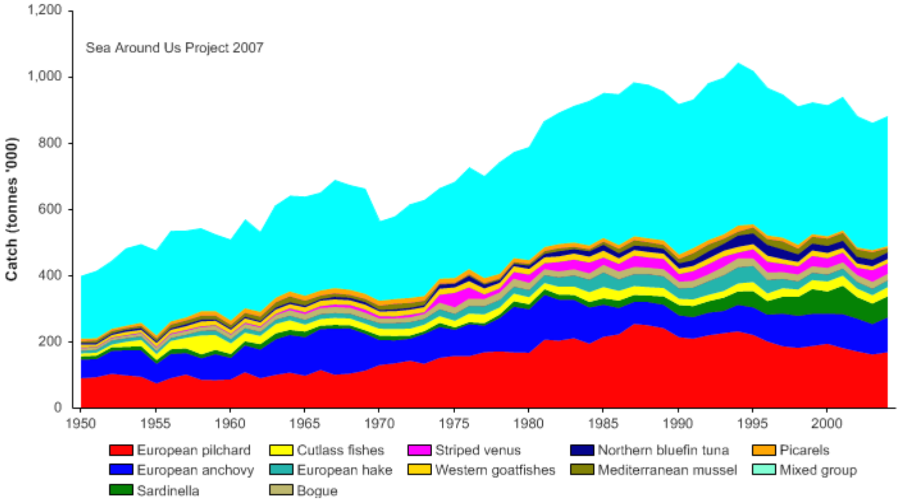

Figure IV-7.4. Total reported landings in Mediterranean Sea LME by species (Sea Around Us 2007).

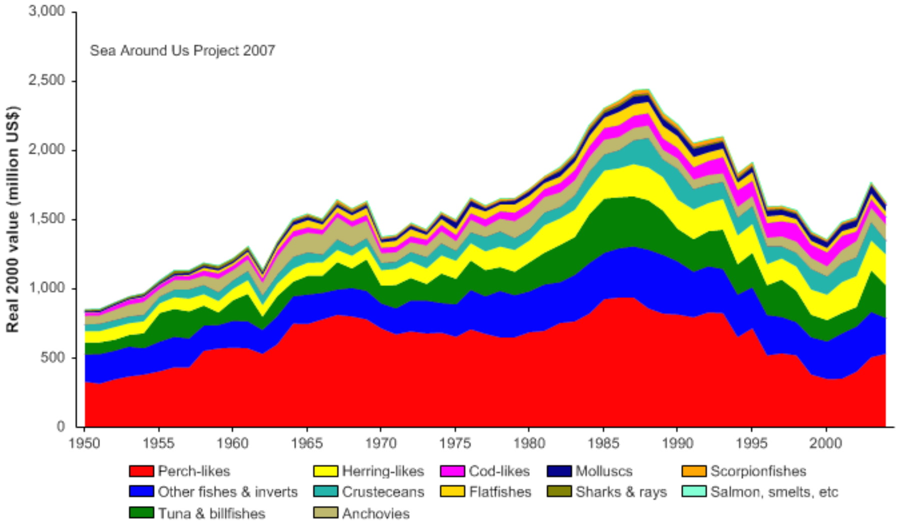

Figure IV-7.5. Value of reported landings in the Mediterranean Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 20% of the observed primary production in 1994, but has since declined to 15% (Figure IV-7.6). Italy has the largest footprint, but overall, the PPR is evenly distributed amongst the Mediterranean countries.

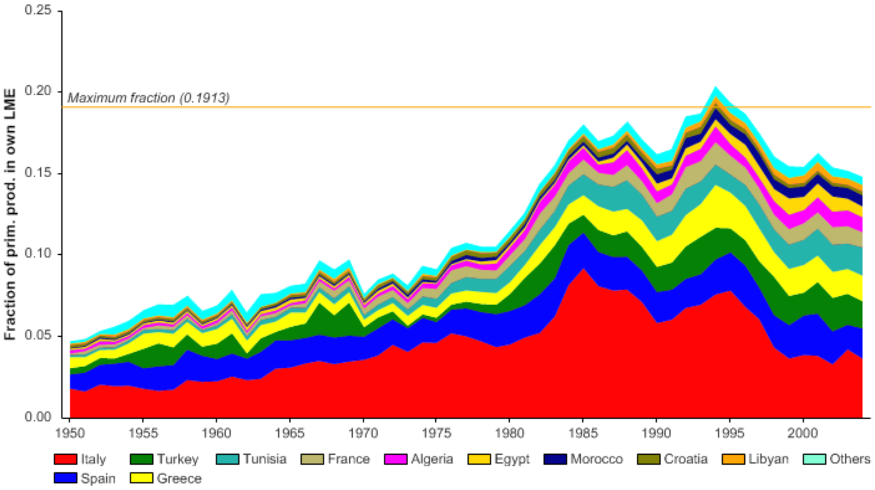

Figure IV-7.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Mediterranean Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has increased until the mid 1980s and has declined since the mid 1990s, when the expansion of the fisheries, particularly offshore, ceased, as suggested by the increase of the FiB index from 1950 to the mid 1980s. Since the mid 1980s, the FiB has stabilized and began to decline in the late 1990s (Figure IV-7.7 bottom), an indication of decline in both the MTI and catch (Pauly & Watson 2005).

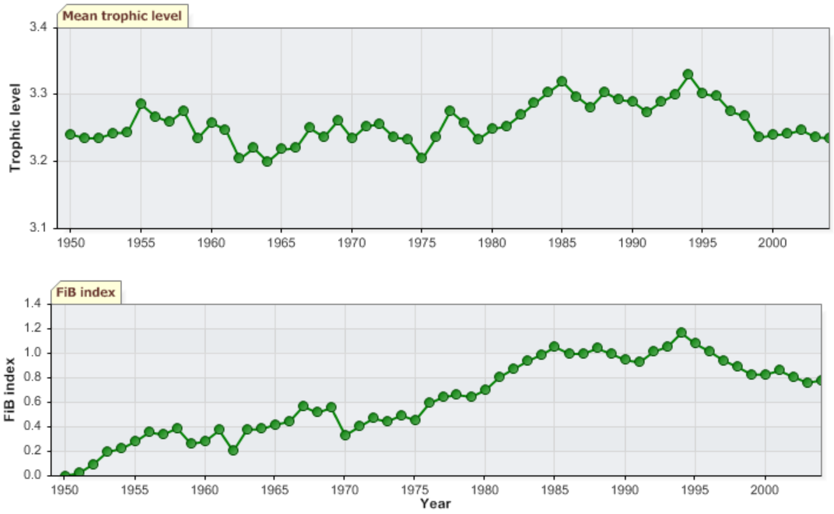

Figure 1V-7.7. trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Mediterranean Sea LME (Sea Around Us 2007).

These trends confirm, along with the contributions by Durand (2000), that substantial 'fishing down' has occurred in the Mediterranean, as originally suggested by Pauly *et al.*

(1998). Demersal fish populations are constantly overfished: shallow areas (within the 3-miles coastal limit or on bottom less than 50 m deep) are illegally trawled and small, illegal mesh sizes are used (UNEP, RAC/SPA 2003). It should also be noted that the ‘fishing down’ is not a result of an increase in the production of low-trophic, farmed organisms (e.g., mussels) being included in the valuation of mean trophic level, as suggested by Pinnegar *et al.* (2003). In fact, if the production from the Mediterranean aquaculture were included in the valuation, the mean trophic level would be higher, because it is, increasingly, high-trophic level fishes (e.g., bluefin tuna) that are being farmed in the Mediterranean (Stergiou *et al.* 2007). In recent years, aquaculture production in the Mediterranean increased from 19,997 tonnes in 1970 to 339,185 tonnes in 2002 (FAO FISHSTAT 2002). The Stock-Catch Status Plots suggest that, based on reported landings statistics, very few stocks have collapsed (Figure IV-7.8, top), and that over 80% of the reported landings originate from fully exploited stocks (Figure IV-7.8, bottom).

Technological improvements in fishing fleets and their increased fishing capabilities in the LME have resulted in a decline in the catch per boat (Caddy 1993), while fishing effort has increased in response to high fish prices. By the 1970s, a substantial portion of the less productive southern shelves was being fished for demersal resources. In the Adriatic Sea sub-area, coastal pollution and eutrophication have been the principal factors driving change in fisheries yields. Fish kills have also occurred in the northern Adriatic from noxious phytoplankton blooms and anoxic conditions. For more information on demersal and pelagic fish and molluscs in the Adriatic, see Bombace (1993).

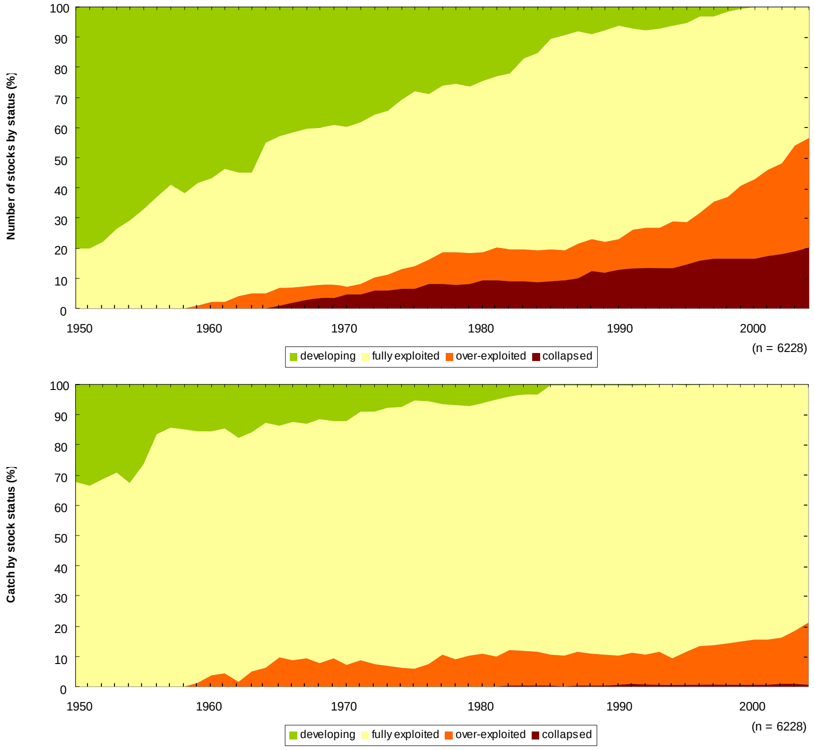

Figure IV-7.8. Stock-Catch Status Plots in the Mediterranean LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.*, this vol. for definitions).

III. Pollution and Ecosystem Health

Anthropogenic pressures on the Mediterranean marine environment include agricultural wastes, airborne particles and river run-off that carries nutrients, pathogens, heavy metals, persistent organic pollutants, oil and radioactive substances. All these pollution sources affect the most productive areas of the Mediterranean marine environment, including estuaries and shallow coastal waters. At the same time, physical changes to its 46,000 Km coastline from human activities are threatening Mediterranean coastal and marine habitats of vital importance in maintaining a healthy ecosystem. Focusing on human activities, 131 “pollution hot spots” have been identified by the countries in the frame of the Strategic Action Programme (SAP) of UNEP. These pollution hot spots are point pollution sources or coastal areas, which may affect human health, ecosystems, biodiversity, sustainability, or economy. Of these hot spots, 26% are urban, 18% industrial and 56% mixed (urban and industrial) (UNEP/WHO 2003). Additionally to the pressures from land based pollution sources and off-shore and shipping activities, biological invasions of alien species and the increasing appearance of Harmful Algal Blooms (HABs) are considered as emerging issues threatening the marine environment of the Mediterranean (EEA 2006). The atmosphere also contributes nitrogenous compounds, contaminants and heavy metals (see Caddy 1993, UNEP 1989).

The Mediterranean Sea LME’s 46,000 km of coast supports an estimated population of 150 million inhabitants along the coast of the LME. Note that this population produces 3.8 billion cubic metres of wastewater each year (www.unepmap.org). Along the Mediterranean coast, 69% of the 601 cities with population above 10,000 (total resident population 58.7 million) operate a wastewater treatment plant, mostly using secondary treatment (56% of the operating plants) (UNEP/MAP/MEDPOL/WHO 2004). However, the distribution of treatment plants is not uniform along the Mediterranean region, the northern coast having a much greater part of its population served by treatment plants than the southern coast. Furthermore, due to increasing population in the cities, poor rate of sewerage connections and failures in treatment plant operation, an important part of the generated municipal effluents is still discharged untreated into the Mediterranean. A further 2.5 million cubic metres of waste water are produced by the 220 million tourists visiting the Mediterranean region every year, especially in summer. Blooms of phytoplankton and benthic diatoms have resulted in local fish kills caused by anoxia. Planktonic blooms and sewage contamination of coastal waters have also caused human health problems associated with the ingestion of contaminated shellfish (see UNEP/FAO 1990, Caddy 1993, UNEP/MAP 2004).

Agriculture is the largest non-point contributor of pollutants to the Mediterranean (UNEP/MAP 2001). The EEA reported in 2001 that the large river basins like the Rhone and Po basins are subjected to heavy agricultural pressures. “The first six drainage regions, following a tentative ranking of the risk of soil erosion and nutrient losses, are found in peninsula Italy, Sicily, Sardinia, Greece, Turkey and Spain (EEA, 1999c) with an estimated annual minimum agricultural load (excluding Croatia, Egypt, Libya, Malta land Slovenia) to the Mediterranean Sea of 1.6 million tonnes nitrogen, 0.8 million tonnes phosphorus and 1.7 million tonnes TOC” (reports.eea.europa.eu). Intensive aquaculture is undoubtedly a matter of concern for the Mediterranean marine coastal environment, since it can induce pollution and can lead to conflicts with other users (UNEP/MAP/MEDPOL 2004).

Rivers are important conveyors of industrial pollutants to the Mediterranean, especially the Po, Ebro and Rhône rivers (UNEP/MAP 2003). Industrial wastewater is either discharged directly to the sea or through municipal sewerage systems, outfalls, uncontrolled disposal sites and rivers. There are more than 200 petrochemical and energy installations, basic chemical industries and chlorine plants located along the narrow Mediterranean coast and catchment basins of rivers, including at least 40 major oil refineries, in addition to cement plants, steel mills, tanneries, food processing plants, textile mills and pulp and paper mills (UNEP/MAP 2001). Petrol refineries are dumping 20,000 tonnes of petrol per year into the sea. Discharges during routine unloading account for 60% to 70% of the oil pollution in the Mediterranean. EEA estimates that 50% of the land area is at risk of erosion (reports.eea.europa.eu, 2001). A recent survey carried out by MAP through the MED POL Programme resulted in the preparation of the National Baseline Budget of emissions and releases in the Mediterranean region. The database showed that the sectoral contribution to the overall industrial loads (e.g. 86.1% of biological oxygen demand (BOD) comes from food processing, farming and oil refining; 97.3% of lead in effluents comes from inorganic chemical plants and fertilizers manufacturing (UNEP/MAP 2006).

IV. Socioeconomic Conditions

UNEP/MAP.org predicts the population of the coastal states of the Mediterranean will reach 600 million by 2050. Urban growth rates are high for the Mediterranean and it is likely that in 50 years the population will shift from essentially rural to urban (www.unepmap.org). In terms of wealth, the EU countries have 90% of the GDP for the Mediterranean, with GDP per capita values twelve times higher than in north African countries (www.unepmap.org). Anthropogenic nutrient enrichment and eutrophication caused by runoff and polluted river discharges are a major concern both for fisheries and tourism revenues. In 1998, the Barcelona Declaration of the Mediterranean NGOs for Sustainable Development attested that the Mediterranean was at that time the site of 35% of the world's trade in hydrocarbons, of 15% of the chemicals trade, and of 17% of world trade. The UNEP/Mediterranean Action Plan (www.unepmap.org) reports that 42% of the coastal zone is under artificial land cover and that by 2025, half the coastal zone will be covered by roads, ports, airports and industrial and power facilities.

Fisheries production has increased in many areas and is of major economic importance. Mariculture production of mussels and oysters has also increased. Production from aquaculture increased from 78,000 ty^{-1} in 1984 to 248,000 ty^{-1} in 1996, according to the EEA (http://reports.eea.europa.eu).

V. Governance

Governance of the Mediterranean Sea LME involves 21 countries and the European Union. The countries differ in their stages of economic and institutional development and in their capacities to address biodiversity issues in the context of sustainable development. The Mediterranean became the first region to adopt an Action Plan – the Mediterranean Action Plan (MAP) in 1975, under the UNEP Regional Seas Programme. This was followed by the adoption of the Convention for the Protection of the Mediterranean Sea against Pollution (Barcelona Convention) in 1976, which entered into force in 1978, and a succession of six landmark protocols (www.unepmap.org/html/homeeng.asp). The MED POL Programme and six Regional Activity Centres are responsible for the implementation of respective components of the MAP. In 1996 the Mediterranean Commission on Sustainable Development was set up as an advisory body for defining a regional sustainable development strategy for the Mediterranean Sea. The Action Plan and Convention have since been amended to reflect the emphasis on sustainable development and biodiversity conservation (see Caddy 1993, UNEP 1989). MEDPOL is a pollution monitoring and assessment programme that began in the mid-1970s.

GEF is supporting an LME project to help the Mediterranean countries jointly address critical threats to the coastal and marine environment, and to promote ecosystem-based management of coastal and marine resources (Lascaratos 2006). GEF projects involve the conservation of wetlands and coastal ecosystems, and the building of country capacity. Through a TDA adopted by the Contracting Parties to the Barcelona Convention in 2004, the participating countries have analysed factual and scientific information on transboundary concerns and their root causes, and have set priorities for action (see Mediterranean Action Plan 1999). Decline in biodiversity, fisheries, and seawater quality, along with human health risks and the loss of groundwater dependent coastal ecosystems were identified as the major environmental concerns of the basin. In addition, they are determining national and regional policy, legal and institutional reforms and investments needed to address the priorities within the LME. They have also committed to pollution reduction for specific pollutants with specific timetables and targets. Two SAPs were prepared and adopted in 1997 and 2003 respectively: SAP-MED for land-based sources of marine pollution and SAP-BIO, the Strategic Action Programme for the conservation of Mediterranean Marine and Coastal Biological Diversity. The SAP-MED has now formed the basis for the National Action Plans of each country, finalized and endorsed by the Contracting Parties in 2005.

A new Strategic Partnership for the Mediterranean Sea Large Marine Ecosystem supported by GEF, UNEP, the World Bank and a large number of additional national and international donors, has recently been adopted by the GEF Council and will be implemented as from 2008. The strategic partnership is addressed to all the countries of the Mediterranean and to all international cooperation Agencies and donors. The Partnership will serve as a catalyst in leveraging policy/ legal/ institutional reforms as well as additional investments for reversing degradation of this damaged large marine ecosystem, its contributing freshwater basins, its habitats and coastal aquifers. The major threats to be collectively addressed are environmental challenges including climate change; population growth, tourism and urbanization; loss of biodiversity and the unsustainable use of fisheries. Programmes have been developed in conjunction with a review of the European Union’s Common Fisheries Policy and illustrate increasing international coordination of scientific studies of fisheries resources and the biological and oceanographic environment. In 2006 the 10th anniversary Euro-Med Summit in Barcelona adopted an initiative, Horizon 2020, to reduce and control, with the help of a coalition of partners, major Mediterranean pollution “hot spots” by the year 2020.

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V BLACK SEA

V-8 Black Sea LME

S. Heileman, W. Parr, and G. Volovik

The Black Sea LME is almost cut off from the rest of the world's oceans, connected only through the Istanbul Strait, a 35 km natural channel, as little as 40 m deep in places. The Black Sea is linked to the Mediterranean Sea by the narrow Bosphorus and Dardanelles Straits, and to the shallow Sea of Azov by the Kerch Strait in the north. The LME covers a surface area of about 460,150 km^2,including the Sea of Azov. of which 2.21% is protected (Sea Around Us 2007). The northwestern part of the Black Sea is shallow but in other places its waters reach a depth of more than 2,200 m. The Black Sea catchment area entirely or partly extends over 18 countries: Austria, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Georgia, Germany, Hungary, Moldova, Slovakia, Slovenia, Romania, Russia, Turkey, Ukraine, Yugoslavia-- about one third of the area of continental Europe and containing in excess of 160 million people. Every year, Europe's second, third and fourth largest rivers, (the Danube, Dnieper and Don, carry about 350 km^3 of river water into the Black Sea. As a consequence of its almost landlocked nature and lack of circulation in its deep waters, the LME is particularly vulnerable to environmental stresses originating from human activities in the catchment area, especially the Danube, Dnieper and Don River basins. Book chapters and articles pertaining to this LME include Mee (1992), Caddy (1993), Zaitsev & Mamaev (1997), Black Sea Commission (2002), UNEP (2002), Daskalov (2003), Borysova *et al.* (2005) and Paleari *et al.* (2005).

I. Productivity

The LME is considered a Class I, highly productive ecosystem (>300 gCm^{-2}year^{-1}). High primary production is associated with fluvial discharge (Balkas *et al*. 1990) as well as natural winter production (Sur *et al*. 1994, Nezlin *et al*. 1999). In addition, data from the CZCS and the Advanced Very High Resolution Radiometer indicated the presence of patches of upwelling in summer in some areas of the Black Sea (Sur *et al*. 1994, Shalovenkov 2000). Historically important seagrass as well as macroalgal communities, for example the red alga *Phyllophora* sp. and the brown alga *Cystoseira barbata*, contribute to benthic primary production in shallow areas.

A strong density stratification, which effectively inhibits vertical mixing, results in permanent anoxia within almost 90% of the Black Sea's volume (below 200 m), making this LME the largest anoxic basin of the global ocean. The deep anoxic layer with its high hydrogen sulfide content is a 'dead' zone. Marine life is confined to the upper layer, while the bottom is void of invertebrates and fish in most parts of the Black Sea.

Chemical profiles in the deep basin demonstrate that the whole water column of the Black Sea can be divided into 4 sub-layers, based on its oxygen content; namely:

- The oxygenated upper layer, which is relatively thick (80-90m) in the coastal margins, becoming much thinner (40m) in deeper waters.
- The oxycline, in which oxygen concentrations decrease steeply This extends down to only 60-70m in the cyclonic gyre but may reach as much as 150m depth in the coastal margins. Since the oxycline is thicker in the coastal margin, the oxygen gradient is lower in the coastal zone than in the open sea.

- The suboxic zone, in which oxygen levels decline slowly to where sulphide-bearing water begins.
- The anoxic (sulphide-bearing) layer, extending down to the sea bed.

The nutrient content of seawater is also related to oxygen status. Surface nutrient concentrations were usually low, since they are sequestered by phytoplankton, seaweed and higher plant growth, where sufficient light is available. Surface nutrient concentrations exhibit pronounced seasonality, with maximum concentrations occurring in late winter/early spring.

Below the mixed surface water layer, lies a nutrient-rich cold intermediate layer, separated from the surface layer by a rapid change in temperature (the thermocline) or salinity (halocline). This lies within the suboxic zone. The depths of the oxygen saturated and suboxic zones varies from coastal waters to the interior basin, depending on the thickness of the brackish upper layer and ventilation rate of the halocline waters. The nitrate and phosphate profiles indicate nutrient deficiency in the near surface waters and then display maxima within the halocline. Phosphate profiles also exhibit a second maximum at the anoxic boundary of the deep basin. These features appear at different depths with region, being consistently shallower in the cyclonic gyres where the permanent halocline displays a ‘dome’ shape.

Large changes in livestock numbers have occurred in Black Sea coastal countries since 1960. For example, livestock numbers reached a clear maximum in 1988, just prior to the economic collapse, fell sharply to 1997, and the numbers of cattle, pigs, sheep and goats continued to fall until 2003 (by 33, 26 and 31%, respectively), while poultry increased (by 23%)in the same time period). During the period 1988-2003, numbers of cattle fell by 64%, pigs by 62%, sheep and goats by 67% and poultry by 21%. By 2003, there was a major decrease in mammalian livestock numbers (44-67%) compared with the 1960 values.

The increasing costs of sheep production in particular have resulted in lower consumer demand for lamb products. The number of poultry has increased dramatically since 1960 due to the adoption of more intensive and cheaper production practices, bringing with them increasing demand.

During the late 1960s, there was a major change in agricultural production in the region (‘the Green Revolution’), which involved the use of large amounts of fertilisers as well as the establishment of extensive animal farms (Mee & Topping 1999). The subsequent increased riverine nutrient input, particularly from the Danube River, resulted in severe eutrophication and greatly enhanced primary production, including frequent abnormal phytoplankton blooms in the Black Sea LME (Balkas *et al*. 1990, Sur *et al*. 1994, Mee & Topping 1999). This and other factors promoted dramatic changes in the ecosystem in recent decades (Black Sea Transboundary diagnostic Analysis 2007).

When compared to livestock figures, similarly dramatic changes have happened with regard to the use of inorganic fertilisers in arable farming. This is shown dramatically by Romanian data (Black Sea TDA 2007) indicating that in 1960 only very low levels of inorganic fertilisers were applied, but by 1988 the amount of inorganic nitrogen fertiliser had increased 27-fold and inorganic phosphorus fertiliser 7-fold. Following the economic collapse and independence of Romania, fertiliser application rates fell to below the levels applied in 1970, with a continuing decrease still evident in 2003. Levels applied in 2003 were about one third of those applied in 1988 (Black Sea Transboundary Diagnostic Analysis 2007).

The structure of the Black Sea ecosystem differs from that of the neighbouring Mediterranean Sea in that species variety is lower and the dominant groups are different. However, the abundance, total biomass and productivity of the Black Sea are much higher than in the Mediterranean Sea. Plankton community composition and biomass suggest that improvements are taking place, albeit that a reduction in organic enrichment is key to this recovery.

Formerly "dead" areas of the NW Shelf sediment are once again colonised by biota, with evidence of biodiversity continuing to increase. However, the once massive area dominated by Zernov's *Phyllophora* (a red seaweed) field has decreased hugely in area, having been replaced by other, opportunistic macroalgae. Similarly, during the last two decades, the area covered by eelgrass (*Zostera*) has decreased tenfold in shallow waters. The *Phyllophora* field once provided a habitat for 118 species of invertebrates and 47 species of fish. The Black Sea macrozoobenthos is represented by approximately 800 species, and the fish fauna by 171 species. There are 320 bird species in the Danube Delta and 4 species of Mammals are found in the Sea.

Higher species richness in shallower waters is associated with good dissolved oxygen conditions whilst in deeper areas there is lower diversity due to natural oxygen depletion with increasing depth in the Black Sea. Consequently, the number of macrobenthic species decreases rapidly with increasing depth - only the polychaete worm *Notomastus profundus* is found below a depth of about 120 m. Species diversity is high in the Black Sea LME, with a total of 3,800 species having been identified (Zaitsev & Mamaev 1997). Four species of mammals inhabit the LME: the monk seal (*Monachus monachus*), the bottlenose dolphin (*Tursiops truncatus ponticus*), the common dolphin (*Delphinus delphis ponticus*) and the harbour porpoise (*Phocaena phocaena relicta*).

The invasion of *Mnemiopsis leidyi* (a comb jelly) contributed to a catastrophic decline in fish productivity in the 1980s. The subsequent invasion of another comb jelly (*Beroe ovata*), which feeds on the original invader, means that opinions are now split as to whether *Mnemiopsis* is still has a major impact on fish communities and catches.

The number of registered alien species at the regional level amounts to 217 (parasites and mycelium excluded). Nearly half of them (102) are permanently established, and a quarter - highly or moderately invasive (20 and 35 species respectively). This high ratio of invasive aliens suggests a serious impact on the Black Sea native biological diversity, with negative consequences for human activities and economic interests.

Between 1996 and 2005 a total of 48 new alien species were recorded, which represents over 22 % of all registered aliens. The majority belong to phytoplankton (16) and zoobenthos (15), followed by zooplankton (8), fish (5), macroalgae (3) and mammals (1).

Habitat status is a critical component of maintaining high levels of biodiversity within the Black Sea. The status of marine habitats is therefore assessed. All 5 habitats within the coastal margin ecotones category are considered to be in a critical status in at least one country; both types of benthic pelagic habitat (neritic and open sea) are considered critical in at least one country; and 13 of the 37 types of benthic habitat are considered to be critical in at least one country. No data were available on Russian Black Sea habitats. The ecosystem(s) of the Black Sea are, therefore, seriously damaged and in need of legal protection. Those habitats most at risk include the neritic water column, coastal lagoons, estuaries/deltas and wetlands/saltmarshes.

Oceanic fronts *(*after Belkin et al. 2009***)***: A major front has been recently described from satellite data (Figure V-8.1). It extends along the 50-m isobath from Cape Tarhankut (Crimean Peninsula) southwestward toward the Bulgarian coast, with the cross-frontal surface temperature step of up to 4°C and salinity step of up to 1 ppt (Belkin *et al*. 2009). This front develops in winter and peaks in February-March. Another large-scale front is associated with the Rim Current that flows around the Black Sea. Even though this front largely follows the shelf edge, it is less robust because the Rim Current meanders and spawns eddies and rings. Estuarine fronts off the Dnijeper and Dnijester River mouths and off the Danube River delta are expected, as well as a front off Kerch Strait that connects the Azov Sea and Black Sea; these fronts have not been studied in detail.

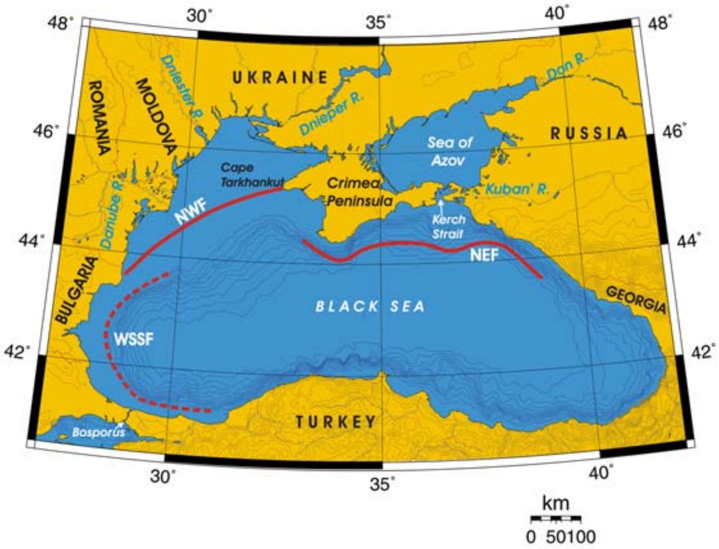

Figure V-8.1. Fronts of the Black Sea LME. NEF, Northeast Front; NWF, Northwest Front; WSSF, West Shelf-Slope Front (after Belkin 2009).

Black Sea SST (after Belkin 2009):
Linear SST trend since 1957: -0.08°C.
Linear SST trend since 1982: 0.96°C.

The thermal history of the Black Sea since 1957 was non-uniform. The all-time maximum of 16.1°C achieved in 1966 has not been exceeded since then. Long-term cooling from 1966 through 1987 switched to long-term warming from 1988 through 2001. The all-time minimum of 13.8°C in 1987was followed by a switch to the long-term warming through 2001. Even though the 50-year trend of SST from 1957-2006 was slightly negative, -0.08°C, the 25-year trend of SST from 1982-2006 was strongly positive, 0.96°C.

Given the strong year-to-year variability of the Black Sea SST, any trend analysis would strongly depend on the choice of end points. For example, Ginzburg et al. (2004) processed nighttime satellite SST during the period from November 1981 to December 2000 to find a positive trend of the Black Sea mean SST of approximately 0.09°C per year, which is more than twice the warming rate found in this study. Note that the year of 2000 was one of the warmest years since 1967, which explains the very rapid warming rate obtained by Ginzburg et al. (2004) from the 1981-2000 data. From our data, the most rapid warming was observed from 1987 through 2001 when the mean SST rose from 13.8 to 15.8°C, a 2.0°C increase in 14 years, at an average warming rate of 0.14°C/year. Since the Black Sea is land-locked, having a very limited water exchange with the Mediterranean Sea through Turkish straits, the observed recent warming of the Black Sea could only have been caused by large-scale atmospheric forcing. The debate is on whether the North Atlantic Oscillation (NAO) has played a key role in the Black Sea long-term variability and whether the Black Sea went through regime shifts following the NAO switch from one wind regime to another (Kazmin and Zatsepin, 2007).

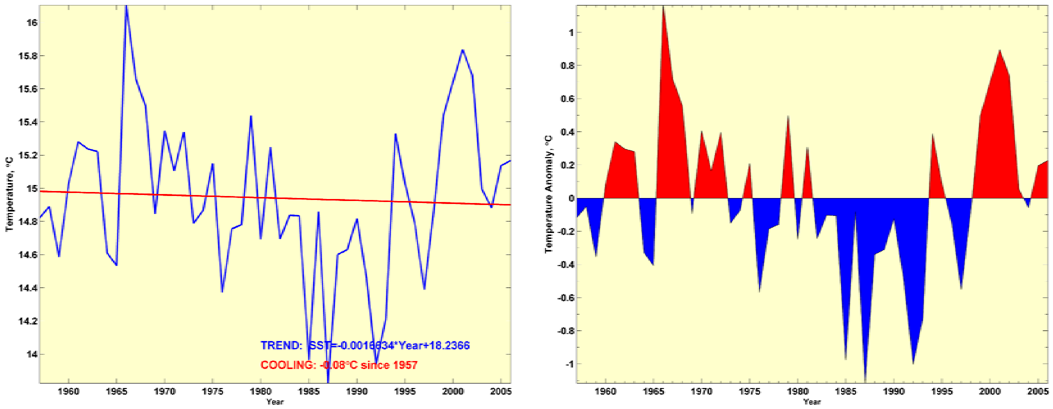

Figure V-8.2 Annual mean Black Sea LME SST, 1957-2006 and SST anomalies in the Black Sea, 1957-2006, based on Hadley climatology, (after Belkin, 2009).

Black Sea LME Trends in Chlorophyll and Primary Productivity: The LME is considered a Class I, highly productive ecosystem (>300 gCm^{-2}year^{-1}).

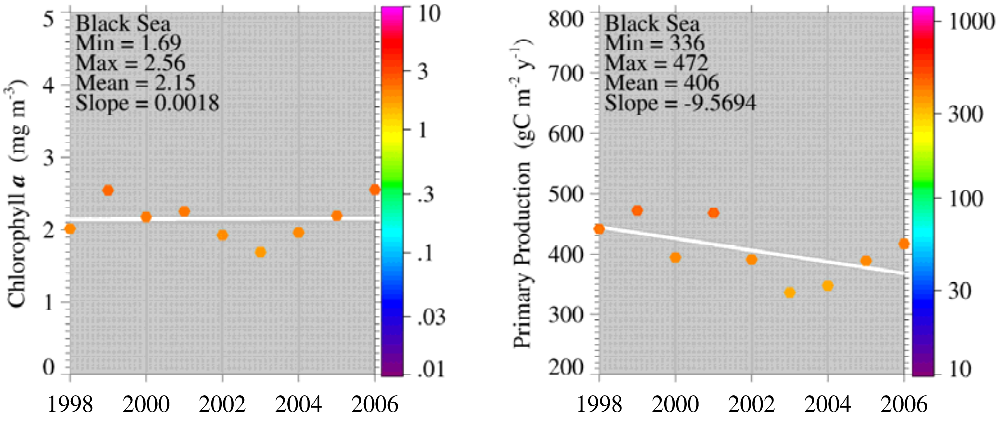

Figure V-8.3 Black Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Marine fisheries are an important economic sector in the countries bordering the Black Sea LME, and virtually all its commercial fish stocks are shared among the bordering countries. In addition to capture fisheries, there is a long history of sturgeon aquaculture in the Azov Sea and more recently, the cultivation of mussels, oysters, shrimp and some finfish (FAO 2005). Prior to the 1970s, there were abundant stocks of several valuable species in the LME, such as tuna (*Auxis rochei rochei* and *Thunnus thynnus*), swordfish

(*Xiphias gladius*), mackerel (*Scomber japonicus*, *S. scombrus*, *Trachurus mediterraneus and T*. *trachurus*), turbot (*Psetta maxima*) and sturgeon (*Acipenser* sp.). In the early 1970s, the stocks of small planktivorous species such as anchovy (*Engraulis* sp.) increased considerably, which might have been a result of the transition of the LME from an oligotrophic to eutrophic state caused by nutrient enrichment (Caddy 1993). These species, which were then fished on an industrial scale, constituted about 65% of the catch in the mid-1980s, while sprat and the smaller variety of horse mackerel made up about 20% (Prodanov *et al*. 1997).

Total reported landings in this LME showed several peaks and troughs, driven primarily by the fluctuation in the landings of European anchovy, with a peak landing of 790,000 tonnes recorded in 1984 (Figure V-8.4). The landings have increased following a precipitous decline from 1989 to 1991, however, have not returned to the level achieved in the mid 1980s. The value of the reported landings reflected the trend in the landings, peaking in 1985 at about 1.3 billion US$ (in 2000 real US$; Figure V-8.5).

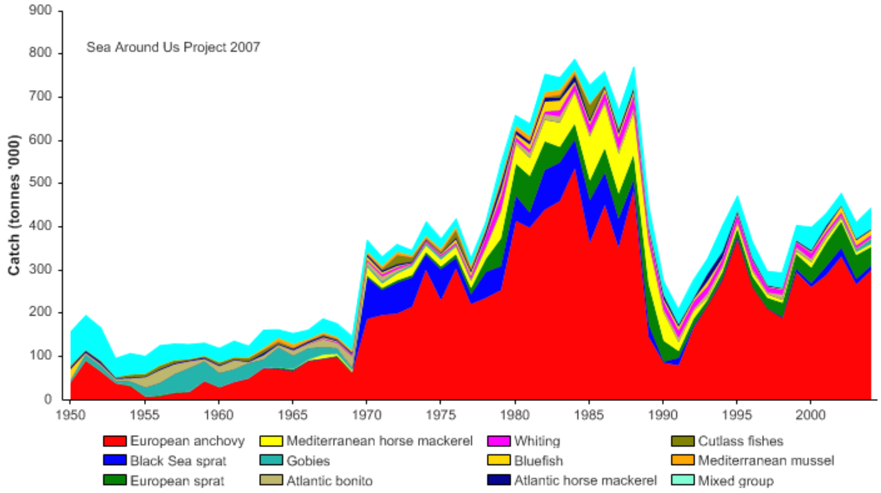

Figure V-8.4. Total reported landings in the Black Sea LME by species (Sea Around Us 2007).

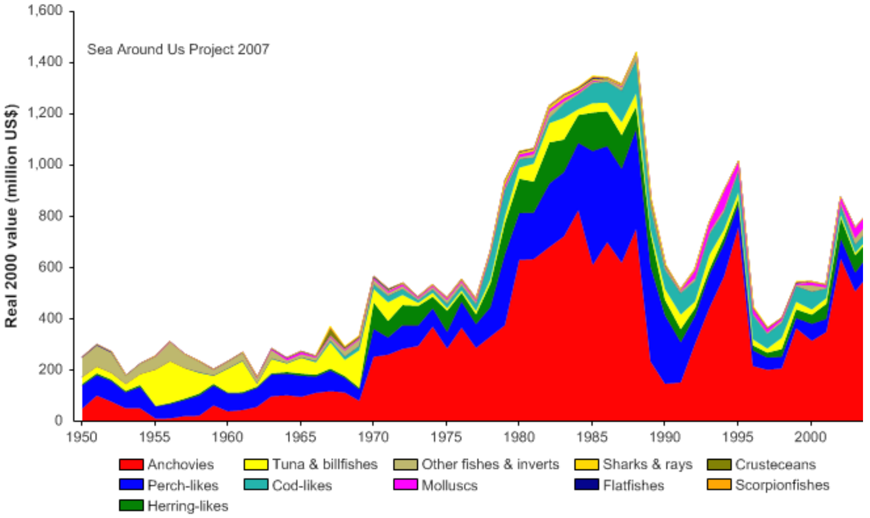

Figure V-8.5. Value of reported landings in the Black Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 18% of the observed primary production in the 1983, but has declined in recent years to 8% (Figure V-8.6). Turkey has by far the largest ecological footprint in the LME.

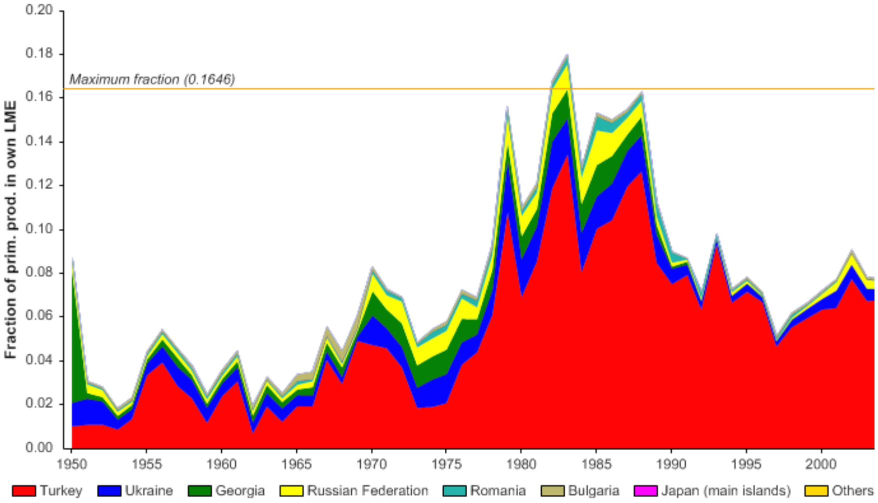

Figure V-8.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Black Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has been on a decline since the 1950s, with very low values being observed in the 1990s (Figure V-8.7 top). The increase in the FiB index from the 1970s to the mid 1980s is driven by the increased reported landings during this period (mainly of European anchovy). In contrast, the decrease in the MTI values since 1990 is not countered by an increase in landings, thus the FiB index has also declined in the early 1990s (Figure V-8.7 bottom). Together, these recent trends indicate a 'fishing down' of the food web in the LME (Pauly *et al*. 1998).

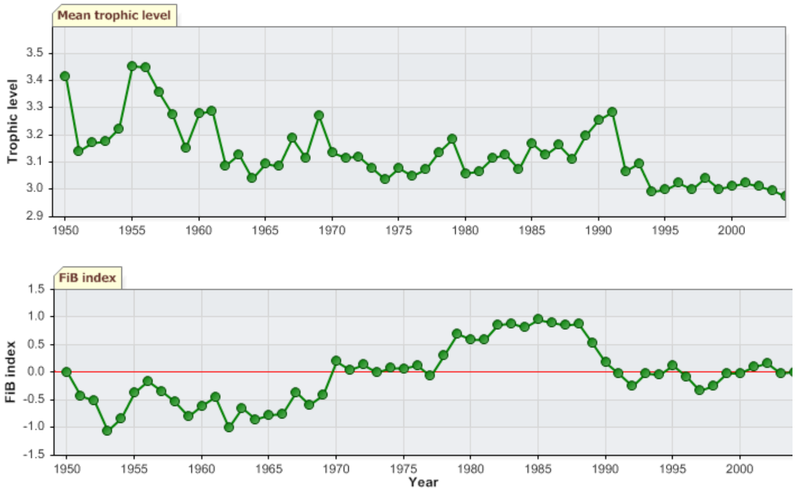

Figure V-8.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Black Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate a high level of collapsed stocks (Figure V-8.8, top) with close to 90% of the reported landings coming from overexploited stocks (Figure V-8.8, bottom).

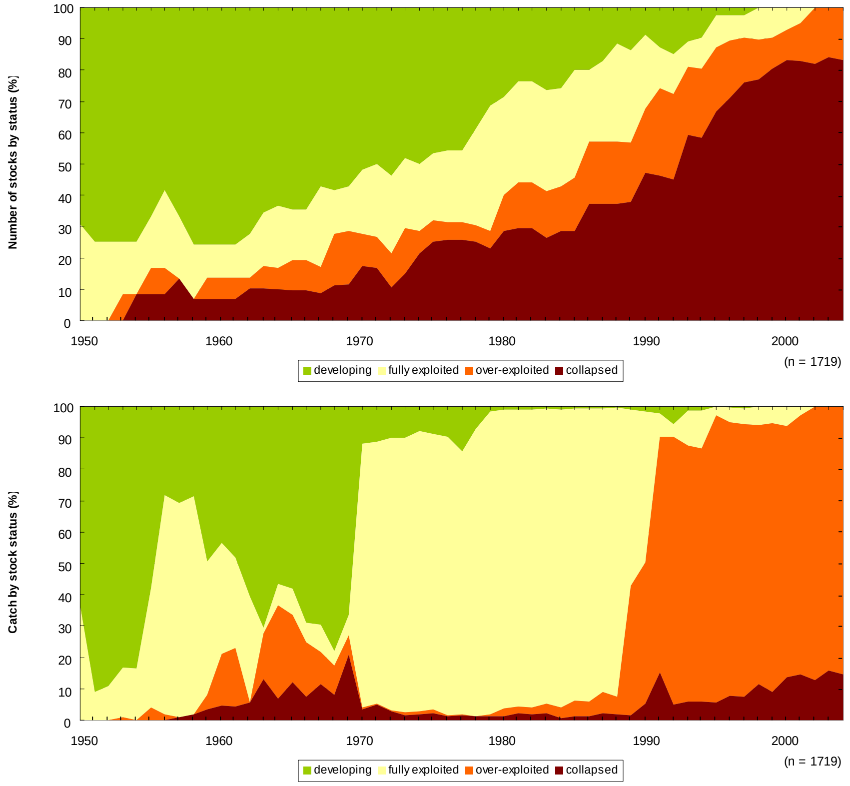

Figure V-8.8. Stock-Catch Status Plots for the Black Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.*, this vol. for definitions).

Intense and unregulated fishing pressure (including illegal fishing) in the 1960s-1970s led to severe overexploitation of most of the LME's major fish stocks (Caddy 1993, Black Sea Commission 2002, UNEP 2002). Only five of the 26 commercial stocks fished in the 1960s-1970s were viable by the 1980s (Black Sea Commission 2002). Large pelagics, especially tuna and swordfish, were heavily exploited with the introduction of purse seining in the 1960s and 1970s and through large-scale surface longline and gill net fisheries in the 1980s (Caddy 1993). Landings of turbot, migratory pelagics and anadromous species, especially sturgeon, have declined to low levels in recent decades (Caddy 1993). Some valuable species such as mackerel, bonito (*Sarda sarda*), horse mackerel (Trachurus *mediterraneus*), pike (*Esox* sp.), perch (*Sander* sp.), roach (*Rutilus* sp.) and bream (e.g., *Abramis* sp.) have practically disappeared. By the early 1970s, most of the demersal resources were also being intensively exploited (Caddy 1993). This has been exacerbated by destructive fishing practices such as catching of under-sized fish (UNEP 2002). The dramatic fall in the Black Sea LME's fish catch was most pronounced for small pelagic species, especially anchovies, with a four-fold reduction in the catches between 1988 and 1991 (FAO 2005), although the landings of these species have partially recovered over the past decade (Figure V-8.4).

In addition to overfishing, increasing eutrophication is thought to have contributed to the decline in the Black Sea fisheries (Gucu 2002, Daskalov 2003) (see Pollution and Ecosystem Health). An alien ctenophore, *Mnemiopsis leidyi*, which invaded the Black Sea in the 1980s (Vinogradov *et al*. 1989), is also thought to have played an important role in this decline, as this active mesozooplankton and ichthyoplankton feeder out-competed anchovy for edible zooplankton and consumed their eggs and larvae (Kideys 1994). However, Gucu (2002) argues that *M. leidyi* may play a minimal role in the decline of the Black Sea's fish stocks, particularly as anchovy stocks have started to recover despite the continued presence of *M. leidyi* in the LME.

The decline in the commercial fish stocks in the Black Sea LME has been identified as a major transboundary problem by the Black Sea TDA (UNEP/GEF 1997). However, some stocks, such as anchovy, horse mackerel and shad (*Alosa* sp.), have begun to show signs of recovery, while others are still depleted (Black Sea Commission 2002, FAO 2005).

III. Pollution and Ecosystem Health

Pollution: In recent decades, the Black Sea LME has suffered significant ecological perturbation as a result of pollution, principally from land-based sources (Mee 1992). Intense land-based industrial and agricultural activities, uncontrolled urban development in the river basins and coastal areas as well as sea-based activities have led to an overall moderate level of pollution in this LME (UNEP 2002). Pollution is severe in coastal hotspots, 49 of which have been identified and include the industrial centres on the coast and along the rivers (UNEP/GEF 1997). Non-compliance with national water quality standards for wastewater discharges has been reported for most of the Black Sea coastal states (Black Sea Commission 2002). Most pollutants enter the LME through the international rivers, mainly the Danube but also the Dnijeper, Dnijester and Don (Balkas *et al*. 1990). Nevertheless, a large body of evidence suggests that nutrient loads to the Black Sea from the Danube River have fallen substantially over the last 10-15 years (Lipan 2006).

The most significant process degrading the LME has been the massive nutrient enrichment of the sea by nitrogen and phosphorus, largely as a result of agricultural, domestic as well as industrial sources (Mee & Topping 1999). A study by the Black Sea Environmental Programme suggests that, in 1992, 70% of the nutrient inputs were coming from the six Black Sea countries while the remaining 30% came from the non-coastal countries, mostly of the upper Danube (Mee & Topping 1999). Atmospheric deposition of nitrogen was considerable (Black Sea Commission 2002) but the data for pollutants remain incomplete (Black Sea TDA, 2007). In 1999, the average yearly input of nutrients from agriculture and other human activities amounts to 647,000 tonnes of nitrogen and 50,000 tonnes of phosphorus (Mee & Topping 1999). As previously mentioned, eutrophication has caused dramatic changes in the structure of the Black Sea ecosystem (see also Habitat and Community Modification). Reductions in both N and P concentrations have been observed in upper/idle reaches of the Danube during the 2000s, but not in the lower reaches, suggesting that excess nutrients stored in the catchment are finally being flushed from soils, sediments and groundwaters as a result of previously improved nutrient regulation.

Another problem of major general concern is the discharge of raw or insufficiently treated sewage directly into the sea or into rivers (Mee & Topping 1999). Analyses of faecal steroids in coastal sediments taken from throughout the LME indicate chronic sewage contamination in some locations (Readman *et al*. 2005), although microbiological pollution is mostly a localised problem.

Contamination by toxic chemicals such as pesticides and heavy metals does not appear to be a basin wide problem. Elevated concentrations of heavy metals in bottom sediments and biota near river mouths as well as ports and priority point pollution sources are now decreasing (Black Sea Commission 2002). Pesticides are mostly introduced through rivers and streams discharging from agricultural areas. However, as a result of economic change, the use of these substances has decreased considerably and no longer presents a major hazard, except where their use was very intensive in the past. Elevated concentrations of lindane as well as other isomers of hexachlorocyclohexane (HCH) along the coastal areas influenced by the Danube River indicate the application of this pesticide in the Danube River Basin (Black Sea Commission 2002). In fact, concentrations of HCHs at sites influenced by the Danube Delta were found to be among the highest recorded globally (Fillmann *et al*. 2002). While the concentrations of DDTs and PCBs were not especially high in relation to levels worldwide, low DDE/DDT ratios indicated fresh inputs and hence current usage of DDT within the region (Fillmann *et al*. 2002), or inappropriate storage of expired pesticides (Black Sea Commission 2002; Black Sea TDA 2007).

Although current levels of oil pollution are not high in the open Black Sea, oil continues to threaten coastal habitats as a result of accidental and operational discharges from vessels as well as from land-based sources. The highest concentrations of total hydrocarbons in sediments are associated with discharges from Odessa, Sochi and the Danube River, of which the latter also is the major contributor of fresh oil to the Black Sea (Readman *et al*. 2005). Offshore exploration of oil and gas constitutes an additional source of oil pollution (Black Sea Commission 2002; Black Sea TDA 2007). The threat of a major oil spill is increasing as a result of increased tanker traffic and the construction of new oil terminals in the region. Another threat is the continual release of contaminated ballast water by large ships.

Erosion, dumping and coastal construction have contributed to high levels of suspended solids in some coastal areas (UNEP 2002). As an enclosed sea, the LME is particularly vulnerable to pollution by solid waste dumped from ships and coastal towns. Any floating or half-submerged waste inevitably finds its way to the shore, contributing to the high accumulation of garbage on the beaches (Mee & Topping 1999).

Habitat and community modification: The coastal habitats of the Black Sea LME have been severely impacted as a result of anthropogenic factors including pollution, coastal development, alteration of freshwater inflow, introduction of alien species and overfishing (UNEP 2002). The Black Sea TDA identified eutrophication as one of the major threats to the Black Sea environment, which still remains a priority problem (Lipan 2006). Severe eutrophication of the LME in the past three decades has significantly modified the structure and functioning of the ecosystem as a whole (Zaitsev 1993, Bologa *et al*. 1995, Zaitsev & Mamaev 1997, Mee & Topping 1999). The trophic cascade mechanism driven by uncontrolled fishing and eutrophication was invoked by Daskalov (2003) to explain the alterations in the structure and dynamics of the Black Sea LME. These changes first became evident in the 1980s, with abnormal phytoplankton and harmful algal blooms (Caddy & Griffiths 1990, Zaitsev 1993, Zaitsev & Mamaev 1997). Changes also occurred in the structure of the zooplankton community, with several fodder zooplankton species having either disappeared or substantially decreased in number in some areas (Kideys *et al*. 2000). Meanwhile, some zooplankton species adapted to thrive in eutrophic conditions either appeared or increased in quantity (e.g., the dinoflagellate *Noctiluca*). However, these are often regarded as ‘dead end’ species as they do not serve as prey for zooplankton or the rest of the food chain (Mee & Topping 1999).

Another change that occurred in the Black Sea ecosystem was the considerable increase in the biomass of jellyfish. A dramatic increase in the abundance of the large scyphozoan (*Rhizostoma pulmo*) occurred in the early 1970s (Zaitev & Mamaev 1997) while in the early 1980s, another species (*Aurelia aurita*) became dominant (Shushkina & Musaeva 1983). By the late 1980s however, this species was replaced by the invading *M*. *leidyi* (Vinogradov *et al*. 1989). This ctenophore contributed to the dramatic changes in the structure of the ecosystem and is also thought to have contributed to the collapse of the Black Sea fisheries (Mee & Topping 1999). The levels of *M*. *leidyi* were subsequently reduced, however, by the introduction of one of its predators, another ctenophore, *Beroe ovata* (Black Sea Commission 2002; Black Sea TDA 2007).

The development of hypoxic conditions in the shallow, otherwise oxic habitats of the northwestern Black Sea LME as well as the reduction in light penetration in shallow areas impacted by eutrophication led to massive loss of bottom living flora and fauna. Among the most notable cases was the sudden and catastrophic collapse of the northwest shelf system, as demonstrated by the sharp reduction of the Zernov's *Phyllophora* field (a submerged meadow of red algae). This undersea meadow shrank from 10,000 km^2 to 500 km^2 in the 1990s while its biomass decreased from 10 million to 500,000 tonnes (Black Sea Commission 2002). The loss in the *Phyllophora* field was disastrous because of its valuable resources and, more importantly, because of its unique biocenoesis with its specific fauna as well as its habitat value for a large number of juvenile and bottom dwelling fish. The Black Sea brown alga, *Cystoseira barbata,* began disappearing from the coastal waters of Ukraine and Romania in the 1980s. This large perennial alga, unable to survive in the eutrophic coastal waters, was replaced by filamentous green and red algae.

Hypoxic conditions were also accompanied by fish and zoobenthos mass mortality each year. Vast amounts of dead plants and animals covered the beaches of Romania as well as western Ukraine between 1973 and 1990. The biological losses over this 18-year period were estimated as 60 million tonnes of bottom animals including 5 million tonnes of fish (Black Sea Commission 2002). The benthos community structure of the shelf and nearshore areas was significantly modified. For instance, some areas showed a predominance of polychaete and oligochaete worms and species such as *Mya arenaria*, which are better adapted to low-oxygen conditions (Caddy 1993).

There are some signs of benthic community recovery, but this recovery is far from being total. From the dark days of its decline into the severely degraded ecosystem that it once was (in 1990, 80% of the NW Shelf was considered to be a 'dead zone'), the Black Sea represents a pattern of adaptation rather than one of true recovery. Invasive species, not (or rarely) present in the 1960s now occupy (and dominate) critical ecological niches. To a large extent mussels, which once acted as a huge filter for the overlying water, have now been replaced by tunicates (sea squirts), which fulfil a similar role; and the once huge *Phyllophora* (a red seaweed) field has overwhelmingly been replaced by fine filamentous algae. Between the Danube and Dniester river inputs, very rapidly growing green algae (*Enteromorpha* and *Cladophora)* have largely been replaced by more robust *Polysiphonia elongata*. However, *Cystosiera*, which dominated before the 1960s, is not yet re-established in this area.

Human activities have affected other communities of the LME. For example, until 1966, dolphins were hunted but their numbers declined from over 1 million to under 300,000 and this practice was banned (Mee & Topping 1999). The deterioration in the state of the ecosystem must also have impacted their numbers (Mee & Topping 1999). The accidental capture of marine mammals by fishing gear is a particularly serious problem for the harbour porpoise. Other marine mammals are critically endangered and the monk seal is virtually extinct in this LME (Black Sea Commission 2002; Black Sea TDA 2007).

Degradation of rivers and estuaries in the Black Sea region has also affected the population of migratory species of fish. For instance, the construction of dams and hydraulic structures kept anadromous species like sturgeons from their natural spawning grounds in the estuaries of Danube and Dnijeper Rivers. These anadromous species currently depend on artificial breeding (Black Sea Commission 2002). Increased salinity in the Sea of Azov, due to the reduction of freshwater inflow related to irrigation schemes, has modified the migratory pattern of many fish species and has also changed the species composition of the ichthyofauna (Caddy 1993). The health of the Black Sea ecosystem has started to show some improvement in recent years, as a result of several measures and initiatives at national as well as international levels (See Governance) (Black Sea Commission 2002).

IV. Socioeconomic Conditions

Since ancient times, people have depended on the Black Sea LME for various economic activities (Ascherson 1995). The coastal zone, defined as one 'administrative unit' (oblast, Municipal area, etc.) inland from the coast, is densely populated with approximately 20 or 30 million inhabitants depending on whether the Istanbul administrative unit is included in the total. This unit has a short Black Sea coastline. More than 4 million tourists visiting the coast in summer (Black Sea Commission 2002). The Sea has six coastal countries: Bulgaria, Georgia, Romania, the Russian Federation, Turkey and Ukraine. The 17 countries in the Black Sea drainage basin have diverging socio-economic as well as political structures. Bulgaria and Romania became EU members in 2007. Turkey is a candidate for European Union membership. In the immediate area of the Black Sea LME and in its river basins, there is virtually every type of heavy industry, including oil refining, metallurgy, chemicals, coal, pulp and paper production as well as energy production (hydraulic, thermal, nuclear). Agriculture is another important activity in the Black Sea Basin. In the coastal and marine areas, shipping, fisheries and tourism are important revenue-earners.

Fisheries overexploitation and environmental degradation of the Black Sea LME have had serious economic and social consequences for the bordering countries. For example, the value of the annual reported landings declined from about 2 billion US$ in the 1980s to about 500 million US$ in the late 1990s (Sea Around Us 2007). The worst affected country has been Turkey, which in the 1970s and 1980s relied on the Black Sea for 80% of its supply of fish. Despite the recent upward trend in the Black Sea fisheries, economic returns have not recovered, due to the dominance of the catch by the low-value anchovy stock, while higher valued species have remained depressed or continued to decline (FAO 2005). The fisheries collapse has also created a crisis in employment in the fisheries sector. The total job losses resulting from the collapse of Black Sea fisheries has been estimated at some 150,000 (UNEP 2002).

Pollution of the Black Sea LME by sewage as well as harmful chemicals poses a threat to human health, both from the consumption of contaminated seafood and direct contact with polluted waters. The degradation of the Black Sea LME environment has also had a major impact on recreational activities, with regular beach closures due to sewage discharges affecting the region's tourist industry. The loss of income from tourism could be at least 400 million US$, assuming a modest loss in revenue of 10 US$ per visitor (UNEP 2002).

V. Governance

The Black Sea LME countries have embarked on several initiatives at national and regional levels to address the environmental problems in this LME. If Bulgaria, Romania and Turkey were to accede to the European Union, the strict European legislation would benefit the Black Sea environment (Black Sea Commission 2002). A fisheries convention is being negotiated by the six Black Sea States to adopt an ecosystem approach for the management of the region's fisheries. Reforms in policy, laws, institutions and investments are now being supported by GEF in each country for nitrogen abatement from the agricultural, municipal as well as industrial sectors.

MARPOL, which was ratified by all Black Sea countries, declared the Black Sea as a 'Special Area' for protection where countries agreed to apply more rigorous environmental standards. These provisions have, however, never been applied, partly because of a lack of port facilities for receiving and treating oily wastes and garbage from visiting ships. Major regional frameworks include the Black Sea Regional Seas Programme and the Bucharest Convention on the Protection of the Black Sea against Pollution and its four Protocols. The convention is implemented by the Commission on the Protection of the Black Sea against Pollution (Black Sea Commission - www.blacksea-commission.org). The Odessa Ministerial Declaration on the Protection of the Black Sea Environment was signed by the countries of the Black Sea Region in 1993 in order to set goals, priorities and timetable for remedial actions.

GEF is supporting 12 projects for environmental improvements in this LME and its drainage basin. The UNDP-GEF Black Sea Ecosystem Recovery Project is addressing basin wide eutrophication issues through reform of agricultural policies, improved municipal and industrial wastewater treatment, rehabilitation of key basin ecosystems and strengthening the legislative framework (www.blacksea-environment.org). The Black Sea Environmental Programme (BSEP) was launched in 1993. Among the most important achievements of BSEP were the TDA and SAP. The SAP focuses on three major issues: controlling pollution, conserving and restoring marine and coastal ecosystems, as well as promoting sustainable use of the coastal areas. The GEF-supported project 'Developing the Implementation of the Black Sea Strategic Action Plan' has been completed. This project facilitated the development of the National Black Sea Strategic Action Plans and supported institution-building at the national and regional level for the development as well as implementation of such plans. The Black Sea Commission implements the provisions of the Bucharest Convention and the SAP. Other GEF-supported projects include the Strategic Partnership for Nutrient Reduction in the Danube River and Black Sea and Control of Eutrophication, Hazardous Substances and Related Measures for Rehabilitating the Black Sea Ecosystem.

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VI ROPME Sea Area (Regional Organisation for the Protection of the Marine Environment)

VI-9 Arabian Sea LME

S. Heileman , P. Eghtesadi-Araghi, and N. Mistafa

The Arabian Sea LME lies in the northwestern Indian Ocean between the Arabian Peninsula and India, and is bordered by Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, United Arab Emirates and Yemen. It covers an area of about 3.9 million km^2, of which 0.21% is protected, and contains 1.84% and 0.62% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). Three sub-systems, each with distinct physical, physio-chemical and biological characteristics can be identified within the LME: the Western Arabian Sea along the African coast; the Central Arabian Sea bordering Iran; and the Eastern Arabian Sea bordering the coasts of Sri Lanka, India and Pakistan (Dwivedi & Choubey 1998). An extensive interchange of surface waters occurs between this LME and the Somali Coastal Current and Bay of Bengal LMEs. Freshwater run-off from the Indus River, the Arvand (Shattolarab) [Euphrates, Dejla and Karoon] and Tigris Rivers also influences this LME. Book chapters and reports pertaining to this LME are by Baars *et al*. (1998), Bakun *et al*. (1998), Desai & Bhargava (1998), Dwivedi & Choubey (1998) and UNEP (2006).

I. Productivity

The Arabian Sea LME is considered a Class I, highly productive ecosystem (>300$gCm^{-2}year^{-1}$). The LME is strongly influenced by a monsoon regime, which causes significant seasonal variations in marine productivity (Baars *et al*. 1998, Desai & Bhargava 1998). During the southwest monsoon (June-September), strong southwesterly winds blow across the Arabian Sea, producing intense upwelling along the Oman and Somalia coasts. This is the most intense large-scale seasonal coastal upwelling system in the world (Bakun *et al*. 1998), making the Arabian Sea one of the most productive regions of the world's ocean (Codispoti 1991). Desai & Bhargava (1998) estimated the rates of primary, secondary and tertiary production, as well as fishery potential of the Indian EEZ.

Despite its high primary productivity, the abundance of coastal pelagic fish is anomalously low and catch of this group is not consistent with other similar world regions (Bakun *et al*. 1998). In fact, their production is similar to that of large oceanic pelagic fish such as tunas. An explanation for these anomalies is sought in the extremely dissipative feature of the region's physical systems. A combination of trophic enrichment, as well as concentration and retention processes provides a favourable reproductive regime for coastal pelagic fishes. Surface mixing due to the intense monsoon winds and strong current flows as well as wind-driven surface transport in the western and northern part of this LME disrupt these processes, periodically resulting in unfavourable feeding conditions for coastal fish larvae. On the other hand, the offshore transport of coastal production coupled with the strong monsoonal wind circulation and prevalence of strong current jets may favour the highly-evolved life-cycle strategies of oceanic tunas.

More than 330 species of corals, 500 species of molluscs, 200 species of crabs, 20 species of marine mammals and more than 1,200 species of fish are found in the LME (Fouda *et al*. 1998).

Oceanic fronts (Belkin et al. (2009). The Arabian Sea features several fronts, whose development is governed by the seasonal monsoon winds and their reversals (Figure VI-9.1). The most stable, seasonally persistent front develops in the Gulf of Aden. This front cuts across the Persian Gulf, from the Arabian Peninsula to the Somali coast, with the cross-frontal temperature range up to 5°C. Upwelling fronts are ubiquitous off the Pakistan coast and, to a lesser extent, off the western coast of India; these fronts are also seasonal and their development is similar to the seasonal evolution of major upwelling frontal zones off Northwest Africa and off the U.S. West Coast, in the California Current System. A meso-scale front is observed near the entrance to the Persian Gulf (Belkin *et al*. 2009).

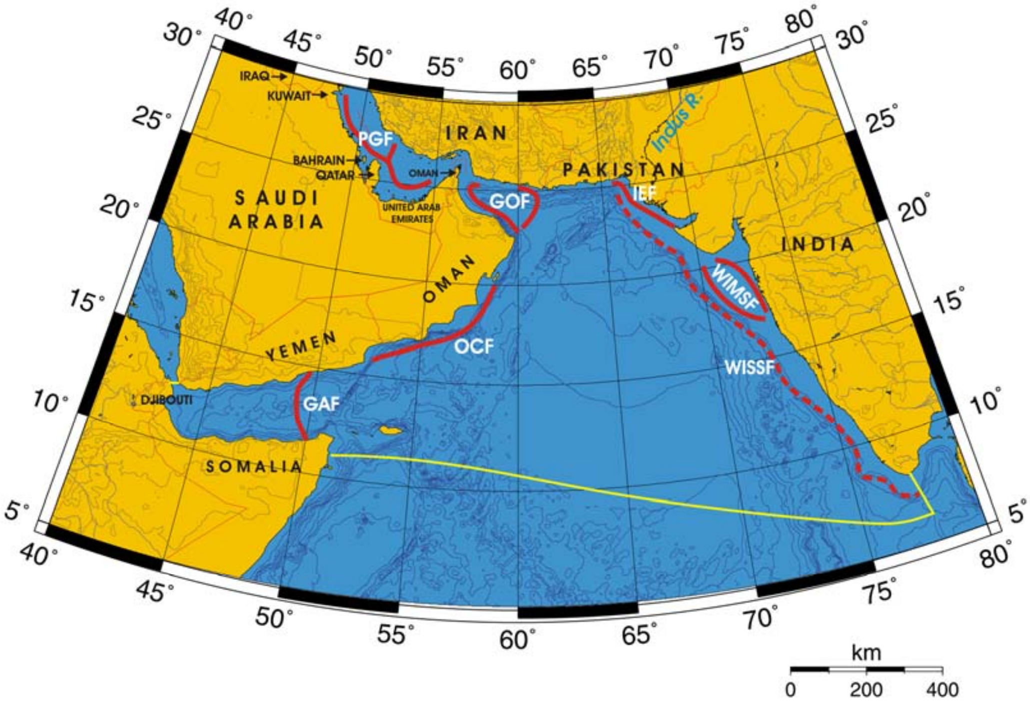

Figure VI-9.1. Fronts of the Arabian Sea LME. GAF, Gulf of Aden Front; GOF, Gulf of Oman Front; IEF, Indus Estuarine Front; OCF, Oman Coastal Front; PGF, Persian Gulf Front; WIMSF, West Indian Mid-Shelf fronts; WISSF, West Indian Shelf-Slope Front (most probable location). Yellow line, LME boundary. After Belkin et al. (2009).

Arabian Sea SST (after Belkin 2009)
Linear SST trend since 1957: 0.42°C.
Linear SST trend since 1982: 0.26°C.

Like all Indian Ocean LMEs, the Arabian Sea warmed slowly and steadily. Its interannual variability has an average magnitude of approximately 0.5°C. The most pronounced event, the all-time minimum of 1975, was likely caused by large-scale forcing since it occurred simultaneously across the entire northern Indian Ocean, including the Red Sea LME and the Bay of Bengal LME. The all-time maximum of 1998 occurred simultaneously with most Indian Ocean LMEs and only one year before a near-all-time maximum of 1999 in the Red Sea.

The rapid warming between 1985 and 1987 ushered in the modern warm epoch in the Arabian Sea. This warming occurred nearly synchronously with a similar warming in the

Somali Current LME. It is likely that the Somali Current transported the warm signal to the Arabian Sea. Alternatively, both events may have been caused by a large-scale atmospheric forcing that spanned the entire northwest Indian Ocean.

Our results compare favorably with a recent study by Kothawale et al. (2007) who used the Arabian Sea SST data from 1901-2002 and found a significant warming trend of 0.7°C between 1901 and 2002 (cf. our warming rate of 0.42°C/50 years between 1957-2006 or 0.84°C/100 years), and an accelerated warming of 0.16°C/10 years between 1971 and 2002 (cf. our rate of 0.10°C/10 years between 1982 and 2006).

Most extreme surface temperatures are observed in the Persian Gulf. In 1998, following a major El Niño, local SST here reached 34°C, which caused mass mortality of corals and widespread bleaching of coral reefs (Rezai et al., 2004). Additionally recent bleaching events in hermatypic corals due to high temperatures between 10.08.2007 and 28.08.2007 amounting to approximately 20% of bleached branching corals *Acropora* was observed in Kish Island (northern Persian Gulf) (Maghsoudlou 2008).

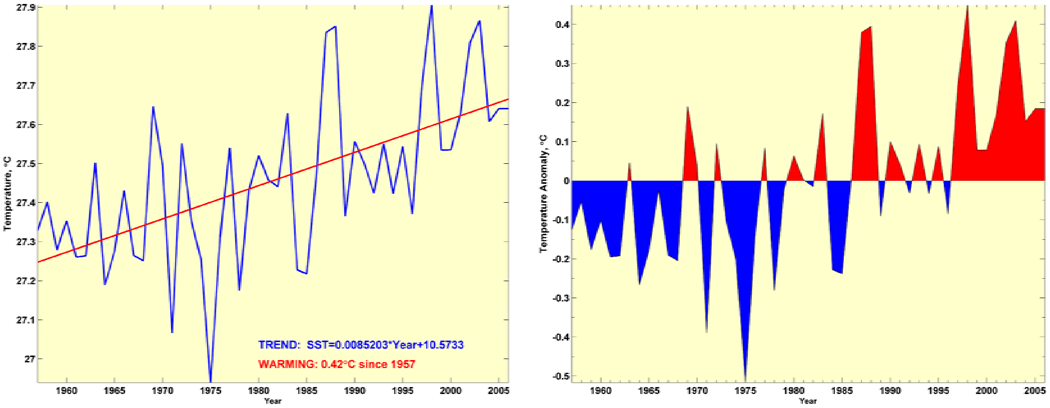

Figure VI-9.2 Arabian Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Arabian Sea LME Trends in Chlorophyll and Primary Productivity: The Arabian Sea LME is considered a Class I, highly productive ecosystem (>300gCm^{-2}year^{-1}).

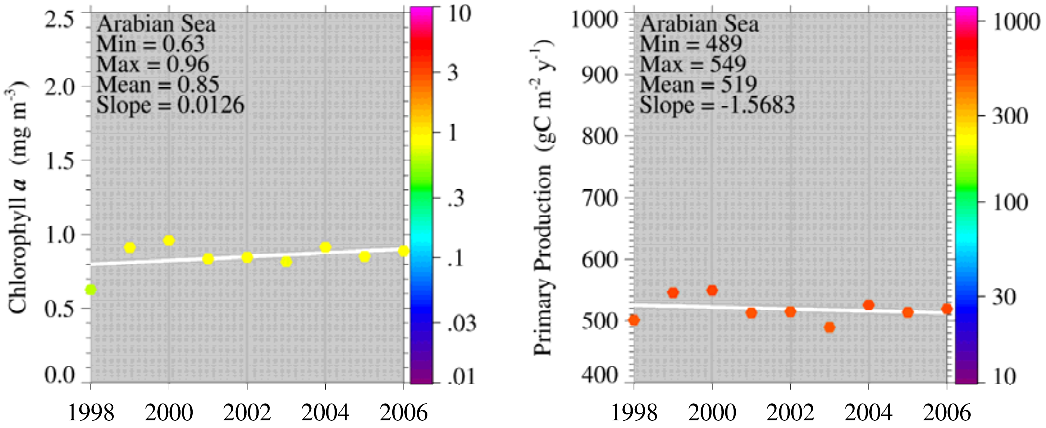

Figure VI-9.3 Arabian Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The fisheries of the Arabian Sea LME are multi-gear and multi-species and include both artisanal and commercial sectors, with the former being dominant. Among the major exploited groups are Indian oil sardine (*Sardinella longiceps*), caught mainly off India's west coast (Bhathal 2005), as well as drums and croakers (Family Sciaenidae), however, nearly half of the reported landings in the LME are identified only as 'marine fish' (included in 'mixed group' in Figure VI-9.4) which can cause difficulties in diagnosis of various marine indicators. Fisheries for large oceanic pelagic fishes in the region are substantial and lucrative (Bakun *et al*. 1998). Total reported landings increased steadily, reaching 2 million tonnes in 1992 (Figure VI-9.4). The Arabian Sea LME is one of the six LMEs in which reported landings have remained relatively constant or shown increases over the past few decades (FAO 2003), however, precautionary allowable catch levels have been recommended for these LMEs to ensure that fisheries remain sustainable (Sherman 2003). According to FAO (2005a), the increase in total reported landings may be attributed to an increase in fishing effort. The value of the reported landings reached 1.6 billion US$ (in 2000 value) in 2003 (Figure VI-9.5).

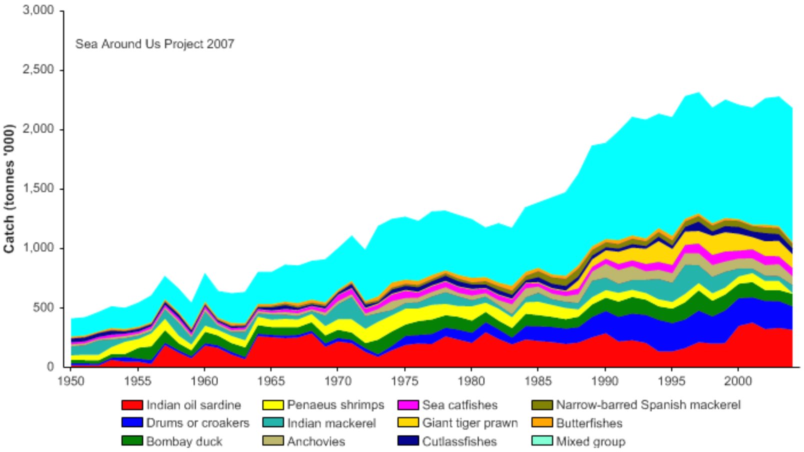

Figure VI-9.4. Total reported landings in the Arabian Sea LME by species (Sea Around Us 2007).

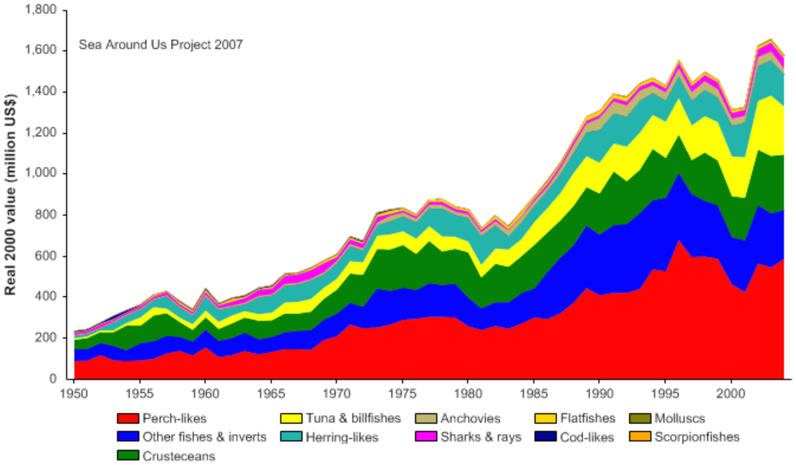

Figure VI-9.5. Value of reported landings in the Arabian Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 20% of the observed primary production in the mid 1990s, but has since declined to 17% (Figure VI-9.6). India has the largest ecological footprint in the LME, with other bordering countries such as Pakistan and Iran also accounting for a large share of the footprint.

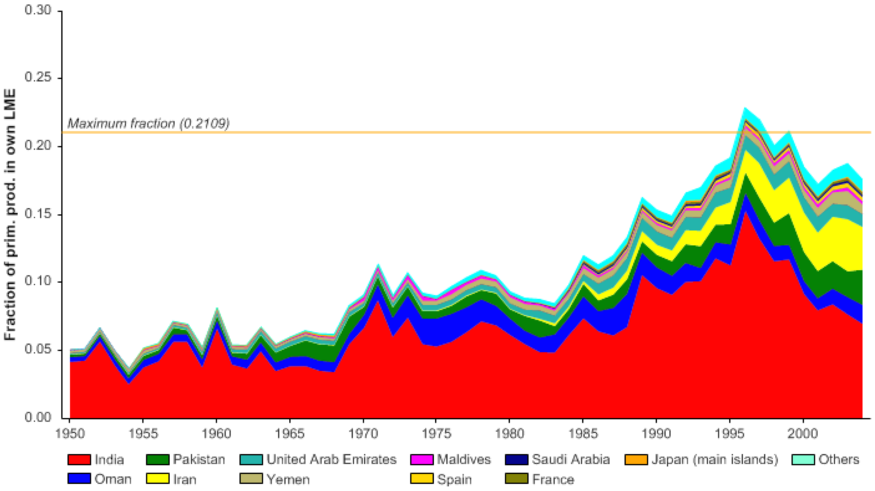

Figure VI-9.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Arabian Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

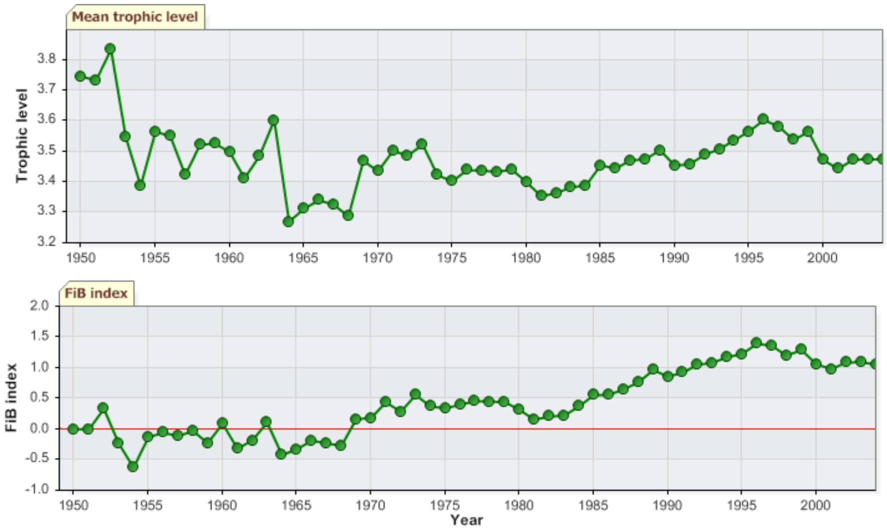

Figure VI-9.7. Marine trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Arabian Sea LME (Sea Around Us 2007).

From the early 1980s to late 1990s, both the mean trophic level of the reported landings (i.e. the MTI; Pauly & Watson 2005, Figure VI-9.7 top) and the FiB index (Figure VI-9.7 bottom) showed an increase, consistent with a spatial (offshore) expansion of fisheries targeting high trophic level large pelagic fishes in the region. However, the mean trophic levels computed without the landings of tuna and other large pelagic species, as proposed by Pauly & Palomares (2005), show a steady decline from 1975 to 2004. Such a decline agrees with Bhathal (2005) and Bhathal & Pauly (in press), who found, for India, a strong fishing down effect when the national data are disaggregated by State and Union Territories.

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stocks in the LME have been rapidly increasing, to about 50% in 2004 (Figure VI-9.8, top), but that over 80% of the catch is still taken from fully exploited stocks (Figure VI-9.8, bottom).

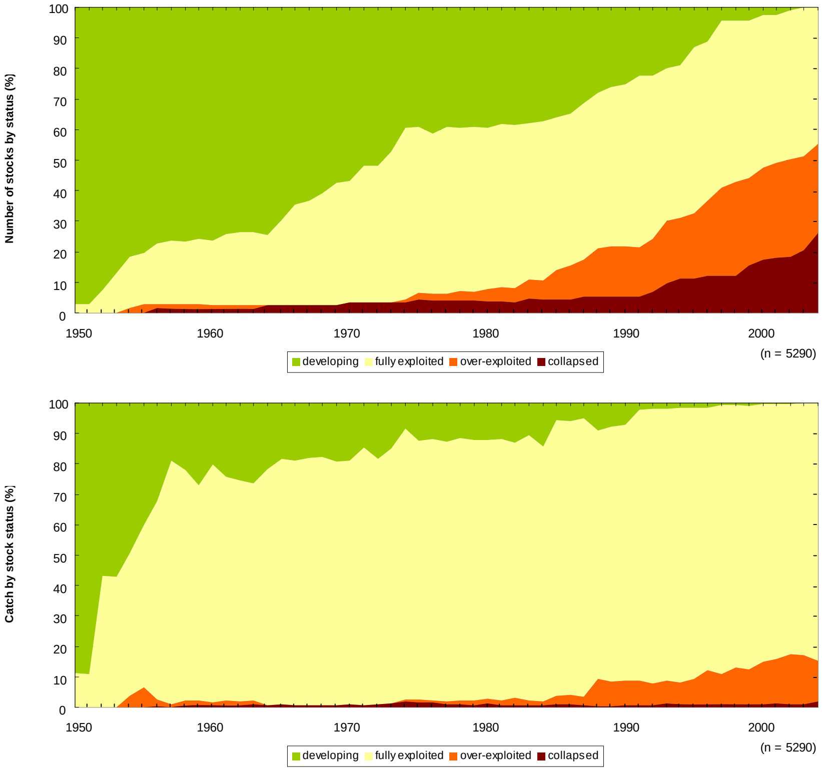

Figure VI-9.8. Stock-Catch Status Plots for the Arabian Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al,* this vol. for definitions).

Overexploitation was assessed as moderate in the LME (UNEP 2006). Fleet overcapacity remains a significant issue in the region, particularly for shrimp fisheries in countries such as Kuwait, Pakistan and Saudi Arabia (FAO 2005a). For instance, stock assessments in Pakistan indicated that the size of the shrimp trawler fleet is almost three times that required for MSY. Despite the increase in total catch, as a result of heavy fishing pressure, especially on inshore stocks in all the bordering countries, catches of certain preferred species have declined dramatically over the last 10 years (Dwivedi & Choubey 1998, FAO 2005a). India's marine fisheries production has reached a plateau and, at best, only a marginal increase is predicted in the near future. Most major stocks are fully exploited and any further increase can only be expected from exploitation of deep-sea resources. In Oman, demersal stocks are already overexploited and some high value fish have shown considerable declines. The state of the fishery resources in

Somalia is little known. While it is thought that Somalia's inshore marine resources are lightly exploited, those targeted by both the artisanal and industrial sectors may have declined in the past few years. Shrimp and finfish resources off the coast of Kuwait and Saudi Arabia are already intensely exploited and catches of major finfish species are declining. Overexploitation is likely to be a contributing factor, as indicated by fish length/age distributions (FAO 2005a).

While UNEP (2006) suggested that bycatch and discards and destructive fishing practices are limited in the LME, large quantities of bycatch are taken by both commercial and artisanal shrimp trawlers (FAO 2005a). In fact, the total bycatch of demersal fish is probably much higher than the recorded landings. Various types of destructive fishing gear, including shrimp trawl nets and explosives, have contributed to localised fish population declines and habitat degradation in the region.

Population expansion is expected to continue to put pressure on the coastal resources in this LME. Several surveys have indicated the presence, outside the traditional fishing grounds, of unexploited demersal and pelagic fish stocks, for example, of mesopelagic lanternfishes (e.g., Shotton 1997). Utilisation of these stocks, however, would require further research and assessment, as well as the introduction of suitable fishing and processing technology (FAO 2005a).

III. Pollution and Ecosystem Health

Pollution: Overall, pollution was assessed as severe in coastal hotspots but in other places it is evaluated to be of moderate value overall (Eghtesadi et al. 2002). The major issues in these hotspots are oil hydrocarbons and heavy metals (Al-Majed Butayban 2006). Other pollution hotspots are found at the mouths of some rivers (e.g., Tigris, Euphrates, Karun, Hileh and Monds Rivers) and domestic and industrial sewage outfalls. The massive increase in population and rapid economic growth in coastal areas are leading to the release of vast quantities of untreated sewage and industrial wastes into the sea through sewers and rivers, resulting in highly polluted coastal areas (Dwivedi & Choubey 1998). Marine pollution also arises from sea-based activities, including marine transportation and offshore oil exploration and production activities. The potential for transboundary impacts of pollution is significant in the LME, with monsoons playing a significant role in the long-range transport of Persistent Toxic Substances (PTS) in the region (UNEP/GEF 2002).

Sewage, fertilisers and other effluents have resulted in eutrophication in coastal areas (e.g., Karachi). Fish-kills in some localities such as off the Karachi coast and Gawadar Bay have been attributed to harmful algal blooms caused by the growing pollution (Abbani *et al*. 1990). Coastal water quality at the Iraq-Kuwait border has declined as a result of increased agricultural pollution due to the draining and subsequent loss of the filtering role of the Mesopotamia marshlands (UNEP 2001). As a consequence of growing economic activity as well as rising production and use of consumer items, the generation of solid wastes from both land-based sources and ships is increasing rapidly. Throughout much of the LME, the coastal zone is becoming a repository for solid wastes because of inadequate waste collection and disposal facilities in the region. Heavy metal deposition has been increasing in localised areas, for example, off Maharashtra and Gujarat (Dwivedi & Choubey 1998) and the coastal area at the mouth of the Indus River (Tariq *et al*. 1993).

Large quantities of hazardous waste have exacerbated the waste management problem in the Arabian Sea countries, and these as well as organo-metallic compounds are of regional concern (UNEP/GEF 2002). Observations after the Persian Gulf War showed moderate marine pollution by PTS. Non-pesticide chemicals are more significant for the

Persian Gulf countries due to major activities in the petroleum sector. Pockets of high contamination of PAHs have been recorded in coastal areas receiving effluents from highly industrialised zones (Beg *et al*. 2001). In India and Pakistan, chlorinated pesticides are more prominent due to major agricultural activities in these countries. Large amounts of pesticides are deposited in coastal areas and high concentrations have been noted, for example, off the Bombay coast (Dwivedi & Choubey 1998). Since persistent organic pesticides such as aldrin, chlordane, DDT, dieldrin and others are either banned or not registered in the Arabian Sea countries, their presence in the environment may be due to their excessive use in the past and there is evidences of their presence in muddy fine sediemts (Eghtesadi-Araghi 2005; Eghtesadi, P., G. Riazi, et al. 2002). There is increasing evidence that some toxic substances are entering the food chain, with low levels of accumulation of organochlorine pesticide residues in marine fauna and flora and wildlife (UNEP/GEF 2002). Mass mortalitiy of Dolphins near Chabahar was referred to as a possible example of this event.

The LME has one of the highest oil pollution risks in the world, as a consequence of the concentration of offshore petroleum installations, tanker loading terminals, and the large volume of oil transportation (Al-Majed Butayban 2006). In 2003, the region (with the exception of Oman) produced about 27% of the world's oil while holding 57% of the world's crude oil reserves. The LME contains one of the world’s busiest oil tanker routes, with more than 70% of the oil produced in the northern areas transported through the Arabian Sea. Significant levels of marine pollution have been detected around coastal petroleum refining and shipping localities from which oil, grease, and other hydrocarbon compounds are released into coastal waters (Al-Majed Butayban 2006). Six out of 20 worldwide cases of oil spills greater than 10 million gallons have occurred in the ROPME region (SOMER 2003). Roughly 1 to 2 million barrels of oil are spilled into the region’s waters every year from the routine discharge of ballast water and tanker slops, as well as from the 800 offshore oil and gas platforms (Hinrichsen 1996). Between 1998 and 2002, a total of 25 oil spill incidents took place, spilling an estimated 10,000 – 1.8 million gallons of oil (SOMER 2003).

Habitat and community modification: Coastal habitats in the Arabian Sea LME include numerous deltas and estuaries with extensive inter-tidal mudflats, wetlands, mangroves, coral reefs and seagrass beds. Physical damage to marine and coastal habitats is of major concern in the region (Al-Majed Butayban 2006), with habitat and community modification assessed as moderate in the Arabian Sea LME. Throughout the LME, coastal habitats and the biodiversity they support are subject to increasing pressures arising from human activities, including those related to war . For instance, massive coastal development projects in most of the countries have resulted in changes to vast coastal areas (Al-Majed Butayban 2006). Climate change is expected to exacerbate the vulnerability of the LME’s coastal habitats to an increasing range of stresses especially on coral reefs as they are very vulnerable to temperature changes (ROPME Sea Area 2008).

Mangrove forests are among the most threatened habitats in the LME. The mangrove forest along the Indus Delta constitutes the largest arid climate mangrove forest of the world. This national heritage, however, is quickly disappearing (Saifullah 1997). The reduction in the flow of the Indus River by dams and barrages is probably the most serious threat to the delta. Mangrove cover in the delta has been reduced by 50% from 2,600 km^2 in the late 1970s to 1,300 km^2 in the mid-1990s (Pernetta 1993). A reduction of mangrove area is evident in other countries bordering this LME. In western and southern India, much of the originally extensive mangrove stands have been removed (Wells *et al*. 2003). There are few remaining mangrove stands in some areas in Oman and Yemen (Al-Muscati *et al*. 1995, Baldwin 2005). In the Persian Gulf, the extent of mangroves has been declining as a result of coastal development, with only about 125-

130 km^2 remaining. More than 40% of the Saudi Arabian coast has been filled in and 50% of the mangroves lost (Jameson *et al*. 1995). Coastal development and urbanisation are thought to contribute to the declines in abundance of demersal fish stocks in the Persian Gulf (FAO 2005a).

As a result of the extreme environmental conditions, the development of coral reefs is generally limited to a few areas (Pilcher *et al*. 2000). Although large parts of these reefs are in a pristine state, they are subjected to increasing environmental threats from coastal development, dredging, land reclamation, overexploitation, pollution and recreational activities in all the bordering countries (Pilcher & Alsuhaibany 2000, Pilcher *et al*. 2000, Wilson *et al*. 2002). Furthermore, coral bleaching has already caused extensive damage to reefs throughout this LME. The reefs in Somalia and Yemen are generally considered to be in good condition, although they have been affected by bleaching and outbreaks of crown of thorn starfish, among other threats (PERSGA/GEF 2003). Bleaching events in 1996 and 1998 led to near-complete mortality of the reefs in Bahrain, Qatar, Saudi Arabia and the United Arab Emirates (Pilcher *et al*. 2000). The reefs of the Lakshadweep islands were reported to have lost between 43–87% of the live coral cover during the 1998 bleaching event, whereas in the Gulf of Kutch less than 30% of the corals were destroyed (Pet-Soede *et al*. 2000). Reefs in Iran, Kuwait and Oman have varying live coral cover and in some areas have been impacted by bleaching, pollution and other anthropogenic pressures (Pilcher *et al*. 2000). Recent oil and gas installation construction has severely damaged Iran's reefs.

The Persian Gulf exhibits marked seasonal variability in oceanographic factors. Extremes of temperature characterize the region and constrain the development of coral reefs. Coral reefs in the Persian Gulf are routinely exposed to annual ranges of temperatures that exceed the temperature extremes reported for any other reef area in the world (Coles, 1988). Normal winter water temperatures in the Persian Gulf rank among the lowest recorded on coral reefs (Downing, 1985; Coles, 1988). In the shallow waters of the southern Persian Gulf , salinity exceeds 50 ppt and reaches 70 ppt in some places (Grandcourt, 2003). Its reefs are bathed by high salinity water of > 45 ppt due to the substantial excess of evaporation (up to 3000 mm y^{-1}), and the Persian Gulf's annual water input (< 50 mm y^{-1}), and the Gulf's annual water temperature fluctuations of > 25^o C, depending on location, are amongst the highest known for reef areas (Sheppard and Loughland, 2002).

Some coastal areas in the Persian Gulf have been affected by the drying out of the Mesopotamia Marshlands of Iraq (UNEP 2001). Considering that the Tigris-Euphrates basin is the largest river system draining into the Gulf, reduced discharge and changes in river flow patterns and quality will have an important impact not only on inland freshwater habitats, but also on the marine environment in the northwestern Gulf. The draining of these marshlands has posed serious threats to the wildlife and to the ecological balance of vast areas, affecting water quality and the spawning grounds of shrimp and migratory species of fish, with harmful impacts on regional fish resources.

V. Socioeconomic Conditions

In 2002, the countries bordering the Arabian Sea LME had a total population of about 1.2 billion, a large part of which is concentrated in coastal areas, particularly in cities such as Mumbai and Karachi. Rapid economic growth accompanied by high population growth and increased urbanisation has been associated with increasing pollution levels and the destruction of fragile coastal habitats.

Marine fisheries generally play an important role in the national economies of some of the countries, providing an important source of foreign exchange earnings, employment and food to a large number of people. In India, where more than 70% of fisheries catches come from the Arabian Sea LME, almost 6 million people are employed in the fisheries sector which contributes nearly 1.5% of GDP. This country’s annual export of marine products is worth 1.2 billion US$. In Oman’s economy the fisheries sector is considered to be the second most important, whereas it is the third most important in Yemen, with a total contribution to this country's GDP of about 15%. In contrast, the contribution of the fishing industry to the economy of the Persian Gulf countries is small relative to the oil industry. Nevertheless, in these countries the sector is important in that it provides the main economic activity and employment for numerous coastal villages (FAO 2005a). Population expansion in the Arabian Sea countries, particularly India, will continue to place increasing pressures on the marine resources of this LME. Overexploitation and habitat destruction could have significant negative socioeconomic impacts, especially since some of these countries (India, Iraq, Pakistan, Somalia and Yemen) are considered to be Low-Income Food-Deficit countries (FAO 2005b).

V. Governance

Governance in this LME is made complex by the multiplicity of national boundaries and EEZs as well as the large expanse of international open waters. A number of international, regional and bilateral environmental agreements and other legal instruments have been adopted by the ROPME (Regional Organisation for the Protection of the Marine Environment) countries. ROPME was established in 1979 with eight member states: Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates. ROPME acts as the secretariat of the Kuwait Action Plan for the Protection and Development of the Marine Environment and the Coastal Areas, which was established under the auspices of the UNEP Regional Seas Programme. The eight countries have adopted the Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution and its two protocols (Protocol concerning Marine Pollution resulting from Exploration of the Continental Shelf and Protocol for the Protection of the Marine Environment against Pollution from Land-Based Sources). The Gulf of Aden comes under the Programme for the Environment of the Red Sea and Gulf of Aden, of which Saudi Arabia, Somalia and Yemen are members (see the Red Sea LME).

India and Pakistan, along with Bangladesh, Maldives and Sri Lanka support the South Asian Seas Action Plan (SASAP), established in 1995 under the UNEP Regional Seas Programme and with the South Asia Cooperative Environment Programme acting as secretariat. The overall objective of SASAP is to protect and manage the marine environment and related coastal ecosystems of the region in an environmentally sound and sustainable manner. Although these regional initiatives have made a significant positive impact towards the protection of the marine environment and coastal areas, the region is still faced with major environmental challenges. A holistic ecosystem approach is needed for the conservation and sustainable development of the Indian Ocean LMEs, including the Arabian Sea LME.

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VII South Asian Seas

VII-10 Bay of Bengal LME

S. Heileman, G. Bianchi and S. Funge-Smith

The Bay of Bengal LME is a relatively shallow embayment in the northeastern Indian Ocean encompassing the Bay of Bengal, Andaman Sea and Straits of Malacca. It is bordered by Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand. The LME covers an area of about 3,660,130 km^2, of which 0.49% is protected, and contains 3.63% and 0.12% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). It is influenced by the second largest hydrologic region in the world, the Ganges-Brahmaputra-Meghna (GBM) Basin, which covers nearly 1.75 million km^2 spread over five countries (Bangladesh, Bhutan, China, India and Nepal).

Located in the tropical monsoon belt, the LME is strongly affected by monsoons, storm surges, cyclones and tsunamis. During the northeast monsoon, an anticyclonic gyre forms in the Bay and reverses during the southwest monsoon (Wyrtki 1973, Longhurst 1998). The LME shows considerable spatial and temporal variability because of seasonal river discharges, particularly the surface water along the coast. Monsoon rain and flood waters produce a warm, low-salinity, nutrient and oxygen-rich layer to a depth of 100 - 150 m; this layer floats above a deeper, more saline, cooler layer that does not change significantly with the monsoons (Dwivedi & Choubey 1998). Large quantities of fresh water and sediment discharged into the LME have also contributed to the formation of the largest mangrove system in the world, the Sunderbans, covering an area of 12,000 km^2 and shared by India and Bangladesh. Books and book chapters, reports and articles pertaining to this LME include Dwivedi (1993), Aziz *et al*. (1998), Desai & Bhargava (1998), Dwivedi & Choubey (1998), Ittekot *et al.* (2003), Silvestre and Pauly (1997), Silvestre *et al.* (2003) and UNEP (2006).

I. Productivity

The Bay of Bengal LME can be considered a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}).While large nutrient input from river run-off supports high primary production in coastal waters, the central parts of the bay are less productive because of the absence of large-scale mixing or upwelling (Dwivedi 1993). The presence of different water masses in coastal areas has produced sub-systems along the coast that differ in their environmental characteristics and community composition. These sub-systems are described by Dwivedi (1993). Secondary production is highest in the post-monsoon period (October to January) and lowest during the monsoon period from June to September (Desai & Bhargava 1998). Zooplankton biomass is low near the shore but increases towards the EEZ boundary (Desai & Bhargava 1998). Further information on biological production and fishery potential in India's EEZ is given in Desai & Bhargava (1998). Wetlands, marshes, mangroves, backwaters and coastal lakes play an important role in overall productivity (Dwivedi 1993). The coastal forested areas of Sri Lanka and Malaysia are biodiversity hotspots, with a large number of threatened endemic plants and animals (Aziz *et al*. 1998).

Oceanic fronts (after Belkin et al. (2009)): The principal front in the Bay of Bengal is maintained by the huge fresh outflow from the Ganges-Brahmaputra estuary (Figure VII-10.1). This is a year-round front, whose cross-frontal TS-ranges vary seasonally. Another estuarine front is maintained by the Irravadi River outflow in the northern

Andaman Sea. In both cases the location of estuarine fronts coincides with the shelf break. A front east of Sri Lanka has been recently described from satellite data (Belkin *et al*. 2009); its origin is related to the wind-induced upwelling off the east coast of Sri Lanka. A bathymetrically-trapped front exists along a sill at the northern entrance to the Palk Strait between India and Sri Lanka.

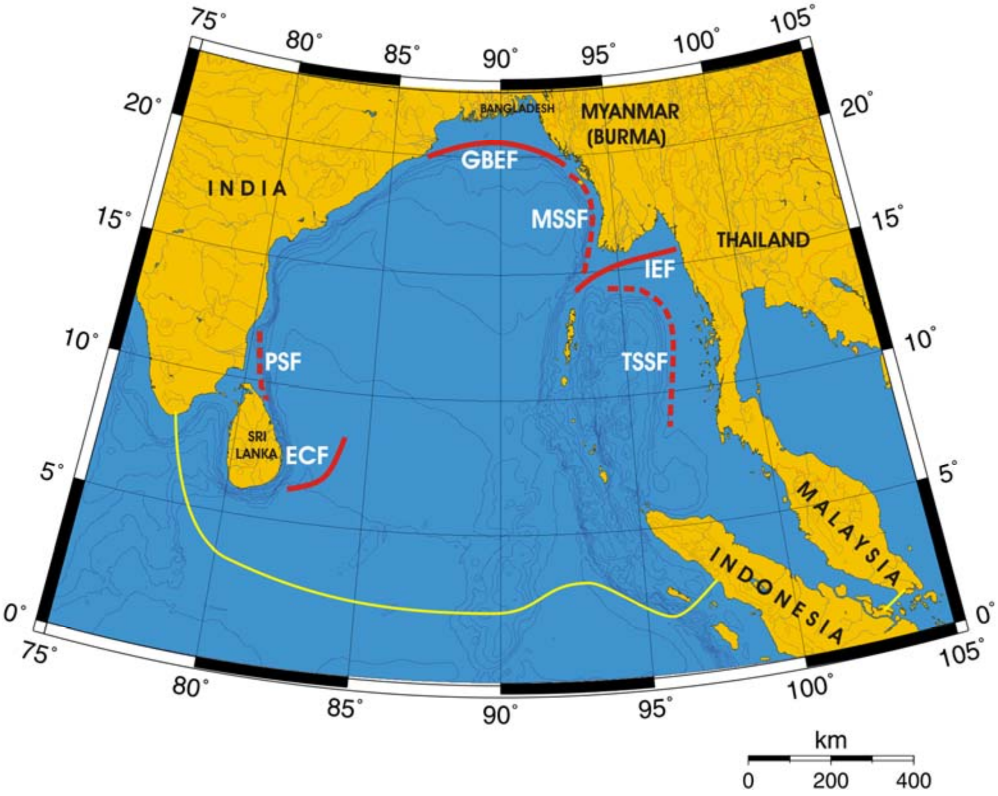

Figure VII-10.1. Fronts of the Bay of Bengal LME. ECF, East Ceylon Front; GBEF, Ganges-Brahmaputra Estuarine Front; IEF, Irravadi Estuarine Front; MSSF, Myanmar Shelf-Slope Front; PSF, Palk Strait Front; TSSF, Thailand Shelf-Slope Front. Red dashed lines, most probable locations of fronts. Yellow line, LME boundary. Belkin et al. (2009).

Bay of Bengal SST (after Belkin 2009
Linear SST trend since 1957: 0.50°C.
Linear SST trend since 1982: 0.24°C.

The steady, slow warming of the Bay of Bengal was modulated by quasi-regular interannual variability with an average magnitude of <0.5°C. The dominant mode of variability has a scale of 3 to 5 years, whereas decadal variability is not distinct. The all-time maximum of 1998 occurred simultaneously with other Indian Ocean LMEs and could be linked to El Niño 1997-1998. It is more difficult to correlate other extrema with similar events elsewhere since the Bay of Bengal LME has no immediate LME neighbors. For example, the all-time minimum of 1961 has no contemporary counterparts elsewhere in the Indian Ocean and therefore must be explained locally.

The temperature history of the Bay of Bengal is strongly coupled with its salinity regime, since the upper layer stability here is largely dependent on the freshwater discharge of three great rivers, the Ganges, Brahmaputra and Irrawaddy. The river discharge is seasonal to the extreme, governed by the Indian monsoon, which brings heavy precipitation to the Indian subcontinent (e.g. Salahuddin et al. 2006). Therefore interannual variability of the Indian monsoon largely determines the river discharge, hence salinity regime and eventually SST variability, in the Bay of Bengal. The Bay of Bengal is not spatially uniform, notwithstanding the existence of a quasi-stationary gyre circulation encompassing the Bay. The horizontal non-uniformity is caused by the perennially low salinity in the northern Bay owing to the Ganges-Brahmaputra river discharge. As a result, the upper mixed layer in the northern Bay is much shallower than in the south. The boundary between these two regimes runs zonally along ~15°N (Narvekar and Kumar 2006). This separation of the Bay of Bengal into two parts, northern and southern, with different SST regimes, must have important ecosystem ramifications.

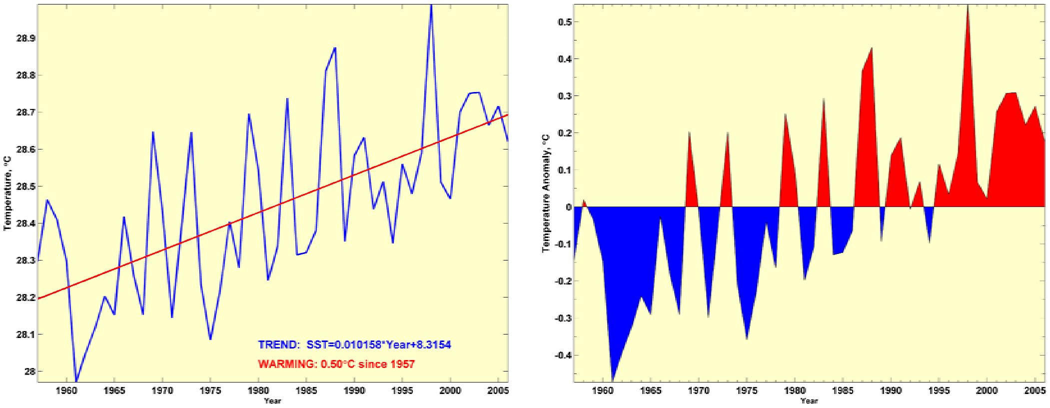

Figure VII-10.2. Bay of Bengal LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Bay of Bengal LME trends in Chlorophyll and Primary Productivity: The Bay of Bengal LME can be considered a Class I, highly productive ecosystem (>300 $gCm^{-2}yr^{-1}$).

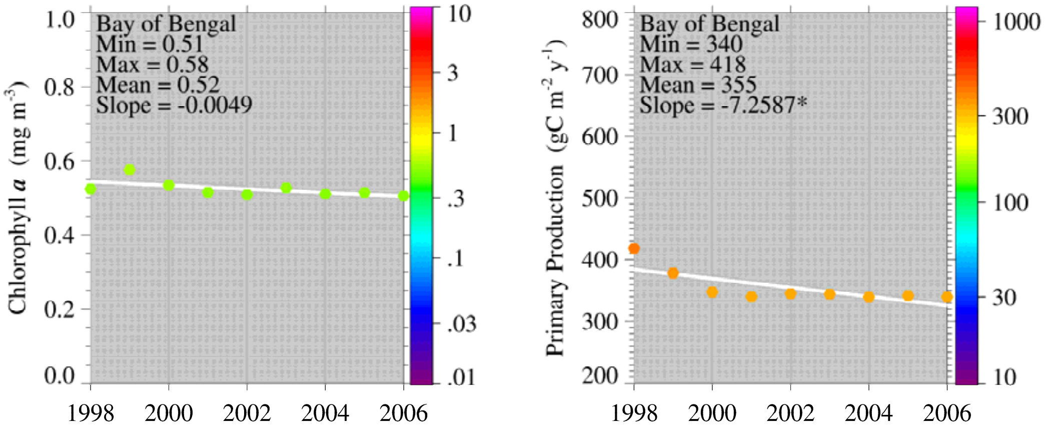

Figure VII-10-3. Bay of Bengal LME annual trends in chlorophyll a (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Fisheries of the Bay of Bengal LME target a wide range of species, including sardine, anchovy, scad, shad, mackerel, snapper, emperor, grouper, pike-eel, tuna, shark, ornamental reef fish, shrimp, bivalve shellfish and seaweed (Preston 2004). Catches from commercial and subsistence fishing equal or exceed those from industrial fisheries. In Bangladesh, for example, less than 5% of marine landings are estimated to come from industrial fishing, with the rest coming from the artisanal sector (Hossain 2003; Chuenpagdee *et al.* 2006). During the last decade, some countries have developed offshore fishing for tuna, notably Indonesia, Thailand and Sri Lanka and while most of the tuna catch comes from coastal fisheries, offshore fisheries provide the majority of export-grade tuna (Preston 2004). Crustacean catch is slightly less than 15% of the total catch, with penaeid shrimp accounting for about 40% of the total crustacean catch and being the major export earner (FAO 2003). Most of the countries are also major producers of farmed shrimps, with Thailand and Indonesia among the world's top producers (FAO 2005a).

Statistics on fisheries catch and effort are highly fragmented, especially in the artisanal and subsistence fisheries, two very important sectors in the region (Preston 2004). There are also indications that a continuous increase in the reported landings, particularly of unidentified fishes (included in 'mixed group' in Figure VII-10.4), may be a product of deficiencies in the underlying statistics, rather than improvements in the performance of the fisheries in the LME (Figure VII-10.4. If so, such deficiencies would have serious implications on the effectiveness of the fisheries management regimes in the LME and would also affect the value of the reported landings, which, according to Figure VII-10.5, rose to about over 2.7 billion US$ (in 2000 real US$) in 2004.

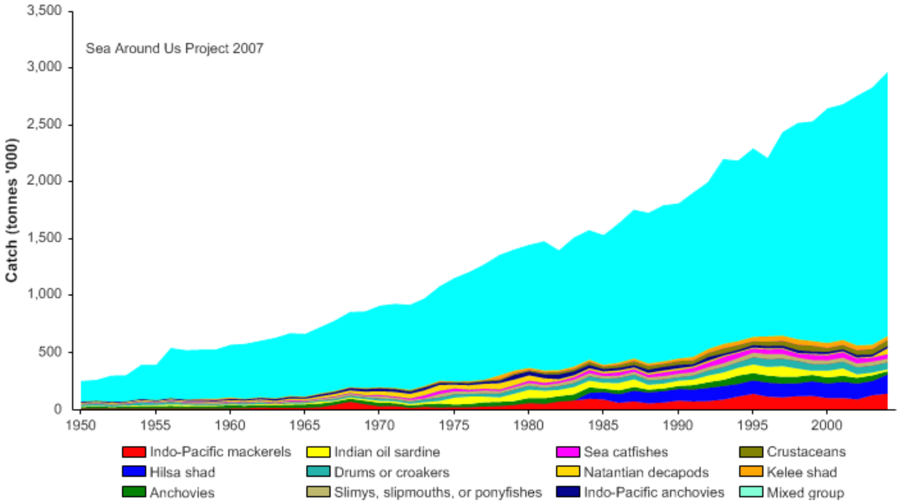

Figure VII-10.4. Total reported landings in the Bay of Bengal LME by species (Sea Around Us 2007).

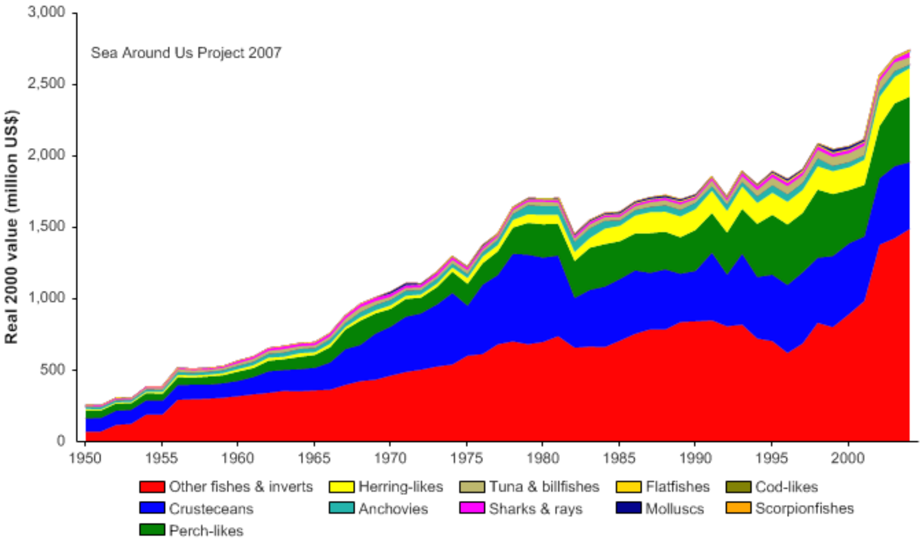

Figure VII-10.5. Value of reported landings in the Bay of Bengal LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME has increased over the years, and reached 20% of the observed primary production in 1998 (Figure VII-10.6). Such high PPR is another indication that the reported landings for this LME may be exaggerated. Bordering countries, namely India, Myanmar, Malaysia and Thailand account for the largest shares of the ecological footprint in the region.

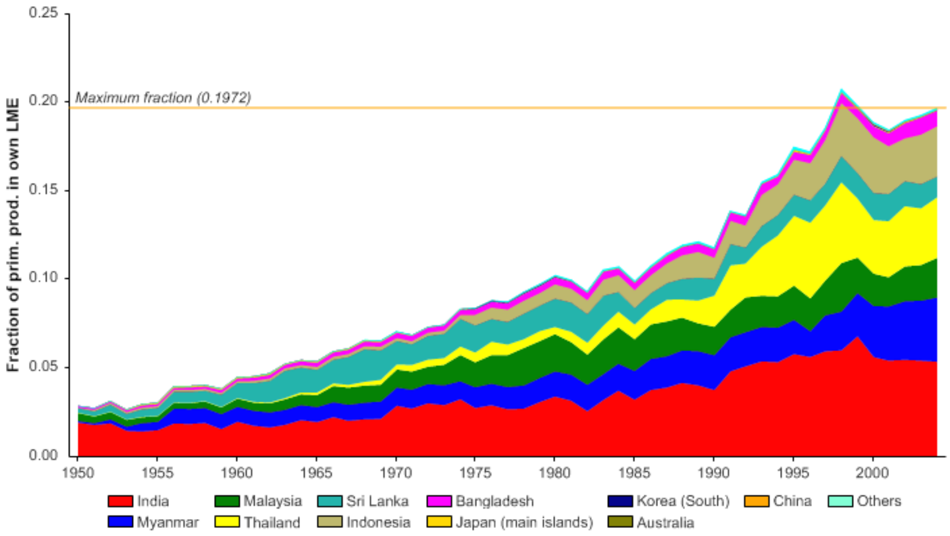

Figure VII-10.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Bay of Bengal LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) show a steady decline over the past 50 years (Figure VII-10.7 top) while the FiB index increased over the same period (Figure VII-10.7 bottom). Due to the nature of the underlying landings statistics, it is not possible to draw any reasonable conclusions from these indices, however, a detailed analysis of the MTI and FiB index of Western India, based on independently validated catch data from the States and Union Territories (Bhathal 2005), found that a 'fishing down' of the food webs (Pauly *et al.* 1998) is indeed occurring in the region (Bhatal and Pauly, in press).

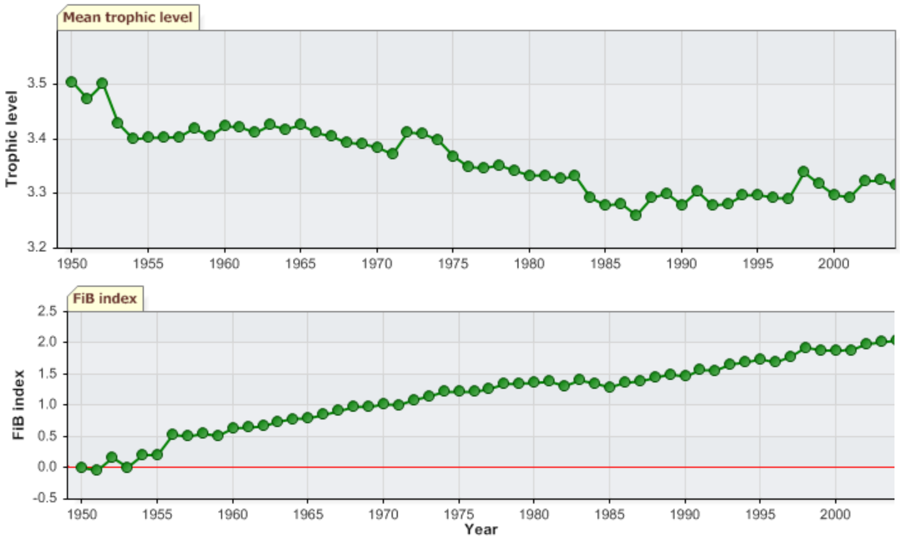

Figure VII-10.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Bay of Bengal LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stocks in the LME is low but on the rise (Figure VII-10.8, top), with over 80% of the reported landings from fully exploited stocks (Figure VII-10.8, bottom). Again, the questionable quality of the underlying landings statistics must be noted.

As should be expected, given the amount of fishing pressure present in this LME (Gelchu and Pauly 2007), both the catch per unit effort and the average size and weight of the catches have been on a decline (Preston 2004). Excess fishing capacity in many of the region's coastal fisheries is reducing the productivity of the local stocks and threatening their long-term sustainability (Preston 2004). In fact, intensive fishing has been identified as the primary force driving biomass changes in the LME (Sherman 2003). These changes are well illustrated on the southeast coast of India, where high density of coastal fishing craft is inducing changes in the ecosystem, as evident in the trophic level declines (Bhathal 2005, Vivekanandan *et al*. 2005). India, for example, is experiencing serial depletions of coastal fish stocks, where the increase in its fisheries catch is maintained only by the expansion of its range. Indeed, there are now signs that this expansion phase has reached its limit, with stagnation of its catch (Bhathal 2005). Other indicators of unsustainable resource use are described in the Bay of Bengal LME national reports for a wide range of resources including finfish, shark, crustacean, mollusc and echinoderm (Preston 2004).

Destructive fishing practices of various kinds are commonplace in the LME. Continued growth of commercial fishing effort, especially by trawlers, is increasing the fishing mortality of non-reef species. In the southern Indian maritime states of Tamil Nadu and

Andhra Pradesh, the decline in the catch has been associated with an increase in unregulated trawling for shrimps.

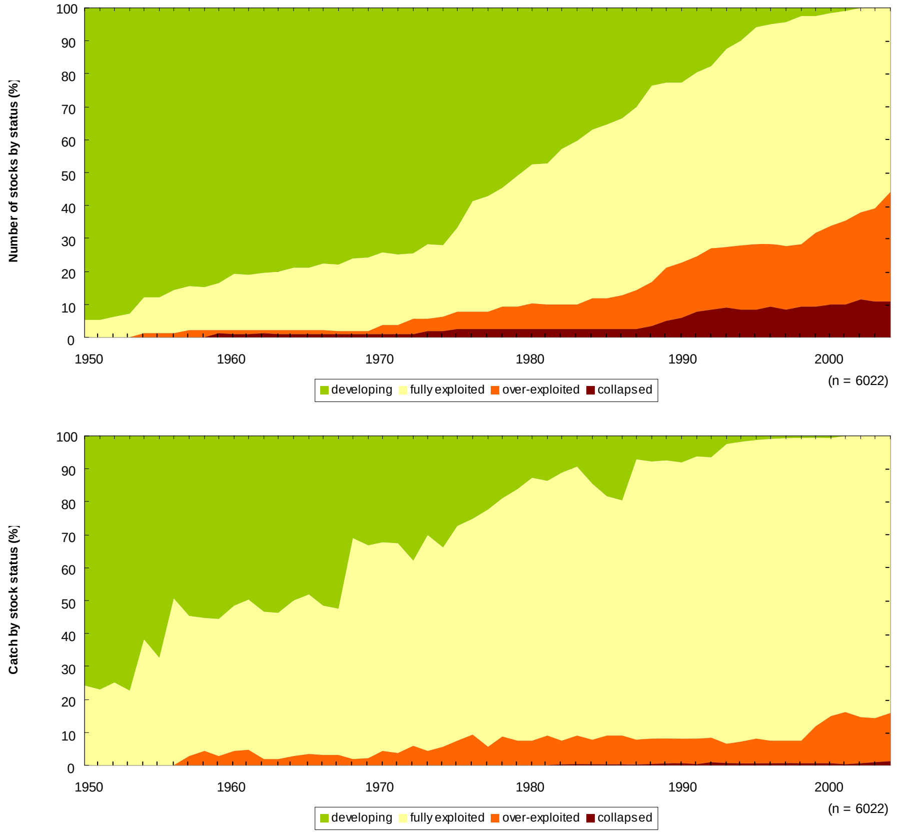

Figure VII-10.8. Stock-Catch Status Plots for the Bay of Bengal LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Excessive bycatch is of concern, although all captured fish are generally used either for human consumption or as aquaculture feed. The accidental capture of endangered fish species, dolphin and sea turtle is also of concern. The large-scale collection of fish and shrimp larvae for aquaculture using destructive methods may be seriously damaging wild stocks of both shrimp and other species (FAO 2005a), which typically make up more than 99% of the catch (Preston 2004). Dynamite fishing, often for small pelagic species, and the use of cyanide and other toxins for capturing ornamental and live food fish, are both increasing, and may lead to long-term damage, not only to the target resources, but to their associated habitats (FAO 2002, Preston 2004).

Expanding human populations of the Bay of Bengal LME region has created an increasing demand for fish as a source of animal protein. Furthermore, trade liberalisation and rising demand for export have contributed to the rapid development of marine fisheries and aquaculture in recent years. The steady decline in the abundance of the fisheries resources is expected to continue, despite a number of regulatory measures in force in some of the bordering countries. Bilateral or multilateral collaboration would greatly assist the efforts of individual countries in addressing the problem of overexploitation, given the transboundary nature of most of the fish stocks.

III. Pollution and Ecosystem Health

Pollution: Human activities are causing serious environmental degradation, threatening the sustainable management and health of the near-coastal waters. Among the major threats to the LME's health and productivity is pollution from land-based sources, particularly related to sewage, agriculture, aquaculture and industries (Kaly 2004, Samarakoon 2006). These are also the main land-based pollution categories of transboundary significance in the region. The mobilisation of pollutants through rivers, run-off and floods, as well as cross-border movements of pollutants through international rivers, are of concern (Kaly 2004). Pollution from sea-based sources (oil spills, oil exploration and production) is also among the main recognised threats (Kaly 2004).

Sewage was identified as a major priority issue (Chia & Kirkman 2000). This includes nutrients, POPs, household chemicals, medical wastes, excreted pharmaceuticals and sediments. The use of chemicals and irrigation in agriculture and aquaculture, as well as sediment inputs to the coastal areas compounds this problem. High amounts of organic and inorganic nutrients reach the LME (Kaly 2004). Although the ecological effect of nutrient enrichment of the coastal environment of the LME are poorly documented and understood, reported localised problems of eutrophication, hypoxia and algal blooms are likely to be related. Over the past 20-30 years, an increase in both the frequency and persistence of algal blooms in coastal waters and enclosed sea areas in India has been reported (Sampath 2003). The GBM river system is a major recipient of waste from industries in Bangladesh and India. High levels of pesticides can be found along the coast, especially near cities and ports (Dwivedi 1993).

Pollution by suspended solids is common to the entire LME, including the Andaman Sea. Although sediment mobilisation occurs with urban and port developments, the most important sources are probably deforestation together with agriculture and aquaculture (Kaly 2004). The GBM river system delivers 30% of the world's total load of river sediment (Milliman & Meade 1983), and provide high turbidity in the coastal waters, as has been shown in satellite photos.

Oil spills are a major concern. There is heavy oil tanker traffic between Japan and the Middle East, with the main shipping route passing south of Sri Lanka before entering the Straits of Malacca. Along the Indian coastline, there is also intense shipping traffic, and associated chronic oil pollution through operational discharge of waste, mostly by medium and small ships where installation of oil-water separators is not mandatory (Sampath 2003). Increasing shipping activity and increasing emphasis on offshore oil exploration in many countries of the region makes the northern Indian Ocean very vulnerable to oil pollution.

Habitat and community modification: Among the coastal habitats of the Bay of Bengal LME are several wetlands of international importance (WRI 2005). Six areas of critical biological diversity are the Sundarbans, Palk Bay and the Gulf of Mannar, the Marine (Wandur) National Park in the Andaman and Nicobar Islands, the Maldives Atolls, Mu Ko Similan National Park and Mu Ko Surin National Park in Thailand. The Sundarbans, a UNESCO World Heritage Site, represents the most economically important production forest and natural wildlife habitat in Bangladesh.

Extensive habitat modification has occurred, but was considered to be moderate in Bangladesh, India, and Sri Lanka, and severe in the Andaman Sea. The major problems are sedimentation and siltation, reclamation, coastal aquaculture, illegal fishing, and oil pollution, as well as global warming and sea level rise (Angell 2004). Climate change is likely to have severe impacts on the LME as it is closed in the north, preventing the migration of endemic species to higher latitudes. The impact on the ecosystem of the recent start of dredging in the Gulf of Mannar for the Sethusamudram Ship Canal is also of grave concern.

Weakened traditional common property management, growing human population in coastal areas, and development of brackish water shrimp farming have contributed to the increasing pressure on mangrove forests and their resources in the last few decades (Angell 2004, Samarakoon 2004). With a few exceptions, most mangrove habitats in the Bay of Bengal LME region are degraded or threatened. For instance, in the Sundarbans, some 150,000 ha of mangrove forest disappeared during the past 100 years, as a result of reclamation for agriculture settlement sites, industrial estates and roads (Govindasamy *et al*. 1997). More than half of the total area (some 208,220 ha) of Thailand's mangrove forests disappeared between 1961 and 1993 (GESAMP 1993). Between 1991 and 1995, approximately 50,000 ha of coastal wetlands along the east coast of India were converted to shrimp farms (Government of India 2002). In Sri Lanka, mangrove conversion to shrimp ponds has considerably reduced mangrove forest (Joseph 2003). Agriculture and land reclamation for urban settlements have also reduced the mangroves and peat swamps of the Malacca Straits by about 50-60% (Thia-Eng *et al*. 1997). Similarly, the Merbok mangroves in Malaysia, with one of the highest recorded levels of species diversity in the world, have been reduced by about 65% through conversion to rice paddies, shrimp farms and housing estates (Samarakoon 2004).

Among the pressures on the region’s coral reefs are destructive fishing practices, siltation and pollution, unplanned tourism development and coral mining (Angell 2004) are prominent. Coral reefs have also been damaged by bleaching, as a consequence of periodic increases in sea surface temperatures. The most notable bleaching event occurred in 1997-1998, and caused extensive bleaching and in numerous instances, over 90% mortality of corals, in some parts of the LME (Wafar 1999, Chou *et al*. 2002, Wilkinson 2002). Pollution and related disease are also threatening some reefs. For instance, oil spills and ballast water discharges are a significant threat to 85% of Thailand’s reefs (Angell 2004). Destructive fishing practices such as the use of cyanide and explosives are a major cause of coral reef degradation in most of the countries, particularly in Indonesia, where 67%-98% of the reefs are seriously degraded. Furthermore, reefs are generally depleted of high value food fish due to the demand for both the local tourism industry and export. Although this practice has been banned, coral mining has destroyed coral reefs in many areas, including in Sri Lanka, India and, to a lesser extent, in Bangladesh. Only the Maldives government has had some success in reducing this destructive practice by subsidising the import of alternative materials.

Extensive damage to coastal and marine habitats was caused by the tsunami of 26 December 2004 (CORDIO 2005a, 2005b, IUCN/CORDIO 2005). Places along the coast that were most affected were those that have been previously disturbed by anthropogenic activities. For example, mangroves and vegetated coastal dunes seem to have dissipated the wave energy and provided protection to coastlines, coastal inhabitants and infrastructure. Surveys have shown significant damage to coral reefs over extensive areas from mechanical damage, deposition of debris, sand, silt, and rubble, as well as impacts on the diversity of benthic organisms and fish. Fish populations, which in many cases were depleted by overexploitation, showed varying levels of impact, seemingly correlated with loss of habitat. In general, a higher impact was observed on smaller fish, notably damselfish, gobies, butterfly fish and wrasse; this may have adverse consequences for the ornamental fish trade.

The impact of the tsunami is also very visible on turtle nesting sites (Kulkarni 2005, CORDIO 2005b). The nesting beaches of leatherback, green, hawksbill and olive ridley turtles in South Andaman, Little Andaman and the Nicobar Group of islands have almost vanished. Sand and sediment deposited on sea grass beds will have a long term-impact on dugongs, which feed in these areas. Severe beach erosion has occurred at all sites, with some beaches suffering over 50% reduction in width and up to one meter loss in height.

IV. Socioeconomic Conditions

The eight countries bordering the Bay of Bengal LME include some of the most populous in the world, with India, Indonesia and Bangladesh being among the world's top ten. An estimated 400 million people live in the LME's catchment area (Preston 2004). The LME and its natural resources are of considerable social and economic importance to the bordering countries, with activities such as fishing, shrimp farming, tourism and shipping contributing to food security, livelihoods, employment and national economies. Marine fisheries make a modest contribution to the GDP of the bordering countries, with the exception of the Maldives, where this sector contributes 11% to GDP and 74% of the country's export commodities (FAO 2005a). Primary export commodities are shrimp and tuna, which make a significant contribution to national foreign exchange earnings. For example, in Bangladesh, fisheries account for more than 11% of annual export earnings, while in Indonesia, the value of fisheries exports amounted to about US$1.6 billion in 1998 (FAO 2005a).

Rapid development of aquaculture, mainly of shrimp, in the extensive coastal and brackish-water areas has made a significant contribution to the growth of national export earnings, and aquaculture is now an important element in both the local and national economies. Based on statistics in FAO (2005b), the combined output of the region's farmed shrimp and fish in 2003 was estimated at about 5.3 million tonnes, equivalent to 35% of total production from capture and aquaculture. It should be noted, however, that these statistics are based on the countries' total production, and not only that from the LME, although most of the aquaculture production comes from the LME. Tourism also makes a substantial contribution to the national economies of some of the Bay of Bengal LME countries. Coastal tourism in western Thailand, Peninsular Malaysia, Sri Lanka and the Maldives continue to gather momentum and is being promoted in India and Bangladesh.

Many of the region's poor are dependent primarily or entirely on marine resources, and have few, if any alternatives to fishing, even when overfishing is clearly occurring (Preston 2004, Samarakoon 2004). Fisheries also provide employment for millions of people. For example, in Indonesia, over 5 million people are directly involved in fishing and fish farming. Together with their families, they make up at least 4 percent of the total population (FAO 2005a). In Bangladesh, this sector provides income to some 1.5 to 2 million full-time and around 12 million part-time fishers, while in the Maldives, fisheries account for 20% of employment. Fisheries also make a very important contribution to the national diet in the bordering countries (FAO 2005a). For example, about two-thirds of Bangladesh, Indonesia and Sri Lanka national protein supply comes from fish. This is even higher in Mayanmar, where fish makes up 80% of the animal protein for most people.

The socioeconomic impacts of over-exploitation were assessed as severe in the Bay of Bengal LME countries, particularly for the millions of poor coastal fisher families. Increasing fishing effort and declining resources are leading to increased competition for access to these resources, with negative impacts, especially on poorer resource users (Townsley 2004). Reduced benefit flows from resource use lead to reduced livelihood security, including reduced food security. The localised decline of fisheries resources also forces resource users to migrate to other areas in search of new opportunities. This creates new vulnerabilities for those affected as it means abandoning familiar environments and social support networks. Without the capacity to adopt alternative strategies, poorer groups continue to exploit fisheries resources, further exacerbating the decline of the resources (Townsley 2004).

Pollution is affecting both critical habitats in coastal and marine areas, and the livelihoods that depend on them. Those making direct use of these resources see decreasing access to resources, declining environmental conditions that may affect their access to safe water and necessary livelihood resources and specific health risks generated by increased pollution (Townsley 2004). Over 60% of reported diseases in the two countries are linked to pollution discharged from point and diffuse sources. Pollution impacts are often particularly severe in coastal areas where pollution from multiple sources may be concentrated.

The coastal and marine habitats of the Bay of Bengal LME serve as nursery areas for fish and shellfish species that contribute substantially to income, livelihood, food security and employment in the bordering countries. These benefits are lost or threatened when such habitats are destroyed. The extent to which this affects other countries around the LME is unclear, but the interconnectedness of marine ecotones suggests that there are likely to be impacts, particularly in adjacent areas but also potentially further away (Townsley 2004; Bhattacharya and Sarkar 2003). For instance, distant fisheries may be affected by the destruction of habitats that are critical to the life cycle of their target species.

Many of the marine and coastal environmental problems faced by the Bay of Bengal LME are inextricably linked with the large populations of the region's coastal areas, and their impoverished status. Continued population growth, and the increasing concentration of people in coastal areas will exacerbate these problems in the future. Unless addressed, environmental degradation and unsustainable resource use practices will reduce the capacity of fisheries to provide sustenance and income for coastal people, thus leading to increased poverty in a spiralling effect. Preston (2004) notes the growing need to address coastal management, pollution, fishery management and alternative livelihood issues in parallel.

V. Governance

The LME is bordered by Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand. At the national level, environmental and fisheries regulations and management initiatives have been developed by the countries bordering the LME (Edeson 2004, FAO 2005a). However, their results have been mixed, with effectiveness hampered largely by inadequate implementation, surveillance and enforcement. Attempts to conserve coral reefs focus on the establishment of MPAs. These may be internationally recognised biosphere reserves or nationally established marine protected areas or parks (Angell 2004). For instance, the Sundarbans and the Gulf of Manner were named biosphere reserves in 1986 and are recognised by UNESCO under their 'Man in the Biosphere' programme. The effectiveness of these MPAs, however, varies considerably. Problems include intrusion of local fishers, weak to non-enforcement of MPA regulations, and lack of coordination among responsible government agencies.

A multitude of international, regional, and sub-regional organisations and programmes operate in the Bay of Bengal LME. The only regional fisheries management organisation whose jurisdiction extends into the LME is the Indian Ocean Tuna Commission. There are also numerous stakeholder groups and policy frameworks (Aziz *et al*. 1998). In March 1995, the South Asian Seas Action Plan (SASAP) was adopted by Bangladesh, India, Maldives, Pakistan and Sri Lanka. The South Asia Cooperative Environment Programme is the Action Plan secretariat. Although there is not yet a regional convention, SASAP follows existing global environmental and maritime conventions and considers the Law of the Sea as its umbrella convention. One of SASAP's priorities focuses on National Action Plans and pilot programmes to implement the GPA.

The regional Bay of Bengal Programme (BOBP) started out in 1979 as a fisheries development oriented-programme, and moved progressively towards fisheries management. The BOBP has been succeeded, in a reduced form, by the Bay of Bengal Programme Inter-Governmental Organisation, which continues to promote responsible management of small-scale fisheries and related activities. This organization has a membership of Maldives, India, Sri Lanka and Bangladesh and focuses largely on coastal fisheries related issues of these countries.

Recognising the need for integrated and coordinated management of their coastal and near-shore living marine resources, the eight countries bordering the LME have embarked on the development of a Bay of Bengal Large Marine Ecosystem Project with support from GEF to address critical threats to the coastal and marine environment, and to promote ecosystem-based management of the LME's coastal and marine resources. This project has recently been endorsed by GEF and will be implemented 2008-2013 by FAO with the aim of increased national institutional capacity in participating countries. Through this process, the outcomes will be a Trans-boundary Diagnostic Analysis, including assessments of critical coastal/marine habitats providing a location-specific assessment of critical transboundary concerns and the identification of "hotspots". As a part of regional cooperative arrangements, a permanent, partially financially-sustainable institutional arrangement will be established, that will support the continued development and broadening of commitment to a regional approach to BOBLME issues. The Strategic Action Plan that will be developed will guide future BOBLME Programme activities leading to improved wellbeing of rural fisher communities through incorporating regional approaches to resolving resource issues and barriers affecting their livelihoods.

The BOBLME will be largely based around regional and sub-regional activities for collaborative ecosystem approaches leading to changes in sources and underlying causal agents contributing to trans-boundary environmental degradation. The programme also envisages action to promote the restoration of depleted stocks and develop a better understanding of the BOBLME's large-scale processes and ecological dynamics. Basic health indicators in the BOBLME will be established as part of this. As a goal over the longer-term, and foreseen within the Strategic Action Plan, the sustained commitment from the BOBLME countries to collaborate will be achieved through adoption of an agreed institutional collaborative mechanism.

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VIII EAST ASIAN SEAS

VIII-11 Gulf of Thailand LME
VIII-12 Indonesian Sea LME
VIII-13 North Australian Shelf LME
VIII-14 NW Australian Shelf LME
VIII-15 South China Sea LME
VIII-16 Sulu-Celebes Sea LME
VIII-17 West-Central Australian Shelf LME

VIII-11 Gulf of Thailand LME

S. Heileman and R. Chuenpagdee

The Gulf of Thailand LME is located in Southeast Asia and bordered by Cambodia, Malaysia, Thailand and Vietnam. It covers a surface area of about 400,000 km^2, of which 0.80% is protected, and contains about 0.46% of the world's coral reefs and 18 major estuaries (Sea Around Us 2007). The mean depth is 45 m and maximum depth 80 m (Piyakarnchana 1989, 1999). The tropical climate is governed by the northeast and southwest monsoon regimes, which have profound effects on the conditions within the Gulf (Piyakarnchana 1989, 1999). Geographically, the LME can be divided into the inner and outer Gulf. The inner Gulf is primarily influenced by river outflow while the outer Gulf is influenced by seawater intrusion from the South China Sea. Water circulation is complex and influenced by tides and wind as well as differences in water densities. These and other aspects of the oceanography and biogeochemical characteristics are discussed in Wyrtki (1961) and Longhurst (1998). Book chapters and reports pertaining to this LME are by Piyakarnachana (1989, 1999), Talaue-McManus (2000), Pauly & Chuenpagdee (2003) and UNEP (2005).

I. Productivity

This LME is considered a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}). Its high primary production is the result of high nutrient input through rivers and from agricultural fertilisers, household sewage and shrimp farms (Piyakarnchana 1999). The Chao Phraya watershed is the largest watershed in Thailand, covering approximately 35% of the nation's land, and draining an area of 157,924 km². Nutrient content and dissolved oxygen levels vary seasonally in the inner Gulf, with most nutrients except nitrate being higher and oxygen concentration being lower, in the rainy season. Peaks in phytoplankton densities are correlated with the rainy season. Higher productivity also occurs close to estuaries. Increasing input of nutrients is leading to the occurrence of phytoplankton blooms, including Harmful Algal Blooms (HABs) (Piyakarnchana 1999). The coastal development in the GoT has been very rapid during the last decade especially for medium and small industries. Shrimp farming, on the other hand, has been largely terminated in the inner Gulf area. This is likely to affect the productivity in the LME.

Oceanic fronts: The Gulf of Thailand Front (GTF) is the only major front within this LME located near its boundary, at the entrance to the Gulf (Figure VIII-11.1). This front is largely a salinity front between low-salinity waters of the Gulf, diluted by the Mekong River outflow, and the saline waters of the South China Sea. The salinity contrast between the Gulf waters and South China Sea waters varies seasonally and interannually depending on the Mekong River discharge and the South China Sea circulation that brings Mekong River waters into the Gulf. This contrast can be as high as 3 ppt across the front (Belkin & Cornillon 2003, Belkin *et al*. 2009). The attendant thermal front has the cross-frontal range of 2°C to 3°C. The monsoon plays a major role in the front's seasonal evolution since the Mekong River discharge is largely monsoon-dependent; the snowmelt component of the Mekong runoff is of secondary importance.

*G**ulf of Thailand SST*** (after Belkin 2009):
Linear SST trend since 1957: 0.40°C.
Linear SST trend since 1982: 0.16°C.

In general, the thermal history of the Gulf of Thailand shows a moderate-to-slow warming, which is strongly correlated with the one of the South China Sea LME, as could be expected since the Gulf of Thailand is the largest gulf of the South China Sea. The relative magnitude of corresponding peaks and troughs is however different among these LMEs. The Gulf of Thailand's steady, slow warming was modulated by relatively strong interannual variability with year-to-year variations exceeding 0.5°C. The SST peak of 1998 stands out. This event was likely related to the El Niño 1997-98. Other pronounced events are:

(1) near-all-time minimum of 1963, simultaneous with an SST minimum in the South China Sea LME;

(2) absolute minimum of 1976, which corresponds to a minimum in the South China Sea.

The major warm event of 1998 caused the first extensive coral bleaching in the Gulf in April-June 1998, which resulted in severe degradation of coral reefs; the smaller warm event of 2003 caused mild bleaching (Yeemin, 2004).

Seasonal variability of vertical stratification plays a significant role in the Gulf of Thailand's thermal regime (Yanagi et al., 2001). Stratification is best developed in spring owing to strong surface heating and weak winds. The Mekong River runoff also affects stratification over most of the Gulf. The above parameters – incident solar radiation, winds and runoff – eventually depend on monsoon, therefore interannual variability of monsoon is expected to strongly modulate the SST regime of the Gulf.

Figure VIII-11.1. Fronts of the Gulf of Thailand LME. GTF, Gulf of Thailand Front. Yellow line, LME boundary (from Belkin et al. 2009).

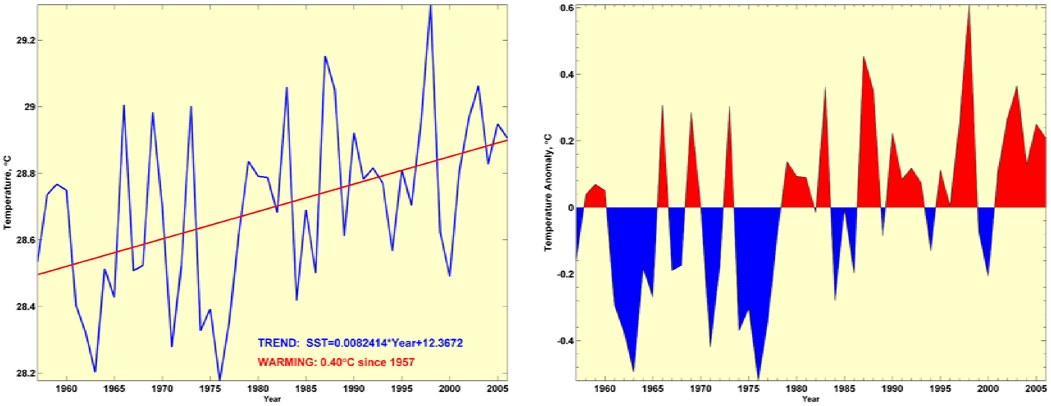

Figure VIII-11.2. Gulf of Thailand LME, annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Gulf of Thailand LME Trends in Chlorophyll and Primary Productivity: This LME is considered a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}).

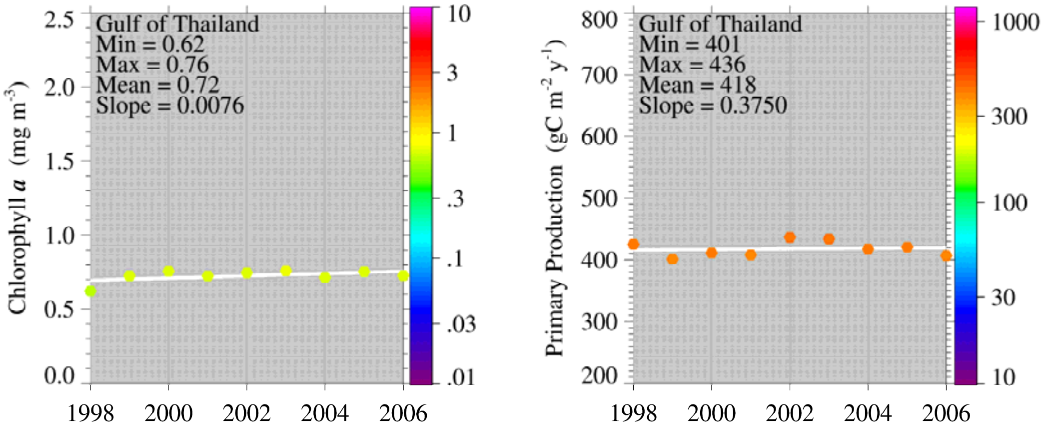

Figure VIII-11.3. Gulf of Thailand LME, trends in chlorophyll *a* and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The catch composition of the Gulf of Thailand LME is a tropical multi-species mix and includes food fish, trash fish, squid and cuttlefish, shrimp, shellfish and crab. Until the early 1960s, the fisheries were dominated by small pelagics (mainly Indian mackerels, *Rastrelliger* spp. and anchovies, *Stolephorus* spp.), which were caught by artisanal fishers for the local market (Pauly & Chuenpagdee 2003). In the 1960s, the introduction of trawl gear led to the development of demersal trawl fisheries (Piyakarnchana 1989, Chuenpagdee and Pauly 2004), targeting threadfin bream (*Nemipterus* spp.), big-eye (*Pempheris adspersa*), lizardfish (*Saurida elongata*), croaker (*Johnius* sp., *Larimichthys* sp., *Pennahia* sp.), shrimps (*Penaeus* spp.), flatfish and squid.

Total reported landings rose to over a million tonnes in 1969, but this is probably due to misreporting of fish caught outside the Gulf. After 1969, the landings declined to less than 500,000 tonnes by the late 1970s, but gradually returned to 700,000 tonnes by 2004 (Figure VIII-11.4). Again, a large fraction of the increased landings in recent years was probably caught outside of the LME, particularly for large pelagic species such as tuna. Note the high level of 'mixed group' in the reported landings, due to the poor quality of the underlying statistics which report a majority of the landings simply as unidentified marine fish. The value of the reported landings peaked at about 1.1 billion US$ (in 2000 real US$) in 1968 (Figure VIII-11.5).

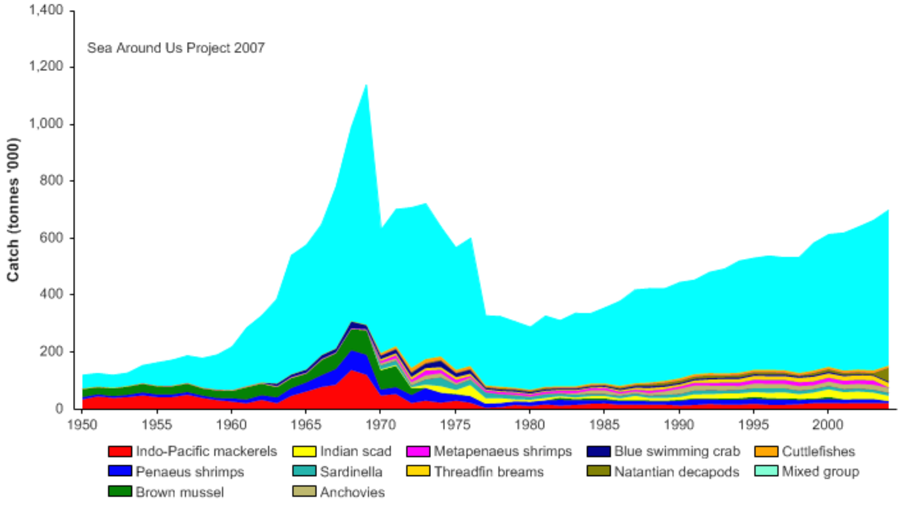

Figure VIII-11.4. Total reported landings in the Gulf of Thailand LME by species (Sea Around Us 2007).

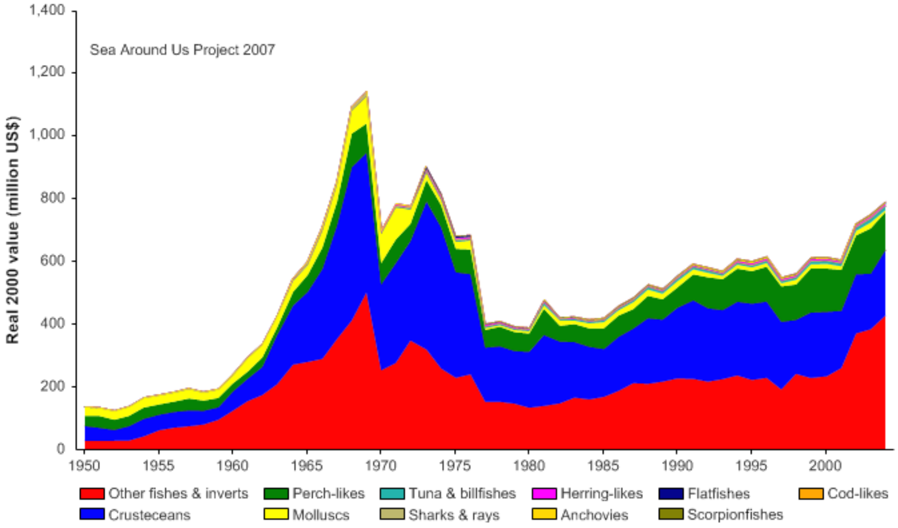

Figure VIII-11.5. Value of reported landings in the Gulf of Thailand LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME peaked in the early 1970s at 30% of the observed primary production, and following a period of low PPR, has reached this level in recent years (Figure VIII-11-6). The countries bordering the LME, namely Thailand, Malaysia and Vietnam, account for most of the ecological footprint in this LME.

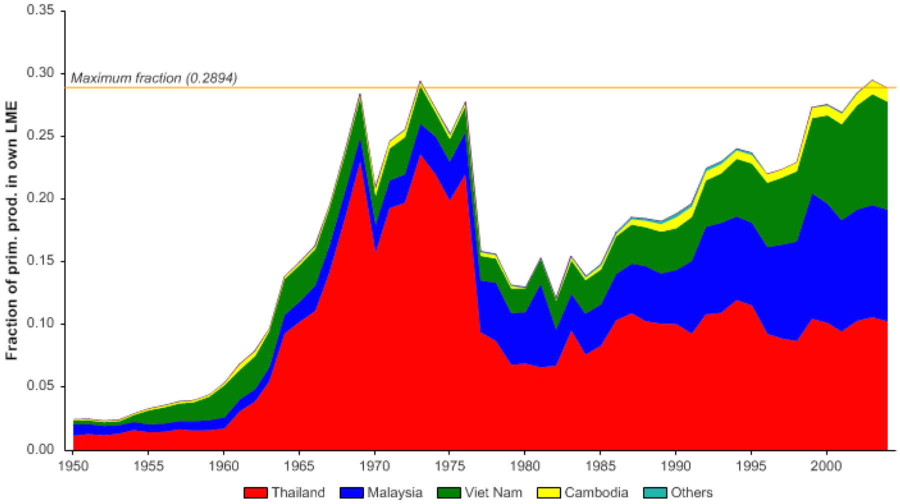

Figure VIII-11.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Gulf of Thailand LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The trends in the mean trophic level (i.e., the MTI; Pauly & Watson 2005) and the FiB are indicative of growing fisheries in the LME (Figure VII-11.7). However, due to the poor taxonomic details in the underlying landings statistics (Figure VII-11.4), it is highly likely that such diagnosis is incorrect.

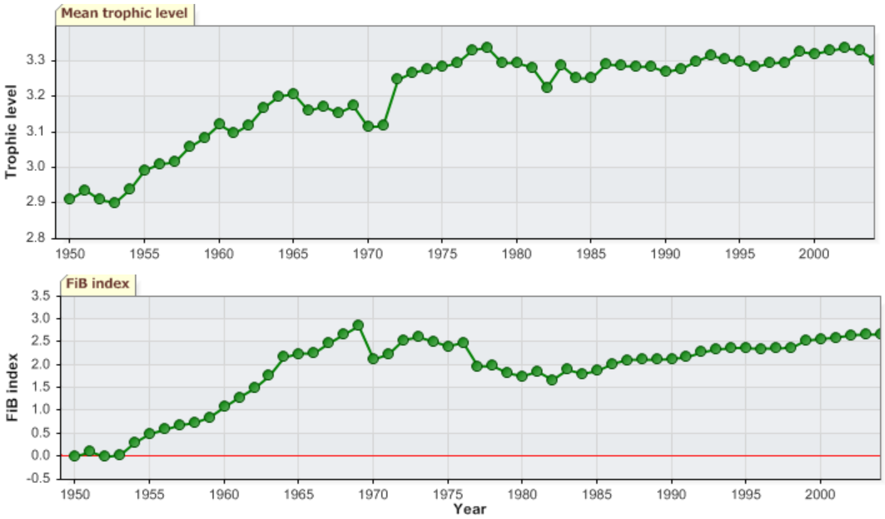

Figure VIII-11.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Gulf of Thailand LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that over 60% of the stocks in the LME are either collapsed or overexploited (Figure VIII-11.8, top), and that they contribute over 60% of the catch (Figure VIII-11.8, bottom). Again, the high degree of taxonomic aggregation in the underlying statistics must be noted in regards to problems in the interpretation of these plots.

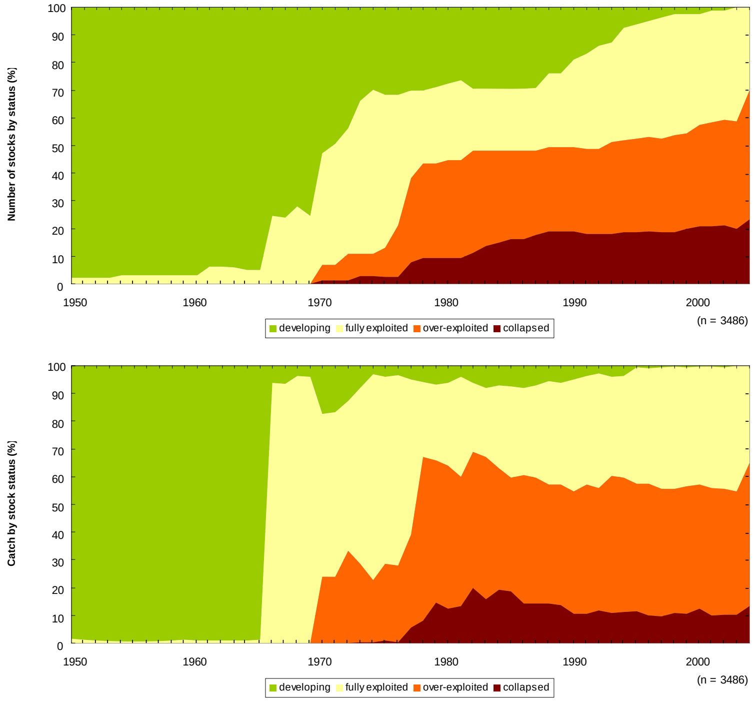

Figure VIII-11.8. Stock-Catch Status Plots for the Gulf of Thailand LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

There is, in spite of uncertainties in the available statistics, much evidence that fishing has impacted the LME at the ecosystem level and has become a primary driving force of biomass change. A 'fishing down' of the food web (Pauly *et al*. 1998) has been documented for the Gulf of Thailand (Christensen 1998, Pauly & Chuenpagdee 2003) and is fundamentally altering ecosystem structure and impacting its productive capacity. Overfishing caused by overcapacity of the local trawl fisheries is well documented (e.g., Pope 1979, Pauly 1979. Christensen 1998, Piyakarnchana 1999, Pauly & Chuenpagdee 2003, Silvestre *et al*. 2003, Chuenpagdee & Pauly 2004) and the South China Sea TDA, which includes the Gulf of Thailand LME, has identified loss in fisheries productivity as a major transboundary issue in this region (Talaue-McManus 2000). As a consequence of high fishing effort by non-selective trawl gear, its demersal catch composition has changed towards smaller individuals and a mix of predominantly small, short-lived species or 'trash fish' (Pauly & Chuenpagdee 2003). There is also a rapid decrease in the catch per unit effort, from over 300 kg per hour in the early 1960s to 50 kg per hour in the 1980s, and a further decline to 20-30 kg per hour in the 1990s (Eiamsa-Ard & Amornchairojkul 1997).

In addition to overexploitation, destructive fishing was found to be severe in the region (UNEP 2005) and the use of small meshes in trawl nets has contributed to overexploitation of the local demersal fish stocks (Christensen 1998). Impacts from fishing with explosives and poisons are also severe, particularly on coral reefs (Bryant *et al*. 1998, Talaue-McManus 2000, (UNEP SCS 2008) and other types of fishing gear, such as push nets and mackerel purse seines, have contributed further to the unsustainable condition of the local fisheries (Pauly & Chuenpagdee 2003). Excessive bycatch is also a severe problem (UNEP 2005). Small mesh sizes and minimal use of bycatch-exclusion devices have resulted in massive overexploitation of fisheries resources as bycatch. Yet, discarding is insignificant, as virtually all of the bycatch is utilised, with smaller 'trash' fish taken in trawls being used as aquaculture feed. There is widespread capture, either intentional or accidental, of rare, threatened and endangered species such as turtles and dugong, by artisanal and commercial fisheries. In 2003 an international training course on the use of turtle excluder devices (TEDs) and juvenile and trash excluder devices (JTEDs) was conducted by the Southeast Asian Fisheries Development Center in cooperation with FAO and GEF to train participants in how to minimize bycatch in the fisheries of Southeast Asia, particularly in the excluding of turtles from shrimp trawling. Substantial, though unquantified, levels of bycatch are also produced by distant waters fleets, through use of blast fishing and poison, and in the shrimp fry fisheries, where juvenile fishes are often discarded (UNEP SCS 2008).

Fish stocks in the inner Gulf have been affected by rapid environmental deterioration, including eutrophication, HABs and oxygen depletion (Eiamsa-Ard & Amornchairojkul 1997, Piyakarnchana 1999). The relative effects of environmental deterioration and overexploitation on the region’s fisheries resources need to be further explored but, at the same time, there is growing recognition that there is an urgent need for Thailand to reduce and manage fishing capacity (Stobutzki et al. 2006; Pauly & Chuenpagdee 2003, Ahmed et al. 2007).

As with the neighbouring LMEs, the status and future viability of the fisheries are not well-understood, and there are significant gaps in data. In fact, the status of many fisheries may be summarised as Illegal, Unreported and Unregulated (IUU; UNEP 2005). Based on present consumption and population growth patterns, pressure on the fisheries resources is likely to increase significantly in the immediate future and overexploitation is expected to remain severe or get worse if adequate measures are not taken to address this problem (UNEP 2005). A substantial reduction of fishing effort, especially of bottom trawlers, may reduce the fishing pressure on the local stocks and slow further ecological degradation in the region (Pauly & Chuenpagdee 2003; Stobutzki et al. 2006; Ahmed et al. 2007).

III. Pollution and Ecosystem Health

Pollution: Rapid economic development and population growth in the coastal areas have caused pollution that is severe in localised coastal hotspots (UNEP 2005). Liquid wastes from domestic, agricultural and industrial sources, as well as sediments and solid wastes are the major land-based pollutants affecting the coastal areas (Talaue-McManus 2000, Fortes 2006). Outflow from the Chao Phraya River, is critical to the productivity of the system, especially since it contains nutrients and other substances, including pollution. As a consequence, problems such as eutrophication, sedimentation, and shallowness of the inner Gulf are common. Pollution has potential transboundary impacts due to the possibility of long-shore transport of pollutants as a result of the water circulation pattern on the Sunda Shelf (Talaue-McManus 2000). Water quality is lower than acceptable standards in the inner Gulf region, especially at river mouths, the popular tourist spots along the coast and near certain islands. Many cities have no sewage treatment and discharge raw sewage directly into the coastal areas (UNEP 2005).

Eutrophication is a growing problem, due to the increasing input of nutrients from land-based sources (Piyakarnchana 1999). The increased nutrient loading has caused phytoplankton blooms in several areas, reducing water clarity as well as dissolved oxygen in bay areas and this pattern is reportedly spreading. There have been frequent occurrences of toxic and non-toxic algal blooms, as well as cases of paralytic shellfish poisoning in parts of the region (Talaue-McManus 2000).

High levels of suspended solids have severe impacts in coastal waters throughout most of the region (UNEP 2005). Major changes in turbidity and levels of suspended sediments have resulted from activities such as extensive deforestation, logging, land reclamation, dredging and urban development. Pollution from solid wastes is also severe in localised areas, particularly around many towns and villages where waste management is poor or non-existent.

The use of agricultural pesticides and industrial effluents creates a significant problem in some areas such as near river mouths and industrial discharges (UNEP 2005). Releases of chemical and other forms of pollution from shipping in harbours also commonly occurs since regulations and controls relating to ship-derived pollution are rarely enforced. Pollution by petroleum hydrocarbons and the occurrence of oil spills have been reported in the Gulf (Piyakarnchana 1999).

Habitat and community modification: Habitat and community modification was assessed as severe (UNEP 2005), with land use and land cover changes being the major contributors (Piyakarnchana 1999). The causes of mangrove destruction along the coastlines bordering the South China Sea, including the Gulf of Thailand LME, include conversion to aquaculture ponds, particularly of shrimp, clear felling of timber for woodchip and pulp production, land clearance for urban and port development and human settlements and harvest of timber products for domestic use (UNEP 2004a). However, as noted by Talaue-McManus (2000) and UNEP (2004a), shrimp culture appears to be the most pervasive economic imperative for mangrove conversion in the region. In 1961, mangrove forests surrounding the LME covered 367,000 ha, but by 1991 this was reduced to 173,600 ha, with at least three out of 24 provinces having lost all their mangrove forests (Piyakarnchana 1999). The clearing of these forests has led to a deterioration of the coastal zone (Piyakarnchana 1999). From a global perspective, the major transboundary issues surrounding the loss of mangrove habitats include the loss of unique biological diversity and the loss of mangrove services (UNEP 2004a).

Over the past 15 years, progressive degradation of coral reefs in several locations of the South China Sea (including the Gulf of Thailand LME) has been noted, with reefs located near large human population centres having suffered the most serious degradation (UNEP 2004b). Rapid population growth, coastal development, land-based pollution, tourism, overfishing and destructive fishing practices all contribute to this decline (Sudara & Yeemin 1997, Talaue-McManus 2000, UNEP 2004b). Heavy sedimentation resulting from various anthropogenic disturbances in the coastal areas and poor land use practices in the watersheds has also impacted the region’s reefs (Sudara *et al*. 1991). In addition, global warming of the sea surface has caused considerable and widespread damage to the LME’s reefs after the severe 1998 bleaching event (UNEP 2004b). A comprehensive reef survey programme covering 251 sites in the Gulf of Thailand showed 16.4% of the reefs to be in excellent condition, 29% good, 30.8% fair and 23.8% poor (Chou *et al*. 2002).

Seagrass beds are subjected to a number of threats from various sources, the root cause being associated with coastal human populations (UNEP 2004c). High sediment loads associated with deforestation (including of mangroves), dredging and land reclamation; fluctuation in freshwater input due to irrigation and land clearing; increased pollution; coastal development; and destructive fishing methods are among the causes of degradation of the region’s seagrass habitats (UNEP 2004c). There is evidence of widespread modification of seagrass habitats throughout the region. For example, between 20% to 50% of seagrass beds in Malaysia and Thailand have been damaged (Talaue-McManus 2000) and Vietnam has lost an estimated 40% to 50% over the past two decades (UNEP 2004c).

Ecosystem health may deteriorate further as a consequence of expected future increases in pollution and habitat modification (UNEP 2005). Despite increasing measures for pollution mitigation and control (e.g., sewage treatment), environmental quality is likely to worsen, primarily because of the predicted increase in deforestation and agriculture, as well as a major increase in population overriding the improvements in infrastructure. Some positive steps are being taken to address habitat modification, including mangrove rehabilitation programmes, watershed protection and establishment of marine protected areas. Both the direction of change and the rates of environmental deterioration or improvement, however, will depend on the success of ongoing and planned interventions.

IV. Socioeconomic Conditions

The population in the Gulf of Thailand LME region is 112 million (Talaue-McManus 2000; UNEP 2005). For the larger South China Sea region, some 270 million people (5% of the world's population) inhabit coastal areas and this population is expected to double in the next three decades. The LME and its resources have provided important benefits to the region's coastal communities, with fisheries, mariculture and tourism being key economic activities in the bordering countries. Marine fisheries, in particular, play a significant socioeconomic role. Subsistence fishing is the major activity of large numbers of people outside of the main urban and industrial centres. Fisheries are an important source of food, employment and foreign exchange. Despite nutritional requirements and current population growth rates, South China Sea countries in general are net exporters of fishery products (Talaue-McManus 2000). Fishing contributes about 2% to the GDP of Thailand, which is a major world exporter of fishery commodities and among the leading exporters of farmed shrimp (FAO 2005).

The socioeconomic impacts of overexploitation of fisheries and environmental deterioration are significant (UNEP 2005). There have been reduced economic returns and loss of employment from the collapse of fisheries in the region. Higher investment is now required per unit of commercial catch, reducing the profitability of fishing enterprises. The degradation of mangrove forests, seagrass and coral reefs, critical for fish spawning, feeding and recruitment, has also contributed to declining fish catch, especially in near-shore areas. This has had a marked negative impact on the livelihoods of poor artisanal fishing communities. Competition for fisheries resources among fishers has also been increasing.

The socioeconomic impacts of pollution include economic losses in mariculture and the shellfish industry as a result of high levels of toxicity and HABs and risk to human health. Other socioeconomic impacts of pollution are associated with the costs of clean-up and coastal restoration. Land-use conflicts have also arisen. The socioeconomic impacts of habitat and community modification range from slight to severe (UNEP 2005), primarily because of reduced capacity of local populations to meet basic human needs and loss of employment. Other impacts include loss or reduction of existing and future income and foreign exchange from fisheries and tourism and increased risks to capital investment (e.g., failure of coastal aquaculture projects in many parts of the region, costs of restoration of modified ecosystems and intergenerational inequity).

V. Governance

Governance of the LME is shared by the four bordering countries. A range of measures and programmes has been established to arrest and reverse overexploitation as well as environmental degradation in the LME. Following on its adoption of the FAO Code of Conduct for Responsible Fisheries, the Thai Department of Fisheries issued licensing regulations to control the number of trawlers and push nets. The number of registered trawlers has gradually decreased from about 10,500 units in 1980 to 8,000 units in early 2000 (DoF 2002). The Ministry of Agriculture and Cooperatives in Thailand governs the Department of Fisheries. The Ministry of Natural Resources and Environment governs coastal resources and the environment. The countries have made a commitment to devolve authority for natural resources management from state to community and from central to more local levels of government (Ratner *et al*. 2004). For instance, in Thailand the 1999 Decentralization Act has placed a range of decision-making powers with sub-district government units (Tambon Administrative Organisations).

The Gulf of Thailand LME comes under the UNEP-administered East Asian Regional Seas Programme. The Action Plan for the Protection and Development of the Marine and Coastal Areas of the East Asian Region was approved in 1981, and currently involves 10 countries. There is no regional convention. Instead, the programme promotes compliance with existing environmental treaties and is based on member country goodwill. The Action Plan is steered from Bangkok by its coordinating body, COBSEA. The East Asian Seas Regional Coordinating Unit serves as the secretariat and is responsible for coordinating the activities of governments, NGOs, UN and donor agencies and individuals in caring for the region's marine environment. Other regional action plans include the ASEAN Strategic Plan of Action on the Environment, ASEAN Cooperation on Transboundary Pollution and Regional Action Programme for Environmentally Sound and Sustainable Development. Regional research programmes include the International Cooperative Study of the Gulf of Thailand for the sustainable management of the Gulf, sponsored by the UNESCO Intergovernmental Oceanographic Commission-Sub Commission for the Western Pacific (IOC-WESTPAC), the Southeast Asian Programme in Ocean Law, Policy and Management and the Southeast Asia START Global Change Regional Centre.

The Council of Directors of the Southeast Asian Fisheries Development Centre approved a programme for the ‘regionalisation’ of the FAO Code of Conduct in 1998. It has also produced three volumes of Regional Guidelines for Responsible Fisheries in Southeast Asia — Responsible Fishing Operations, Responsible Aquaculture and Responsible Fisheries Management (SEAFDEC 2003). The Asia-Pacific Fishery Commission is assisting its member countries to achieve accelerated fisheries development and management.

To help address the problems in the coastal fisheries of Asia, the WorldFish Centre joined forces with fisheries agencies from Bangladesh, India, Indonesia, Malaysia, The Philippines, Sri Lanka, Thailand and Vietnam and the Asian Development Bank, to implement the project ‘Sustainable Management of Coastal Fish Stocks in Asia’ (TrawlBase project) between 1998 and 2001 (Silvestre *et al*. 2003). Among the main achievements of this partnership was the development of a database called ‘Fisheries Resource Information System and Tools’ (FiRST), which contains trawl research survey data and socioeconomic information for selected fisheries, and facilitates its analysis. The project has also strengthened national capacity in coastal fisheries assessment, planning and management, and illustrated the benefits of collaborative efforts in addressing issues of regional concern.

GEF is currently supporting three projects involving this LME. The project 'Reversing Environmental Degradation Trends in the South China Sea and Gulf of Thailand' aims to foster and encourage regional collaboration and partnership in addressing transboundary environmental problems between all stakeholders and at all levels. The project also seeks to enhance the capacity of the participating governments to integrate environmental considerations into national development planning. A comprehensive TDA for the South China Sea, which includes the Gulf of Thailand LME, has been produced under this project.

The project 'Building Partnerships for the Environmental Protection and Management of the Seas of East Asia' (PEMSEA) aims to enable the East Asian Seas Region to collectively protect and manage its coastal and marine environment through inter-governmental and inter-sectoral partnerships (www.pemsea.org). Through partnership building, the project will help countries to develop scientifically-based environmental management strategies and action plans in order to deal with land-based pollution, promote closer regional and sub-regional collaboration in combating environmental disasters arising from maritime accidents as well as increase regional commitments in implementing international conventions that they ratify. The project 'East Asian Seas Region: Development and Implementation of Public-Private Partnerships in Environmental Investments' aims to build confidence and capabilities in public-private sector partnerships as a viable means of financing and sustaining environmental facilities and services for the protection and sustainable use of the marine and coastal resources of the East Asian Seas region.

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VIII-12 Indonesian Sea LME

S. Heileman

The Indonesian Sea LME is situated at the confluence of the Pacific and Indian Oceans, and is bordered by Indonesia and East Timor. It covers an area of 2.3 million km^2, of which 1.49% is protected, and contains 9.98% and 0.75% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). Indonesia is one the world's largest archipelagic nations, with a coastline exceeding 84,000 km. The warm ocean acts as a 'heat engine' of global atmospheric circulation, with complex ocean-atmospheric dynamics, including the ENSO phenomenon. The convergence of three tectonic plates – the Eurasian, the Indo-Australian and the Pacific Plates – makes the region geologically as well as topographically diverse. Many of Indonesia's islands are subject to tectonic instability including volcanic activity. Seasonal monsoons, during which ocean currents reverse directions, exert a significant influence on the LME. The seas around Indonesia have complex and rapid currents owing to energetic tides over rough topography and also owing to the Indonesian Throughflow, which is the flow and exchange of oceanic water between the Pacific and Indian Oceans. Books, book chapters, articles and reports pertaining to this LME are Dalzell & Pauly (1989), Morgan (1989), Pauly & Martosubroto (1996), Pitcher *et al.* (2007), Zijlstra & Baars (1990) and UNEP (2005).

I. Productivity

The Indonesian Sea LME is considered a Class I ecosystem with high productivity (>300 $gCm^{-2}yr^{-1}$). The Banda Sea and the Aru Basin in particular, are areas of extensive seasonal upwelling and downwelling related to the monsoonal system. During upwelling periods, biomasses and productivity at all levels in the food chain are greatly enhanced (Zijlstra & Baars 1990). Stocks of small pelagic fish were also found to be considerably higher during the upwelling period. The changing oceanographic conditions in this LME also influence phytoplankton and zooplankton species composition.

The region is located in the Indo-West Pacific centre of biodiversity, supporting mega-diversity (Roberts *et al*. 2002). For example, more than 500 species of reef-building corals, 2,500 species of marine fish, 47 species of mangroves and 13 species of seagrasses are found in this region (Chou 1997, Tomascik *et al*. 1997, Veron 2000, Spalding *et al*. 2001). The pelagic realm is an important habitat, which supports high biodiversity of large and small migratory marine species, including a wide variety of cetaceans, including the blue, fin and humpback whales and other species that frequently migrate through the region (Kahn & Pet 2003).

Oceanic fronts Belkin et al. (2009): Straits connecting this LME with the other marginal seas are sites of front formation due to topographic effects caused by flow constrictions (Figure VIII-12.1). Internal tide interaction with sills in these straits is one of such front-genetic processes. Local (basin-scale) fronts are observed east of Borneo (EBSSF), northeast of Sulawesi (NESF), east of Halmahera (EHF), in the eastern parts of the Java Sea (EJSF) and Flores Sea (EFSF), across the Makassar Strait (MaSF), in the Molucca Sea (MoSF) and in the southern Banda Sea (SBSF).

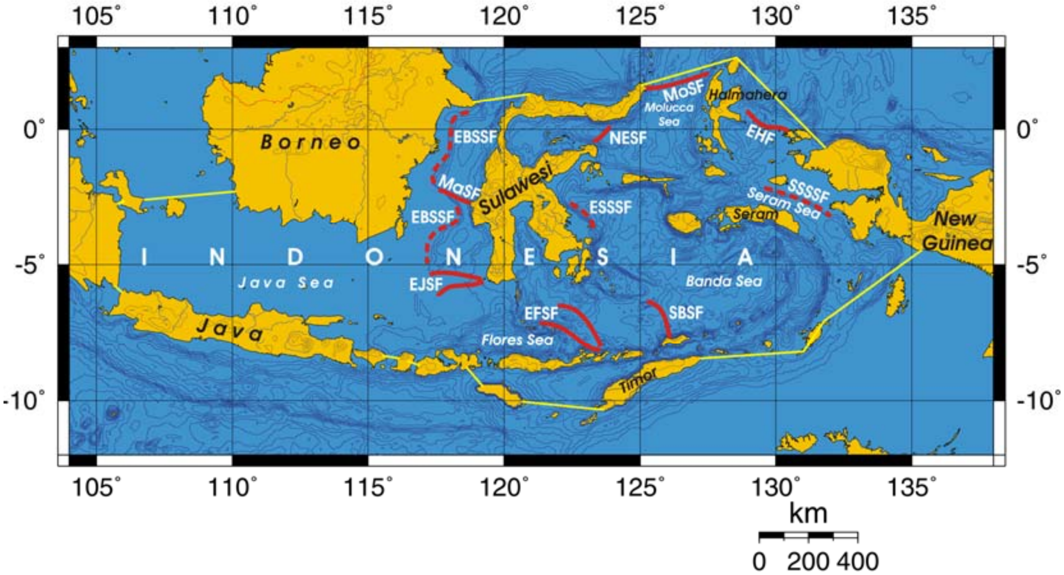

Figure VIII-12.1. Fronts of the Indonesian Sea LME. EBSSF, East Borneo Shelf-Slope Front; EFSF, East Flores Sea fronts; EHF, East Halmahera Front; EJSF, East Java Sea fronts; ESSSF, East Sulawesi Shelf-Slope Front; MaSF, Makassar Strait Front; MoSF, Molucca Sea Front; NESF, Northeast Sulawesi Front; SBSF, South Banda Sea Front; SSSSF, Seram Sea Shelf-Slope Front. Dashed lines show most probable locations of shelf-slope fronts. Yellow line, LME boundary. After Belkin et al. (2009) and Cornillon (2003).

Indonesian Sea SST (after Belkin 2009)
Linear SST trend since 1957: 0.53°C.
Linear SST trend since 1982: 0.24°C.

The thermal history of the Indonesian Sea since 1957 included brief cooling through 1967 and steady warming ever since (Figure VIII-12.2). The all-time minimum of 1967 occurred simultaneously with the all-time minimum in the Sulu-Celebes Sea LME and only a year prior to the all-time minimum of 1968 in the West-Central Australian Shelf LME and a minimum of 1968 in the North-West Australian Shelf LME.

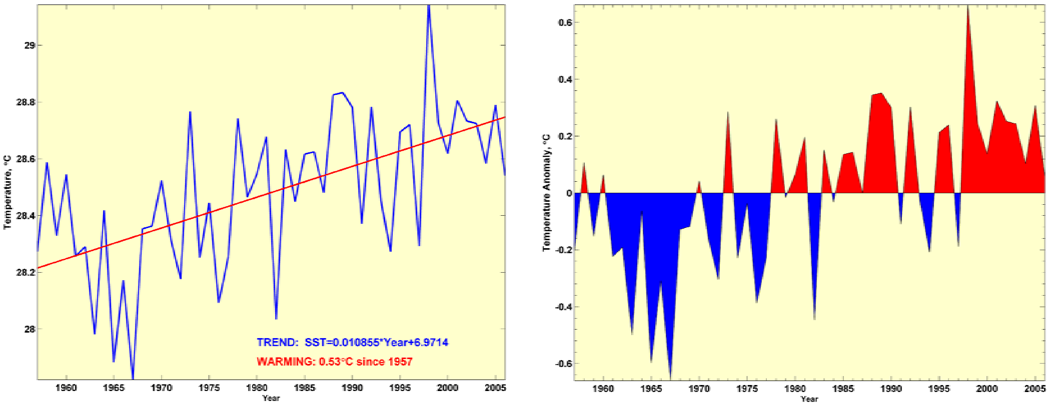

Figure VIII-12.2. Indonesian Sea LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

This sequence of events can be explained by advection of the low-temperature signal of 1967 from the Indonesian Sea toward Western Australia with the Indonesian Throughflow. The 1982 minimum occurred simultaneously in the North and Northeast Australian Shelf LMEs, but not off Western Australia; this can be explained by the long-time variability of the circulation pattern. The 1998 all-time maximum was likely caused by El Niño 1997-98. Despite the relatively uniform SST field, local anomalies up to 10°C are generated by the Indonesian Throughflow and tides, e.g. east of Bali in the Lombok Strait, where SST drops to 16°C vs. 28°C in adjacent waters (Vantier et al., 2005, p. 56).

Indonesian Sea LME trends in Chlorophyll and Primary Production: The Indonesian Sea LME is considered a Class I ecosystem with high productivity (>300 gCm^{-2}yr^{-1}).

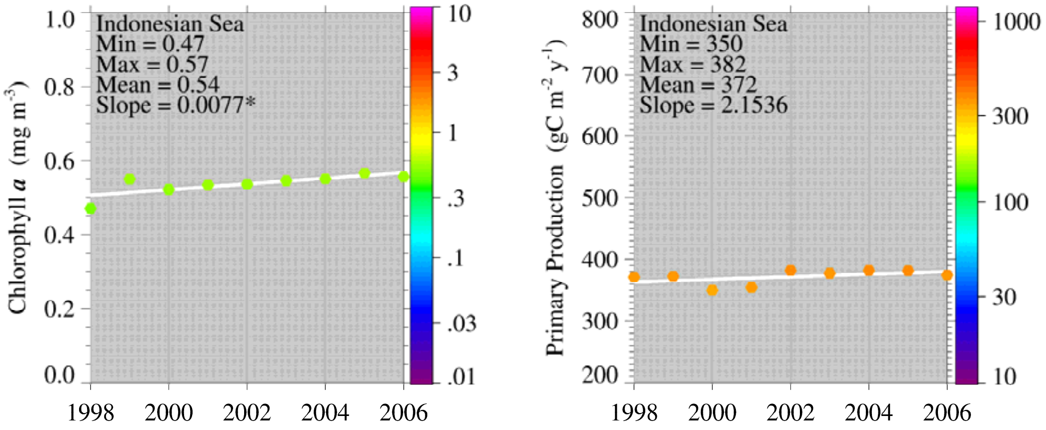

Figure VIII-12.3. Indonesian Sea LME annual trends in chlorophyll *a* (left) and primary productivity (right), 1998 – 2006. Values are color coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The fisheries of the Indonesian Sea LME are very complex and diverse, reflecting the region's extraordinarily heterogeneous geography and species variance (Pauly & Martosubroto 1996; FAO 2005). While most of the catch comes from its artisanal sector, industrial fisheries contribute considerably more in terms of value, since they target high-value shrimp and tuna stocks. Major species caught in the LME include tuna, sardines, anchovy, mackerel, as well as a range of reef fishes (Morgan 1989). Reef fisheries are vital to subsistence fishers and their families in the region but are also important in supplying high value products for expanding international, national and local markets (Cesar *et al*. 2000). Aquaculture of shrimps in coastal ponds has also increased rapidly during the last two decades in Indonesia.

As noted by Kahn & Fauzi (2001) for the adjacent Sulu-Celebes Sea, but also applicable in the Indonesian Sea, great uncertainties exist on the status of the local fish stocks due to serious discrepancies in fisheries data and a potentially significant level of Illegal, Unreported and Unregulated (IUU) catches. Total reported landings in the LME have increased steadily from the 1950s, with a sharp increase from less than half a million tonnes to over one million tonnes in the mid 1970s (Figure VIII-12.4). This distinct increase in the reported landings may be associated with developments related to the declaration of the EEZ. In 2004, the total reported landings reached 2.2 million tonnes and the value of the reported landings, showing a trend similar to landings, reached close to US$1.2 billion (in 2000 US dollars) in 2004 (Figure VIII-12.5)..

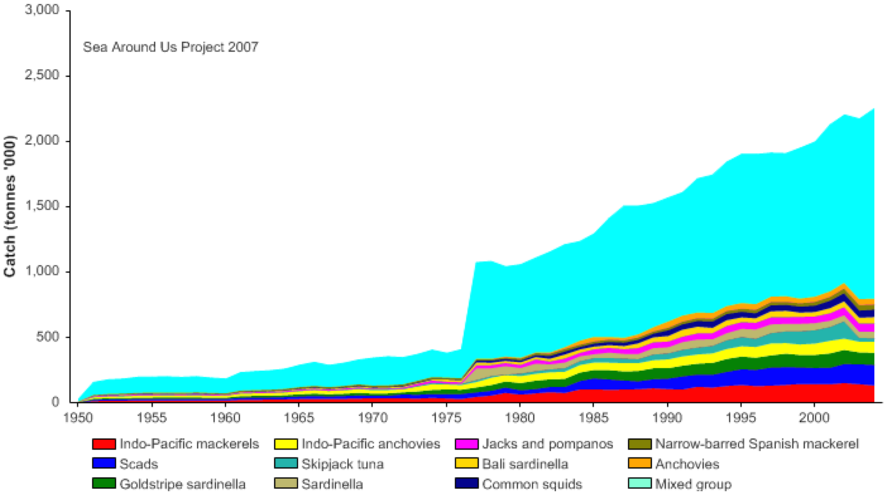

Figure VIII-12.4. Total reported landings in the Indonesian Sea LME by species (Sea Around Us 2007).

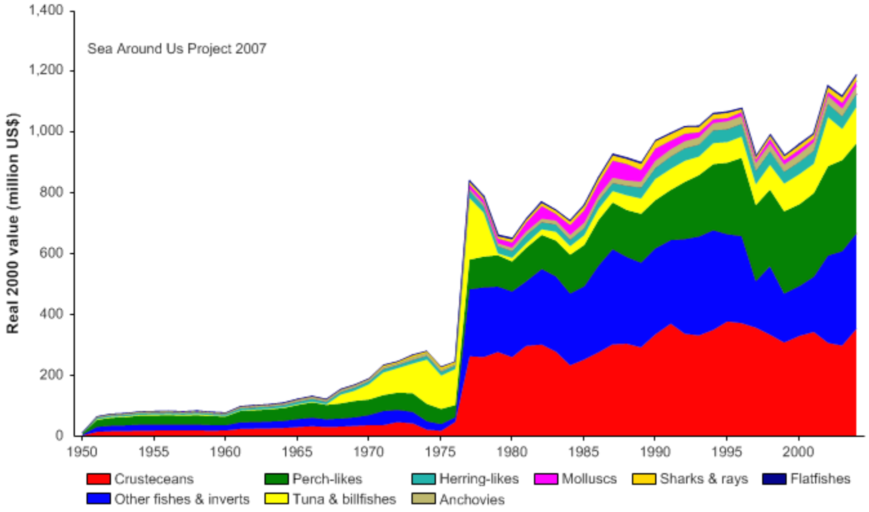

Figure VIII-12.5. Value of reported landings in the Indonesian Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is increasing, and is currently at 30% of the observed primary production (Figure VIII-12.6). Indonesia and Thailand account for the largest shares of the ecological footprint in the LME.

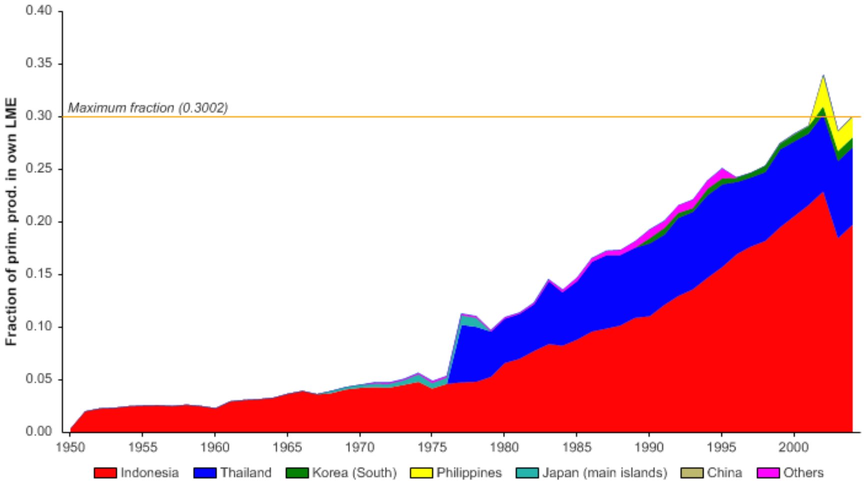

Figure VIII-12.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Indonesian Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of fisheries landings (i.e. the MTI; Pauly & Watson 2005) shows an increase from the early 1980s, an indication of increased reported landings of high trophic species such as tuna (Figure VIII-12.7 top). Such interpretation is also inferred by the increase in the FiB index during the same period (Figure VIII-12.7 bottom) denoting a steady expansion of the fisheries in the region. It must, however, be noted that these indices may be skewed by the high level of unidentified fishes in the underlying landings statistics.

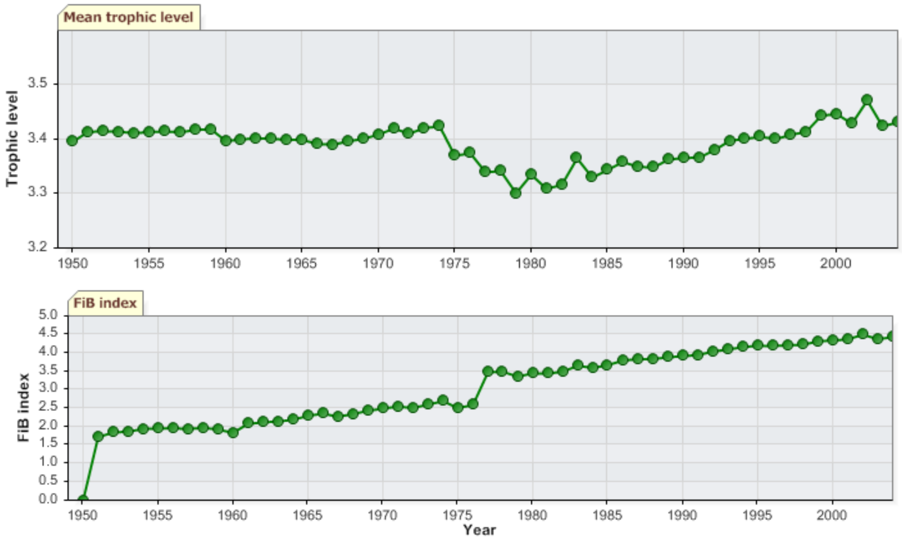

Figure VIII-12.7. Mean trohpic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Indonesian Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that only a small number of the stocks in the LME are either overexploited or have collapsed (Figure VIII-12.8, top) with 80% of the catch from fully exploited stocks. Again, the high level of taxonomic aggregation in the underlying landings statistics must be noted here.

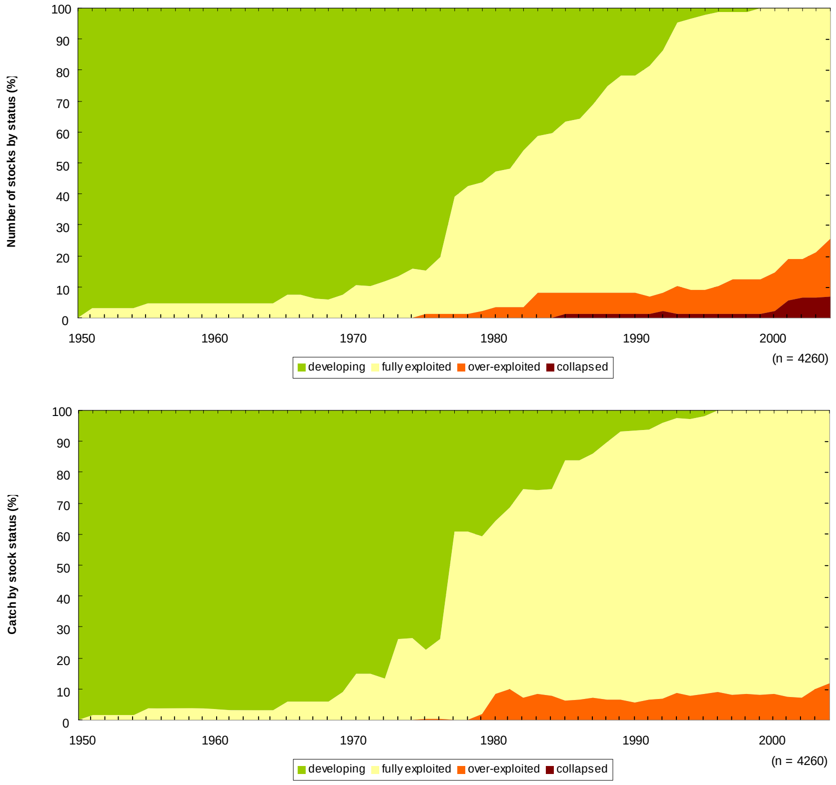

Figure VIII-12.8. Stock-Catch Status Plots for the Indonesian Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Overexploitation is widespread in this LME, with many fish stocks exploited well beyond the biological limits (Dwippongo *et al.* 1987), especially in the coastal zone, which is exploited by 85% of Indonesian fishers (Hopley & Suharsono 2000). In addition, foreign fleets continue to threaten Indonesia's fisheries, but again, accurate data on the extent, the number of vessels and their mode of operations are inadequate (Kahn & Fauzi 2001, Perrin *et al*. 2002). Coral reefs have been exploited for a long time, even in the more remote areas of Eastern Indonesia (Palomares & Heymans 2006), and are now considered to be under severe fishing pressure. Of particular concern is the live reef fish trade in the Southeast Asian region, including in the Indonesian Sea LME. The use of fish poisons to catch aquarium and food fishes is a serious problem in many Pacific countries, but more so in Indonesia and the Philippines (Johannes & Riepen 1995). Use of explosives is also of a grave concern throughout the region (see Pollution and Ecosystem Health).

About 85% of aquarium fish traded internationally has been caught using cyanide, targeting about 380 species from a few families such as Labridae, Pomacentridae, Chaetodontidae, Pomacanthidae and Scaridae (Pratt *et al*. 2000). The live food fish trade primarily targets groupers (especially *Epinephelus* spp. and *Plectropomus leopardus*), Napolean wrasse (*Cheilinus undulates*) and barramundi cod (*Cromileptes altivelis*) (Pet & Pet-Soede 1999). Because of their particular life-history attributes, groupers are highly susceptible to overexploitation and the targeting of their spawning aggregations is a serious concern (Licuanan & Gomez 2000). In addition to taking adult groupers for direct food consumption, the live reef fish food trade also involves capture of wild fry and fingerlings supplying the grouper mariculture industry in Southeast Asia, predominantly in Taiwan and Thailand (Sadovy & Pet 1998).

Over the past several centuries many of Indonesia's coral reefs have been heavily and chronically overfished, with a major loss of productivity and cascading effects to other components of the ecosystem. Overexploited stocks include many species of reef fish such as groupers and threatened and endangered species such as sea turtle and dugong. Benthic invertebrate species such as sea cucumbers, trochus and clams are also overexploited, particularly around major coastal population centres. Overexploitation of pelagic species such as shark, tuna and billfish is also evident. Catch per unit effort for these fisheries has declined sharply, as has the size of fishes caught. There have also been local extinctions and reductions in market availability (UNEP 2005). Of major importance in this context has to be the realization that much of the true catch may not be accounted for by official landings statistics, e.g., as shown for northern Sabah, Malaysia (Teh et al. 2007). While these examples pertain to other LME areas, the same problem applies to the Indonesian Sea LME.

The problem of excessive bycatch was assessed as severe (UNEP 2005). However, there are little or no discards because virtually all of the bycatches, except those produced by distant waters fleets and through the use of blast fishing and poisons, are consumed. Sharks are also caught as bycatch in trawl as well as tuna long-line fisheries. Perrin *et al*. (2002) noted that bycatch is a major threat to all marine mammals in Indonesian waters, especially to cetaceans and dugong, and can lead to major losses in biodiversity. Impacts of destructive fishing on fisheries resources and marine habitats are increasingly becoming a problem, even within national parks (Pet-Soede & Erdmann 1999, UNEP 2005). There is a widespread habitat destruction of coral reefs from blast and poison fishing including extensive damages to soft-bottom communities from trawling (see Pollution and Ecosystem Health). The impacts of destructive fishing have major transboundary implications, both in terms of target species population dynamics and in terms of international market demand. Although these practices are illegal, regulations are difficult to enforce, especially in remote areas.

III. Pollution and Ecosystem Health

Pollution: Urban expansion and industrialisation have resulted in coastal pollution from domestic, agricultural and industrial wastes in the Indonesian Sea LME. Industrial forms of water pollution are concentrated in the major urban centres, primarily the large cities of northern Java. Oil spills, slowly degrading toxic wastes from chemical as well as non-chemical industries, agricultural runoff and heavy metals threaten coastal waters. This has resulted in severe pollution in some areas, such as Sunda (UNEP 2005). Because of inadequate sewage disposal and treatment throughout the region, microbiological pollution is severe, especially around urban centres. Eutrophication is also severe around urban centres, particularly in areas with limited water circulation and where sewage, agricultural and/or industrial discharges are present.

Siltation rates in this LME are among the highest in the world (Hodgson & Dixon 1992). Pollution by suspended solids is severe in coastal waters, particularly in north Java and Sumatra, with high turbidity over wide areas. Close to the major urban centres, the affected zone extends up to 50 km offshore (Hopley & Suharsono 2000). This has mostly resulted from extensive deforestation in many watersheds, compounded by high rates of erosion as well as industrial mining. Solid waste is a severe problem locally, particularly in the Java Sea and around the cities, towns and villages where waste management is inadequate.

Chemical pollution from agricultural pesticides and industries is severe in localised areas. Mercury contamination from gold mining is widespread and is generating serious health as well as environmental risks in Indonesia (Limbong *et al*. 2003). Studies conducted by Kambey *et al*. (2001) showed that mercury levels in the tissue of fish near gold mines were higher than levels recommended by the WHO for total restriction on fish consumption. The disposal of toxic materials from mines via submarine tailings placement is of special relevance to Indonesian marine life (Perrin *et al*. 2002). In the next decade, the world's biggest copper and gold mine situated in Indonesia will discharge more than one billion tonnes of tailings over a wide area. This LME forms part of both the main and Ultra Large Crude Carrier oil tanker routes between the Indian and Pacific Oceans. Furthermore, there is regular discharge of ship ballast waters in this LME. In addition to spills, chronic pollution from oil production facilities and refineries is evident in some areas such as Sunda (Hopley & Suharsono 2000).

Habitat and community modification: The Indonesian Sea LME has a large diversity of coastal habitats, including extensive mangroves, coral reefs and seagrass beds. The area of Indonesia's mangroves has been estimated to range from 24,000 km^2 (Tomascik *et al*. 1997) to 42,500 km^2 (Wilkinson *et al*. 1994), representing over two thirds of the area of mangroves in Southeast Asia. Seagrass beds are even more extensive (30,000 km^2 according to Tomascik *et al*. 1997). Estimated coral reef areas range from 50,000 to 90,000 km^2 (Spalding *et al*. 2001) to 85,707 km^2 (Tomascik *et al*. 1997). Overall, habitat and community modification was assessed as severe in the Sunda and Wallacea sub-regions, and moderate in the Sahul (UNEP 2005). Extensive cutting for timber, conversion for aquaculture and other forms of coastal development, heavy siltation, pollution and destructive fishing have caused major fragmentation and reduction in mangrove area. For example, more than 30% of the mangroves in north Java disappeared during the last 150 years. About 80% of the reefs are at extremely high risk of further damage from human activities (Bryant *et al*. 1998, Burke *et al*. 2002). In the last 50 years, the proportion of degraded reefs has increased from 10% to 50% (Hopley & Suharsono 2000). In central Indonesia, 40% of coral reefs are currently classified as being in poor condition and only 6% in excellent condition (Hopley & Suharsono 2000).

Damage to coral reefs from the use of explosives and poisons is catastrophic. Johannes & Riepen (1995) forecast the collapse of the live fish industry in Indonesia and this does appear to be happening in many areas (Bentley 1999). On regularly bombed reefs, coral mortality can range from 50% to 80%, even in National Parks (Pet-Soede & Erdmann 1999). The effects of cyanide fishing are multiple. In addition to being broken to retrieve stunned fish, corals are also bleached by the cyanide (Johannes & Riepen 1995) and recovery may take up to half a century (Cesar 1996). As reefs become damaged and unproductive, they are abandoned by fishers who move to new reefs to continue this pattern of destruction. Indonesian coral reefs are also impacted by pollution. Reefs subject to land-based pollution (sewage, sedimentation and/or industrial pollution) show 30% to 50% reduced diversity at 3 m and 40% to 60% reduced diversity at 10 m depth relative to unpolluted reefs (Edinger *et al*. 1998). This implies a dramatic, rapid decrease in Indonesian reef-based fisheries resources. Mining and quarrying of coral is another significant threat to the LME's coral reefs and is widespread at both subsistence and commercial levels, despite being banned by various provincial governments (Hopley & Suharsono 2000). Indonesia's reefs have also been impacted by the 1997-1998 El Niño event that triggered widespread bleaching, with western and west-central Indonesia most affected.

Modification of coastal habitats has resulted in major changes in population structure as well as functional group composition, notably on coral reefs, and massive changes in ecosystem services of coral reefs and mangroves (DeVantier *et al*. 1999). For instance, the important nursery and feeding ground role of mangroves as well as seagrass beds for fish and marine mammals have been lost over extensive areas. Habitat modification and loss have also contributed to the decline in populations of marine mammals such as dugong (Marsh *et al*. 2001). Habitat degradation has significant transboundary implications in terms of reduced fish recruitment and impacts on migratory species as well as on biodiversity throughout the region.

Unless there are improvements in regulation and expansion and improved management of protected areas, the health of the LME is likely to deteriorate further primarily because of the predicted increases in fisheries, deforestation, agriculture, aquaculture, mining and industrialisation as well as a major increase in population without the required improvements in infrastructure.

IV. Socioeconomic Conditions

The population of Indonesia as a whole is about 222 million in 2006 (Indonesian Central Statistics Bureau, 2006), with some 200 million people living in the LME region. The total population is expected to double to 400 million by 2035. Subsistence farming and fishing are the major activities of large numbers of people outside the main urban centres. Most of the approximately 6,000 coastal communities are directly dependent on the sea as their primary source of food and income (Dahuri & Dutton 2000). Coastal and marine industries, including oil and gas production, transportation, fisheries and tourism, account for 25% of the nation's GDP, in addition to employing a significant percentage of Indonesia's workforce (Dahuri & Dutton 2000).

The socioeconomic impacts of overexploitation of fisheries include reduced economic returns as well as loss of employment of fisher families, conflicts between user groups, loss of food sources for human and animals and injury or loss of human life from diving accidents (Johannes & Djohani 1997). Losses in revenue to the Indonesian economy as a result of poaching by foreign boats may top four billion US dollars (Perrin *et al*. 2002). The reefs of Indonesia provided annual economic benefits of US$1.6 billion per year in 2002, based on their value in food security, employment, tourism, pharmaceutical research and shoreline protection. However, over the next 20 years, human impacts, notably overfishing, destructive fishing and sedimentation, could cost Indonesia some US$2.6 billion (Burke *et al*. 2002). The cost from fish bombing alone over the next 20 years will be at least US$570 million (Cesar 1996, Pet-Soede *et al*.2000), while the economic loss from cyanide fishing is estimated to be US$46 million annually (Hopley & Suharsono 2000).

Pollution has severe socioeconomic impacts, especially around major urban centres and coastal villages (UNEP 2005). Water pollution is found in virtually all populated and/or highly industrialised areas of Indonesia and is known to cause massive fish kills, harvest failure from aquaculture and threats to human health (Dahuri 1999, Hopley & Suharsono 2000). Habitat and community modification impact local fisheries, cause increased beach erosion and have adverse consequences for tourism, due to loss of aesthetic value and the cost of mitigation measures.

V. Governance

The Indonesian Sea LME is governed by Indonesia and the recently independent state of East Timor. Indonesia uses the ‘Archipelagic Doctrine’ to define its territorial waters;

most of this LME is within archipelagic waters. Marine governance in Indonesia is very complex as there are three levels of government – district, provincial and national – with marine jurisdiction. The government has sponsored the Coral Reef Rehabilitation and Management Programme, a 15-year initiative aimed at strengthening the management of the country's coastal resources while considering the needs of coastal communities. Since the 1980s, there have been major advances in the regional capacity for development of policy and legislation based on sound science. For example, a 'critical mass' of regional expertise now resides in government, inter-governmental agencies, academic institutions and NGOs. There is also an extensive literature on the marine environment in Indonesia that is published locally in the Indonesian language.

An urgent priority regarding the management of the country's coastal and marine living resources is the development of a functional, integrated network of MPAs (UNEP 2005). This must be accompanied by the establishment of substantial no-take zones as well as the development of appropriate policy and legal frameworks. The National Parks Service manages six National Marine Parks and several other Terrestrial National Parks with marine areas. These parks cover a total sea space of 41,129 km^2, equivalent to 1.3% of the country's territorial and archipelagic seas (Putra & Mulyana 2003). Indonesia is developing co-management strategies for improving the management of these parks.

The LME falls within the UNEP-administered East Asian Regional Seas Programme (see Gulf of Thailand LME). Indonesia participated in the GEF-supported project 'Regional Programme for Marine Pollution Prevention and Management in the East Asian Seas region' from 1994 to 1999. This country is also participating in the GEF-supported PEMSEA (see Gulf of Thailand LME) and Bay of Bengal LME projects (see Bay of Bengal LME and www.fao.org/).

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VIII-13 North Australian Shelf LME

M.C. Aquarone and M. Furnas

The North Australian Shelf LME is a tropical sea lying between the Pacific and the Indian Oceans. It extends from the Timor Sea to the Torres Strait and includes the Arafura Sea and Gulf of Carpentaria. The LME covers an area of nearly 800,000 km^2, of which 2.17% is protected, and contains 0.70% of the world's coral reefs (Sea Around Us 2007). A broad continental shelf links Australia with eastern Indonesia and Papua New Guinea. Despite high local currents, there is very little net exchange of water between the Pacific and Indian Oceans through the shallow Torres Strait. It is bordered by the Timor Trough to the north. The Indonesian Throughflow, a warm-water current flowing from the Pacific into the Indian Ocean, crosses the north-western part of this LME and plays a vital role in driving the world's climate system, carrying up to 10,000,000 cubic meters per second from the Pacific Ocean into the Indian Ocean. The Throughflow is of particular importance to Australia since it helps warm the sea surface of the Indian Ocean and is a major driver of climate in northern Australia. The region has a monsoonal climate and tropical cyclones are common seasonal events. A report pertaining to this LME is given by UNEP (2003).

I. Productivity

The North Australian Shelf LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}), although offshore areas are more oligotrophic (Rothlisberg et al., 1994). Northern Australian waters are dominated by picoplankton-sized cyanobacteria, although the large colony-forming N-fixing cyanobacterium Trichodesmium is often abundant in these waters. Nutrient discharge from rivers is restricted to the summer wet season and is highly variable within and between years. Tidal mixing is a major contributor to the nutrient dynamics of this generally shallow LME. Bottom friction acts in a manner analogous to wind stress on the surface to mix the water column. Monsoonal winds and tropical cyclones also contribute to nutrient enrichment of shelf waters in this LME. Well-developed mangrove creeks occur along much of the coastline which is characterized by fine sediment and low relief. Tropical cyclones have a pronounced effect on the continental shelf and on the coastal ecosystems. The episodic rainfall that accompanies cyclonic weather systems can be a major source of freshwater to the region, causing widespread flooding. Supra-tidal mud flats are found along coastal areas throughout the region, particularly the arid and dry-tropical coastline in areas of low relief of the southern Gulf of Carpentaria. These flats concentrate salt and nutrients for extended periods following tidal inundations and rainfall, then release salty, nutrient-laden water into the coastal zone (Wolanski and Ridd, 1990). The quantitative contribution of these processes to the coastal zone is not well known.

Temperature and salinity measurements of the Indonesian Throughflow and the South Equatorial Current which flow into the LME region were made as part of the World Ocean Circulation Experiment. Volumetric estimates of the Indonesian Throughflow are still not well constrained, but are known to vary with large-scale climate variability processes such as ENSO. Surface waters in the Timor and Arafura Seas are generally lower in salinity than adjacent oceanic waters due to higher precipitation. High salinities can occur in many coastal areas due to enhanced evaporation, particularly at the end of the dry season. For information on the marine environment around Australia, see CSIRO (2007). A general description of oceanographic processes affecting the nutrient dynamics and productivity of Australian marine ecosystems is given in the State of the Environment Report (www.ea.gov.au/index.html). For more information on productivity, see Furnas (2002) and Rothlisberg et al. (1994).

Oceanic fronts (Belkin and Cornillon, 2003; Belkin et al., 2009): The Gulf of Carpentaria is the largest physiographic province within this LME and is surrounded by a major seasonal coastal front (Gulf of Carpentaria Front, GCF) (Figure VIII-13.1). The offshore Cape Arnhem Front (CAF) and Cape York Peninsula Front (CYPF) emerge seasonally near the northwest and northeast entrances to the Gulf, respectively. Farther west, the coastal Arafura Sea Front (ASF) is observed north of Arnhem Land, while the coastal Joseph Bonaparte Gulf Front (JBGF) develops in the southern part of the Timor Sea. In the past, a significant amount of pelagic fishing activity has been concentrated in the region of the Arafura Sea Front. These fronts are likely to play an important role in the ecology of commercially important prawns (Belkin and Cornillon 2003).

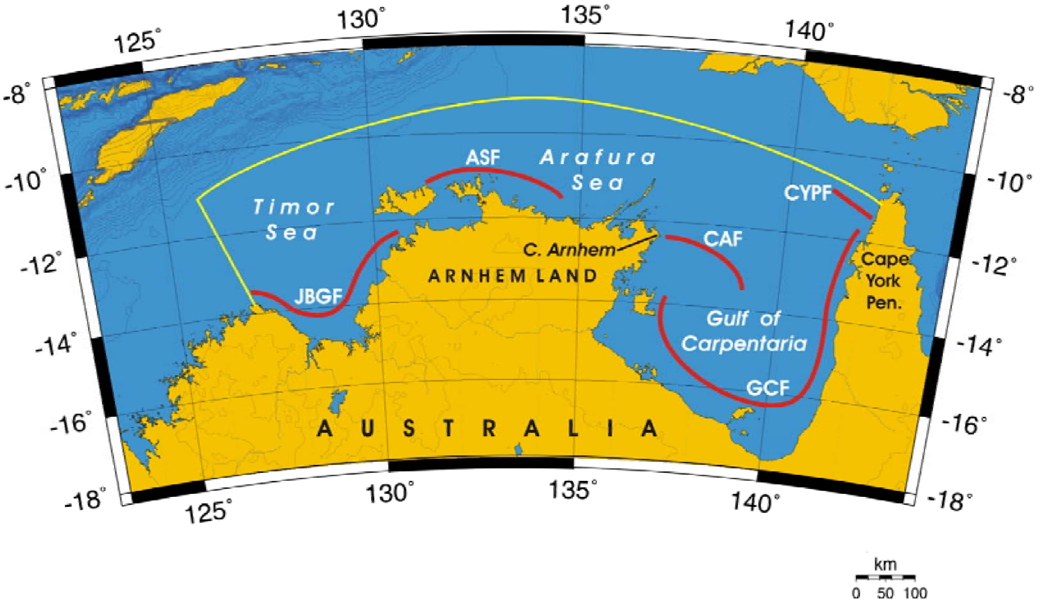

Figure VIII-13.1. Fronts of the North Australian Shelf LME. ASF; Arafura Sea Front; CAF, Cape Arnhem Front; CYPF, Cape York Peninsula Front; GCF, Gulf of Carpentaria Front; JBGF, Joseph Bonaparte Gulf Front. Yellow line, LME boundary. After Belkin et al. (2009) and Belkin and Cornillon (2003).

North Australian Shelf SST (after Belkin 2009)
Linear SST trend since 1957: 0.42°C.
Linear SST trend since 1982: 0.17°C.

Like the adjacent Indonesian Sea LME, the North Australian Shelf LME underwent a cooling that lasted through 1977, after which SST rose steadily (Figure VIII-13.2). The observed similarity of thermal histories of these LMEs is expected since the North Australian Shelf is oceanographically connected to the Indonesian Sea by the Indonesian Throughflow. The all-time minimum of 1976-77 is similar to the 1976 all-time minimum observed in the Northwest Australian Shelf LME. The all-time maximum of 1998 coincided with the El Niño 1997-98 which had significant oceanographic impacts throughout the Indonesian Archipelago and along the western Australian coast. The warm event of 1988 occurred simultaneously with the Sulu-Celebes LME, Northeast Australian Shelf LME, East-Central Australian Shelf LME, and only a year later in the

Southeast Australian Shelf LME. The twin peaks of 1970-1973 occurred simultaneously in the adjacent Northeast Australian Shelf LME and the East-Central Australian Shelf LME, especially the warm event of 1973. Interannual variability of SST in this LME is substantial, partly explained by the very shallow upper mixed layer in the tropics.

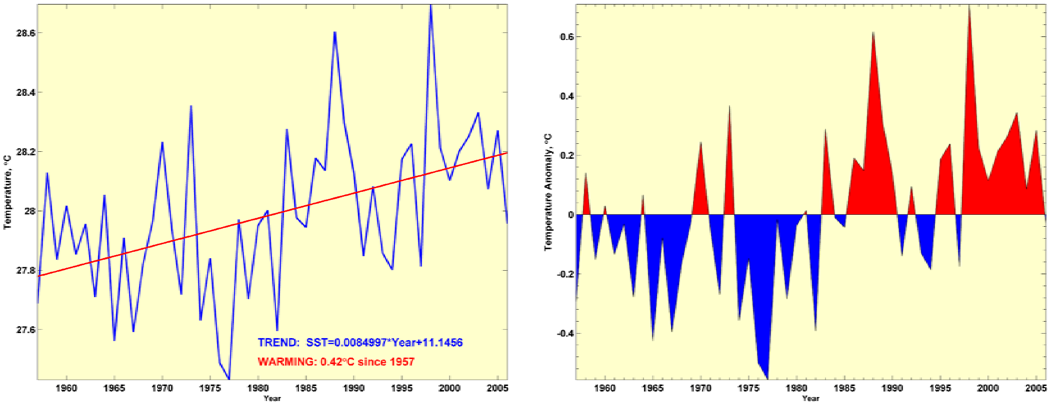

Figure VIII-13.2. North Australian Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2008).

***North Australian Shelf LME Chlorophyll and Primary Productivity*:** The North Australian Shelf LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}), although offshore areas are more oligotrophic (Rothlisberg et al., 1994). These estimates are largely based upon ocean color satellite imagery and the optical properties of northern Australian waters are poorly characterized at present.

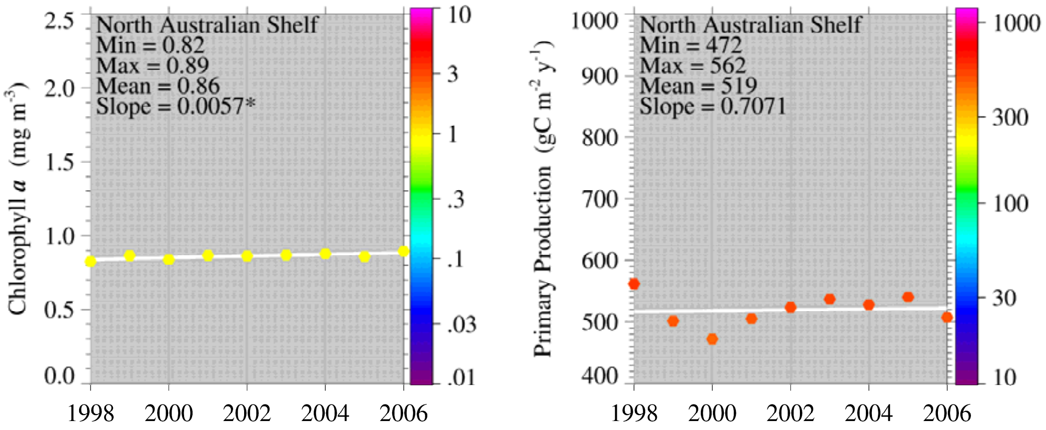

Figure VIII-13.3. Estimated North Australian Shelf trends in chlorophyll *a* (left) and primary productivity (right) from ocean color imagery, 1998 – 2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O Reilly and K. Hyde.

II. Fish and Fisheries

Fish stocks in the North Australian Shelf LME are small but diverse. The level of endemism in the northern Australian LMEs is low, with most species distributed widely in the Indo-West Pacific region. Commercially fished species in the LME include northern prawns (Gulf of Carpentaria and Joseph Bonaparte Gulf), threadfin bream, skipjack tuna, Indo-Pacific anchovies, mud crab, barramundi, salmon, shark, Spanish mackerel, as well as snappers and reef fish. About half of the reported landings consist of mixed taxa (Figure VIII-13.4). In the Arafura Sea and Gulf of Carpentaria, the prawn fishery is almost fully exploited. Crustaceans and molluscs dominate the catch, particularly in the Gulf of Carpentaria where prawns are targeted. Shark populations have been significantly depleted as a result of the shark fin fishery. Information on Australia's fisheries is provided by FAO (www.fao.org/fi/FCP/FICP_AUS_E.ASP). Total reported landings grew steadily to ~87,000 tonnes in 2004 (Figure VIII-13.4). The value of the reported landings showed a general increase, with a maximum value of just under US$300 million (in 2000 US dollars) in 2001 (Figure VIII-13.5). Penaeid shrimps and tuna are the two most important groups in terms of value.

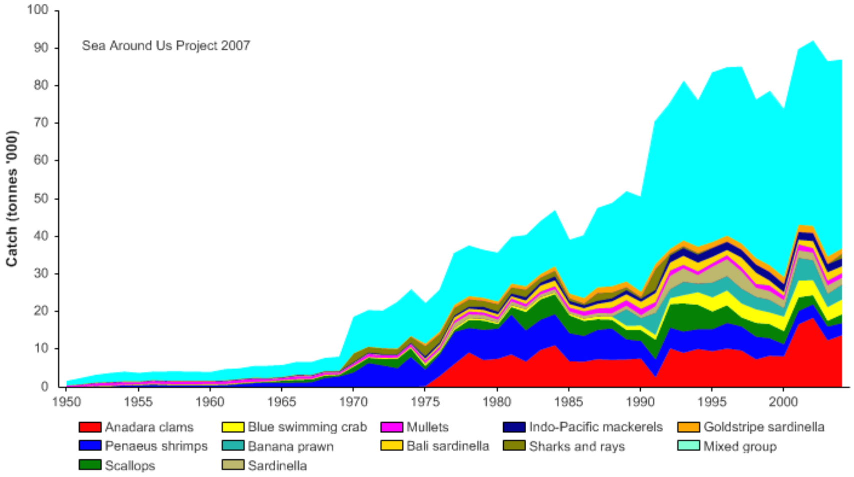

Figure VIII-13.4. Total reported landings in the North Australian Shelf LME by species (Sea Around Us 2007).

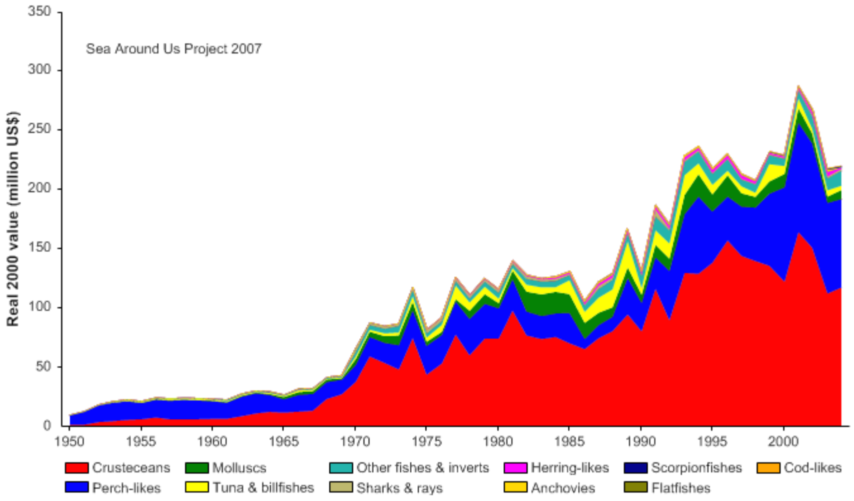

Figure VIII-13.5. Value of reported landings in the North Australian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is still below 2%--much lower than other LMEs of comparable characteristics (Figure VIII-13.6) although this is not surprising given the high rates of *in* *situ* recycling. Australia, Indonesia and Thailand account for the largest share of the ecological footprint in the LME.

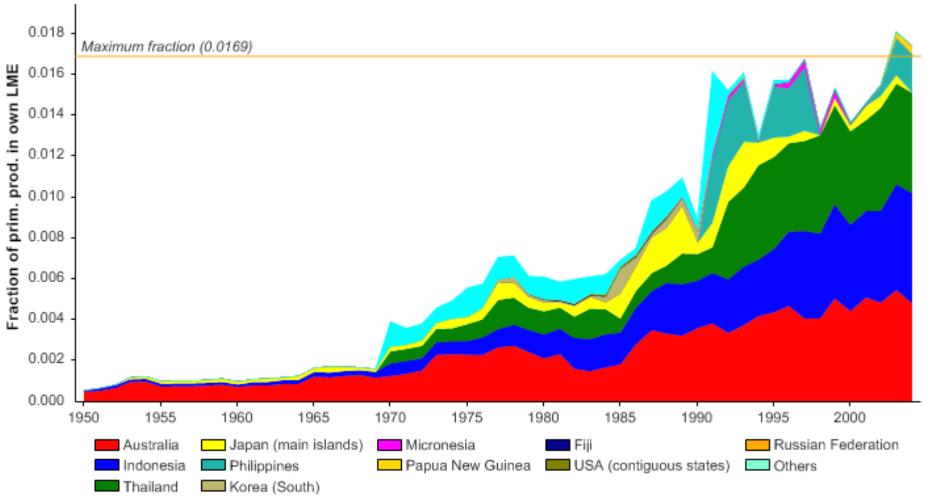

Figure VIII-13.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the North Australian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The long term trend of the mean trophic level (i.e., the MTI; Pauly & Watson 2005) for this LME is one of a decline from 1950 to the mid 1980s (Figure VIII-13.7, top), indicating a 'fishing down' of the food web (Pauly *et al.* 1998); followed by an increase, which coincides with the increased landings of tuna and other large pelagic species. The pattern is confirmed by the FiB index (Figure VIII-13.7, bottom), which also suggests a steady expansion (Pauly & Watson 2005).

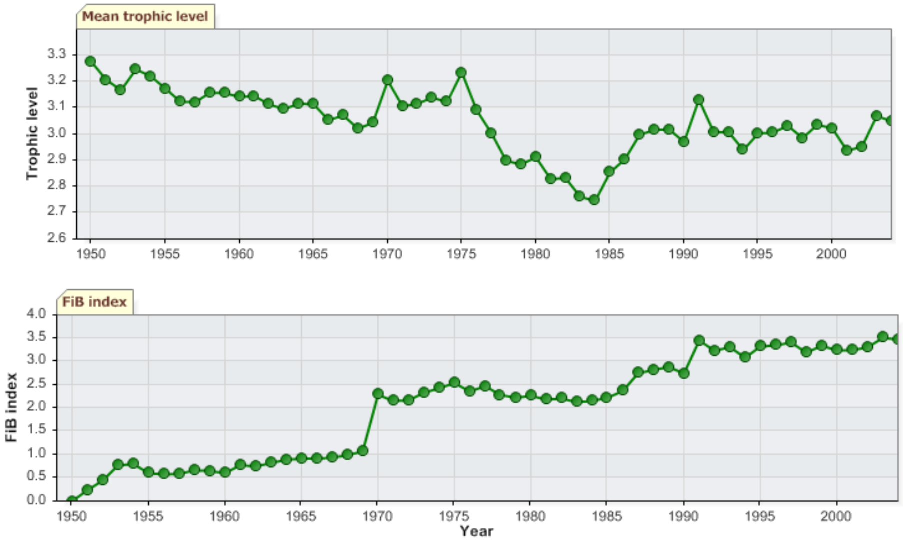

Figure VIII-13.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the North Australian Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that only a few of the exploited stocks can be considered collapsed or overexploited (Figure VIII-13.8, top). The majority of the reported landings come from fully exploited stocks (Figure VIII-13.8, bottom).

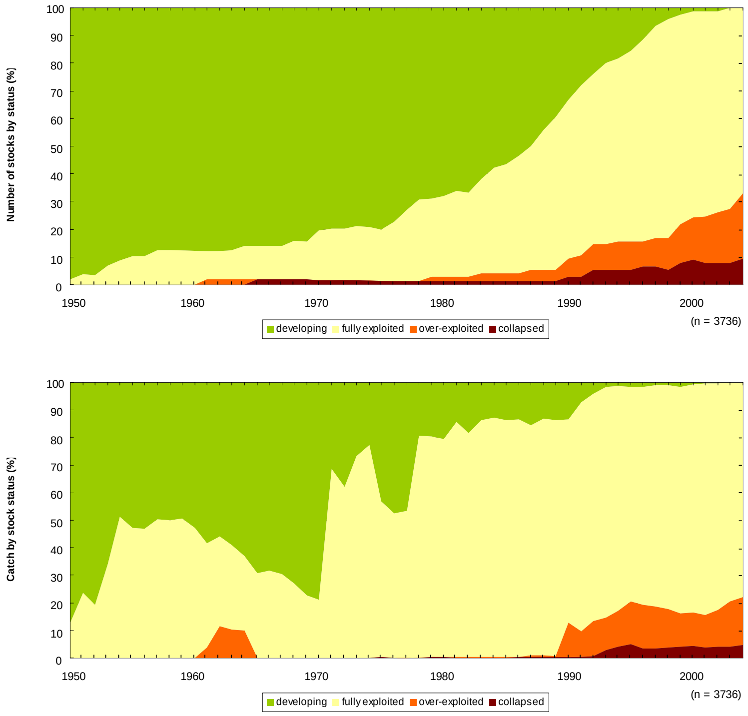

Figure VIII-13.8. Stock-Catch Status Plots for the North Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

The LME is threatened by an increase in shipping, mining activity in adjacent watersheds and by the production and transportation of oil and other hydrocarbons. Ships empty of cargo that enter the ports of northwest Australia are ballasted with water collected in the last port of call. This ballast water has been shown to contain organisms including bacteria, viruses, algal cells, plankton and the larval forms of many invertebrate and fish species. One significant introduction of an exotic mollusc (Zebra mussel) was found and contained at an early stage in one coastal port. The source was either a small fishing vessel or yacht. There are accidental discharges of contaminants through spills and shipping accidents. The dominant human impacts are related to fisheries and terrestrial runoff from deforestation, overgrazing by livestock, and certain agricultural practices. Compared with most countries, however, these impacts are quite modest. For more information on marine pollution in this LME, see Environment Australia (www.ea.gov.au) and a technical paper from EA on marine disturbances.

IV. Socioeconomic Conditions

Many residents are involved in the marine-related sectors of the economy. There are economically significant aquaculture activities, at a number of coastal sites, based on oyster pearls, and to a much lesser extent, prawns. Industry (mining, oil and gas extraction), shipping and tourism are major economic activities. Marine and coastal-based forms of tourism are important both in terms of domestic and international tourism. A significant proportion of the local Australian population is involved in recreational fishing and boating. Tourists prize the coral reefs and the natural and largely unspoilt marine environment. There are, however, social, cultural, economic and environmental impacts caused by tourism. Tourism may affect the lifestyle of residents in ways they perceive as intrusive. Australia's Aborigines, and the Torres Strait Islanders who occupy parts of the far northeast of the land area, have traditionally made considerable use of reef and coastal resources. The FAO (see website above) provides information on the characteristics and socioeconomic benefits of Australia's fishing industry.

V. Governance

The North Australian Shelf LME lies off the coast of the states of Western Australia, Northern Territory and Queensland. Some governance issues in this LME pertain to the Aboriginal coastal populations, who have considerable rights regarding their traditional use of coastal habitats. However, coastal population densities throughout much of this region low. Australian fisheries resources are managed under both Commonwealth and State/Territory legislation. The demarcation of jurisdiction and responsibilities among these various governments has been agreed to under the Offshore Constitutional Settlement, under which the states and territories have jurisdiction over localised, inshore fisheries. The Commonwealth has jurisdiction over transboundary, foreign and offshore fisheries or those extending to waters adjacent to more than one state or territory. Each government has separate fisheries legislation and differing objectives. Under the Environment Protection and Biodiversity Conservation Act 1999, the Commonwealth Government now has a framework that helps it to respond to current and emerging environmental problems. An important goal is to ensure that the exploitation of fisheries resources is conducted in a manner consistent with the principles of ecologically sustainable development. This includes the need to assess the impact of fishing activities on non-target species and the long-term sustainability of the marine environment. Illegal and unlicensed fishing activity is a significant and ongoing problem in the region. By agreement with Indonesia, groups of Indonesian fishers retain rights to fish at a number of offshore island and reef sites using traditional craft and methods. For more information on the governance of Australia's fisheries, see the FAO website given above.

Reserves have been declared to help protect rocky shore habitats and marine life, provide opportunities for research and education conserve Australia's cultural heritage and help boost ecotourism. In 2001, a Government-held consultation process indicated strong community support to further protect these aquatic reserves. The marine tourism industry has produced a code of conduct that covers issues such as anchoring, removal of rubbish, fish feeding and the preservation of World Heritage values. Australia declared a 200-nautical-mile EEZ in 1978. The LME falls within the UNEP-administered East Asian Regional Seas Programme.

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VIII-14 Northwest Australian Shelf LME

M.C. Aquarone and M. Furnas

The Northwest Australian Shelf LME extends from Northwest Cape to the Timor Sea. It encompasses a wide area of about 900,000 km^2, of which 0.68% is currently protected in reserves, and contains 1.17% of the world's coral reefs and 0.02% of the sea mounts (Sea Around Us 2007). Topographical features such as the Exmouth Plateau, the Rowley Shelf and the Sahul Shelf are found in this LME, which is positioned on the path of the Indonesian Throughflow, a low-salinity warm-water current flowing from the Pacific into the Indian Ocean. The Timor Sea is characterized by warm surface temperatures year-round and generally lower salinities than in the adjacent Indian Ocean. The Indonesian Throughflow warms the LME's sea surface and increases rainfall over Western Australia. Rainfall is strongly seasonal, with a predictable summer wet season and recurrent seasonal cyclonic disturbances. Tropical cyclones are common summer (Nov-Apr) events that exert pronounced effects on the continental shelf and on the coastal marine ecosystems. The rainfall that accompanies cyclonic weather systems is a major source of freshwater to the region, causing widespread though episodic flooding. Menon (1998) and UNEP (2003) have published a book chapter, and a report, respectively, on this LME.

I. Productivity

The Northwest Australian Shelf LME is considered a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1}). This estimate is largely based upon satellite imagery of the region where relatively few direct productivity measurements have been made (Jitts, 1969; Furnas, 2007). In some areas most of the phytoplankton biomass and productivity has little or no surface expression (Furnas, 2007). Brief episodes of very high primary productivity (1-8 g C m^{-2} d^{-1}) have been recorded in the vicinity of North West Cape which are linked to localized upwelling against the narrow continental shelf and enhanced vertical mixing (Hansen et al., 2005; Furnas, 2007). Productivity at North West Cape is higher during ENSO periods when transport in the Leeuwin Current is reduced. The LME supports diverse phytoplankton including the normally dominant picoplankton, but regionally or episodically, populations of diatoms or Trichodesmium can dominate. Temperature and salinity measurements of the Indonesian Throughflow and the South Equatorial Current were made as part of the World Ocean Circulation Experiment. More information is provided at www.marine.csiro.au.

The LME is characterised by high-energy and internal wave tidal regimes. Surface spring tides can reach 8 m at coastal sites in the Kimberly region of NW Australia (e.g. Broome). The sub-surface regime along the continental slope is also characterized by well-developed and persistent internal tides and internal waves generated by interactions between tidal currents and local bathymetry. These waves typically break on the mid-shelf, leading to enhanced vertical mixing. Tidal mixing is a major contributor to nutrient dynamics. Bottom friction acts in a manner analogous to wind stress on the surface to mix the water column and resuspend sediment and organic material from the bottom. Shelf upwelling and cyclonic disruptions also contribute to nutrient inputs in this LME. Because of the high levels of mixing and resuspension, the continental shelf supports a diverse demersal fish community. For a general understanding of oceanographic processes affecting nutrient dynamics and the productivity of Australian marine ecosystems, see the State of the Environment Report (www.ea.gov.au/index.html) and Furnas (2002).

Oceanic fronts: (Belkin et al. 2009) This vast shelf is the source area of the Leeuwin Current that flows poleward along the west coast of Australia carrying warm and low-density tropical waters far south. Seasonal evolution of the frontal pattern over this shelf is somewhat similar to that west of Northwest Africa and west of the U.S. West Coast. Variations in the strength of the Leeuwin Current are linked to changes in sea level in the western Pacific Ocean and the strength of the Indonesian Throughflow. Year-to-year variations in flow have a strong influence on the productivity and fisheries yield along the western Australian coast. In summer, a multitude of small-scale fronts develops that form a chaos-like spatial pattern. As the season progresses, these small-scale fronts apparently coalesce into large-scale (hundreds km long) coherent filaments that persist for weeks and months. Tidal mixing over this shelf is deemed important, although no stable tidal mixing fronts have been detected within this LME.

Northwest Australian Shelf SST (Belkin, 2009)
Linear SST trend since 1957: 0.42°C.
Linear SST trend since 1982: 0.24°C.

This LME is interesting in that its interannual and decadal variability are small compared with other LMEs (Figure VIII-14.2). Indeed, the magnitude of interannual and decadal variability in temperature is less than 0.5°C. The only significant warm event, the all-time maximum of 1998, was associated with the El Niño 1997-98. The cold event of 1976, when SST anomaly was about -1°C relative to the long-term trend, can be associated with the cold event of 1976-77 in the North Australian Shelf LME. This is a rare example of a large signal confined to just two contiguous LMEs that comprise a relatively small area. Another cold signal, of 1968, was likely advected from the Indonesian Sea LME, where a cold event occurred in 1967. The proposed advection route is consistent with the circulation pattern (Feng et al. 2003).

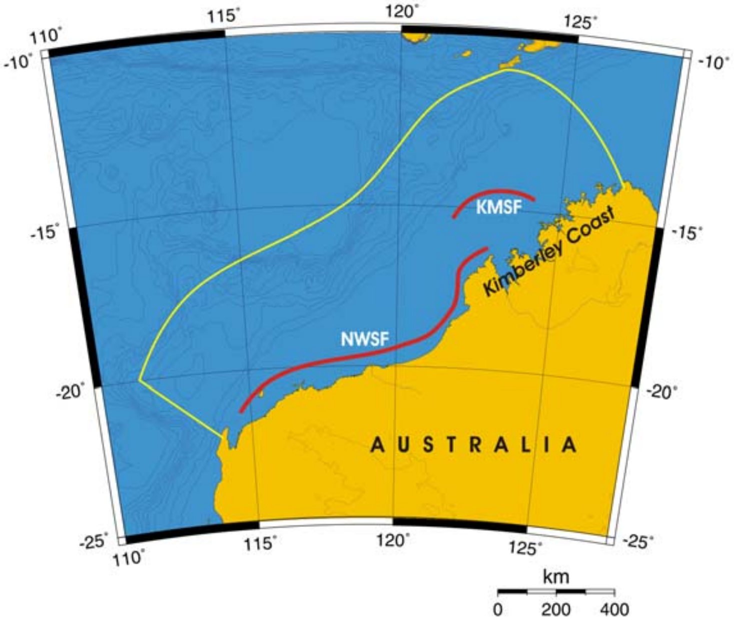

Figure VIII-14.1. Fronts of the Northwest Australian Shelf LME. KMSF, Kimberley Mid-Shelf Front; NWCF, Northwest Coastal Front. Yellow line, LME boundary. After Belkin et al. (2009).

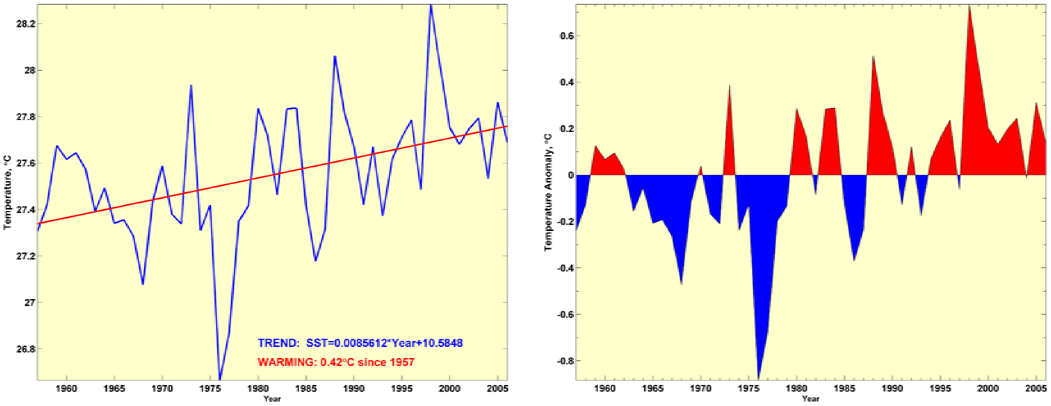

Figure VIII-14.2. Northwest Australian Shelf LME annual mean SST (left) and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Northwest Australian Shelf LME Chlorophyll and Primary Productivity: The Northwest Australian Shelf LME is considered a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1}).

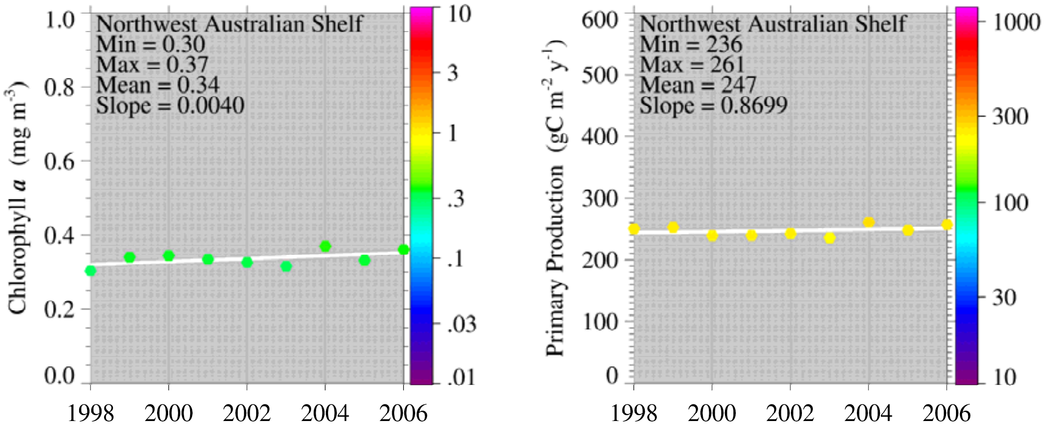

Figure VIII-14.3. Estimated Northwest Australian Shelf trends in chlorophyll *a* (left) and primary productivity (right), 1998 – 2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde.

II. Fish and Fisheries

Northwest Australian shelf waters are relatively nutrient-poor and unable to sustain large fish populations. The level of endemism in northern Australian LMEs is low, with most species distributed widely in the Indo-West Pacific region. Seasonal aggregations of plankton feeding whale sharks and manta rays occur off Ningaloo Reef, which begins at North West Cape. This LME once supported an extensive pearl shell fishery along the coast. Following depletion of stocks, this fishery has been replaced by a harvesting and grow-out aquaculture industry at a number of sites along the coast. This LME and the adjacent Northern Australian Shelf LME are major suppliers of large pearls to the international market. A small prawn fishery is located in the southern part of the LME, principally in Exmouth Gulf, near North West Cape. Reef fisheries occur in the Rowley

Shoals, Scott Reef and Ashmore Reef, a chain of coral atolls at the edge of the LME's wide continental shelf. The former site is a marine reserve. The latter two sites are primarily fished by traditional Indonesian fishermen using traditional boats, methods and gear. Demersal species fished in this LME include *Lethrinus*, *Nemipterus*, *Saurida* and *Lutjanus*, which historically have been fished by foreign fleets. Small domestic trap fisheries for *Lethrinus*, *Lutjanus* and *Epinephelus* exist in areas subjected to little trawling. Other exploited groups include *Anadara* clams, scallops and goldstripe sardinella, as well as a significant number of unidentified taxa (Figure VIII-14.4). Fishing for shark fins in the northern part of the LME has greatly depleted shark populations. FAO provides information on Australia's fisheries industry (www.fao.org). Total reported landings show a series of peaks in the 1990s over 50,000 tonnes with a record landings of 61,000 tonnes in 1999 (Figure VIII-14.4). From the early 1990s to 2004, the value of the catch increased sharply, then fluctuated between US$80 million and US$140 million (in 2000 US dollars; Figure VIII-14.5).

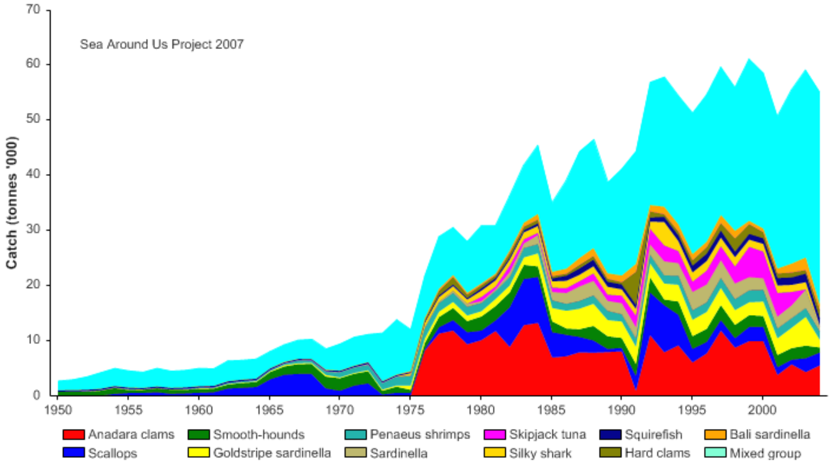

Figure VIII-14.4. Total reported landings in the Northwest Australian Shelf LME by species (Sea Around Us 2007).

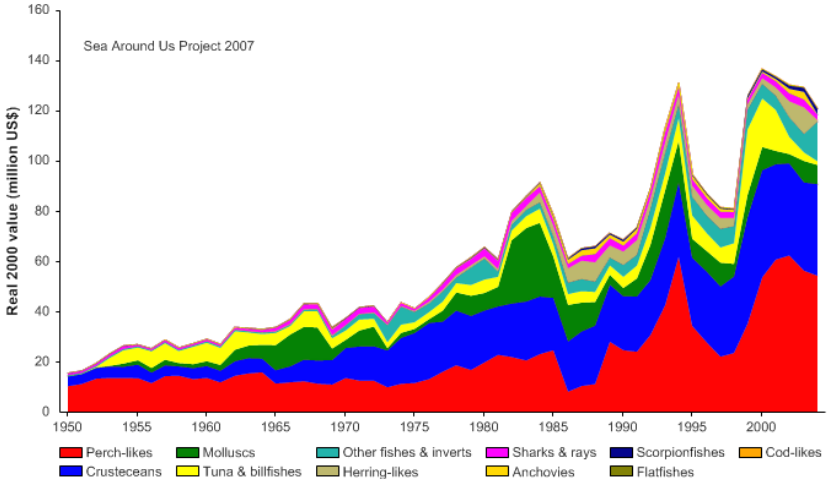

Figure VIII-14.5. Value of reported landings in the Northwest Australian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME has reached 2.5% in the 1990s with Australia and Indonesia accounting for the largest share of the ecological footprint (Figure VIII-14.6).

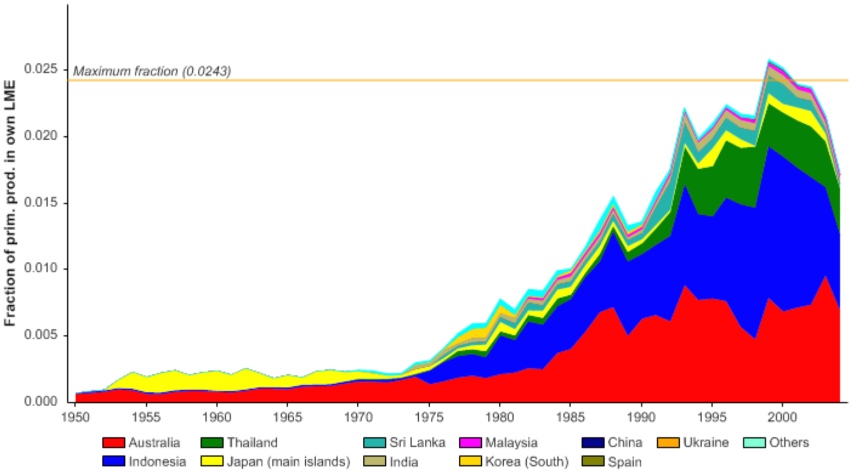

Figure VIII-14.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Northwest Australian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Since the mid 1980s, both the mean trophic level (i.e. the MTI; Pauly & Watson 2005; Figure VIII-14.7, top) and the FiB index (Figure VIII-14.7, bottom) showed an increase, likely a result of geographic expansion of the fisheries and targeting of large and medium pelagic species.

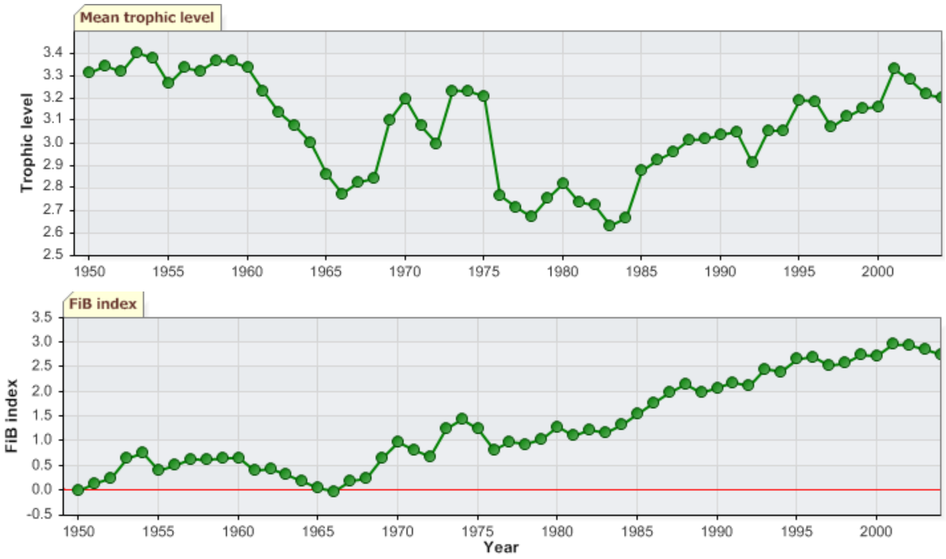

Figure VIII-14.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Northwest Australian Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that approximately 50% of the stocks have collapsed or are overexploited in the LME (Figure VIII-14.8, top). The reported landings are largely supplied by fully exploited stocks (Figure VIII-14.8, bottom).

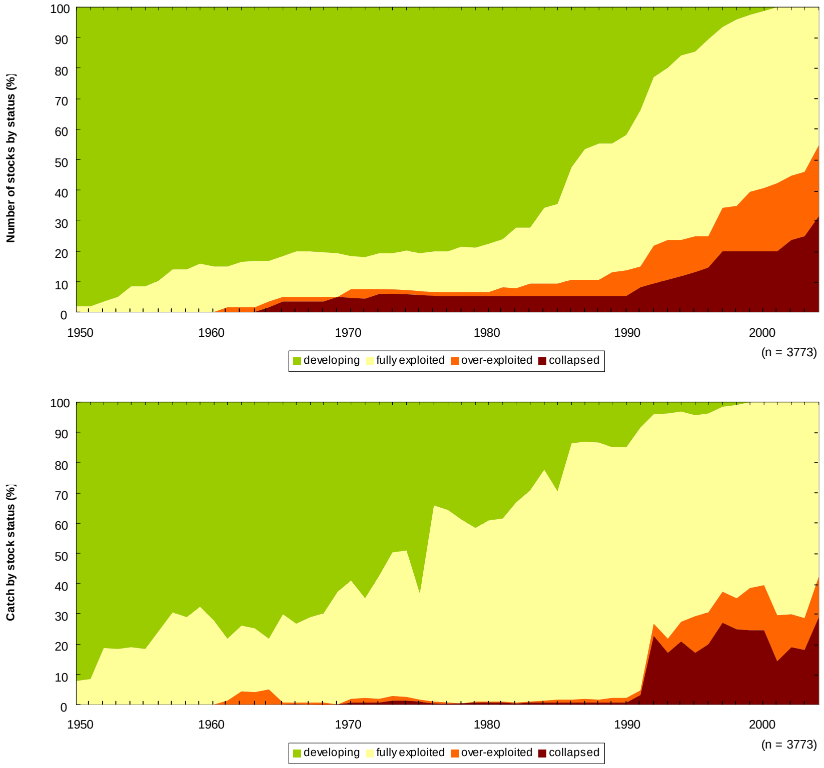

Figure VIII-14.8. Stock-Catch Status Plots for the Northwest Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

The LME is threatened by an increase in shipping and the development of extensive offshore oil and gas deposits. The shelf and adjacent continental region are a major international source of iron ore, other minerals, ammonium, liquefied natural gas and other petroleum products. These exports are likely to increase for the foreseeable future. Ships empty of cargo (chiefly iron ore and LNG) that enter the ports of Northwest Australia are ballasted with water collected in the last port of call. This ballast water has been shown to contain organisms including bacteria, viruses, algal cells, plankton, and the larval forms of many invertebrates and fish. There are accidental discharges of contaminants through spills and shipping accidents. This LME's coastal marine parks, home to a variety of plants, corals, fishes and marine mammals, are impacted to varying degrees by tourism. In general, numbers of tourists are still relatively low due to the remote nature of much of this LME and its bordering land mass and effects are largely localized. There is pressure, however, for increased development of tourism infrastructure. Activities associated with recreational fishing, SCUBA diving and boating have the potential to affect the coastal environment around regional towns through pollution of the water by boats and the disturbance of species and habitats. Recreational fishermen tend to target reef ecosystems and remove larger predatory species. The effects of this selective removal of fish are largely unknown. A significant source of environmental impacts is the provision of infrastructure to support the oil and gas, and mining industries and to a lesser extent, tourism (airports, power generation facilities, accommodation, sewage treatment and disposal facilities, moorings and marine transport). This infrastructure is expanding rapidly and being located in fragile or pristine environments that are susceptible to disturbance and fragmentation. For more information, see Environment Australia for marine (www.ea.gov.au/soe/) and coastal pollution (www.ea.gov.au/coasts) issues, and the State of the Environment Report (www.ea.gov.au/SOE).

IV. Socioeconomic Conditions

FAO provides information on the characteristics and socioeconomic benefits of Australia's fishing industry (www.fao.org/fi/FCP/FICP_AUS_E.ASP). There has been exploration for oil and natural gas. A number of significant gas, and to a lesser extent, oil fields have been discovered and large-scale development of these fields is being undertaken at a range of sites (Scott Reef, Barrow Island, Dampier), principally to support exports of LNG. Hydrocarbon production and export is expected to be a significant economic activity within the region, requiring extensive infrastructure development and growing regional populations. Industry, shipping and tourism are major economic activities. Marine and coastal-based tourism is a relatively small-scale activity but important both in terms of domestic and international tourism. Some tourism activities (e.g. whale shark watching at Ningaloo Reef) are directly dependent upon marine resources and conservation activities in other LMEs.

V. Governance

The Northwest Australian Shelf LME lies off the coast of the state of Western Australia, close to Indonesia. Some governance issues in this LME pertain to fisheries management and to the establishment of marine reserves (including Ningaloo Marine Park). Indonesian fishermen using traditional craft and methods are allowed to fish at designated sites at the northern end of this LME. After examining several possible management regimes for this LME, the government of Australia divided the area into three zones and closed two of them to trawling. It is thought that there will be an expansion of trap fishing in the two closed areas after the species composition changes induced by trawling are reversed. See the North Australian Shelf LME for information on fisheries and tourism governance. The LME falls within the UNEP-administered East Asian Regional Seas Programme.

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VIII-15 South China Sea LME

S. Heileman

The South China Sea LME is bordered by China, Indonesia, Malaysia, Philippines, Taiwan and Vietnam. It covers an area of 3.2 million km^2, of which 0.31% is protected, and contains 7.04% and 0.93% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). Coastal waters are relatively shallow (less than 200 m) and are influenced by marine as well as by river and terrestrial inputs. The South China Sea Basin and Palawan Trough are deeper than 1,000 m. Numerous rivers (120) drain a total catchment area of 2.5 million km^2 into the LME. Most of the region lies within the sub-tropical and equatorial zones and the climate is governed by the northeast and southwest monsoon regimes. The northern and central parts of the region are affected by typhoons during the southwest monsoon months, bringing intense rains and destructive winds to coastal areas. This LME is particularly sensitive to ENSO, which has caused significant changes in rainfall patterns, for example, in Indonesia and Malaysia. Major oceanographic currents include those generated by the seasonal monsoons. Waters from the LME may flow seasonally into the Sulu Sea and Java Sea, contributing to the Indonesian Throughflow. The component subsystems of this LME have been documented in Pauly & Christensen (1993). Other reports pertaining to this LME are listed in the references (see also Talaue-McManus 2000, UNEP 2005).

I. Productivity

The South China Sea LME is a biologically diverse marine ecosystem with a tropical climate. It is considered a Class II, moderate production ecosystem (150-300 gCm^{-2}yr^{-1}). The Indo-West Pacific marine biogeographic province, which includes the South China Sea LME, is well-recognised as a global centre of marine shallow-water, tropical biodiversity (Spalding *et al*. 1997, Tomascik *et al*. 1997). Over 450 coral species have been recorded from the Philippines. Recent estimates suggest that approximately 2 million ha of mangrove forest or 12% of the world total are located in the countries bordering the South China Sea LME (Talaue-McManus 2000). Six species of marine turtles, all considered as either Endangered or Vulnerable by the IUCN, the dugong and several other species of marine mammal included on IUCN's Red List of Threatened Animals occur in this LME. Many of these exhibit transboundary migratory behaviour, which presents major challenges for their conservation.

Oceanic fronts: Fronts observed within this LME (Figure VIII-15.1) are quite diverse (Belkin & Cornillon 2003). The South China Inner Shelf Front (SCISF) and South China Outer Shelf Front (SCOSF) extend along southern China coast from Hainan Island into Taiwan Strait. The Gulf of Tonkin Front (GTF) is of the estuarine origin; the salinity differential across this front is controlled by a massive river discharge into the Gulf, mostly by the Red River. The Vietnam Coastal Front (VCF) is largely caused by wind-induced coastal upwelling and is thus strongly monsoon-dependent. The West Luzon Front (WLF) appears as a relatively broad frontal zone southwest of the Luzon Strait; it is likely caused by the inflow of the Pacific waters; the wind-induced upwelling also contributes to frontal maintenance.

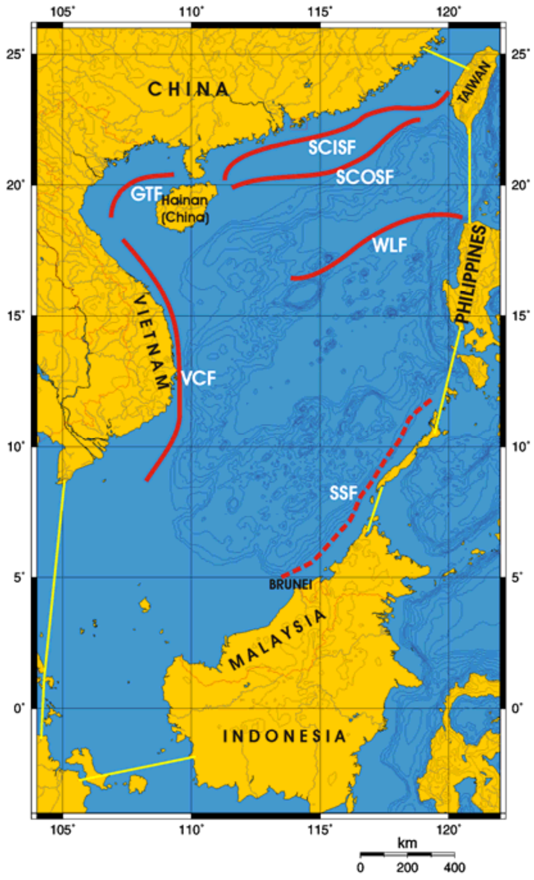

Figure VIII-15.1. Fronts of the South China Sea LME. GTF, Gulf of Tonkin Front; SCISF, South China Inner Shelf Front; SCOSF, South China Outer Shelf Front; SSF, Shelf-Slope Front (the most probable location); VCF, Vietnam Coastal Front; WLF, West Luzon Front. Yellow line, LME boundary. After Belkin et al. (2009) and Belkin and Cornillon (2003).

South China Sea SST (Belkin, 2009)
Linear SST trend since 1957: 0.80°C.
Linear SST trend since 1982: 0.44°C.

The thermal history of the South China Sea (Figure VIII-15.2) is strongly correlated with the Gulf of Thailand LME and largely decorrelated from other neighboring LMEs. The all-time maximum of 1998 is an exception since this event was linked to the global El Niño 1997-98. Interannual and decadal variability in the South China Sea are relatively small. The observed stability of the South China Sea can be partly explained by the existence of the so-called South China Warm Pool (Li et al., 2007); such warm pools are known to be relatively stable owing to anticyclonic circulations that enclose them; a good example of a large-scale warm pool is a gyre in the western part of the Sargasso Sea. The South China Warm Pool changes seasonally and interannually (He et al., 2000): it grows in summer and shrinks and retreats to the southwest in winter, and it is modulated by the ENSO (El Niño-Southern Oscillation).

A recent study of the ERA-40 reanalysis and other data sets, including HadISST and SODA (Simple Ocean Data Assimilation), has shown that "due to the impact of global climate warming, the winter and summer monsoon flows became weak over the offshore area of China and its adjacent ocean after 1976, which caused the weakening of winter and summer sea surface wind stresses, especially the meridional sea surface wind stresses, and obvious increase of SST in the area." (Cai et al., 2006, p. 239).

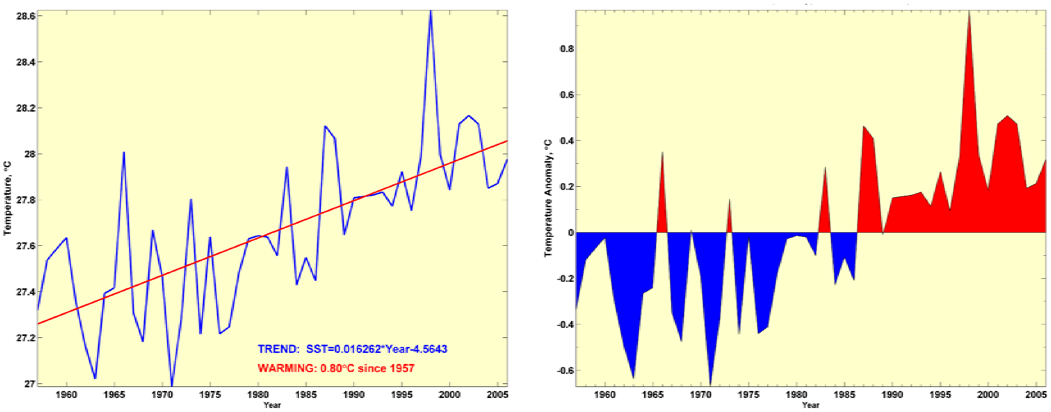

Figure VIII-15.2. South China Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

South China Sea LME Chlorophyll and Primary Productivity**: South China Sea LME** is considered a Class II, moderate production ecosystem (150-300 gCm^{-2}yr^{-1}).

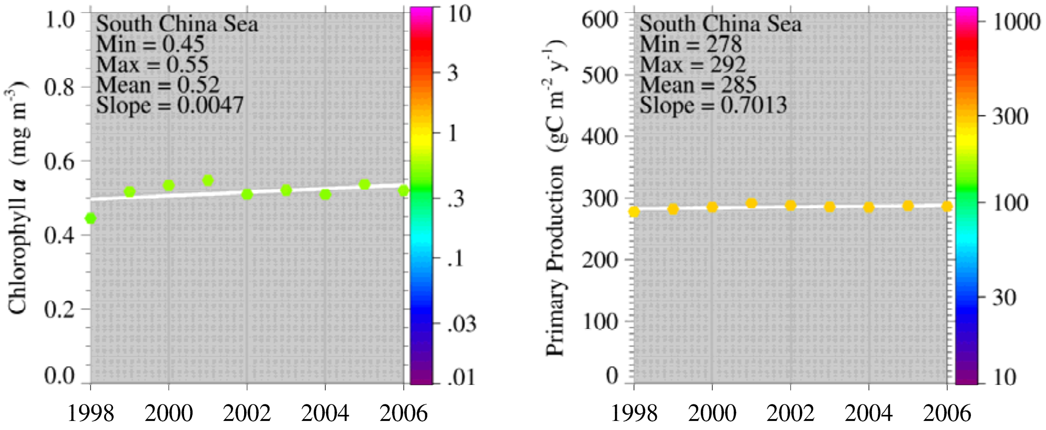

Figure VIII-15.3. South China Sea trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

I. Fish and Fisheries

Reported landings from the South China Sea LME are in the order of 6 million tonnes (Figure VIII-15.4), although substantial uncertainty is associated with these figures. The marine fisheries are important to the food security and economy of the bordering countries and targeted groups include flying fishes, tunas, billfishes, mackerels and sharks for the pelagic species, and a large array of demersal fish and invertebrates, especially penaeid shrimps. There is also a high percentage of reef fish and other small coastal pelagic fishes such as herring, sardine and anchovy in the landings. Like adjacent LMEs, the status and future viability of fish stocks of this LME are not well understood, and there are significant gaps in the available data with many fisheries that may be classified as Illegal, Unreported and Unregulated (IUU; UNEP 2005). The steady increase of the reported landings, from 600,000 tonnes in 1950 to over 6 million tonnes in 2004 (Figure VIII-15.4) is primarily due to a significant increase in the landings of unidentified fishes (included in 'mixed group'), which account for two-third of the landings in recent years. In general, a high proportion of unidentified catches in landings statistics is a symptom of deficiencies in a reporting system, and therefore, we should be wary of the large, continuous increases reported in this LME. Due to the large increase in the reported landings, the value of the landings also rose steadily, reaching US$6 billion (in 2000 US dollars) in the early 2000s (Figure VIII-15.5).

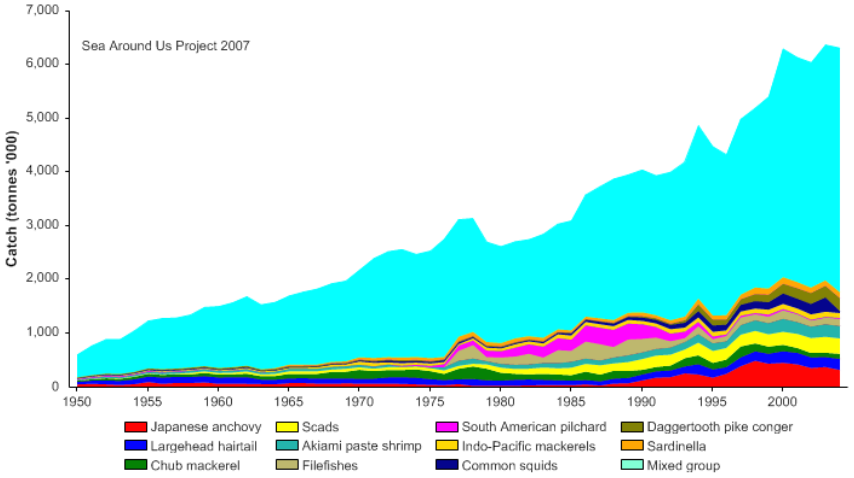

Figure VIII-15.4. Total reported landings in the South China Sea LME by species (Sea Around Us 2007).

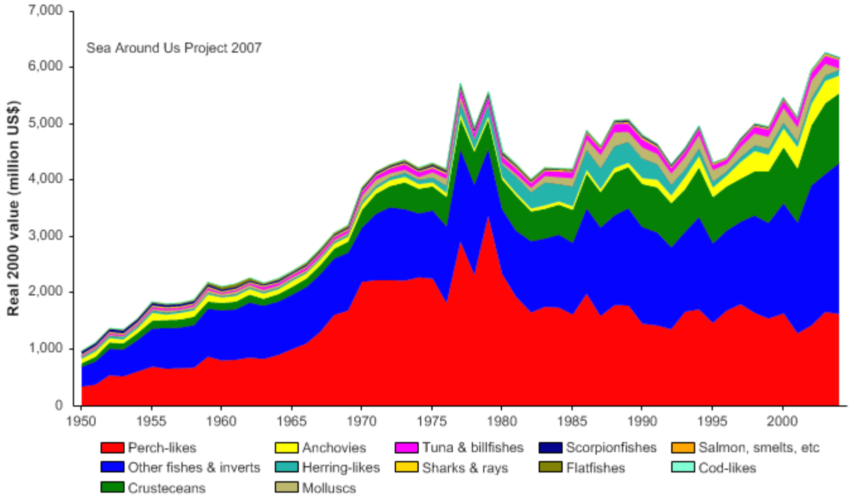

Figure VIII-15.5. Value of reported landings in South China Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is increasing with the reported landings, and is presently over 60% of the observed primary production (Figure VIII-15.6)--yet another indication that the reported landings from this LME may be unrealistically high. China accounts for the largest share of the ecological footprint in this LME.

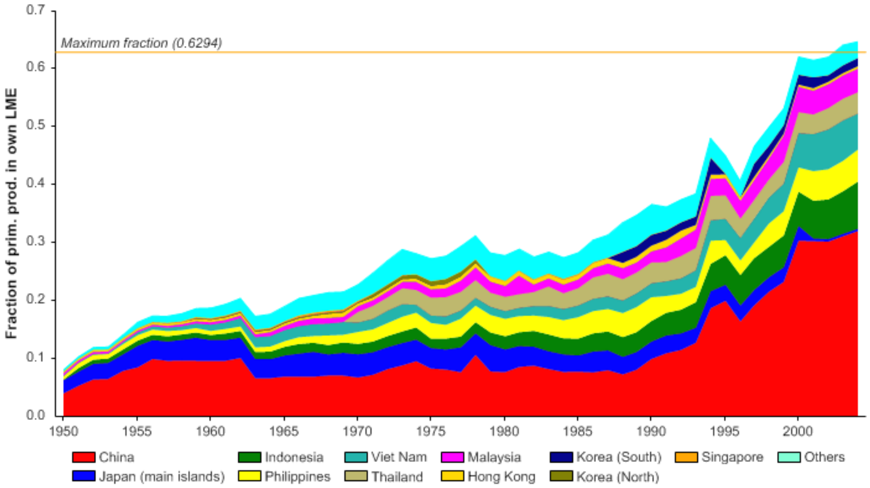

Figure VIII-15.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the South China Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The trends of both the mean trophic level (i.e., the MTI; Pauly & Watson 2005; Figure VIII-15.7 top) and the FiB index (Figure VIII-15.7 bottom) until the mid-1980s are both suggestive of a 'fishing down' in the food web (Pauly *et al.* 1998) with a limited geographic expansion of fisheries with the MTI declining and and the FiB index showing a limited increase.

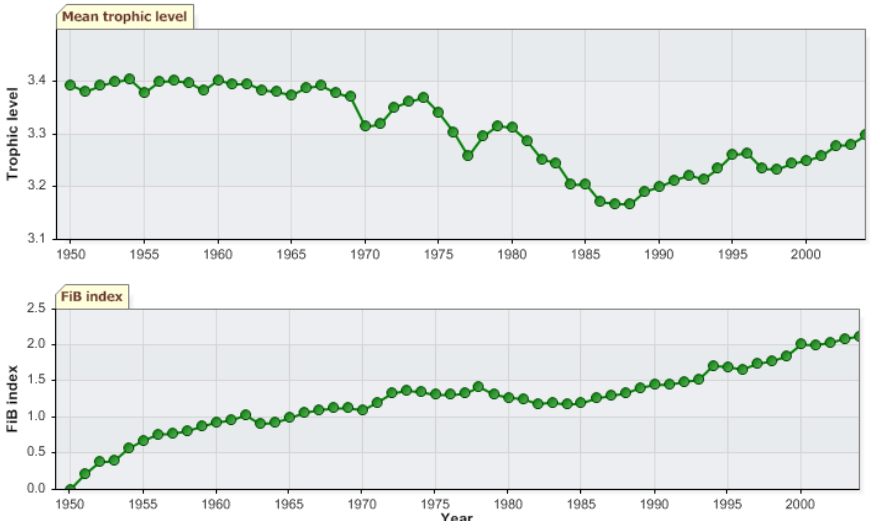

Figure VIII-15.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the South China Sea LME (Sea Around Us 2007).

The trends of these indices from the mid-1980s on, however, is hard to interpret, as the increase in the MTI does not seem to be caused by development of high trophic fisheries such as tuna fisheries (time series of the MTI without tuna catches can be examined at www.seaaroundus.org). Another, more likely explanation for such trends is that the landings statistics for the LME include either catches made outside the LME or exaggerated values. This would also explain why the PPR for the fisheries in the LME is improbably high (Figure VIII-15.6). The Stock-Catch Status Plots indicate that about 40% of the stocks in the LME are collapsed or overexploited (Figure VIII-15.8, top), however, with the majority of the catches supplied by fully exploited stocks (Figure VIII-15.8, bottom). Such diagnosis is probably optimistic, and is again likely a result of the high degree of taxonomic aggregation in the underlying statistics.

While masked in recent years, 'fishing down' of the food web is widespread in most, if not all, countries of the South China Sea LME (UNEP 2005). Moreover, catch per unit effort in most fisheries has declined steadily, an indication of severe overexploitation. The increase was accompanied by a change in the major species in the catch, an indication of massive selective fishing pressure (Yanagawa 1997). Intensive fishing is the primary driving force of biomass change in this LME (Sherman 2003). The South China Sea TDA has identified loss of fisheries productivity as a major transboundary issue (Talaue-McManus 2000) and most of the conventional species have been fully exploited at the basin level (Yanagawa 1997).

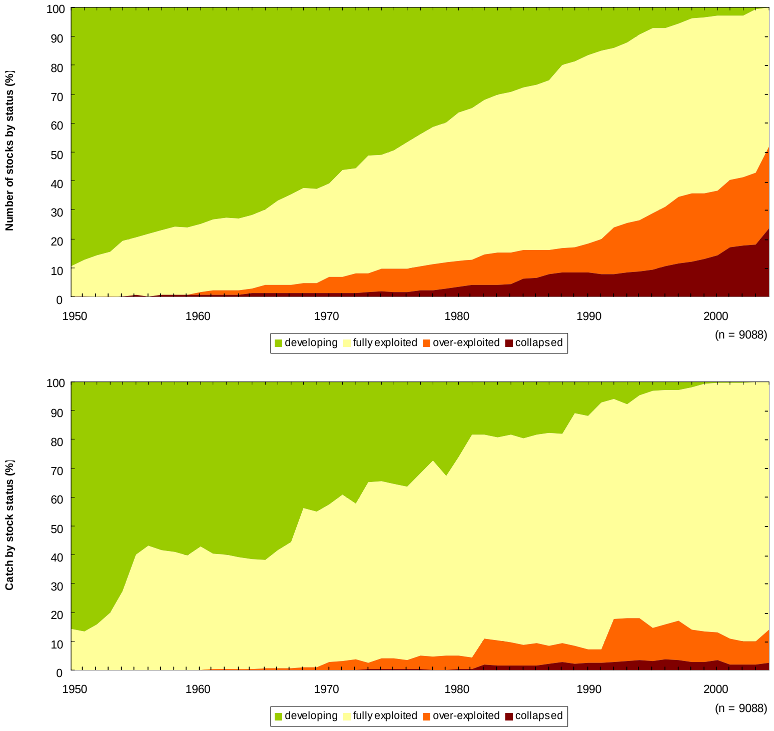

Figure VIII-15.8. Stock-Catch Status Plots for the South China Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Because of their proximity to shore, fringing reefs are heavily exploited by subsistence fishers and about 70% of the coral reefs in the broader region (including Sulu-Sulawesi Sea and Indonesian Seas) is heavily depleted, producing less than 5 tonnes per km^2 per year in comparison with the remaining 30% of reefs that produce about 15 - 20 tonnes per km^2 per year. Moreover, adult fish are scarce in some reefs in the region (McManus 1994). Reduction and loss of reef fish populations may have transboundary consequences if reef interdependence between oceanic shoals and highly exploited fringing reefs of the South China Sea LME is considered (Talaue-McManus 2000).

Oceanic migratory species such as tuna, billfish, sharks and other pelagic species are also overexploited, with potential transboundary impacts (UNEP 2005). Some shark species that migrate throughout the South China Sea LME, are also targeted and often caught as bycatch in the tuna and swordfish fisheries. Currently, high demand for shark products for exotic food, medicinal and ornamental markets (Chen 1996) is causing concern about overexploitation of sharks in the region (Talaue-McManus 2000). Invertebrate species such as holothurians, molluscs and crustaceans are considered to be heavily exploited, partly through overinvestment and encroachment of large-scale commercial operations, including illegal and unreported incursions of vessels from countries outside the South China Sea LME.

Excessive bycatch is a severe problem in this LME (UNEP 2005). The lack of bycatch exclusion devices has resulted in massive overexploitation of species regarded as bycatch in other regions. However, the quantity of discards in the region’s fisheries is insignificant, as virtually all of the bycatch, including turtles, sharks and whales, are utilised. There is also a widespread capture, either intentional or accidental, of rare, threatened and endangered species such as turtles and dugong, by traditional and commercial fisheries. Substantial, though unquantified, levels of bycatch are produced by distant waters fleets, through use of blast fishing and poisons, as well as in the shrimp fry fisheries, where juveniles of all other species are discarded. Destruction by reef bombing and use of poisons is severe, particularly on coral reefs (Bryant *et al*. 1998, Talaue-McManus 2000, UNEP 2005). Massive habitat destruction and fragmentation and changes in population and community structure are occurring from destructive fishing methods in the region. Based on present consumption patterns and population growth rates, the region will have to produce significantly more fish in the future just to meet domestic demand. Pressure on the coastal resources is therefore likely to increase significantly in the near future.

III. Pollution and Ecosystem Health

Pollution: Pollution in the South China Sea LME can be attributed to rapid economic development and population growth in the coastal zone. Overall, pollution was assessed as moderate, but severe in some localised areas (UNEP 2005). Wastes from domestic and industrial sources, agricultural and aquaculture, as well as sediments and solid wastes are the major land-based pollutants affecting coastal areas (Koe & Aziz 1995, Talaue-McManus 2000, Fortes 2006). Inadequate sewage treatment and disposal has led to high faecal coliform bacteria levels in some areas (e.g., Manila Bay). Industries release an estimated minimum of about 430,000 tonnes of Biological Oxygen Demand (BOD) into aquatic systems interacting with the LME (Talaue-McManus 2000). If this is not significantly reduced, the coastal waters of the Sunda Shelf from the Indo-China Peninsula to Malaysia and Indonesia, across to the western Philippine shelf, could become eutrophic. In enclosed bays, harbours, lagoons and in the immediate vicinity of river mouths there has been frequent occurrence of non-toxic algal blooms and HABS, as well as cases of paralytic shellfish poisoning in parts of the region (Talaue-McManus 2000).

High levels of suspended solids are found in coastal waters throughout most of the region. This has resulted from activities such as extensive deforestation in many watersheds, logging, mining, land reclamation, dredging and urban development, compounded by high rates of erosion (Naess 1999). There have been major changes in turbidity and levels of suspended sediments in Malaysia, Vietnam, Philippines, Indonesia (Sumatra and Kalimantan) and Thailand. Suspended solids have caused major changes in biodiversity of benthic communities (UNEP 2005). Pollution from solid waste is severe in localised areas, particularly around many towns and villages where waste management is poor or non-existent.

Data provided on heavy metals, though incomplete, show high levels in localised areas. Vietnam, whose major rivers are all transboundary, reports an annual load of heavy metals of about 100,000 tonnes. In the Northern Economic Zone of Vietnam, the concentration of lead, zinc and copper are 7-10 times the allowable limits. The LME contains some of the world's busiest international sea-lanes and two of the busiest ports in the world, Singapore and Hong Kong (Coulter 1996). This has led to moderate pollution from spills, with episodic discharges from shipping and occasional spills from oil exploration and production. International trade is expected to triple by 2020, much of which will be through the sea, increasing the potential for spills.

Habitat and community modification: Ecological goods and services provided by mangrove systems are estimated to be worth about US$16 billion per year (Naess 1999, UNEP 1999). Southeast Asian reefs are estimated to be worth more than US$2.4 billion per year, based on their contribution to food security, employment, tourism, pharmaceutical research and shoreline protection (Burke *et al*. 2002), while the estimated value of seagrass and coastal swamp areas in the South China Sea region is about US$190 billion per year (UNEP 1999).

Growing coastal populations and development, destructive fishing practices, pollution and siltation have resulted in severe habitat and community modification in this LME (UNEP 2005). Significant expanses of coral reefs have already been degraded or are under severe threat (Chou *et al*. 1994, Bryant *et al*. 1998, Burke *et al*. 2002). Coral reefs are most extensive and also the most threatened in Indonesia and the Philippines, with 50% of Indonesian reefs and 85% of Philippines reefs at high risk (Bryant *et al*. 1998). Recent studies suggest that degraded reefs have incurred reductions in biodiversity and at worse, species extinctions (Talaue-McManus 2000).

The reversing monsoonal pattern of wind and surface circulation facilitates connections between oceanic shoal reefs and those fringing the coastal states. McManus (1994) suggests that planktonic larvae of many coral reef biota from the oceanic shoals of the South China Sea can recruit in the fringing reefs of Sabah, the Philippines, Taiwan, coastal China, the Paracell Islands, Vietnam or in the Natuna Islands (Indonesia), depending on the direction of water circulation. Degradation of the coral reefs in the South China Sea LME will have a major impact on the global heritage of reef biodiversity (Bryant *et al*. 1998).

The original area of mangroves has decreased by about 70% during the last 70 years, with millions of hectares of land, mostly mangroves, having already been converted for shrimp mariculture, industrial development and tourist resorts. A continuation of the current trend would result in all mangroves being lost by the year 2030 (UNEP 1999). The disappearance of mangrove systems on such a large scale has led to sediment erosion, water pollution, loss of biodiversity and a critical loss of nursery habitat for young fish and shellfish. Despite the continuing destruction, significant areas supporting good quality coastal and marine habitats still remain (e.g., Spratly and Paracel Islands; western Palawan, Philippines; Con Dao Islands, Vietnam), both within and outside MPAs.

There is evidence of widespread modification of seagrass habitats throughout the region, with 20% to 50% of seagrass beds having been damaged (Talaue-McManus 2000). Sediments from coastal development, destructive fishing methods and land-based pollution are among the major threats to the region's seagrass habitats. Like coral reefs and mangroves, seagrass beds possess high biodiversity and a number of endangered species like sea cows and marine turtles are known to feed in these areas. Numerous species spend various stages of their life cycles among adjacent mangrove, seagrass and coral reef habitats. Degradation and loss of these critical habitats have led to reduction in the essential ecosystem services they provide in maintaining the high biodiversity and fisheries production of this region.

The health of the South China Sea LME may deteriorate further as a consequence of the expected future increase in pollution and habitat modification (UNEP 2005). Despite increasing measures for pollution mitigation and control, environmental quality is likely to worsen, primarily because of the predicted increase in deforestation and agriculture, as well as a major increase in population overriding the improvements in infrastructure (UNEP 2005). Some positive steps are being taken to address habitat modification, including mangrove rehabilitation programmes, watershed protection and establishment of MPAs.

IV. Socioeconomic Conditions

About 270 million people live in the coastal areas of the South China Sea LME. This population is expected to double in the next three decades. The South China Sea LME contributes to the livelihood of millions of people engaged in trade, tourism, industry, fisheries and oil exploitation. Fisheries remain a significant source of revenue and food. Economic activities include fisheries, mariculture, tourism and mining. The region is a globally important source of minerals, with considerable reserves of oil and gas.

The socioeconomic impacts of unsustainable exploitation of fisheries and environmental deterioration are significant for the newly developed economies of this region (Talaue-McManus 2000, UNEP 2005). There have been reduced economic returns and loss of employment as well as of livelihood from the fisheries collapse. In many areas, fisher families' children are malnourished, as fish consumption has declined from approximately 36 kg $person^{-1}yr^{-1}$ to 24 kg $person^{-1}yr^{-1}$, with consequent high levels of malnutrition (UNEP 2005). The socioeconomic impacts of pollution are mainly related to poverty in the major urban centres (UNEP 2005). Impacts include economic losses to mariculture and the shellfish industry through regular advisories of high levels of toxicity (e.g., Philippines, Vietnam, Indonesia, Thailand), as well as HABs and cases of mercury poisoning. Other impacts are associated with the costs of clean-up and coastal restoration. There have also been losses in recreational value in parts of the Philippines and land use conflicts in Philippines, Thailand and Malaysia.

Habitat modification has resulted in reduced capacity of local populations to meet basic human needs and loss of employment throughout the LME (UNEP 2005). Other impacts include loss or reduction of existing and future income and foreign exchange from fisheries and tourism, loss of charcoal production, economic conflicts between investors and local users, national and international conflicts and increased risks to capital investment (e.g., failure of coastal aquaculture projects in many parts of the region), costs of restoration of modified ecosystems and intergenerational inequity (UNEP 2005).

V. Governance

Most South China Sea nations recognise that their fisheries resources are threatened, but they also need the fishery products to feed their human populations and to sustain industries based on fisheries (Naess 1999). Thus, there is constant competition between socioeconomic and environmental concerns, where the former often win (Naess 1999). Fishing fleets of individual countries are depleting the common resources of the LME, reaping short-term benefits at the cost of others. There are multilateral attempts at improving the current situation of regulation of fisheries, to an ecosystem-wide approach to which all littoral states commit themselves. Management of the goods and services of the South China Sea LME is presently the focus of a Global Environment Facility and World Bank financed effort to support a country driven project for protecting the environment and living marine resources of the South China Sea LME (www.gef.org).

The losses related to overexploitation and habitat degradation, both in biodiversity and in fisheries yield, are important transboundary issues, not only from a biological point of view (i.e. nursery areas, recruitment of larvae, etc.) but also from an economic perspective where the drivers are international demand for aquarium fish, live food fish and prawns, as well as coastal tourism (Talaue-McManus 2000). The present situation and future prognosis indicate that more extensive and intensive intervention is required, including direct on-the-ground community-based conservation programmes. One of the Policy recommendations is the development of a functional, integrated regional network of MPAs (UNEP 2005). Bordering countries already have many legally designated MPAs and some multilateral conservation agreements have been established. Approximately 125 MPAs have already been gazetted (Spalding *et al*. 2001, Cheung *et al*. 2002) and there are also two World Heritage sites: Halong Bay, Vietnam and Puerto Princesa Subterranean River National Park, Philippines. However, insufficient resources for management and enforcement of fisheries and other regulations in many MPAs limit their effectiveness. Just 10-20% of MPAs are considered as effectively managed (Cheung *et al*. 2002).

The South China Sea LME is included as part of the UNEP-administered East Asian Regional Seas Programme. The GEF-World Bank supported projects underway are moving toward an integrated country based ecosystem approach to recover depleted fish stocks, restore degraded habitats, reduce coastal pollution and nutrient over-enrichment, conserve biodiversity and adapt to the effects of climate change.

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VIII-16 Sulu-Celebes Sea LME

S. Heileman

The Sulu-Celebes Sea LME is comprised of the Sulu and Celebes Seas, which are separated from each other by a deep trough and a chain of islands known as the Sulu Archipelago. The LME is bounded by northern Borneo (Malaysia), the southwest coast of the Philippines and Sulawesi Island (northern coast of Indonesia), but most of the LME falls within the archipelagic waters of either the Philippines or Indonesia. The LME covers an area of about one million km^2, of which 1.03% is protected, and contains 6.17% and 0.22% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). A complex oceanography results from the Celebes' strong currents, deep sea trenches, seamounts and active volcanic islands. The LME's tropical climate is governed by the monsoon regime. During the southwest monsoon months, the northern and central parts of the region are affected by typhoons, which bring intense rains and destructive winds to coastal areas. There are more than 300 major watersheds and 14 major estuaries in the region. A report pertaining to this LME is UNEP (2005).

I. Productivity

The Sulu-Celebes Sea LME is considered a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1}). The tropical climate, warm waters, ocean currents and upwellings make this LME one of the world's most biologically diverse marine environments. Located near the confluence of three major biogeographic zones and within the Indo-West Pacific centre of biodiversity, the region supports mega-diversity (Roberts *et al*. 2002, Cheung *et al*. 2002). A significant proportion of the total coral reef area of the Philippines (about 20,000 km^2) is located in this LME. This forms a part of the 'coral triangle', which has the highest coral diversity together with Indonesia and New Guinea (more than 500 reef-building species). In addition, 2,500 species of marine fishes, 400 species of algae, five species of sea turtles and 22 species of marine mammals are found in the LME (Chou 1997, Jacinto *et al*. 2000, Veron 2000).

Oceanic fronts (Belkin et al. 2009; Belkin and Cornillon, 2003): This semi-enclosed sea is connected to other seas of the Indonesian Archipelago via several straits. Flow constrictions within these straits are conducive to front formation (Figure VIII-16.1). The uniformly high surface temperature tends to mask salinity fronts caused by coastal upwelling, whose intensity sharply increases locally owing to orographic and bathymetric effects. Evaporative cooling also contributes to front formation since this process creates a colder and saltier water mass, which is substantially denser than ambient waters. Tidal currents and tidal mixing also play a significant role in front formation, especially off numerous coastal headlands and near straits. The most robust fronts are located in the eastern Celebes Sea.

Sulu-Celebes Sea SST (Belkin, 2009):
Linear SST trend since 1957: 0.62°C.
Linear SST trend since 1982: 0.23°C.

The steady warming of the Sulu-Celebes Sea was accentuated by two warm events, in 1988 and 1998, the latter being of the global scale (El Niño 1997-98). In many locales across this sea, the SST anomaly in 1998 exceeded 2°C; the extreme thermal stress has resulted in widespread restructuring of coral reef communities and numerous coral bleaching events (Vantier et al., 2005, p. 48, Figure 16; Goreau et al., 1997). The warm

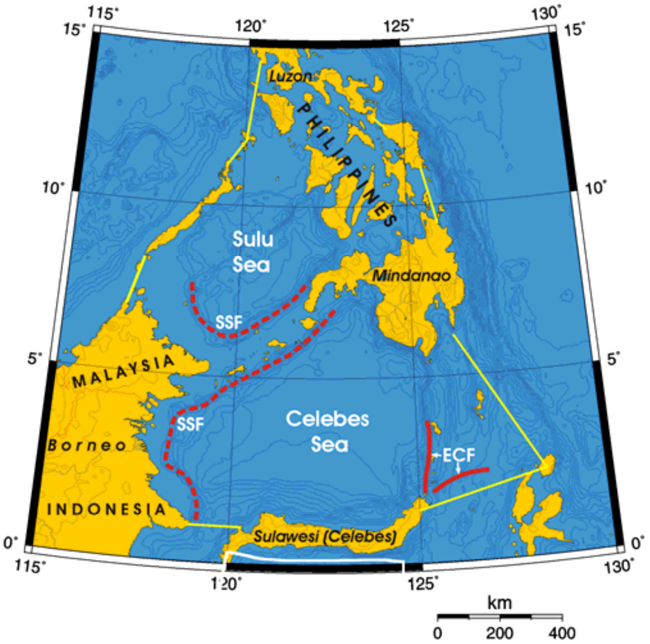

Figure VIII-16.1. Fronts of the Sulu-Celebes Seas LME. ECF, East Celebes fronts; SSF, Shelf-Slope Front (most probable location); Yellow line, LME boundary. After Belkin et al. (2009) and Belkin and Cornillon (2003).

event of 1988 occurred simultaneously in the Indonesian Sea LME, North Australian Shelf LME, West-Central Australian Shelf LME, and Northwest Australian Shelf LME; and only one year prior to the warm event of 1989 in the Southeast Australian Shelf LME. Apparently, the warm event of 1988 was caused by large-scale forcing. The all-time minimum of 1967 occurred simultaneously in the Indonesian Sea LME and, one year prior to the all-time minimum of 1968, in the West-Central Australian Shelf LME. The strong correlation between the Sulu-Celebes Sea's thermal history and adjacent seas could alternatively be explained by oceanic circulation, particularly, the Indonesian Throughflow that flows through this LME (NOAA Ocean Explorer, 2007).

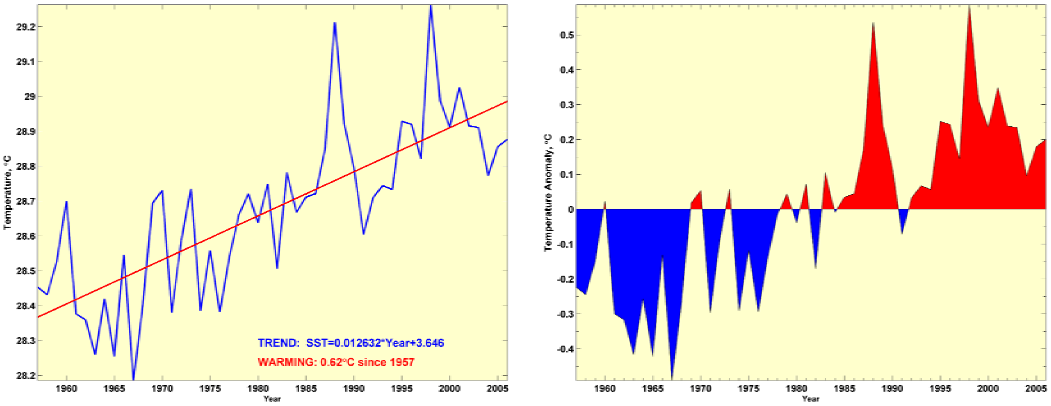

Figure VIII-16.2. Sulu-Celebes LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009) .

Sulu-Celebes Chlorophyll and Primary Productivity: The Sulu-Celebes Sea LME is considered a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1}).

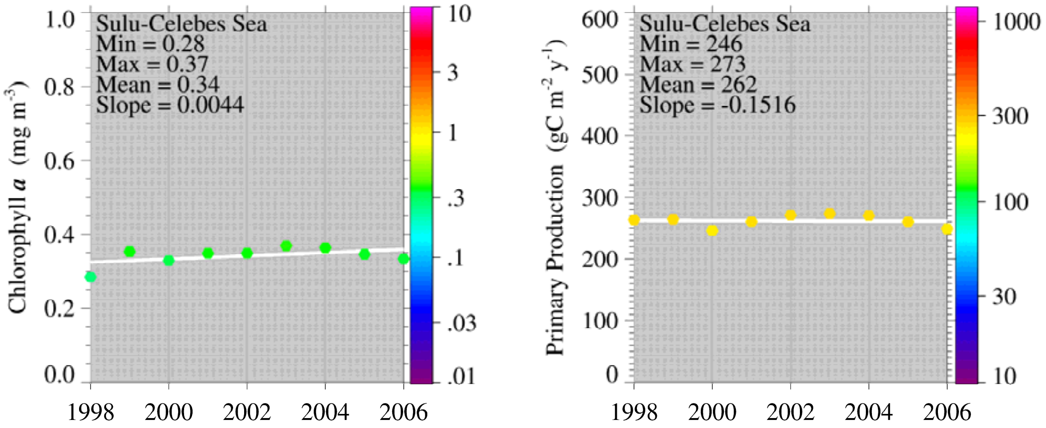

Figure VIII-16.3. Sulu-Celebes Sea: Trends in chlorophyll-*a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II Fish and Fisheries

The fisheries of the Sulu-Celebes Sea LME are multi-gear and multi-species. Reef fisheries provide essential sustenance to artisanal fishers and their families throughout the region while high value fish products are exported to expanding international, national and local markets. Live food and aquarium reef fish exports to Hong Kong and the Chinese mainland have burgeoned since the 1990s (Cesar *et al*. 2000). Aquaculture of prawns, oysters, mussels, fish, seaweeds and other species is an important industry in the three bordering countries (FAO 2000, BFAR 2004). The fisheries of the southwest coast of the Philippines are well-documented, relative to the fisheries from the other parts of this LME (see e.g., Ingles & Pauly 1984, Aprieto *et al.* 1986, Trinidad *et al.* 1993, DA-BFAR 2004). Total reported landings in the LME have increased steadily to one million tonnes in 2004 (Figure VIII-16.4), though a significant proportion of the landings is reported simply as unidentified fishes in the available statistics (included in 'mixed group' in Figure VIII-16.4).

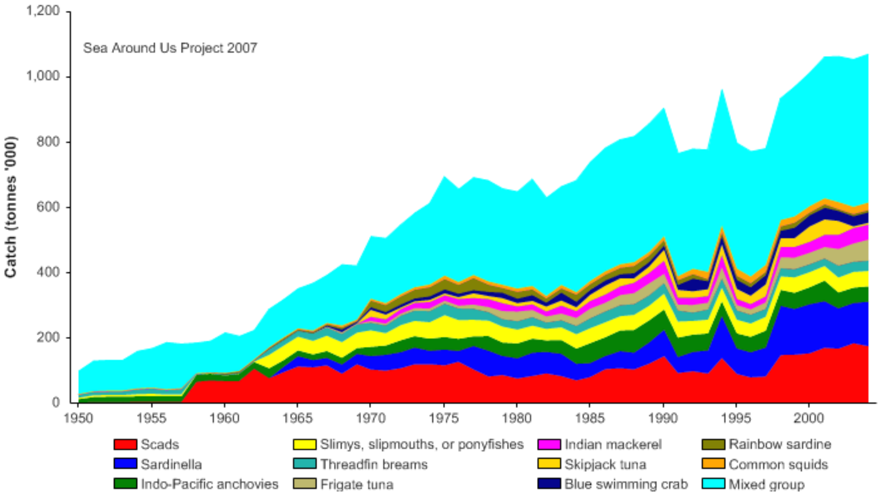

Figure VIII-16.4. Total reported landings in the Sulu-Celebes Sea LME by species (Sea Around Us 2007).

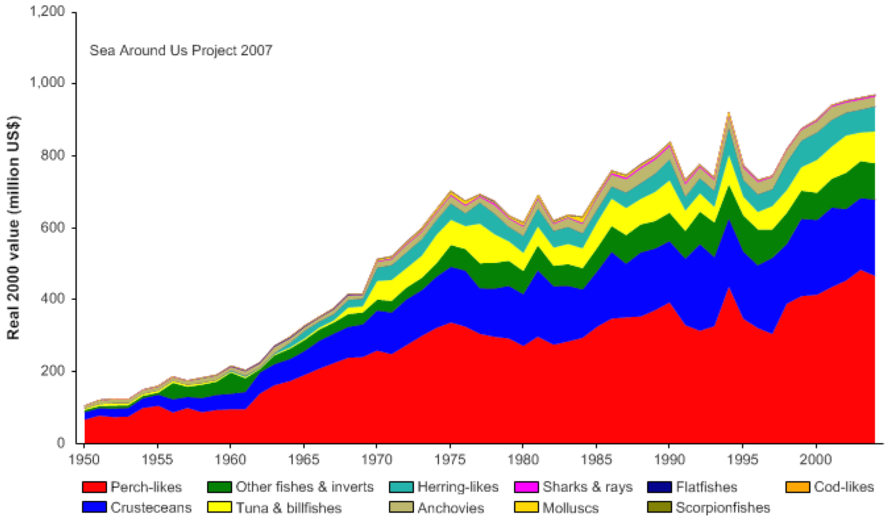

Figure VIII-16.5. Value of reported landings in the Sulu-Celebes Sea LME by commercial groups (Sea Around Us 2007).

The value of the reported landings has also increased, exceeding US$900 million (in 2000 real US dollars) in recent years (Figure VIII-16.5).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is increasing, and has reached 40% of the observed primary productivity in recent years (Figure VIII-16.6), a very high level that is possibly skewed by the large proportion of unidentified fishes in the reported landings. The Philippines account for the largest share of the ecological footprint in the LME.

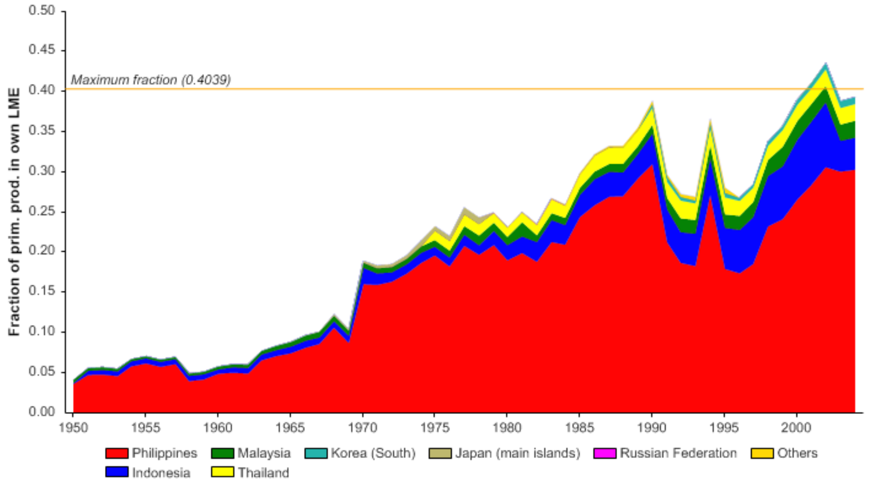

Figure VIII-16.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Sulu-Celebes Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The trend in the mean trophic level (i.e., the MTI; Pauly & Watson 2005) and the FiB is not conclusive, likely due to the poor quality of the underlying landings statistics (Figure VIII-16.7). However, a decline in the MTI can be seen from 1950 to 1974, a period in which the proportion of unidentified fish in the landings statistics was relatively small, an indication that a ‘fishing down’ of the food web (Pauly *et al.* 1998) is perhaps occurring in the LME, only to be drowned out by the high level of taxonomically aggregated catches in recent years.

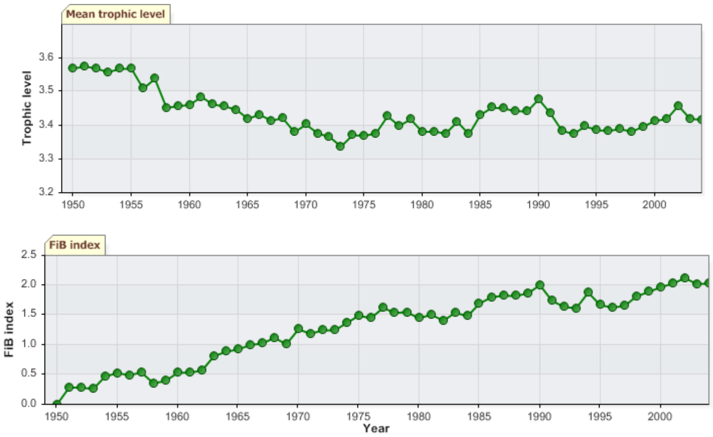

Figure VIII-16.7. Marine Trophic Index (top) and Fishing in Balance Index (bottom) in the Sulu-Celebes Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that about half of the stocks in the LME have collapsed or are currently overexploited (Figure VIII-16.8, top), and that the reported landings are largely supplied by fully exploited stocks (Figure VIII-16.8, bottom). Such diagnosis is probably a result of the high degree of taxonomical aggregation in the underlying statistics.

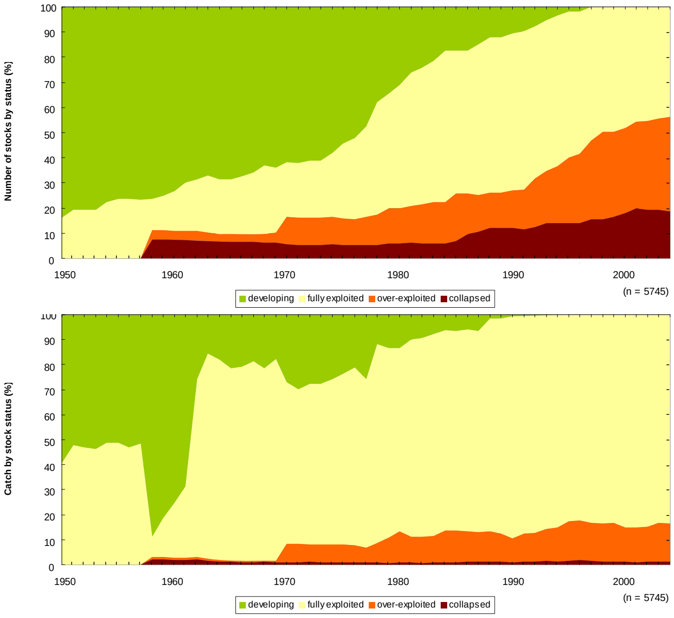

Figure VIII-16.8. Stock-Catch Status Plots for the Sulu-Celebes Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Beyond the archipelagic waters of the Philippines, neither the status nor the future viability of the fisheries in the Sulu-Celebes Sea LME is understood. Great uncertainty exists because of serious discrepancies in fisheries data, which may also be missing a significant quantity of Illegal, Unreported and Unregulated (IUU) catches, possibly as high as 50% of the total catch (Kahn & Fauzi 2001). Unreported catches are high, as has been shown for Northern Sabah (Teh *et al.* 2007). The LME is an attractive fishing ground for illegal fishers, including commercial fishers from throughout Southeast Asia and beyond. Consequently, accurate data on the extent, number of vessels and their mode of operations are rare, despite the likelihood that such illegal activities may have significant environmental and socioeconomic impacts.

Excessive fishing effort and destructive fishing have led to severe overexploitation of fisheries and considerable threat to coral reefs in this LME, with declining catches, particularly in coastal areas (FAO 2000). Statistics from the Philippines (BFAR 1997, DA-BFAR 2004) and Indonesia suggest that, despite increasing catch of some species, CPUE has declined steadily. Over the past few decades, many of the fringing coral reefs have been depleted, with a major loss of productivity and adverse effects to other components of the ecosystem (Licuanan & Gomez 2000). About 70% of the coral reefs in the Philippines are heavily exploited, producing less than five tonnes per km^2 per year, while the remaining 30% produces between 15-20 tonnes per km^2 per year (Licuanan & Gomez 2000). Overfishing has also led to severe depletion of market-sized fishes as well as reduction in population sizes and in some cases, local extinction. This also includes large piscivorous species such as groupers, barracudas, jacks and sharks (Werner & Allen 2000). Bycatch is produced by distant-waters fleets as well as through the use of blast fishing and poisons. Rare and endangered species of turtles as well as marine mammals are also caught incidentally. There are little or no discards in the region’s inshore fisheries, however, since virtually all of the bycatch is utilised by local fishers.

Destructive fishing practices (e.g., dynamite and cyanide fishing on reefs) have severe impacts in coastal areas (Pilcher & Cabanban 2000). Live coral reef fish trade is of particular concern. Use of fish poisons to catch aquarium and food fishes is a rapidly growing problem in many Pacific nations, but is most serious in the Philippines and Indonesia (Johannes & Riepen 1995) with about 85% of the aquarium fish traded caught using cyanide, targeting 379 species from a few families (e.g., Labridae, Pomacentridae, Chaetodontidae, Pomacanthidae and Scaridae) (Pratt *et al*. 2000). The live food fish trade primarily targets groupers (especially *Epinephelus* spp. and *Plectropomus leopardus*) and Napolean wrasse (*Cheilinus undulates*). Because of their particular life-history attributes, groupers are easily overexploited and targeting of their spawning aggregations is of a serious concern (Licuanan & Gomez 2000). In addition to taking adult groupers for direct food consumption, the live reef fish food trade also involves the capture of wild fry and fingerlings supplying the grouper mariculture industry in Southeast Asia, predominantly in Taiwan and Thailand (Sadovy & Pet 1998).

Because of Indonesia’s increasing coastal population, greater commercialisation, continued use of destructive fishing practices and lack of effective regulation and enforcement, depletion of fisheries resources is expected to continue in the LME. However, such a grim outlook on the future of fisheries in the LME may be ameliorated to some degree by improved enforcement of national regulations (e.g., Philippines Fisheries Code) and through successful interventions by government and NGOs.

II. Pollution and Ecosystem Health

Pollution: Rapid industrialisation and economic growth have taken a heavy toll on the environment of the seas of East Asia. Most of the pollutants entering the marine environment come from land-based sources, and have changed virtually every dimension of the coastal and marine environments (Fortes 2006). Pollution in the Sulu-Celebes Sea LME is of particular concern around the major urban centres (UNEP 2005). Major sources of pollution include sewage, industries, agriculture, aquaculture and shipping. Throughout the region, sewage treatment is rudimentary, with raw or primary treated sewage discharged directly into water courses. Microbial pollution is of local significance near to the major urban centres. Eutrophication is most significant in enclosed bays, harbours and lagoons with limited water circulation, particularly where sewage or industrial discharges are present. Pollution is a locally significant problem in areas such as Batangas Bay (heavy metals), urban areas of Mindanao, the Visayan Islands and other industrial and urban areas, with contaminant loads concentrated near discharge points. While pollution from agricultural run-off is not a major problem at the scale of the LME, localised agricultural pollution is widespread. Releases of chemical and, to a lesser extent, microbiological pollution from shipping in harbours, are also common. The Makassar Strait and Celebes Sea LME is a major oil tanker route between Japan and the greater Pacific Ocean, the Indian Ocean, West Asia and Europe, with associated risks of collisions and spills (MPP-EAS 1998).

Suspended solids pose a severe problem in the coastal waters of the Philippines, as a result of extensive deforestation in the region's watersheds (e.g., Hodgson & Dickson 1992, Chia & Kirkman 2000, Burke *et al*. 2002). This is compounded by erosion and siltation rates that are among the highest on Earth. For example, in the Philippines, it is estimated that approximately one billion m^3 of sediment are lost to coastal waters annually (Burke *et al*. 2002)***,*** carrying high loads of particle-bound nutrients. The transboundary impacts of this phenomenon are compounded by sediment-laden waters flowing seasonally into the region around the northern coast of Sabah and to the south of Palawan from the South China Sea LME (Bate 1999). Pollution by solid waste is severe around the larger cities, towns and villages where waste management is generally poor or non-existent.

Habitat and community modification: The Sulu-Celebes Sea LME includes diverse habitats such as estuaries, sandy foreshores, mangroves, seagrass meadows, coral reefs and deep sea. Major causes of modification of these habitats are conversion for aquaculture, destructive fishing practices, agriculture (pollution) and industrial development (dredging, siltation and oil and gas exploration). Overfishing has caused changes in population structures and/or functional group composition (e.g., coral reef fishes). The important fish nursery ground function of large sections of mangroves and seagrass beds has been seriously impaired.

Overall, habitat degradation in the Sulu-Celebes Sea LME was assessed as severe, with extensive degradation particularly of mangroves and coral reefs (UNEP 2005). An estimated 60% - 80% or more of the mangrove resources in the Philippines have been lost (Atmadja & Mann 1994). In 1967, the Philippines Bureau of Fisheries and Aquatic Resources (BFAR) reports showed the existence of 4,200 km^2 of mangrove areas, of which about 1,400 km^2 remains (FAO 2000). The loss of mangroves can be attributed primarily to the illegal conversion into fishponds, indiscriminate cutting for firewood and construction purposes, and reclamation. In Indonesia, up to 10,000 km^2 of land, mostly mangrove forests, were allocated by the government to shrimp farms. By 2001, about 70% of these farms had become unsustainable and were subsequently abandoned (UNEP 2005).

Development of most ports has resulted in foreshore reclamation and channel dredging, while muro-ami[1] (Hopley & Suharsono 2000, Pilcher & Cabanban 2000), blasting (Cabanban 1998) and poison fishing (Pratt 1996) have damaged or destroyed more than 70% of coral reefs throughout the region. According to Burke *et al*. (2002), up to 50% of Indonesia's 51,000 km^2 of reef has already been degraded and 85% is threatened by human activities. Destructive fishing practices are the single largest threat to the region's reefs (Burke *et al*. 2002). BFAR reports have indicated that up to 70% of reefs in the Philippines have been destroyed by rampant dynamite fishing as well as by accumulation of silt from the watershed areas (FAO 2000). Coral cover and fish density on the reefs are decreasing at an alarming rate, even within some protected areas.

Changes in sea surface temperature have also affected the structure of coral reef communities during various coral bleaching events since 1983. For example, in the Philippines Tubbataha National Park, mean live coral cover decreased by about 19% after bleaching in 1998, then remained stable from 1999 to 2001 (Chou *et al*. 2002). There was good recovery of most other bleached areas and, on average, the bleaching events appear to have been less severe than in some other countries (Chou *et al*. 2002, Wilkinson 2002).

Environmental impacts are likely to deteriorate further, primarily because of the predicted increases in forestry, mining and agriculture as well as a major increase in population, without accompanying improvements in infrastructure. The impacts of habitat degradation are likely to deteriorate further or remain stable. In the Sahul area an improvement is expected due to strengthened regulations as well as management of protected areas.

III. Socioeconomic Conditions

National statistics suggest that the total population of the Sulu-Celebes Sea LME region is approximately 33 million (WWF 2001). The region has diverse economic activities, with the major export earners including fisheries, mariculture, agriculture and mining. Service industries, including coastal tourism, also make a substantial contribution to GDP. There is significant offshore oil and mineral exploration, with a potential for substantial expansion in the coming decades. Subsistence farming and fishing are major activities of large numbers of people outside of the main urban centres. The Sulu-Celebes Sea LME's fisheries are an important source of foreign exchange earnings for the three countries (FAO 2000, BFAR 2004). In addition, the countries obtain a significant percentage (up to 70%) of their animal protein from marine fishes (FAO 2000, BFAR 2004). Marine fisheries including fish farming are also an important source of employment in the region (FAO 2000, BFAR 2004).

The socioeconomic impacts of overfishing are severe, with reduced subsistence livelihood and food supply as well as reduced economic returns to small-scale fishers throughout the Philippines and Indonesia. These impacts include loss of employment, conflict between user groups for shared resources, reduced earnings in one area by destruction of juveniles and reproductive stock in other areas (migratory as well as shared stocks) and loss of protected species (e.g., local extinction of dugong in the Philippines).

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[1] Muro-ami involves setting a net over a coral reef into which a group of 10-30 swimmers drive the fish. The swimmers are equipped with weighted lines that are bounced up and down on the reef in an effort to drive out the fish.

The socioeconomic impacts of pollution were assessed as moderate, and include increased risks to human health, increased costs of human health protection, preventive medicine, medical treatment and of clean-up, as well as economic loss in fisheries and reduced fish marketability. Most of these impacts are concentrated around the major urban centres, where there have been significant health issues including cases of mercury poisoning.

The socioeconomic impacts of habitat and community modification were considered to range from moderate to severe (UNEP 2005). Increasing habitat fragmentation on the region's coasts has depleted the wide variety of resources that used to be the main source of sustenance and survival of coastal inhabitants (Fortes 2006). Major economic costs are also accruing from destruction of coral reef habitats. In 2001, the reefs of Indonesia and the Philippines provided annual economic benefits of US$1.6 billion and US$1.1 billion per year, respectively (Burke *et al*. 2002). Over the next 20 years, human impacts on the reefs could cost Indonesia and the Philippines some US$2.5 billion each (Burke *et al*. 2002). Habitat destruction has resulted in loss of income from tourism, loss of opportunity for investment, increased risks to capital investment, and costs of controlling invasive species and of restoration of modified ecosystems (UNEP 2005). Other socioeconomic costs of habitat modification are related to its impacts on fisheries.

V. Governance

Marine resource management and exploitation are, in theory, already controlled by extensive policy and regulatory frameworks. Both the Philippines and Indonesia have moved to decentralised management of marine resources (FAO 2000). The establishment of MPAs is one of the measures taken to address habitat degradation and unsustainable fisheries exploitation in the region. Several hundred protected areas have already been designated (Spalding *et al*. 2001, Cheung *et al*. 2002) and over one hundred more are currently being gazetted. Most protected areas are situated in the Philippines, especially in the Tubbutaha Marine Park. Several small community-based management initiatives have proven to be very successful at protecting coral reefs as well as facilitating replenishment of reef-based fisheries (Russ & Alcala 1996, Sherwood 2002). These successes are not common, however, as only 7% of the total number of MPAs in the Southeast Asian region are effectively managed, while 68% have poor or unknown management (Kelleher *et al*. 1995, Burke *et al*. 2002).

One of the greatest challenges in this LME is non-compliance with existing laws and regulations, which is exacerbated by weak institutional capability for enforcement. In addition, the information base is limited in these countries. However, steps are being taken to address the information gap, with several research initiatives in various agencies (including universities) in the respective countries. An extensive literature exists in the region, much of which is published in the national language, for example, in Indonesia. The Sulu-Celebes Sea LME is included in the UNEP-administered East Asian Regional Seas Programme (See the Gulf of Thailand LME). International agencies such as the UNEP, WWF, Conservation International and GEF have initiated some projects in the region. GEF is supporting several projects in the region (see the Gulf of Thailand LME). GEF has also provided support for the development of a TDA as well as the preliminary framework of a SAP for this LME.

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VIII-17 West-Central Australian Shelf LME

T. Irvine, J. Keesing, N. D'Adamo, M.C. Aquarone and S. Adams

The West-Central Australian Shelf LME extends off Western Australia (WA) from Cape Leeuwin (~34.5°S) to Northwest Cape (~22°S). This LME owes much of its biogeographic unity to the respective connecting influences of the West Australian Current, a northward flow coming from the circulation pattern of the counterclockwise Indian Ocean gyre, and the Leeuwin Current (LC), the only west coast poleward-flowing eastern boundary current in the southern hemisphere. The LC is a major southward flow of warm, low nutrient, buoyant tropical water along this LME's relatively narrow continental shelf, and is responsible for tropical reefs and associated marine flora and fauna flourishing further south than anywhere else in the world (CALM, 1994). In addition to these regional scale currents, there are wind-driven coastal counter currents dominating the circulation close to shore mainly during the austral spring/summer period (Pattiaratchi, 2006). Relatively high energy from sea and swell is a major feature of this LME, but there are embayments and lagoons where waves are restricted or effectively blocked, with sheltered highly biodiverse protected habitats occurring behind offshore limestone reefs in many localities (CALM, 1994). The LME has an extremely narrow shelf, in some areas being merely 40 km wide, and covers an area of nearly 550,000 km^2, about 2% of which is gazetted as a marine protected area (MPA) that contains 0.37% of the world's coral reefs (CALM, 2005a; Sea Around Us, 2007; www.dec.wa.gov.au).

The region has a Mediterranean climate with sea temperatures varying from about 15°C in the south in winter to about 29°C in the north in summer, as described in biogeographic overviews contained within management plans for proposed and existing Western Australian MPAs (see for example CALM, 1996, 2002, 2005a, 2005b and DEC 2006, 2007a, 2007b, 2007c). The marine biodiversity of this LME is characterised by a rather special tropical-temperate mix, varying from predominantly tropical in the north to predominantly temperate in the south. Tropical species from the north are carried southwards by the LC, while temperate and sub-temperate species are carried northwards by coastal counter currents, such as the Capes and Ningaloo currents respectively (Pattiaratchi, 2006). The gradation in the biodiversity is exemplified by the latitudinal variation in the relative proportion of tropical versus temperate fish species along WA's coast, which acts as a good surrogate of overall biodiversity variation (Fox and Beckley, 2005). Superimposed on the tropical-temperate distributions is a proportion of the biota endemic to Western Australia, including, for example, 5% endemic fish species and 25% endemic shallow water echinoderms. Overall, about 10% of the shallow water fauna in this LME are endemic to WA (CALM, 1994).

Some of this LME's ecological highlights include the 270 km long fringing Ningaloo Reef (~22°S), which resides within an MPA that has 30% gazetted as sanctuary zone; the World Heritage listed hypersaline inverse-estuary of Shark Bay (~26°S), which is also an MPA and contains 20,000 km^2 of seagrass meadows and extensive areas of stromatolites; the high-latitude coral reefs of the Abrolhos Islands (~29°S); extensive areas of mangal communities; open coast sandy beaches; long shore-parallel intertidal and sub-tidal macro-algal-dominated limestone reefs; and an overall high biodiversity of mixed tropical/temperate marine species. This LME ranks 7th amongst the world's 18 most biologically diverse marine areas and 2nd as a centre of endemism (Roberts et al., 2002). Recent large multidisciplinary studies have made significant advances in the understanding of the region's biophysical, biogeochemical and ecological dynamics (e.g.

Keesing et al., 2006). UNEP (2003) provides further biogeographical information on this LME.

I. Productivity

The West-Central Australian Shelf LME is a Class III, low productivity (<150 $gCm^{-2}yr^{-1}$) ecosystem. Its coastal waters are oligotrophic by world standards, with recent studies by Koslow et al. (2006) recording annual phytoplankton production at $46gCm^{-2}$ inshore and $115gCm^{-2}$ on the shelf and offshore. Due to its latitudinal range and confluence of tropical and temperate flows, this LME encompasses diverse pelagic and coastal ecosystems. In the southeast Indian Ocean, the West Wind Drift branches northward as the West Australian Current. However, the presence of the southward flowing Leeuwin Current (LC) closer to the coast of this LME effectively suppresses any broad-scale upwelling of deeper, highly productive water, in contrast to other eastern boundary currents where strong upwelling is typical. However, recent studies are showing that localised productivity from upwelling can be associated with sporadic events and near-shore counter currents (see, for example, the research framework of the Western Australian Marine Science Institution: www.wamsi.org.au). Perth Canyon, an incisive, 100 km long and deep (ranging from 200 to 4000 m) canyon, is a highly productive slope feature off Perth (Rennie et al., 2006) characterised by bouts of eddy-induced upwelling, high primary production, and associated aggregations of marine fauna, from large (e.g. whales) to small (e.g. krill).

The LC flows most strongly in winter, extending all the way down the west coast and then eastward along the southern coast of the Australian continent. Comparatively warmer, lower salinity water flows through the Indonesian Archipelago from the Pacific Ocean to the Indian Ocean, and results in lower density water between Indonesia and northwest Australia as compared with the cooler and more saline ocean waters off southwest Australia (Pattiaratchi, 2006). This density difference results in a sea level change of up to about 0.5 m along the Western Australian coast and is the driving force for the Leeuwin Current. Due to the effect of the earth's rotation, water is entrained from the Indian Ocean into the Leeuwin Current, and the Current cools as it propagates southwards; thus, the Leeuwin Current strengthens as it flows southward. The Leeuwin Current weakens in spring/summer, mainly as a result of the relatively strong opposing wind stresses associated with seasonal wind fields. Ridgway and Condie (2004) provide further information on the seasonal evolution of the LC flow and its influence on sea surface temperature throughout the year.

The dynamics of the LC are influenced to a significant extent by inter-annual variability in the El Niño Southern Oscillation and an important feature is the strong eddy activity associated with the instability in the fast southward flow (Waite et al., 2007). These eddies are typically up to about 300 km in diameter and can generate large productivity pulses, drawing significant amounts of water, heat and biomass from the productive shelf and coastal waters into the open ocean. During winter in La Niña years the LC may have a volume transport of 6 million m^3sec^{-1}, while in winter in El Niño years this is about 4 million m^3sec^{-1} (Feng et al., 2003). It has been calculated that the eddies may flush the entire volume of the southwestern Australian continental shelf twice annually carrying phytoplankton biomass equivalent to 40,000 tonnes of carbon offshore each year (Feng et al., 2007). The dynamics of the LC, particularly the large-scale eddy circulation, is known to also have a profound influence on the LME's coastal and offshore fisheries ecology, for example the predictable influence on the inter-annual variability in recruitment of the commercially important Western Rock Lobster.

Within the LC, a deep chlorophyll maximum is a significant contributor to total water column production. Chlorophyll *a*, as an indicator of phytoplankton, peaks in the late autumn / early winter period on the shelf and shelf break, in phase with the seasonal strengthening of the LC and its eddy field. This is consistent with the recent discovery of a deep water chlorophyll maxima representing high phytoplankton levels around 50 m depth in winter (Koslow et al., 2006). Ongoing studies are examining how enhanced flow of the LC in late autumn might lead to nutrient enrichment and heightened primary productivity. These studies are also examining the role of the extensive and highly productive benthic ecosystems of the region (Babcock et al., 2006) and benthic-pelagic coupling on the biogeochemistry of the region. Nutrient budgeting for the region by Feng and Wild-Allen (in press) indicates that about 80% of nitrogen utilised by annual primary production is retained and recycled on the shelf. For more information on the LC and its influence on this LME see Deep Sea Research II special issue, volume 54.

When the LC is flowing strongly during the winter months, it tends to move onto the continental shelf as it approaches Cape Naturaliste. It generally flows close inshore down to Cape Leeuwin and then eastwards towards the Great Australian Bight. In late spring, however, it moves a little offshore to be replaced by a cool northwards counter-current, recently named the Capes Current. The Capes Current commences near Cape Leeuwin and flows northwards past Cape Naturaliste and on beyond Rottnest Island (Pearce and Pattiaratchi, 1999); there is often an associated upwelling region in the lee of Rottnest Island. This in turn dies away about March/April as the strengthening LC moves inshore again. Similarly, a summer counter current (the Ningaloo Current) has recently been identified along the Ningaloo Reef (Taylor and Pearce, 1999), and similar counter currents are known to exist inshore of the Abrolhos Islands. Pattiaratchi (2006) provides a more detailed overview of these and other general circulation patterns off Western Australia.

For an analysis of the association between oceanic fronts and enhanced marine productivity, see Menon (1998). Shark Bay along the coastline is an inverse estuary: along this arid coastline region, the high evaporation rate from shallow embayments without significant freshwater inflows and with restricted tidal exchange creates an environment with a salinity that exceeds that of the seawater, to a maximum of about 65 ppt in its uppermost reaches, where extensive areas of stromatolites occur (CALM, 1996). For a general understanding of oceanographic processes affecting the nutrient dynamics and productivity of Australian marine ecosystems, read the State of the Environment Report (EPA, 2007). For more information on productivity, see www.ea.gov.au.

Oceanic fronts (Belkin et al., 2009): The Leeuwin Current Front (LCF) (Figure VIII-17.1), described in 1980 by Cresswell and Golding (1980), occurs within this LME, although some source waters of this current/front are found farther north, in the Northwest Australian Shelf LME. The Leeuwin Current, flowing poleward along the outer continental shelf, is a relatively shallow and narrow boundary current by global standards, being less than 300 m deep and 100 km wide. Typical current speeds within the Leeuwin Current and its eddies are about 1 knot (50 cm/s), although speeds of 2 knots are common, and the highest speed ever recorded by a drifting satellite-tracked buoy was 3.5 knots. Tropical warm waters spread along this front toward Cape Leeuwin. There is a northward counter current beneath the Leeuwin Current called the Leeuwin Undercurrent. The Leeuwin Undercurrent flows equatorward in a narrow depth zone (typically 250-450 m) and carries relatively high-salinity, oxygen-rich, nutrient- depleted water northward within this LME.

The North Tropical Front (NTrF) merges with the LCF near 25°S. Farther south, the South Tropical Front (STrF) merges with the LCF near 30°S. The LCF and the associated current extend over the shelf break and shelf. They play an important role in the ecology of many tropical species, particularly lobster, since the Leeuwin Current and its extension carry lobster eggs and larvae into the Great Australian Bight. In addition, the high latitude (29°S) coral reef at Houtman Abrolhos (Abrolhos Islands), with its relatively high coral diversity, is established and sustained by the Leeuwin Current, which is also responsible for the presence of corals as far south as Rottnest Island (32°S). A meso-scale Kalbarri Inner Shelf Front (KISF) extends NNW from the Murchison River mouth at 27.5°S.

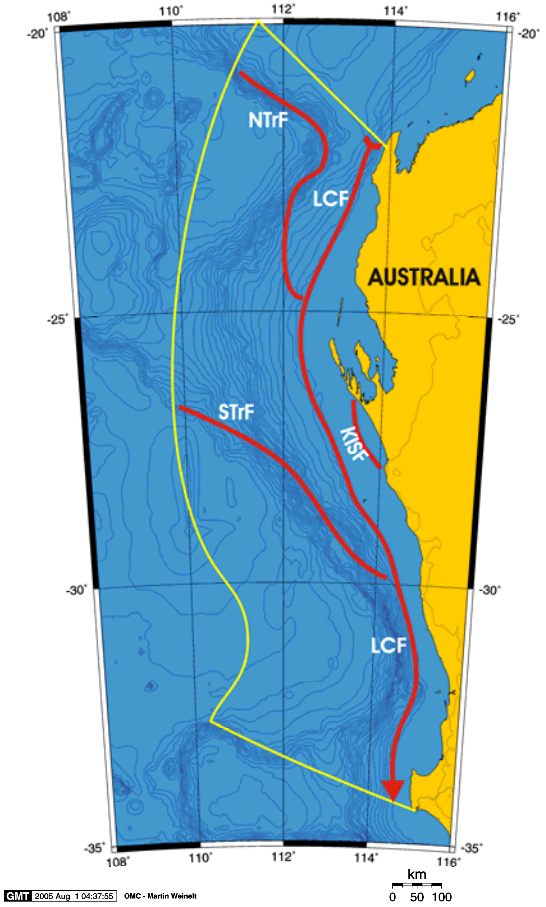

Figure VIII-17.1. Fronts of the West-Central Australian Shelf LME. KISF, Kalbarri Inner Shelf Front; LCF, Leeuwin Current Front; NTrF, North Tropical Front; STrF, South Tropical Front. Yellow line, LME boundary. After Belkin et al. (2009).

West-Central Australian Shelf SST (Belkin, 2009)(Figure VIII-17.2)
Linear SST trend since 1957: 0.82°C.
Linear SST trend since 1982: 0.09°C.

The 25 years since 1957 were rather quiet and relatively cold. The single pronounced cold event of 1968 was also observed in the Sulu-Celebes Sea LME, Indonesian Sea LME, Northwest Australian Shelf LME, and Southwest Australian LME. The cold event of 1968 was preceded by the all-time minimum in the Indonesian Sea in 1967 (and a minimum of 1967 in the North Australian Shelf LME); therefore this low-temperature signal was likely transported by the Indonesian Throughflow from the Indonesian Sea onto Western Australia's shelves, and farther south and east, with the Leeuwin Current, onto the Southwest Australian Shelf LME.

The 25 years from 1982 to 2006, featured strong events with a peak-to-trough amplitude of 1°C. The two warm events of 1983-1984 and 1988-1989 were possibly correlated with moderate El Niños. The all-time maximum of 1998 was likely linked to the extremely strong El Niño 1997-98 (Feng *et al.,* 2003).

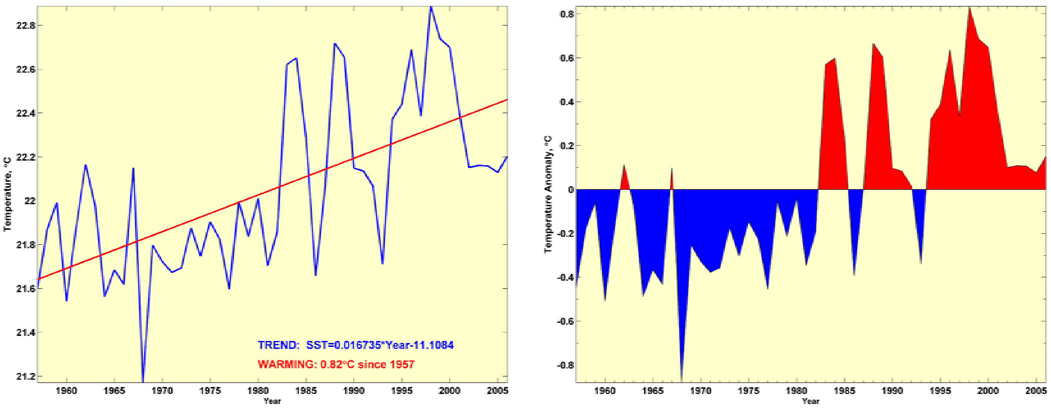

Figure VIII-17.2. West Central Australia Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009)

West-Central Australian Shelf LME Chlorophyll and Primary Productivity: The West-Central Australian Shelf LME is a Class III, low productivity (<150 gCm^{-2}yr^{-1}) ecosystem.

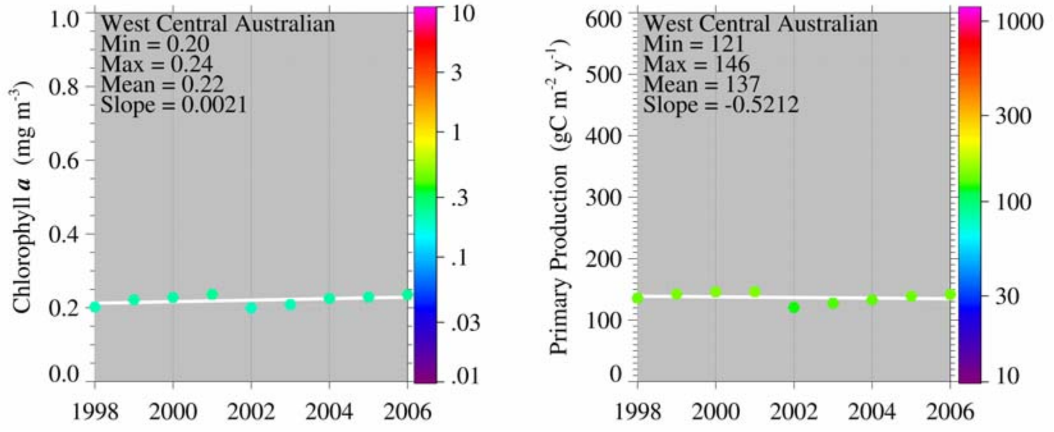

Figure VIII-17.3. West-Central Australian Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery; courtesy of K. Hyde.

II. Fish and Fisheries

Production in Australian waters is limited by low levels of nutrients and as a result, fish populations are relatively small. Many species are endemic to Australia. Although not productive by world standards, there are numerous commercial and recreational fisheries based in the waters of this LME. The commercial fisheries operating in this area tend to be low-volume, high-value fisheries producing fish and shellfish for local consumption and export. Currently there are 16 State-managed commercial fisheries and 5

Commonwealth commercial fisheries within this LME. For details of WA State fisheries see Fletcher and Head (2006) and for Commonwealth fisheries see Larcombe and McLoughlin (2007).

There are commercial fisheries for lobster, abalone, pink snapper, shark, crab, pilchard, prawn and scallop. Constantly changing ocean conditions affect the abundance and distribution of all species in the marine food chain. The commercial fishery for the western rock lobster, *Panulirus cygnus*, within this LME is the largest single-species fishery in Australia. The important finfish fisheries are the Shark Bay Snapper Fishery and the West Coast Purse Seine Fishery; the most significant prawn and scallop trawl fisheries are concentrated in Shark Bay, with some other trawl fisheries further south. Approximately 45% of the waters of this LME out to the 200 m contour are permanently closed to trawling.

Using global data, total reported landings in this LME peaked at around 16,000 tonnes in 1993, followed by a period of a slight dip in the late 1990s, but have returned to 16,000 tonnes in 2004 (Figure VIII-17.4). However, alternate calculations from this LME's portion of State fisheries (Fletcher and Head, 2006) and Commonwealth fisheries (Australian Fisheries Management Authority, pers. comm.) estimate the annual production of commercial fisheries in 2005 to be 30,055 tonnes, valued at US$340 million. Invertebrates such as lobster, scallops, prawns and shrimps account for the largest share of the landings in the LME. The reported landings were estimated to be valued at about US$120 million in 2000 (Figure VIII-17.5).

All fisheries in the area are subject to management plans which embrace the principles of Ecosystem Based Fishery Management (EBFM) as opposed to single target species management approaches (Smith *et al*., 2007). For the 21 managed fisheries in this region, 15 have published Stock Assessments and 16 have published Ecological Risk Assessments (Fletcher and Head, 2006). Of those with published Ecological Risk Assessments, one fishery had inadequate spawning stock levels, one had moderate bycatch species impacts, one had moderate protected species (marine mammal) interactions, two had moderate food chain impacts and one had moderate habitat impacts.

There are some areas that are of particular concern due to over-fishing; for example, the Shark Bay snapper fishery has experienced very high fishing pressure in the past, and following adjustments to management strategies (including prolonged closures), the population of pink snapper has not recovered as expected (Fletcher and Head, 2006). It is thought that wider environmental factors are playing a significant role (e.g. ocean currents affecting young fish, and perhaps water temperature). The most significant Commonwealth managed fishery in this LME is the Western Tuna and Billfish industry. Southern bluefin tuna, yellowfin tuna and broadbill swordfish are subject to overfishing in the broader Indian Ocean (Larcombe and McLoughlin, 2007). The Australian Government is party to a number of international conventions or agreements for the management of highly migratory tunas and billfishes that range far beyond the Australian Fishing Zone – see Larcombe and McLoughlin, 2007.

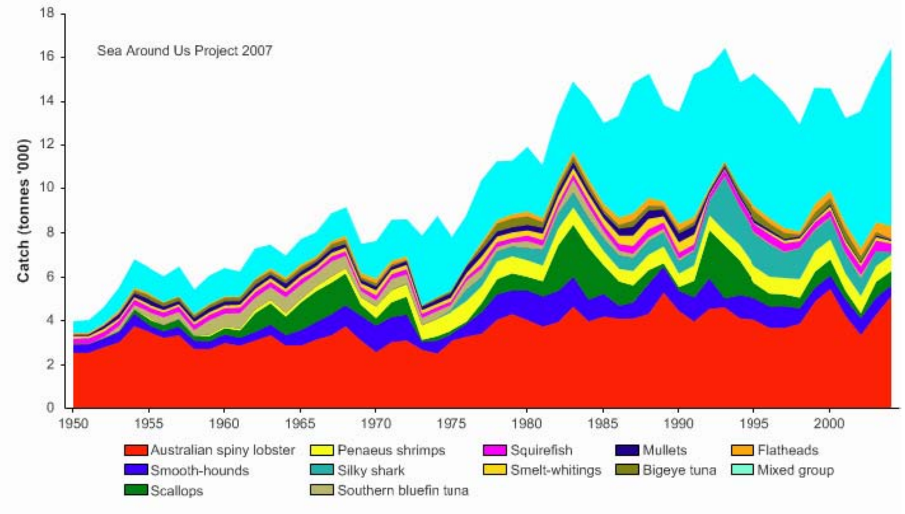

Figure VIII-17.4. Total reported landings in West-Central Australian Shelf LME by species (Sea Around Us, 2007).

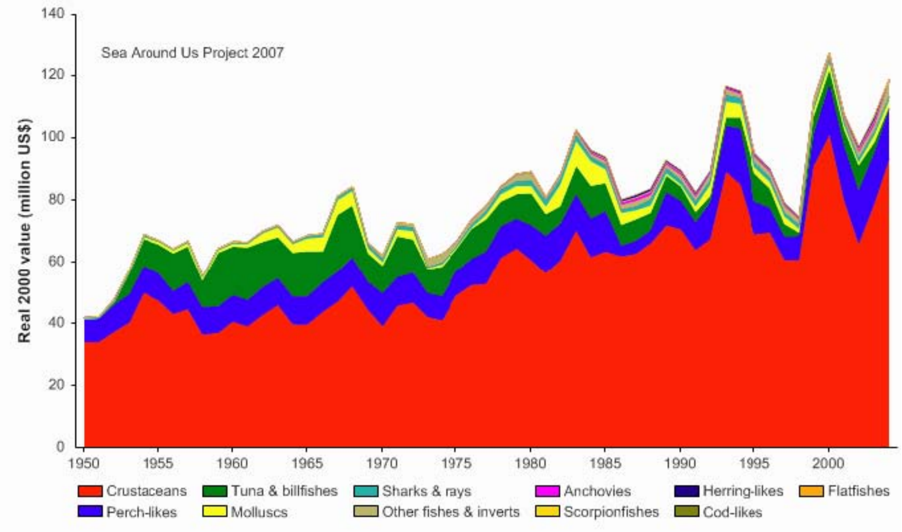

Figure VIII-17.5. Value of reported landings in West-Central Australian Shelf LME by commercial groups (Sea Around Us, 2007).

The primary production required (PPR; Pauly and Christensen, 1995) to sustain the reported landings is very small (less than 1.5%), in line with the low exploitation of the LME (Figure VIII-17.6). Australia has the largest share of the ecological footprint in this LME.

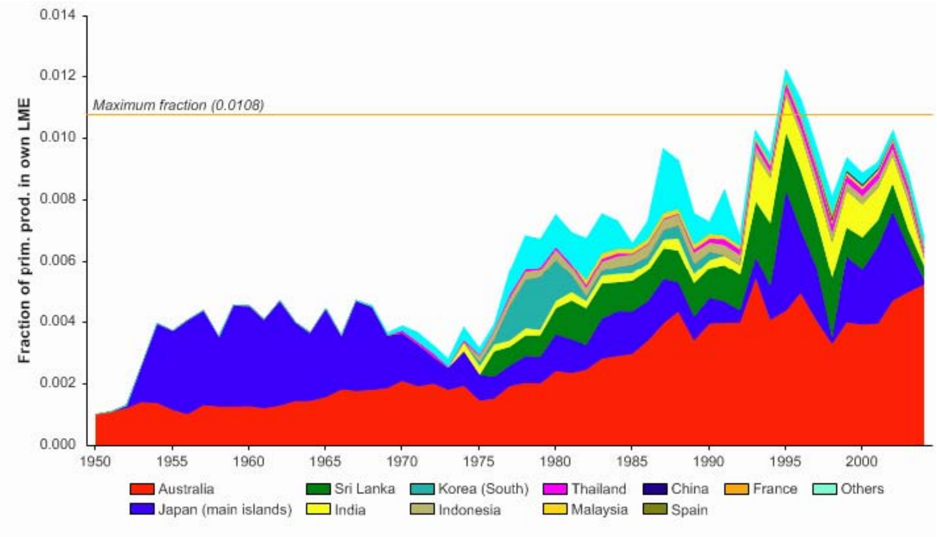

Figure VIII-17.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the West-Central Australian Shelf LME (Sea Around Us, 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level (i.e., expressed through the Mean Trophic Index (MTI); Pauly and Watson, 2005) in the LME was generally low, due to the low trophic level of Australian spiny lobster which accounts for the largest share of the reported landings (Figure VIII-17.7 top). In recent years, however, the MTI is on a rise with the growing share of various fish species in the landings. This transition is also reflected in the Fishing-in-Balance (FiB) index (Figure VIII-17.7 bottom). This LME, thus, shows no sign of a 'fishing down,' in line with the low level of PPR recorded in Figure VIII-17.6.

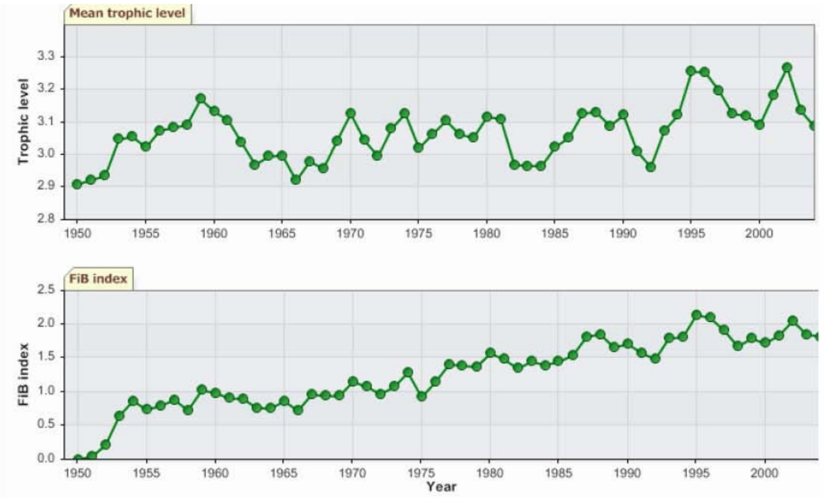

Figure VIII-17.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the West-Central Australian Shelf LME (Sea Around Us, 2007).

There are high levels of recreational fishing but negligible levels of artisanal or indigenous traditional fishing in this LME. The key target species of recreational fishing are western king and school prawns, blue manna crabs, abalone, rock lobster and a variety of finfish including herring, salmon, tailor, whiting, snapper, dhufish and a variety of other highly sought after reef fish species.

The Stock-Catch Status Plots indicate that about 70% of the stocks are deemed as collapsed or overexploited (Figure VIII-17.8, top). It appears that the majority (over 70%) of the reported landings is supplied by fully exploited stocks (Figure VIII-17.8, bottom). However, the editors and Australian contributors wish to acknowledge and advise caution that there are several reasons possible for the apparently reduced status of some species. Among them, Australian management authorities have in many cases limited catches and effort to protect the species from overfishing. Landings of these stocks are therefore lowered, giving the appearance of an overfished condition status in Figure 8. In addition, productivity of some of these fisheries is tightly coupled to environmental variability, in particular ENSO, and this also reduces catches in some years in ways not due to exploitation rate. Catches of all species are subject to annual active management intervention and often include temporally and spatially explicit adaptive management measures to prevent overfishing.

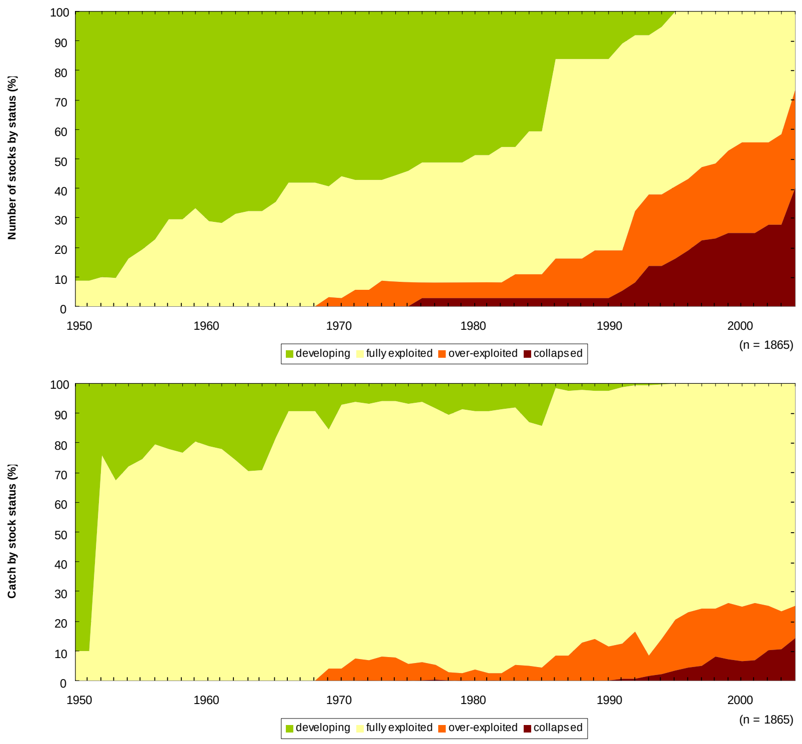

Figure VIII-17.8. Stock-Catch Status Plot for the Western Central Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

The shallow water marine environments of this LME are recognised as having some of the highest marine biodiversity and endemism in the world. Roberts *et al*. (2002) ranked this area 2nd in the world among 18 centers of endemism. Of those 18, this area ranked among the least threatened, ranking 15th in terms of threats from coastal development, overexploitation and pollution. This is in part due to the region's sparse population and relatively low associated level of threatening activities, but also due to the strong legislative framework (see Governance section) and a mature planning framework for marine natural resource management that embraces and includes multiple-use MPAs and Ecosystem Based Management of Fisheries. The State of the Environment Report (EPA, 2007) assessed the condition of the marine environment against a selection of broad indicators in the categories of Degradation of the Marine Environment, Marine Contamination and Introduced Marine Pests. Marine contamination issues affect only a small proportion of the waters of this LME, mainly near ports. Heavy metal contamination is low in the areas where it is monitored. Overall, the report expresses concern that too few places are routinely monitored for degradation and contamination against environmental quality management frameworks. The condition of WA's coastal and shelf waters has historically been poorly monitored, with the exception of certain highly pressured areas, such as Albany harbours, North West Shelf (particularly Dampier Archipelago) and areas which lie on the southern boundary of the LME such as Cockburn Sound and Perth metropolitan coastal waters (EPA, 2007). Relevant reports are available through the Western Australian Department of Conservation and Environment (www.dec.wa.gov.au) and the Environmental Protection Agency (www.epa.wa.gov.au). Western Australia's overall marine and coastal monitoring framework is undergoing a significant expansion as part of the State's MPA implementation and management programs, as discussed in Section V.

Although relatively infrequent, accidental discharges of contaminants, such as from spills and shipping accidents, also place pressure on the region's marine environment. Port and industrial development, pipelines, mining and dredging cause direct physical damage to the marine habitats. Tributyltin (TBT) contamination (a highly toxic ingredient of anti-fouling paint applied to ships and coastal vessels) was widespread throughout the Perth metropolitan region in areas near marinas and ports; however following complete bans in 1991 on the use of TBT on boats less than 25 m long, the effects of contamination have been decreasing (Wells *et al.,* 2008). Another major pressure in the Perth area marine environment is excessive nutrient loads from sewage wastewater outfalls, as well as from industrial and agricultural sources. To a lesser degree, there are also contaminated groundwater and river and estuary discharges.

In respect to the threat from introduced marine species, significant numbers have been recorded along the coast, such as in the port of Geraldton, as well as in certain localities within the Carnarvon and adjacent Shark Bay areas. The most likely vectors are thought to be international and domestic shipping, fishing and recreational vessels (EPA, 2007). The West-Central Australian Shelf LME is therefore threatened by an increase in shipping, especially from ballast water. Ballast water discharges are of concern because of their potential to transport species from their native habitat to new habitats where they may become invasive. Ballast water from shipping has been responsible for introducing more than 250 species, and possibly as many as 500 species, into Australian waters. In response, Australia has introduced mandatory ballast water management requirements to reduce the risk of introducing more unwanted marine species. More than 99% of the approximately 12,500 annual voyages that arrive in Australia comply with these requirements (Beeton *et al.,* 2006).

Tourism, urban development and associated commercial and recreational use along the coastal strip are also placing stress in populated areas of this LME, through coastal development and recreational fishing in particular. Natural embayments along WA's extensive coastline make ideal locations for human settlements, ports and marinas, but this places pressure on shallow water marine habitats from the associated ecological forcings that accompany human usage. Large numbers of people are engaged in recreational activities that have the potential to affect the environment through pollution of the water by boats and the disturbance of species and habitats. For more information on marine and coastal pollution issues see Pogonoski *et al.* (2002), annual State of the Environment reports (EPA, 2007) and Zann (1995).

Recent advances in the understanding and prediction of climate change impacts, places this amongst the most concerning of all fundamental pressures on the marine ecosystems in this LME. The WA region has been subjected to a significantly greater warming trend over the last 50 years than many other parts of the Indian Ocean (Feng *et al.,* 2005; EPA, 2007). Climate modeling under the IPCC A2 greenhouse gas scenario predicts that continued warming will occur and that the warming is a result of local air-sea fluxes, not hydrodynamic structure (Feng *et al*., 2007). The advancing establishment of GOOS (Global Ocean Observing System) in the region, facilitated by the Intergovernmental Oceanographic Commission, will continue to improve the characterization of broadscale hydrodynamic and climatic impacts within WA's LMEs. This is being achieved through, for example, the Indian Ocean Observing System (IndOOS) of the Indian Ocean Panel of CLIVAR/GOOS (www.clivar.org/organization/indian/indian_reference.php), Australia's recently implemented Integrated Marine Observing System (www.imos.org.au) and a number of long-term monitoring networks established and maintained under the auspices of State and Federal natural resource management and maritime transport agencies. Furthermore, Australia's operational ocean forecasting facility, Bluelink, that currently provides ocean forecasts at 10 km grid resolution out to 7 days, is underpinned by data assimilation progressed under the international GODAE program (www.bom.gov.au/bluelink).

IV. Socioeconomic Conditions

The most populous sections of the WA coast are in the city of Perth and two smaller cities, Geraldton and Bunbury. As an island nation, Australia depends heavily on its marine environment for transport and shipping. Fishing is an important marine industry and its highly distributed nature along the coast makes it important socioeconomically for many rural communities. FAO provides information on the characteristics and socioeconomic benefits of Australia's fishing industry (www.fao.org). Aquaculture is a relatively minor activity, except for important pearling operations. The dry, hot climate of this area makes it ideal for solar salt production. Extensive evaporation ponds have been established adjacent to Shark Bay, and there are several other large-scale evaporative salt plants. Marine and coastal-based tourism are important in this LME, both in terms of domestic and international tourism, with recreational fishing a very significant component, in addition to scuba diving, surfing, wind surfing, sailing and boating. Tourists prize the LME's coral reefs and the general natural and unspoiled marine environment. The coral-dominated Ningaloo Reef is an important tourism location with over 200,000 tourists visiting each year. Shark Bay is one of only six World Heritage Areas in Australia that have a marine component. This LME is a breeding ground for the Antarctic-feeding humpback whale. Other cetaceans (including many whale species and large numbers of dolphins), dugong, sharks (including whale sharks), sea lions, sea turtles (six species), sea snakes, manta rays, seabirds, shorebirds, migratory waders and little penguins are amongst the key marine values of this LME. The region is also notable for extensive stands of seagrass meadows, involving many species of seagrasses. In addition to commercial and recreational fishing, this LME supports other important cultural and economic marine values which include aquaculture (e.g. pearling), indigenous and maritime (European) heritage, seascapes, wilderness, marine tourism (e.g. diving, swimming, sailing, water sports), and petroleum development.

V. Governance

Australia has a federal system of government with the states forming the Australian Commonwealth federation. This LME lies adjacent to the State of Western Australia (WA). Australia's exclusive economic zone (EEZ) extends out 200 nautical miles. Within the EEZ, WA State waters generally extend 3 nm offshore, or greater in some areas to encompass islands and archipelagos. The Commonwealth Government's *Environment Protection and Biodiversity Conservation Act 1999* is the principal national instrument for managing human usage and impacts, and for conserving biodiversity in Australia's territory. It is employed in conjunction with the WA State Government's *Environmental Protection Act 1986, Wildlife Conservation Act 1950* and *Conservation and Land Management Act 1984*, the latter of which was amended by the *Acts Amendment (Marine Reserves) Act 1997*, establishing the Marine Parks and Reserves Authority (MPRA) as the vesting body for Western Australia's marine conservation reserves.

Australia is committed to the protection of marine biodiversity and ecological processes and the sustainable use of marine resources through the goals and principles of Ecological Sustainable Development (ESD). This commitment has been ratified through Australia's international responsibilities and obligations under the Convention on Biological Diversity and implemented at a national level by the States and Territories under the Intergovernmental Agreement on the Environment (IGAE), through the development of national strategies. Biodiversity conservation is managed by a strong legislative and planning framework and an extensive system of marine conservation reserves, which, when fully implemented, will cover approximately 35% of this LME's coast length.

In the early 1990s, at a national level, Australia identified a need to protect representative examples of the full range of Australia's marine ecosystems and habitats in marine protected areas. The respective State Governments agreed to establish a comprehensive, adequate and representative system of protected areas covering Australia's Exclusive Economic Zone. As a first step over the past 10 years, a spatial framework was developed and established, named the Integrated Marine and Coastal Regionalisation of Australia (IMCRA), for classifying Australia's marine environment into bioregions that make sense ecologically and that are at a scale useful for regional planning (Commonwealth of Australia, 2006). This captures all Australian waters from the coast to the edge of the Exclusive Economic Zone, excluding Antarctica and Heard and Macdonald Islands. These IMCRA bioregions are consolidated into regional groupings to form a smaller set of Marine Bioregional Planning Regions under Australia's Oceans Policy (www.environment.gov.au/coasts/mbp). This LME encompasses parts or all of 4 of the 7 provincial bioregional units making up the South-West region and 3 of the 8 provincial bioregional units making up the North-West marine bioregional planning region. Development of a Bioregional Profile, identifying the important ecological, conservation and socioeconomic values of the region for the South West, has been released (Department of the Environment and Water Resources, 2007); that of the North West was expected to be released in mid-2008 (see www.environment.gov.au/coasts/mbp/north-west).

Such marine bioregionalisations and descriptive profiles help managers to understand complex ecosystems and their specific management needs. These bioregions are consistent with the development of a National Representative System of Marine Protected Areas (NRSMPA) which aims to establish and manage a system of marine protected areas to contribute to the long-term ecological viability of marine and estuarine systems, in order to maintain ecological processes and systems, and to protect Australia's biological diversity at all levels. The Western Australian Government's existing and proposed system of Marine Protected Areas contributes to the Australian

National Representative System of Marine Protected Areas (www.dec.wa.gov.au) and, when fully implemented, will also result in MPAs situated within all of the LMEs covering Western Australian coastal zone.

Western Australia's MPA framework focuses on the maintenance of marine biodiversity, but also considers socioeconomic marine uses allowing for managed fishing and general tourism as important social uses (CALM, 1994). The framework includes explicit provision for marine sanctuary (no-take) zones and other special purpose zones (e.g. for scientific reference and education) to ensure biodiversity conservation requirements can be met. Often, State and Commonwealth instruments are used to provide contiguous zones of protection. For example, the Ningaloo Marine Park is a state-managed marine park extending 3 nm from the coast, and a Commonwealth Act has been used to extend the effective area of the MPA seaward through the establishment of an adjoining Commonwealth MPA.

Natural resource management (NRM) for the area comes under the jurisdiction of an integrated (State and Federal) national framework, facilitating scientific and institutional consistencies in NRM science and governance. The socioeconomic uses incorporated in NRM regimes centre around fishing, coastal use, nature-based tourism, water sports, scientific research, education and petroleum activities. A best-practice, outcome-based NRM model for adaptive management is employed (ANZECC, 1997). This is supported by a statewide marine science program that services a statutory adaptive management framework based around zoning, compliance (patrol and enforcement), public participation (education/communication/interpretation), management intervention, visitor infrastructure, research, and monitoring (www.calm.wa.gov.au). Key planks of the NRM model are the designation of performance measures (indicators of management effectiveness), management targets (the end points of management) and key performance indicators (quantitative measures of overall management effectiveness), which are regularly and formally assessed under Government legislation, in respect to the effectiveness of management (www.dec.wa.gov.au) by the State's Marine Parks and Reserves Authority.

Fisheries management is also implemented at State (www.fish.wa.gov.au) and Commonwealth (www.afma.gov.au) levels, underpinned by ecosystem-based frameworks rather than more traditional single-species stock management methods. The *Offshore Constitutional Settlement* (OCS) agreement defines the jurisdiction of Commonwealth and State governments, with management of most fish stocks out to the 200 nm limit of the Australian Fishing Zone being managed under state legislation (*Fish Resources Management Act 1994*). Offshore fisheries and those extending across state borders are managed by the Commonwealth Government (*Fisheries Management Act 1991*). Integrated State/Commonwealth institutional instruments are also in use for the management of marine values focusing on maritime and indigenous heritage, tourism, science, education, shipping and extractive industries such as mining, oil/gas exploration and production.

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IX SOUTH PACIFIC

IX-18 East-Central Australian Shelf LME
IX-19 New Zealand Shelf LME
IX-20 Northeast Australian Shelf LME
IX-21 Southeast Australian Shelf LME

IX-18 East-Central Australian Shelf LME

M.C. Aquarone, S. Adams, I.M. Suthers and M.E. Baird

The East-Central Australian Shelf LME extends from the southern edge of the Great Barrier Reef off Fraser Island, Queensland (24.5ºS) to Cape Howe (37.5 ºS), at the southern end of the state of New South Wales. It covers a surface area of 650,000 km^2, of which 2.66% is protected, and contains 0.18% of the world's coral reefs and 0.20% of the world's sea mounts, as well as 15 major estuaries (Sea Around Us 2007). A narrow continental shelf (only 20-60 km wide) that is bordered by the Tasman abyssal plain and a temperate climate characterise the LME. The South Equatorial Current from the Pacific Ocean gyre flows westward towards the Australian coast, bifurcates with the southern branch bending south (left) under the influence of wind stress and topography to become the East Australian Current (EAC, Ridgeway and Dunn 2003). The EAC is Australia's largest current and is typically 30 km wide, 200 m deep and traveling at up to 4 knots (2 ms^{-1}), with a variable annual transport variously estimated as 20-30 Sv (Ridgeway & Dunn 2003 and references therein). For comparison, the EAC has ~5 fold greater volume transport than the seasonally flowing Leeuwin Current on the west coast. The EAC intensifies in the northern part of this LME, before separating from the coast 31-33 ºS, leaving behind a southward trending eddy field. The EAC's mesoscale variability is so large that a single continuous current can often not be identified, and this variability distinguishes it from other western boundary currents. After separation, the EAC retroflects northward and can feed back into the EAC, as an anticyclonic eddy. Further separations and retroflections are evident along the NSW coast around 34 and 37ºS (Ridgeway & Dunn 2003). The eddies are formed at 90 to 180 d intervals driven in part by intrinsic instabilities (Marchesiello and Middleton 2000; Bowen et al. 2005). The anticyclonic eddies may transport considerable amounts of heat into the Tasman Sea, or may turn northeast and coalesce back into the main current. The strengthening of the EAC is predicted to warm Australian waters by 1-2ºC by 2030 and 2-3 ºC by 2070s, particularly off Tasmania (Poloczanska et al. 2007). This has already affected growth rates of commercial fish (Thresher et al. 2007). Ridgeway (2007) and others have noted the remarkable impact of the EAC's southward penetration off Tasmania. Using the Maria Island long term quasi-monthly monitoring station (since 1944), they report the warming rate of 2.3 ºC per century and increasing salinity of 0.34 per century. A book chapter and report pertaining to this LME are Morgan (1989) and UNEP (2003).

I. Productivity

The East-Central Australian Shelf LME is considered a Class III, low productivity ecosystem, <150gCm^{-2}yr^{-1}) (Sea Around Us 2007; www.science.oregonstate.edu/ocean.productivity/). At this latitude, water temperature, levels of wind mixing and light intensity go through seasonal cycles. During the winter, strong winds and cool surface water temperatures enhance vertical mixing processes, breaking down vertical density gradients and allowing nutrient-rich waters to mix into the surface layer. However, the overall productivity of this temperate Australian LME is restricted by the poleward transport of low-nutrient tropical waters along the continent's eastern margin by the EAC. There are no widespread seasonal blooms producing large surpluses of organic matter. Localised coastal blooms occur as a result of wind-driven and current-driven upwelling and occur throughout the year (Ajani, 2001; Baird et al., 2006). Localised blooms can produce ecosystem responses such as red-tides (Dela-Cruz et al., 2003), but are not sufficiently large to support a large demersal fishery such as those which characterise northern hemisphere continental shelf systems.

For a general understanding of oceanographic processes affecting the nutrient dynamics and productivity of Australian marine ecosystems, see the Australian State of the Environment Reports at www.deh.gov.au/soe where the reports are listed by date. For more information on productivity, see Furnas (1995). For information on ocean surface environmental data (currents, temperatures, winds), see the website www.marine.csiro.au for the Commonwealth Scientific and Industrial Research Organisation, CSIRO, and David Griffin's CSIRO site at www.marine.csiro.au/%7Egriffin/. Regularly updated information on climate impact, fisheries and marine sciences, including an online Atlas of Australian Marine Fishing and Coastal Communities is available from the Australian Department of Agriculture, Fisheries and Forestry, Bureau of Rural Sciences at http://adl.brs.gov.au together with lists of publications on species, bycatch, the role of marine reserves and other important topics broken out by regions.

Oceanic fronts: The westward South Equatorial Current impinges on the east coast of Australia and bifurcates, with the two branches flowing north or south, along the coast (Belkin & Cornillon 2003, Belkin *et al*. 2009) (Figure IX-18.1). The southward branch is the East Australian Current (EAC), a strong poleward flowing western boundary current that carries tropical waters into the LME. A distinct front exists between tropical Coral Sea waters and the Tasman Sea waters at between 31-37ºS, the Tasman Front. The EAC is a highly energetic current that shifts between a dominating poleward extension that flows past Tasmania, and a Tasman Front extension, which flows eastward towards Lord Howe Island, eventually forming the East Auckland Current. With currents more than 1 ms^{-1}, water flowing in from the north, surface waters can move though the LME in as little as a month. The poleward extension of the EAC has strengthened due to recent climatic changes, resulting in a significant warming of waters of southern NSW and Tasmania (Cai, 2006).

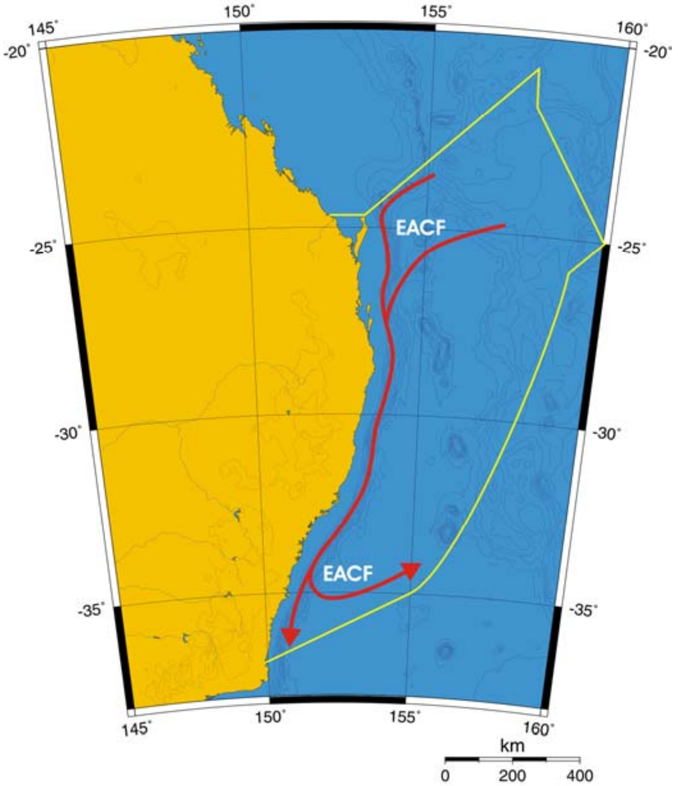

Figure IX-18.1. Fronts of the East-Central Australian Shelf LME. EAC, East Australian Curent; TF, Tasman Front. Yellow line, LME boundary (after Belkin et al. 2009).

East-Central Australian Shelf SST
Linear SST trend since 1957: 0.56°C.
Linear SST trend since 1982: 0.35°C.

The steady warming of the East-Central Australian Shelf was punctuated by two warm events, in 1973 and 1998. The 1973 peak was a large-scale event that occurred simultaneously in the Indonesian Sea LME, North Australian Shelf LME, and Northwest Australian Shelf LME. The above-noted synchronism can only be explained by large-scale atmospheric forcing (teleconnections). Indeed, oceanic advection by currents must be ruled out because the entire Northeast and East Australian coastal and offshore region (basically, most of the Coral Sea and northern part of the Tasman Sea) is dominated by the South Equatorial Current and its extension, East Australian Current, whereas the Indian Ocean inflow via Torres Strait is negligible.

The 1998 all-time maximum was a manifestation of the 1997-98 El Niño. The summer of 1997-1998 was the hottest recorded on the Great Barrier Reef, causing bleaching of two thirds of inshore reefs (Berkelmans and Oliver 1999). Otherwise, the interannual variability of this ecosystem was rather small, with year-to-year variations less than 0.5°C (CSIRO 2007). Causes of the annual variation in the EAC eddies are still a puzzle, driven by intrinsic instabilities (Bowen et al. 2005).

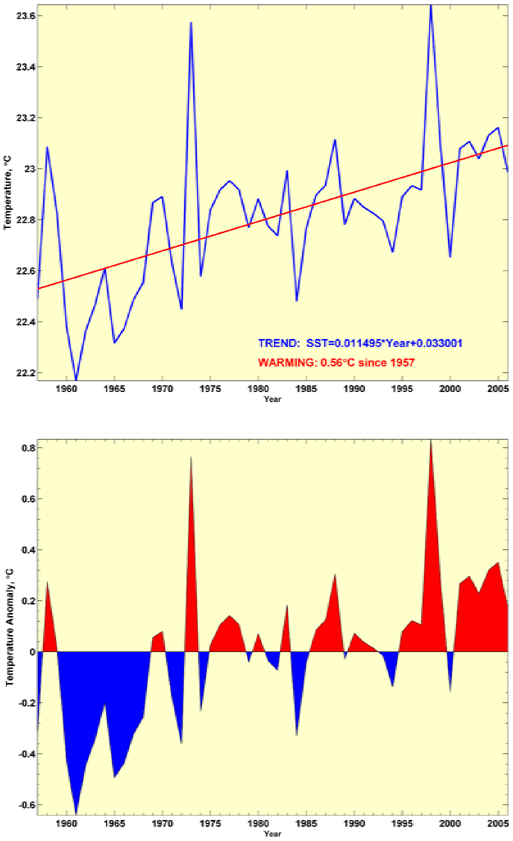

Figure IX-18.2. East Central Australian Shelf LME Mean Annual SST, 1957-2006 (top) and SST anomalies, 1957-2006 (bottom) based on Hadley climatology, after Belkin 2009.

***East Central Australian Shelf LME, Chlorophyll and Primary Productivity*:** The East-Central Australian Shelf LME is considered a Class III, low productivity ecosystem at <150 $gCm^{-2}yr^{-1}$ (Sea Around Us 2007; www.science.oregonstate.edu/ocean.productivity/).

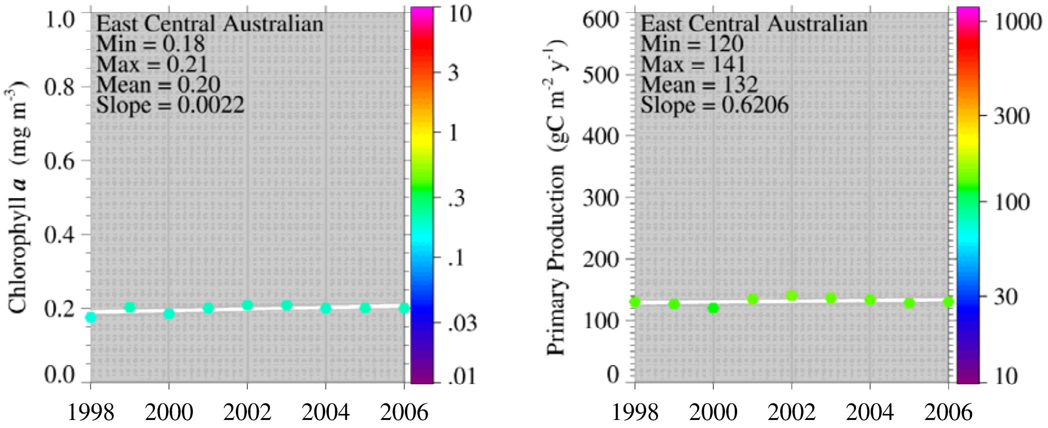

Figure IX-18.3. East Central Australian Shelf trends in chlorophyll a and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Australian waters are relatively nutrient-poor and unable to sustain large fish populations. Approximately 1 in 4 of the 4,482 species found in Australian waters are endemic (Hoese et al. 2006). Off the coast of New South Wales, 1,748 fish species are recorded of which 22% are Australian endemics. For information on South-East Fisheries, see the AFMA websites or DEWR reports. Federal, commercial fishing is not large in the Australian East Marine Planning region (approximates the East Central Australian LME) valued in 2002-2006 at around $320 m and 1% of the national value of commercial fisheries. These AFMA managed fisheries http://www.afma.gov.au/fisheries/default.htm include the East Coast Deepwater trawl fisheries, (10 concessions, using demersal and midwater trawling); the Commonwealth Trawl Sector (formerly South East Trawl Fishery), with nearly 60 concessions, 54 vessels using otter trawl and danish seine methods, some midwater trawling; the Eastern Tuna and Billfish Fishery (ETBF) with over 100 permits, 72 vessels using pelagic longline, minor line (handline, troll, rod and reel). The vast bulk of the landings are restricted to the very narrow continental shelf (Moore et al. 2007). Three of the more significant commercial fisheries are the various estuarine and ocean prawn trawl fisheries to 3 nautical miles, and the federally managed South East Trawl and the East Coast tuna fishery. FAO provides information on Australia's fisheries and the characteristics of the industry (www.fao.org). Reported landings in the LME include mullet, shrimps and prawns, butterfishes and tunas (skipjack, yellowfin and bluefin) and have fluctuated over the last 50 years with peaks in the mid 1970s, late 1980s and early 2000s with over 30,000 tonnes recorded in mid 1970s, late 1980s and again in 2002-2005 (Figure IX-18.4). The value of the reported landings reached nearly 300 million US$ (in 2000 real US$) in the mid 1970s and 100 million US$ in recent years (Figure IX-18.5). For 2000/01, FAO reports landed catch in Queensland fisheries alone at 31,250 tonnes (excluding aquaculture), valued at 741 millions $AUD. The ADL Bureau of Rural Science estimates that the Eastern Central Region's commercial fisheries caught 31,500 tonnes with Gross Value of Products (GVP) at 315 million $AUD in 2002.

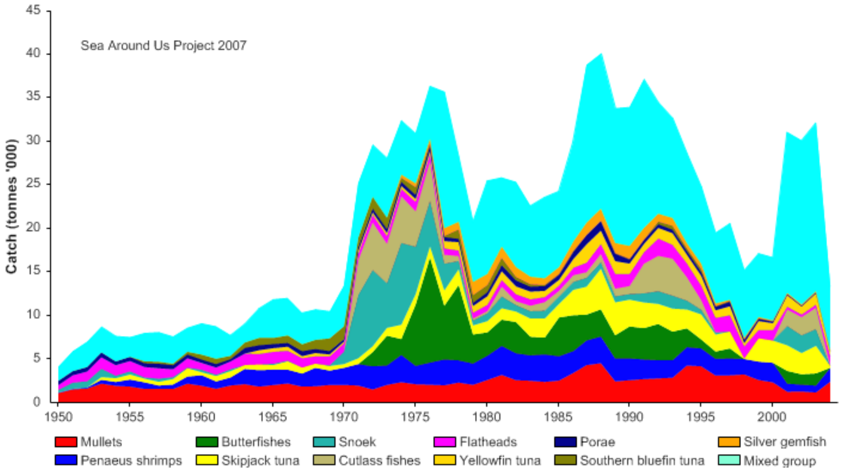

Figure IX-18.4. Total reported landings in the East-Central Australian Shelf LME by species (Sea Around Us 2007). Note that Porae =Blue Morwong.

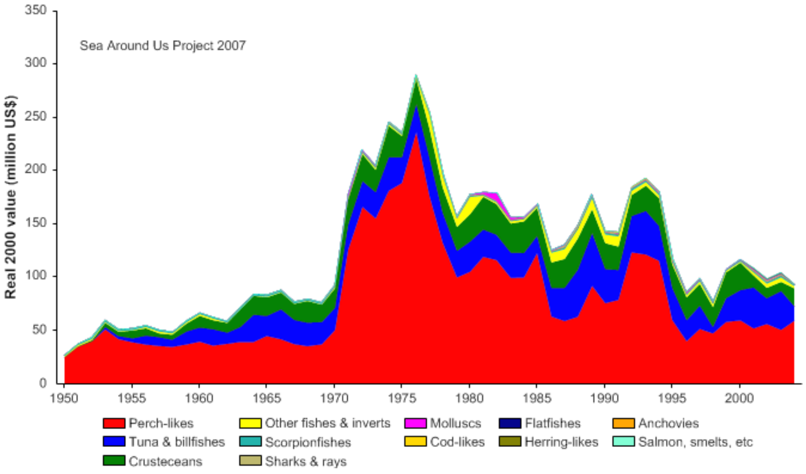

Figure IX-18.5. Value of reported landings in the East-Central Australian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is currently below 4% with Australia and New Zealand, as well as few distant water fishing countries, namely Japan and South Korea, historically accounting for the large share of the ecological footprint (Figure IX-18.6).

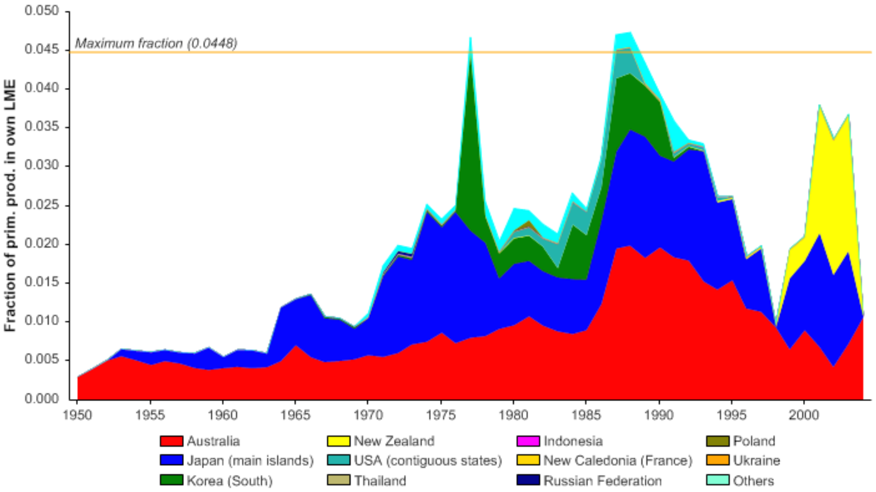

Figure IX-18.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the East-Central Australian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Both the mean trophic level (i.e., the MTI; Pauly & Watson 2005) and the FiB index vary widely and no clear interpretation on the state of the LME or its fisheries can be made based on these indices (Figure 18.7). It is likely that such variation in the two indices is due to the low level of exploitation in the region.

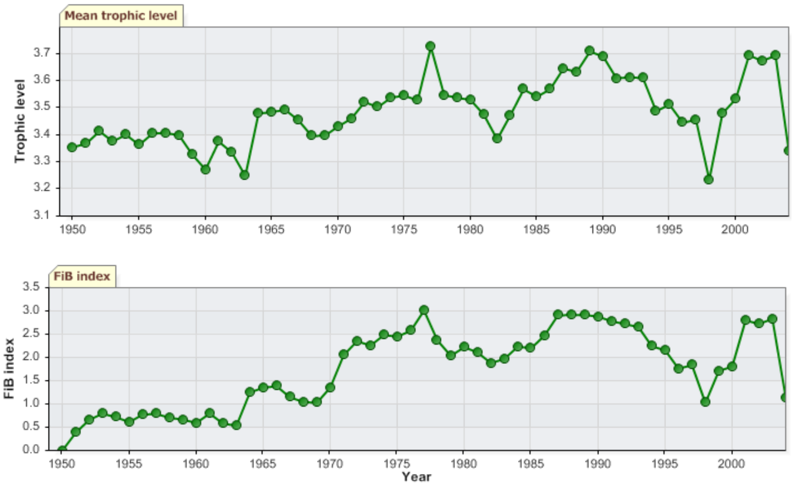

Figure IX-18.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the East-Central Australian Shelf LME (Sea Around Us 2007)

The fluctuations in the reported landings are also making interpretation of the Stock-Catch Status Plots difficult (Figure IX-18.8). Whilst these plots imply approximately 20% and 40% of stocks being collapsed and overexploited, respectively (Figure IX-18.8 top), the causes are complex including changes to gear and management, price and especially multispecies effects (over 200 species are processed by the Sydney Fish Markets, Moore et al. 2007).

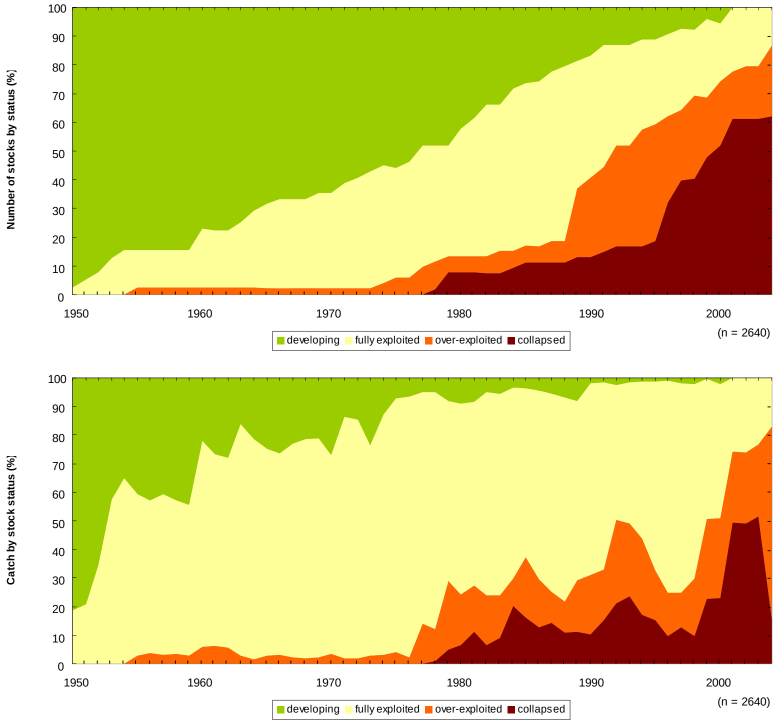

Figure IX-18.8. Stock-Catch Status Plots for the East-Central Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions). See also Moore et al. (2007) for a fisheries status overview.

III. Pollution and Ecosystem Health

The major problems for this coastline are real estate value, urbanization, water quality, freshwater, and beach erosion. The coastline of NSW alone has over 450 coastal discharge sites along the NSW coast, the largest three being off Sydney amounting to nearly 1000 $ML.d^{-1}$ or primary treated sewage. Desalination plants are planned or being constructed for the Gold Coast, Sydney (Kurnell) and Melbourne (at Wonthaggi on the South Gippsland coast). There are no mining activities in the LME but there is potential for sand mining, manganese nodule harvesting, or base/precious metals on the Lord Howe Rise. Sand mining has the greatest potential for NSW in light of beach erosion and construction needs. There is a pilot wave-energy generator at the breakwater of Port Kembla www.oceanlinx.com/ .

For 2005-2006, ports of the East Marine Planning region (mostly Newcastle, Sydney, Brisbane and Port Kembla) accounted for 42% of the nation's exports and 51% of national imports by tonnage (Anon. 2007). These ports accounted for 18% of freight loaded and 67% unloaded by all Australian ports. The busiest sea lanes are through the Coral Sea. The LME may be threatened by an increase in shipping. Ship ballast water has been shown to contain organisms including bacteria, viruses, algal cells, plankton and the larval forms of many invertebrates and fish. Two of Australia's largest three cities and four of the largest 10 ports are located in this LME, and it is the most urbanized coastline in Australia. Pressure is increasing on natural environments, productive agricultural land, water resources, sewage treatment and waste disposal systems. There are environmental impacts caused by tourism and related infrastructure (airports, power generation facilities, accommodation, sewage treatment and disposal facilities, moorings and marine transport). For more information on coastal and marine pollution issues in this LME, see the Australia State of the Environment Reports indexed by date at www.deh.gov.au/soe/index.html.

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IV. Socioeconomic Conditions

Australia's Bureau of Rural Sciences estimates that, on average, 5% of the population of the Eastern Central and Norfolk Regions is employed in the fishing industry (http://adl.brs.gov.au/). FAO provides information on the characteristics and socioeconomic benefits of Australia's fishing industry (www.fao.org/). The Eastern Central region contains 165 towns, and large cities and ports, including Sydney (Port Jackson and Botany Bay), Brisbane, Newcastle, and Port Kembla. Shipping and marine tourism are major economic activities and the cities absorb much of the country's population growth. The Australian Bureau of Statistics http://www.abs.gov.au/ estimates the current coastal population in this LME at 8 million, mostly living in Sydney and Brisbane, with a quarter in the large coastal non-metropolitan centres like Newcastle, Wollongong, Gold and Sunshine Coasts, Coffs and Bundaberg (http://adl.brs.gov.au/).

The largest marine industry is marine tourism, contributing 22% of the national marine industry ($27 billion in value added during 2002-03, The Allen Report 2004). The value of the marine industry (i.e. all recreational and light commercial vessels) in NSW is valued at over $2 billion pa and employs over 11,000 – both figures are almost equivalent to all other states combined (mostly Victoria and Queensland, (www.bia.org.au/data.html). Over a third of the national marine industry employment (36%) is in NSW – and mostly in marine tourism. These figures are more remarkable considering that our estuaries, while numerous (>130) are small and we have the nation's narrowest continental shelf. The Australian Bureau of Statistics estimates at www.abs.gov.au/ausstats/ that, in the entire country, over 5 million Australians take part in recreational fishing in Australia as a leisure activity (i.e. 20% fish at least once a year), with some 120,000 people identified as members of fishing clubs in 1996-97, and that recreational fishing supports about 90,000 Australian jobs especially in industries supplying tackle and bait and recreational boating. The Bureau of Statistics estimates that international tourists spend over $200m on fishing in Australia each year. A survey undertaken by the ABS in the early 1990s showed that recreational fishing accounted for 23,000 tonnes of fish, 2,800 tonnes of crabs and approximately 1,400 tonnes of freshwater crayfish. In NSW the recreational catch is about 30% of the commercial catch, but for 6 major species the recreational catch is actually greater than the commercial. In NSW the recreational fishing fee bought out commercial fishing licenses in 25 estuaries in 2001, now described as recreational fishing havens. Most of Australia's recreational fishing is undertaken along the coast and estuaries of New South Wales, Queensland and Victoria, reflecting both the excellent fishing areas and the geographic spread of Australia's population.

V. Governance

The East-Central Australian Shelf LME is bordered only by Australia and falls within the non-UNEP administered Pacific Regional Seas Programme. In 2003, Australia's Natural Resource Council endorsed a framework for a national cooperative approach to Integrated Coastal Zone Management. State jurisdiction is generally limited to the 3 nautical mile limit, but many state managed fisheries extend into federal waters to 200 nautical miles. Governance issues in this LME pertain to fisheries management and to the establishment of marine reserves. Lord Howe Island (33.5S, 159E) and the Solitary Islands (30.2S off northern NSW) were declared state marine parks in 1998/1999. Four other NSW marine parks have been declared over the past 6 years, which extend out to the 3 nm mile limit of state waters: Cape Byron (22,000 ha), Batemans Bay (85,000 ha), Jervis Bay (21,000 ha) and the largest, Port Stephens-Great Lakes (98,000 ha). The Batemans Bay and Port Stephens parks have been the most controversial with the recreational fishing community that has challenged, in state parliament, the science on which they are based. The NSW Marine Parks Authority (MPA) through NSW Department of Environment and Climate Change aims to establish and manage a system of multiple-use marine parks designed to conserve marine biodiversity, maintain ecological processes and, provide for ecologically-sustainable use, public appreciation, education, understanding and enjoyment of the marine environment. Key issues remaining are larval connectivity amongst areas, and the degree of “spill-over”. See the North Australian Shelf LME (Chapter VIII, this volume) for more information. NSW Department of Primary Industries is the principal agency responsible for conserving the aquatic environment and managing the fisheries resources of this LME. It is responsible for protecting and restoring fish habitats, promoting responsible and viable commercial fishing and supporting aquaculture industries.

The South Pacific Regional Environment Programme (SPREP), a regional intergovernmental organisation now based in Apia, Samoa, was initially established in 1982 as a programme of the South Pacific Commission. SPREP is the primary regional organisation concerned with environmental management in the Pacific, and serves as the Secretariat for three Conventions. The 1986 Convention for the Protection of the Natural Resources and Environment of the South Pacific region entered into force in 1990. The 1976 Convention on the Conservation of Nature in the South Pacific (Apia Convention), came into force in 1990. The Pacific Islands Forum is the key regional political organization in the Pacific representing the 14 Island countries as well as Australia and New Zealand. Australia ratified the United Nations Law of the Sea Convention (UNCLOS) in 1996. The 1995 Convention to Ban the Importation into Forum Island Countries of Hazardous and Radioactive Wastes and to Control the Transboundary Movement and Management of Hazardous Wastes within the South Pacific Region (Waigani Convention) entered into force in 2001. Australia’s indigenous peoples are re-emerging in the environmental management process as a result of native title rights. The Pacific Islands Forum is the key regional political organization in the Pacific, representing the 14 island countries as well as Australia and New Zealand. The Action Plan has identified four broad priorities for the region: natural resources management, pollution prevention, climate change and variability, and sustainable economic development. The Australian Government’s Department of the Environment and Heritage regularly updates a coasts and oceans website at: www.deh.gov.au/coasts/.

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Australian Bureau of Statistics at www.abs.gov.au/ausstats/abs

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IX-19 New Zealand Shelf LME

M.C. Aquarone and S. Adams

The New Zealand Shelf LME stretches across from the subtropics to the sub-Antarctic. It covers a surface area of nearly one million km^2, of which 0.03% is protected, and contains 0.08% of the world's sea mounts (Sea Around Us 2007). The shelf surrounding New Zealand's North Island and South Island vary in width from a few tens to several hundred kilometres. This LME is characterised by its temperate climate, influenced by the warm Tasman and North Cape currents in the north and by the cooler Southland Current in the South. The marine environment is diverse and includes estuaries, mudflats, mangroves, seagrass and kelp beds, reefs, sea mount communities and deep sea trenches. Morgan (1989) and UNEP (2003) pertain to this LME.

I. Productivity

The New Zealand Shelf LME is a Class III, low productivity (<150gCm^{-2}yr^{-1}) ecosystem. See also Bradford-Grieve et al. (2003, 2006). While the southern Plateau region subantarctic water, limited by iron availability, is a low production system, the Chatham Rise, eastern Cook Strait, and the NE shelf are considerably more productive. For a study of ocean fronts and their contribution to marine productivity in this LME, see the National Institute of Water and Atmospheric Research website, www.niwa.co.nz. View a SeaWiFS image of ocean chlorophyll in New Zealand coastal waters at www.niwa.cri.nz. In the southern part of this LME, there is higher productivity in the fiord ecosystems. The current definitive data on marine species in the New Zealand flora and fauna from the National Institute of Water and Atmospheric Research of New Zealand (NIWA) are a maximum of 16,214 species in total, including known, undescribed species.

Oceanic fronts: This LME features several well-defined fronts (Figure IX-19.1) that together determine the ecological regime of the New Zealand shelf (Belkin and Gordon 1996; Belkin and Cornillon 2003; Belkin et al. 2009). In the north, the Tasman Front and its extension associated with the North Cape Current bring warm and salty tropical waters to the east coast of North Island. This influx, together with vigorous tidal mixing thanks to rough bathymetry, is largely responsible for the exceptionally high productivity off the Bay of Islands, where big game fish like marlins and kingfish come unusually close to the mainland coast, forming fishing grounds just a few miles offshore, for example, off Cape Brett. West of North Island, the southern branch of the Tasman Front heads toward Cook Strait. In the south, the Southland Current Front runs northward along the east coast of South Island toward Banks Peninsula. East of New Zealand, the double Subtropical Frontal Zone that consists of the North and South STF extends eastward along the north and south flanks of the Chatham Rise up to Chatham Island and beyond. This double Subtropical Frontal Zone is similar to the double frontal zones found in other subtropical oceans (Belkin, 1988, 1993, 1995, Belkin et al. 2009; Belkin and Gordon, 1996). See also Bradford-Grieve et al. (2006).

New Zealand Shelf SST (Belkin 2009)
Linear SST trend since 1957: 0.11°C.
Linear SST trend since 1982: 0.32°C.

The New Zealand Shelf features strong interannual variability, with a magnitude exceeding 1°C, superimposed over a slow-warming trend (Figure IX-19.2). Any correlation between this LME and the upstream LMEs off Australia can only be rather tenuous since different parts of the New Zealand Shelf are advectively affected by different Australian LMEs. For example, the North Island is oceanographically linked to the Northeast Australian Shelf LME, whereas the South Island is linked to the Southeast Australian Shelf LME. The all-time maximum of 1971 in New Zealand occurred two years prior to the near-all-time maximum of 1973 in the East Central Australian Shelf LME, therefore these events could not have been advectively connected.

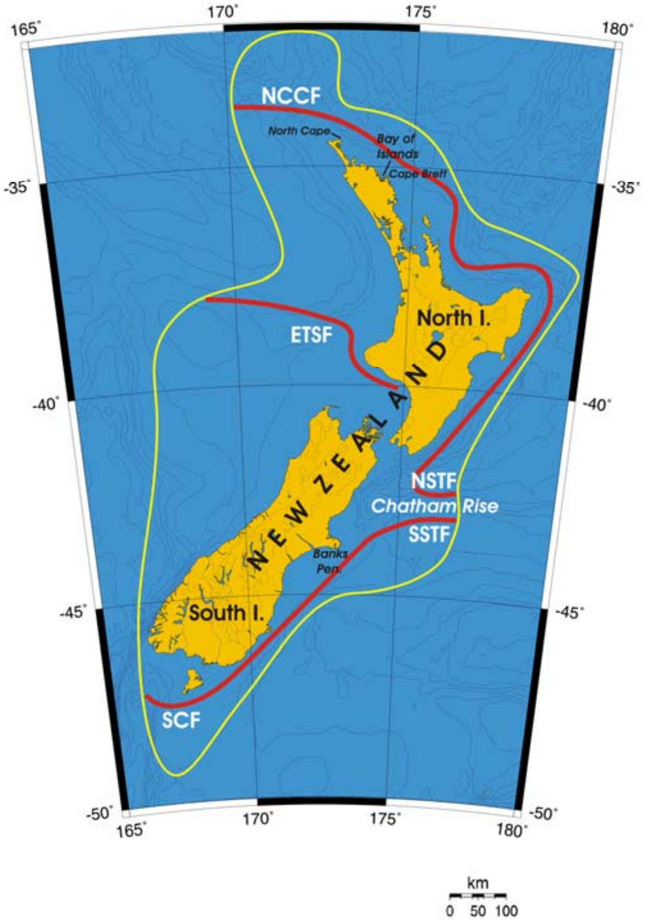

Figure IX-19.1. Fronts of the New Zealand Shelf LME. ETSF, East Tasman Front; NCCF, North Cape Current Front; NSTF, North Subtropical Front; SCF, Southland Current Front; SSTF, South Subtropical Front. Yellow line, LME boundary. After Belkin et al. (2009), Belkin and Cornillon (2003), and Belkin and Gordon (1996).

Another warm peak, of 1974, occurred off New Zealand a year after the 1973 warm peak in the East-Central Australia LME; these events may have been advectively connected. The warm events of 1971-1974 were confined to these two LMEs connected by the East Australian Current and its eastward extensions, namely Tasman Front (TF), North Cape Current Front (NCCF), and East Tasman Sea Front (ETSF) (Figure IX-19.1).

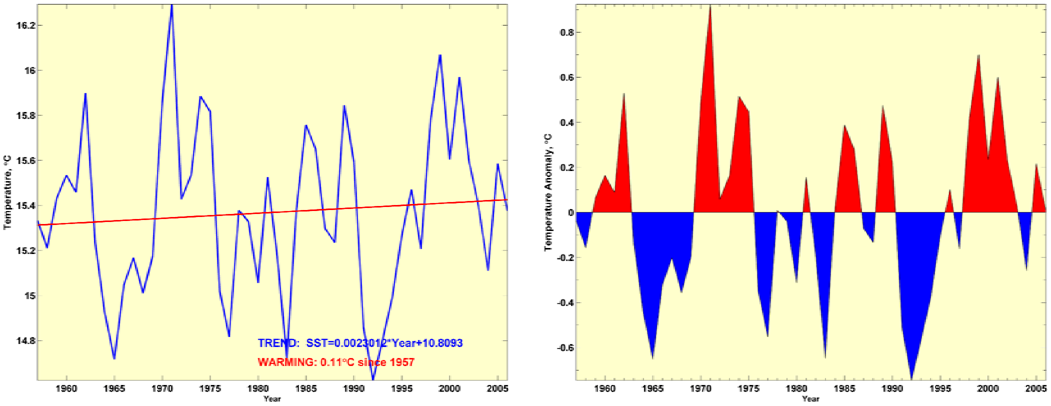

Figure IX-19.2. New Zealand Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

New Zealand Shelf LME Chlorophyll and Primary Productivity: The New Zealand Shelf LME is a Class III, low productivity (<150gCm^{-2}yr^{-1}) ecosystem. See also Bradford-Grieve et al. (2003, 2006).

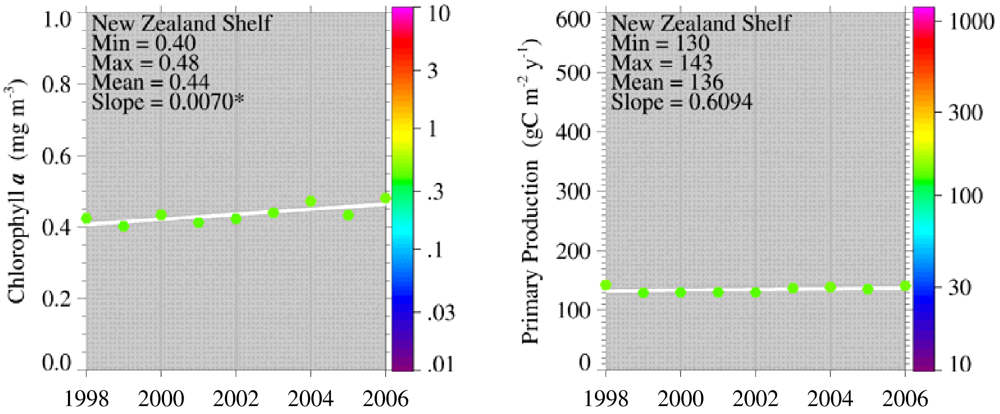

Figure IX 19.3. New Zealand Shelf LME annual trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

I. Fish and Fisheries

The New Zealand Ministry of Fisheries estimates about 750,000 tonnes of seafood is harvested annually from New Zealand's fisheries—70% from deepwater and midwater fisheries, 11% pelagic, 10% farmed species, and 9% from their inshore fisheries. Note that the Chatham Rise and the Southern Plateau, 2 major fishing regions, are not entirely included in the LME. The Ministry also estimates that 20% of the population engages in marine recreational fishing annually and that the expenditure made by recreational fishers to catch five key recreational species is nearly NZ$1 billion per year (www.govt.nz/en-nz). Among the important fisheries in this LME are those for migratory apex predators such as tuna, billfish, and shark, squid, hoki, orange roughy, rock lobster, mussels (cultured) and snapper are key export species. According to the Ministry, the value of fish exports in 2004 grew more than the volume and generated NZ$1.2 billion, NZ$1.0 billion from capture fisheries and NZ$200 million from aquaculture.

Fisheries policies in New Zealand hope to secure a long-term future for the industry by setting sustainable catch limits and providing harvesting rights to benefit all New Zealanders, including the indigenous Maori. Fiords in the southern part of this LME support commercial and recreational fisheries as well as traditional Maori fisheries. Information on the fisheries in this LME is available on the FAO website (www.fao.org/). For information on areas closed to fishing, see the New Zealand Department of Conservation (www.doc.govt.nz/).

Total reported landings show a sharp spike in 1977 of 220,000 tonnes, likely associated with the declaration of the 200 nautical mile Exclusive Economic Zone around this LME by New Zealand, followed by a continuous increase through the 1980s and 1990s and a decline in the 2000s (Figure IX-19.4). The value of the reported landings reached US$583 million (in 2000 US dollars) in 1984, followed by a decline to between US$260 million and US$450 million in recent years (Figure IX-19.5).

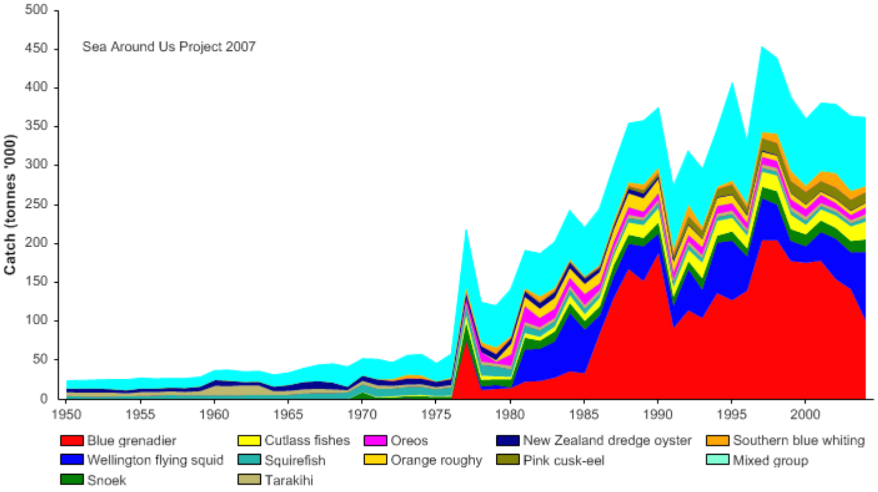

Figure IX-19.4. Total reported landings in the New Zealand Shelf LME by species (Sea Around Us 2007).

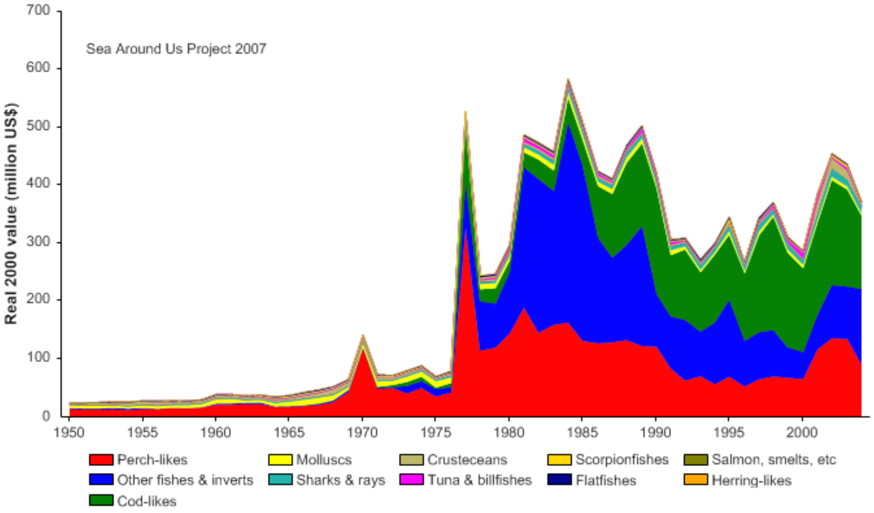

Figure IX-19.5. Value of reported landings in the New Zealand Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings is currently below 4% with New Zealand accounting for the great majority of the ecological footprint in the LME (Figure IX-19.6).

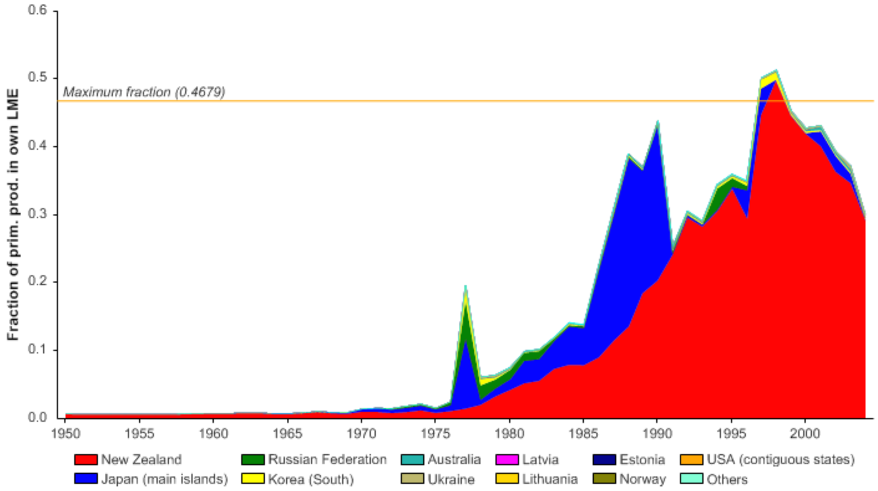

Figure IX-19.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the New Zealand Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has been on a rise since the mid-1970 (Figure IX-19.7, top) as has the FiB index (Figure IX-19.7, bottom). Together with the data presented in Figure IX-19.6, such trends suggest the development of previously under-utilized, high trophic fisheries resources by local as well as foreign fleets.

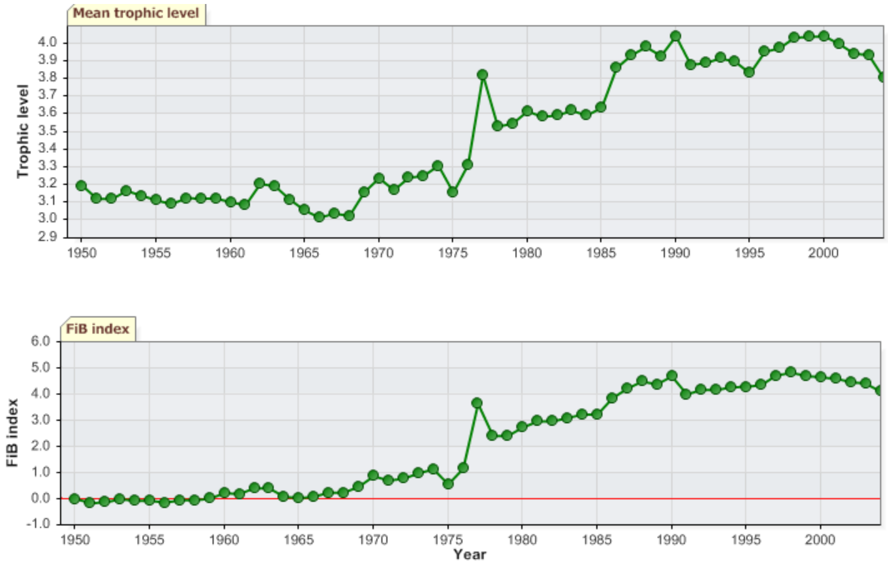

Figure IX-19.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the New Zealand Shelf LME (Sea Around Us 2007).

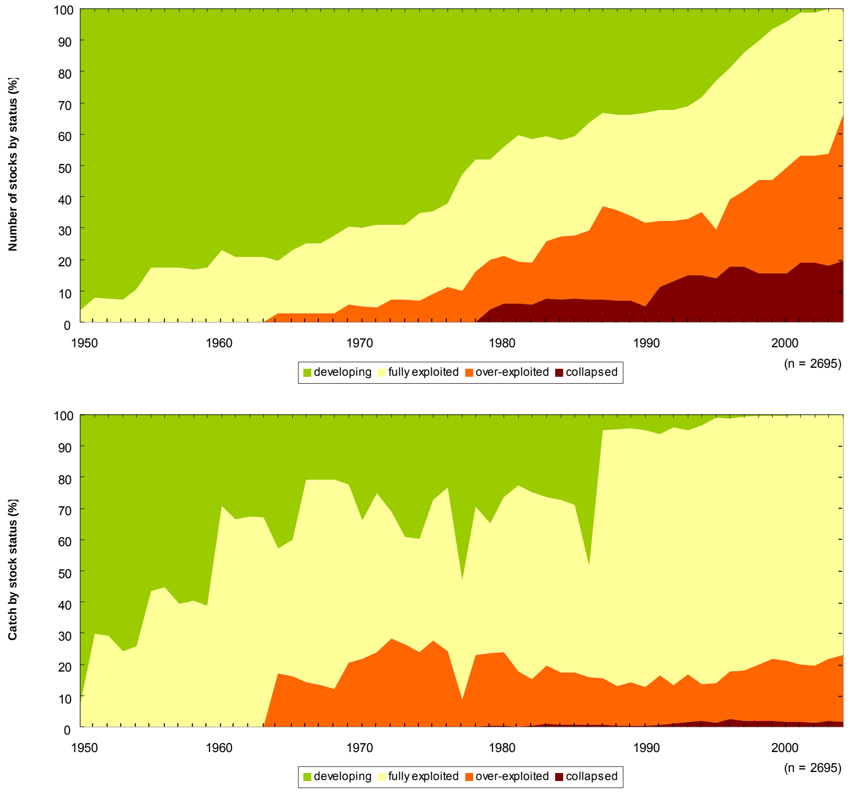

Figure IX-19.8. Stock-Catch Status Plots for the New Zealand Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The Stock-Catch Status Plots for the LME illustrate that more than half of the stocks in the region are currently either overexploited or have collapsed (Figure IX-19.8, top). However, the majority of the reported landings are supplied by stocks classified as 'fully exploited' (Figure IX-19.8, bottom).

III. Pollution and Ecosystem Health

Fisheries impacts on the environment are not completely understood and the data is incomplete. Gill nets pose a risk to marine birds, particularly if set near feeding or breeding areas. Yellow-eyed penguins appear most at risk from nets set by commercial fishermen for bottom dwelling species such as rig and dogfish. The nets are set well within the feeding range of these penguins. Fiord ecosystems in the southern part of this LME are in need of protection. In that region, the crested penguin, *Eudyptes pachyrhynchus*, is at risk. Native flora and fauna are affected by invasions of the Asian kelp, *Undaria*, and toxic micro-algae. Additional information on marine invasions, ballast water, marine toxins, harmful algal blooms and diarrheic shellfish poisoning, is given www.cawthron.org.nz. Studies are underway to assess trawling damage to benthic species and to deepwater seamount habitat.

It has been suggested that changes in sea surface conditions have contributed to the spread of toxic algae and invasive seaweeds in New Zealand waters. Toxic algal blooms occurring in the 1990s have killed marine life and caused illness in humans. Other issues affecting the marine environment are waste and hazardous substances. New Zealand produces a higher rate of municipal waste (two thirds of a tonne per person each year) than most other developed countries. Industrial waste is estimated at 300,000 tonnes a year. Another ecosystem health issue is climate change. Gases released into the atmosphere are enhancing the natural greenhouse effect at a rate that could extensively damage the LME's biophysical systems. Atmospheric levels of carbon dioxide and methane - two of New Zealand's major greenhouse gases – are rising. Studies are underway to assess the impact of terrestrial runoff on coastal ecologies and marine communities.

IV. Socioeconomic Conditions

The population of New Zealand exceeds 4 million and impacts the marine environment through commerce, recreation (including whale watching), indigenous fishing (Maori and Pacific Islanders), commercial fisheries, marine aquaculture, trade, defence and security. The ocean floor is explored and mined for minerals, natural gas and oil. Ports and harbours in this LME are Auckland, Christchurch, Dunedin, Tauranga and Wellington. Statistics New Zealand has developed socioeconomic indicators for the environment that complement the Ministry for the Environment's Environmental Performance Indicators programme (www.stats.govt.nz/). The Ministry of Fisheries estimates direct full-time employment in commercial fisheries and aquaculture at 10,500, and direct and indirect full-time employment in those jobs at 26,000 (www.fish.govt.nz/). Commercially important species are managed under the quota management system (the QMS). The Ministry lists 2,200 persons as holding a quota and a total quota value of $3.5 billion. The Māori now own 40% of quota and have additional involvement in 20% of quota (www.fish.govt.nz/). Recommended TACs for various species for 2006/2007are listed at www.fish.govt.nz/ and in 2006 it was thought that some TAC levels were still too high to be sustainable. Of the 93 stocks on which New Zealand has information for current stock size, 76 (82%) are at or near target levels.

V. Governance

This LME is governed by New Zealand, and is included within the UNEP Pacific Regional Seas Programme. Managing the marine environment is a complex process involving overlapping and conflicting interests, agencies and legislation. Issues arising between commercial fisheries and conservation interests are addressed under different regulations administered by the Department of Conservation and the Ministry of Fisheries. The latter, since the 1930s, has been responsible for the sustainable use of fisheries for the social, economic and cultural well-being of the people. All stakeholders of the marine environment are included in the advancement of sustainable management. There are currently 97 species groupings in the QMS, divided into 629 fishstocks or geographic Quota Management Areas (QMAs). Of the 629 fishstocks, 280 have TACCs (Total Allowable Commercial Catches) of 10 tonnes or less, leaving approximately 349 significant fishstocks that need to be closely monitored (www.fish.govt.nz).

New Zealand is in the process of developing a comprehensive National Oceans Policy which aims to address a range of marine issues including fisheries, maritime transport and protection of the marine environment. New Zealand's Department of Conservation is responsible for marine reserves and for marine mammals such as dolphins, whales, sea lions and fur seals. New Zealand has a number of coastal national parks (Bay of Islands Maritime and Historic Park, Hauraki Gulf Maritime Park).. The New Zealand Biodiversity Strategy (2000) goal includes having 10% of the marine environment in a network of Marine Protected Areas by 2010. For more information on marine reserves see the Department of Conservation website at (www.doc.govt.nz/). The Ministry of Foreign Affairs and Trade is responsible for New Zealand's international effort to address environmental pressures arising from climate change, conservation of species, protection of ocean biodiversity, hazardous substances, and international agreements on environmental goods and services. The Environment Division leads this work and all multilateral environmental agreements, such as the United Nations Framework Convention on Climate Change (ministry web site at www.mfat.govt.nz/).

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New Zealand Ministry of Fisheries at www.fish.govt.nz
www.fish.govt.nz/en-nzFisheries+at+a+glance/default.htm (for labor statistics)
www.fish.govt.nz/en-nz/Press/September+2006/Sustainability (for 2006-2007 TAC statistics)
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IX-20 Northeast Australian Shelf LME

M.C. Aquarone, S. Adams, and J. Brodie

The Northeast Australian Shelf/Great Barrier Reef LME lies in the Pacific Ocean off the coast of the State of Queensland, Australia. It is bounded by the Coral Sea to the east and by the Torres Strait, which separates Australia from Papua New Guinea, to the north, covering an area of 1.3 million km^2 of which 28.06% is protected (Sea Around Us 2007). The LME is characterised by a tropical climate, with tropical cyclones being common seasonal events. The South Equatorial Current, a part of the Pacific Ocean counterclockwise gyre, and the Great Barrier Reef (GBR), a system of coral reefs that stretches 2,000 km along Australia's northeast coast, are notable features of the LME (Brinkman et al., 2002). It has the largest system of corals and related life forms in the world, with 13.51% of the world's coral reefs, in addition to 0.26% of the world's sea mounts (Sea Around Us 2007). Nutrient enrichment is due to land-based sources as well as small upwelling areas and advection while mixing in this LME is due to tidal effects and the wind regime in inshore areas. Intensive fishing is an important force driving the LME but the combined stresses of climate change, terrestrial pollution and over-harvesting are degrading the system, as similar stresses degrade other coral reef systems globally (Pandolfi et al., 2003; Bruno and Selig, 2007). Book chapters and articles pertaining to this LME include Bradbury & Mundy (1989), Morgan (1989), Kelleher (1993), Brodie (1999, 2003), Furnas (2003), Hopley et al. (2007), Johnson and Marshall (2007), and UNEP (2003).

I. Productivity

The Northeast Australian Shelf LME is considered a Category III, low productivity (<150 $gCm^{-2}yr^{-1}$) ecosystem. Ocean currents and wind systems along this coast inhibit the development of highly productive upwelling systems. On this continental shelf, sources of nutrients are Coral Sea surface water, Coral Sea local upwellings of deep sea water, terrestrial runoff and atmospheric inputs. Tidally-induced mixing in the GBR is a major contributor to the nutrient dynamics of this ecosystem. For more information on oceanographic processes in this LME, see Wolanski, 1994, Wolanski et al., 2001 and Brinkman et al., 2002. For large-scale shifts in biomass of the GBR, see Bradbury & Mundy (1989).

There has been a steady accumulation of knowledge and understanding of the structure and dynamics of this system. There is high biological diversity in this LME, with high numbers of rare species. On the GBR are found 350 species of hard corals, along with 1,500 species of fish, 240 species of seabirds, and at least 4,000 species of molluscs (see Brodie 1999). The physical and biological structure of the GBR is complex. For a map of the GBR region, see Kelleher (1993). The abundance of hard corals has been reduced by at least 50% in areas where there is intense crown-of-thorns starfish activity. For more information about the large-scale effects of crown-of-thorns starfish outbreaks on the benthic community, and for the propagation of effects into the fish and plankton communities, see Bradbury & Mundy (1989) and Brodie et al. (2005).

Oceanic fronts: From satellite data (Belkin & Cornillon 2003, Belkin et al. 2009), the GBR is marked by a seasonal thermal front (GBRF) that peaks during the austral winter (Figure IX-20.1). This front is better defined off southern Queensland, whereas the fronts' extension off northern Queensland is less robust. Satellite data analysis revealed another, inner shelf front that runs off the Queensland coast (QISF). This front appears to consist of three segments, northern, central and southern, whose possible connectivity is not yet established. In addition, a coastal region affected by terrestrial material is evident (Brodie et al., 2007) separated from the oceanic regions off the shelf in deeper waters.

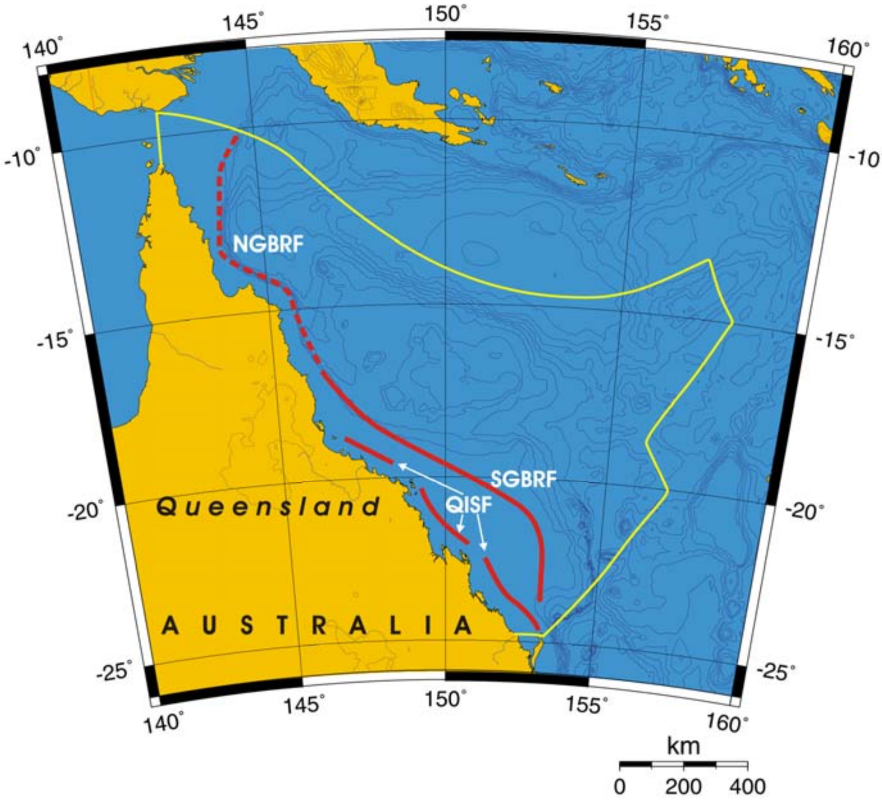

Figure IX-20.1. Fronts of Northeast Australian Shelf/Great Barrier Reef LME. NGBRF, North Great Barrier Reef Front (most probable location); QISF, Queensland Inner Shelf Front; SGBRF, South Great Barrier Reef Front. Yellow line, LME boundary, after Belkin et al. (2009).

Northeast Australian Shelf SST (after Belkin 2009)
Linear SST trend since 1957: 0.46°C.
Linear SST trend since 1982: 0.37°C.

Interannual and long-term variability of SST in this LME (Figure IX-20.2) are correlated with a few neighboring LMEs. For example, the twin peaks of 1970-1973 occurred simultaneously in the North Australian Shelf LME. The local minimum of 1982 occurred at the same time in the Indonesian Sea LME and in the Australian Shelf LME. The all-time maximum of 1998 was a local manifestation of the global warming effect of the El Niño 1997-98. The absolute minimum of 1965-66 occurred concurrently with the Southeast Australian Shelf LME. This cold anomaly probably originated upstream, in the South Equatorial Current.

High SST exceeding the coral colony' tolerance threshold is the primary cause of coral bleaching (Hoegh-Guldberg, 1999; Liu et al., 2003). In 2002, the Great Barrier Reef suffered from the worst coral bleaching event ever, which affected up to 60% and severely damaged 5%, of reefs surveyed (Berkelmans et al., 2004). Further severe bleaching and damage is predicted under the current climate change predictions and in association with ocean acidification (Lough, 2008, Hoegh-Guldberg et al., 2007).

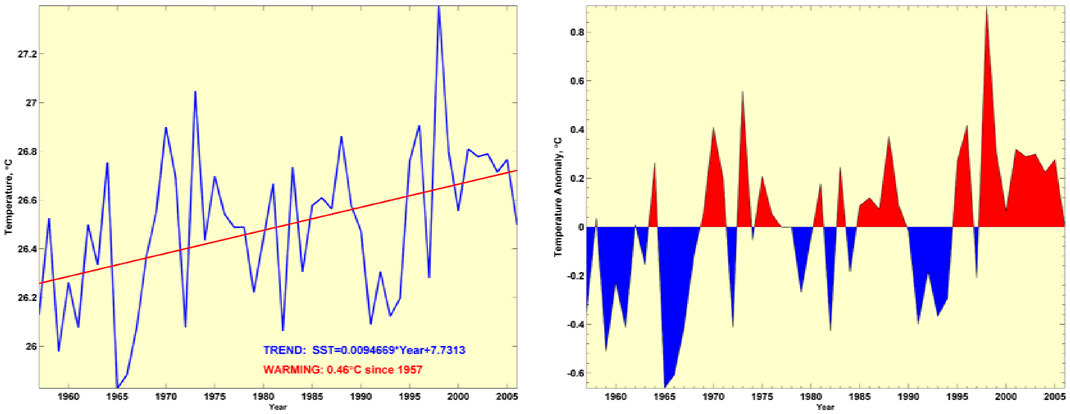

Figure IX-20.2. NE Australian Shelf mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Northeast Australian Shelf Chlorophyll and Primary Productivity The Northeast Australian Shelf LME is considered a Category III, low productivity (<150 gCm^{-2}yr^{-1}) ecosystem.

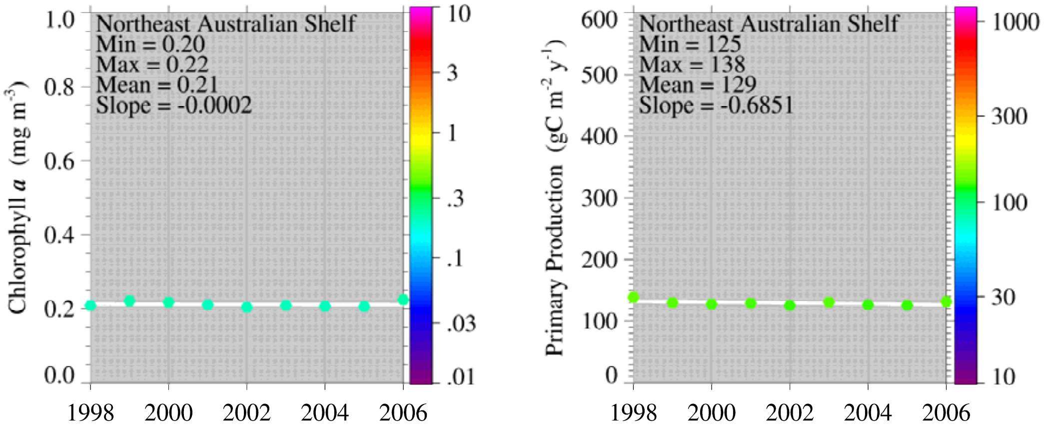

Figure IX-20.3. Northeast Australian Shelf Trends in chlorophyll-*a* and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The relatively nutrient-poor waters of the Northeast Australian Shelf are unable to sustain large fish populations. The trawl fishery (Brodie 1999) targets tiger prawns, banana prawns and king prawns. Commercial and recreational fishing remain important industries in the Northeast Australian Shelf/Great Barrier Reef LME. The commercial sector in the state of Queensland annually harvests about 24,000 tonnes of seafood while the 800,000 recreational fishers in Queensland annually catch between 3,500 and 4,300 tonnes (www.oceanatlas.org). The Bureau of Rural Sciences estimates a total commercial fisheries production in national waters in 2002 at 15,600 tonnes with a value of AU$165 million (http://adl.brs.gov.au/). The annual catch of scallops and prawns is about 8,000 tonnes. Scallops are caught in the southern section of the GBR Marine Park. The Torres Strait prawn fishery is fully-exploited while the Torres Strait lobster is still underexploited. Information on Australia's fisheries is also available on the FAO website (www.fao.org/). Total reported landings of the LME comprised mainly of tunas (mostly of skipjacks but also yellowfin, bigeye and albacore), shrimps and prawns, and squids (from the late 1980s to early 1990s) and recorded 62,000 tonnes in 1990 (Figure IX-20.4). The landings have since declined to about half of the peak landings. The trend in the value reflected that of the landings, rising to about US$250 million (in 2000 US dollars) in 1989 (Figure IX-20.5).

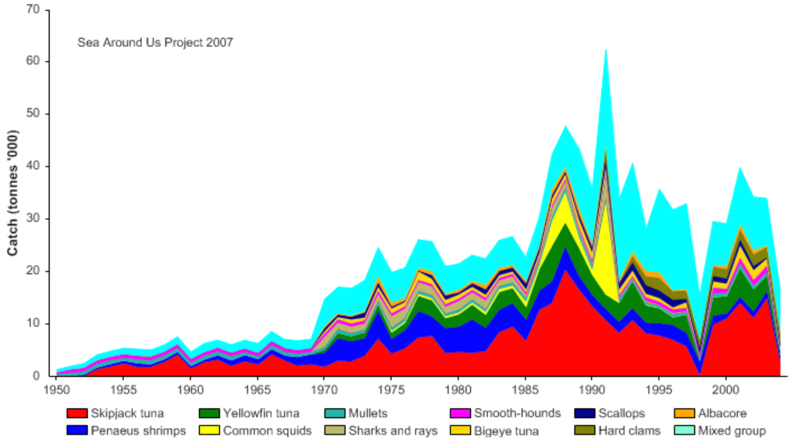

Figure IX-20.4. Total reported landings in the Northeast Australian Shelf LME by species (Sea Around Us 2007)

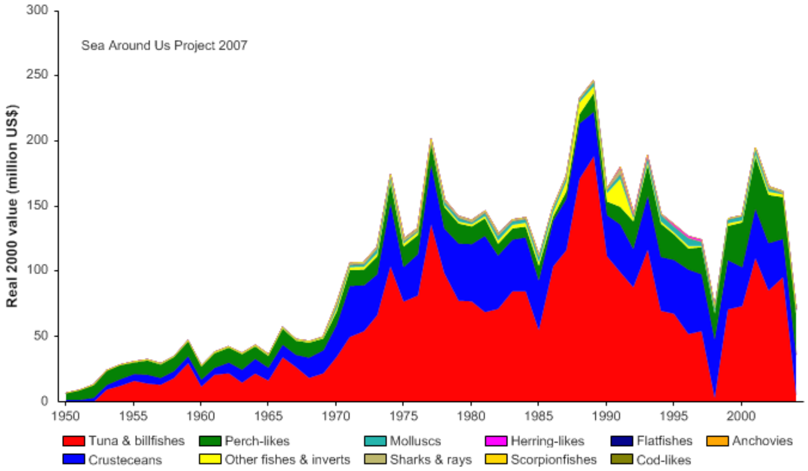

Figure IX-20.5. Value of reported landings in Northeast Australian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 5% of the observed primary production in the late1980s, but still is relatively low, considering the high proportion of high trophic pelagic species in the landings (Figure IX-20.6). Japan, with its distant water tuna fleets, accounts for the largest footprint in the region.

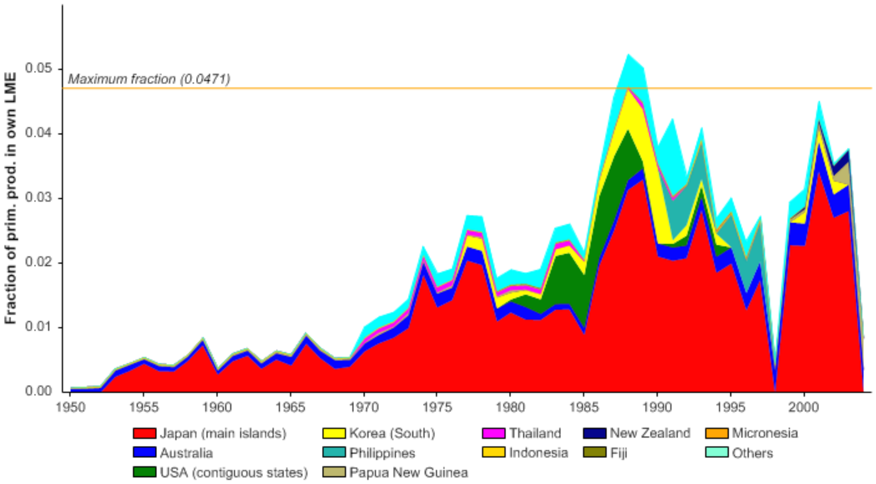

Figure IX-20.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Northeast Australian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005; Figure) in the LME is still high, except for 1998 and 2004 when the landings of tuna were unusually low (Figure IX-20.7, top), while the FiB index has been stable following an increase from 1950 to the mid-1970s (Figure IX-20.7, bottom). These trends imply a growth of fisheries in the region with no clear signs of a 'fishing down' (Pauly *et al*. 1998)..

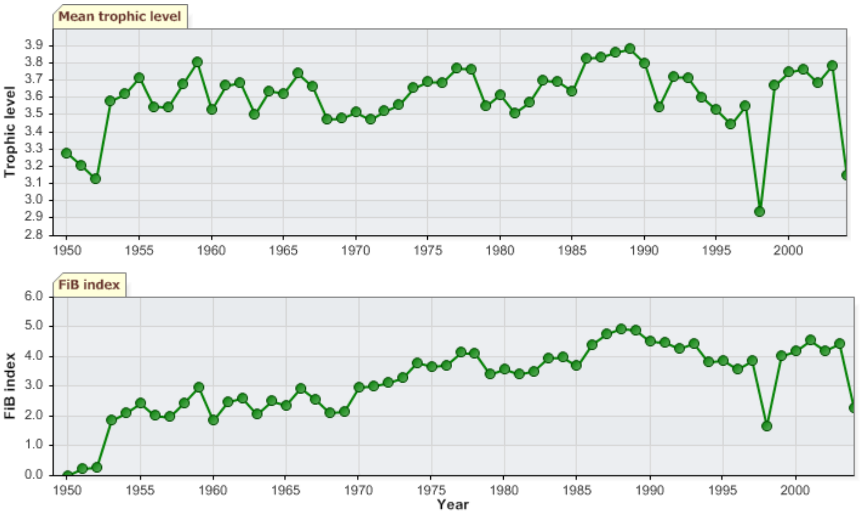

Figure IX-20.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Northeast Australian Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that more than half of the stocks in the region are currently either overexploited or have collapsed (Figure IX-20.8, top) and that half of the reported landings is supplied by such stocks (Figure IX-20.8, bottom).

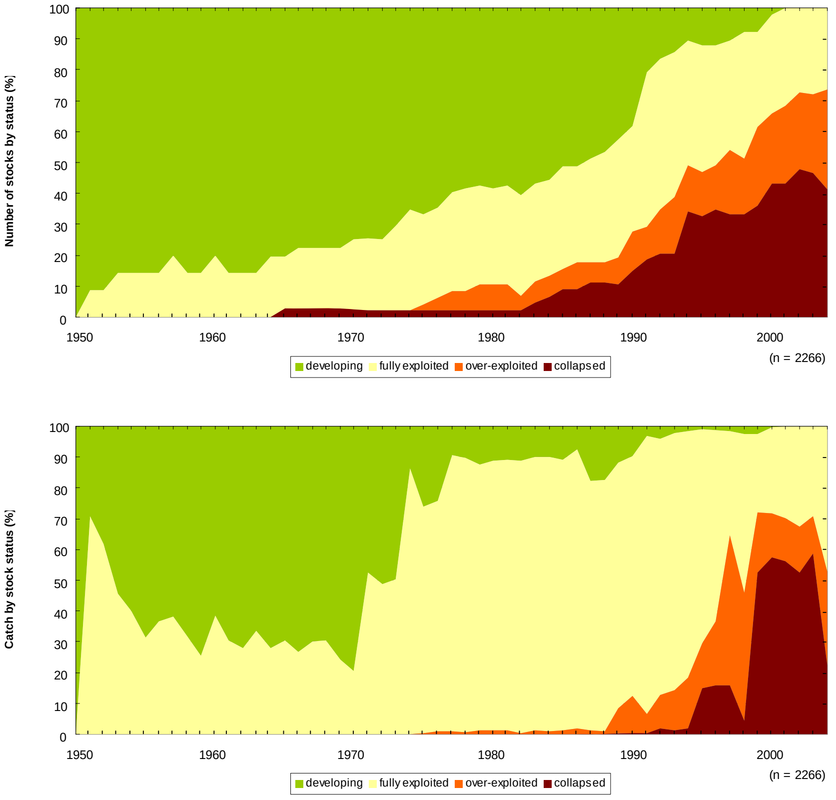

Figure IX-20.8. Stock-Catch Status Plot for the Northeast Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

The Northeast Australia LME has been perturbed by the crown-of-thorns starfish (*Acanthaster planci*) that has devastated reefs (Kelleher 1993). There is uncertainty as to whether the outbreaks are human-induced or a natural part of the ecological variability of the GBR (Brodie 1999). Possible anthropogenic causes are the overfishing of crown-of-thorns predators such as fish or the triton shell, and enhanced nutrient runoff from coastal development (Brodie et al., 2005). The large-scale effects of crown-of-thorns starfish outbreaks on the benthic community have been discussed in Bradbury & Mundy (1989) and in the State of the Environment Report (www.deh.gov.au/soe/index).

The GBR is also threatened by increased shipping. A number of ports line the GBR coastline (Brodie 1999), and navigation in the Torres Strait is intense. Ballast water introductions of toxic dinoflagellates have caused serious ecological problems in other parts of Australia but so far no undesirable introduction has been detected in the GBR region. One significant anthropogenic impact on the GBR region is the change in the water quality of terrestrial runoff (Brodie 1999). Excess nutrients affect coral and coral reef systems (Kinsey 1991). There is considerable evidence that reefs, particularly inshore fringing reefs, are now muddier and have less coral cover and more algal cover (Fabricius et al., 2005). Reef ecosystem damage is evident in a large area of the north-central GBR (Devantier et al., 2006) coinciding with the area known to be exposed to polluted terrestrial runoff (Devlin and Brodie, 2005). Recreational fishermen tend to target reef ecosystems and remove larger predatory species. The effects of this selective removal of fish are largely unknown. Shore-based recreational fishing can affect shore populations of invertebrates that are collected for bait in intensively visited areas.

Environmental impacts on the Great Barrier Reef also stem from tourism. Large numbers of people are engaged in recreational fishing, SCUBA diving and boating. The expanding marine tourism industry is a major contributor to the Australian economy and now supports more than 820 operators, generates $4.2 billion annually, and accommodates 1.8 million visitors each year (www.oceansatlas.org). Activities associated with this level of recreational use can affect the environment through the pollution of water by boats and the disturbance of species and habitats (including mangroves). A major source of environmental impacts is the provision of infrastructure to support tourism (airports, power generation facilities, accommodation, sewage treatment and disposal facilities, moorings, and marine transport, including high-speed ferries). Often, this infrastructure is located in fragile or pristine environments that are susceptible to disturbance and fragmentation. For more information on pollution control in the GBR, see Kelleher (1993).

IV. Socioeconomic Conditions

According to the Bureau of Rural Statistics, the North Eastern Region of Australia has a population of 441,300 of whom 90% reside in 66 medium-to-large coastal towns. (http://adl.brs.gov.au). Employment within the fishing sector is heavily concentrated in the commercial sector, and involves from 1% to 5% of total employment. Total commercial fisheries production for the region in 2002 was estimated at 15,600 t with a GVP of AU$165 million (http://adl.brs.gov.au/). FAO provides information on Australia's fisheries and the socioeconomic benefits of the industry (www.fao.org/fi). Marine and coastal-based tourism is the main industry of the GBR, an internationally recognised tourist site and one of Australia's six World Heritage Sites (see Brodie 1999). In the 1980s, tourism in the GBR was evaluated at 150,000 visitor-days. In the late 1990s, tourism was worth US$1 billion, with 1.5 million visitor-days. Whale-watching takes place off the coast of Queensland. Tourism clearly depends on sustaining environmental and heritage values. Tourism can affect the lifestyle of community residents in ways they perceive as intrusive. In terms of fisheries, for instance, there can be tensions between recreation, commercial and indigenous interests. Traditional fishing by Aborigines and Torres Strait islanders is confined to areas close to Aboriginal communities (Brodie 1999). Shipping is a major activity. Mining including extraction of petroleum is not permitted within the Marine Park boundary. For more information about human uses of the GBR, see Kelleher (1993) and Brodie (2003).

V. Governance

This LME falls within the Pacific Regional Seas Programme (see the East-Central Australian Shelf LME). The main governance issues in this LME pertain to fisheries management and to the Great Barrier Reef Marine Park and Great Barrier Reef World Heritage Area. See the North Australian Shelf LME (Chapter VIII) for more information. For sustainable fishing issues in the GBR, see Kelleher (1993). Under the offshore constitutional settlement between the Australian states and the federal government, the management of most fisheries within the GBR is the responsibility of the Queensland government (Brodie 1999). Fishery Management methods covering recreational and commercial fishing are: input controls (gear restrictions, limited entry licenses, area and seasonal closures); output controls (TAC, ITQs, bag limits and size limits), measures for species and habitat protection. There is often a 'user pays' approach in which users (usually fishers) pay the full cost of supporting management and compliance for their fisheries, including substantial license or access fees (www.fao.org/). In 2003 the Australian Government Representative Areas Program for the GBR was introduced where the area of highly protected status (no take) was increased from 6 to 30 % of the total (Fernandes et al. 2004). More information on the governance of Australia's fisheries is available at the FAO website.

The GBR Marine Park Act was one of the first pieces of legislation in the world to apply the concept of sustainable development to the management of a large natural area. The GBR Marine Park Authority was established in 1975 to manage the multi-use park. The Authority aims to protect the natural ecosystems of the GBR, and ensures that fishing does not have unacceptable ecological impacts on the fished areas and the reefs. For more information on the history and zoning system of the GBR Marine Park, see Brodie (1999) and Kelleher (1993). Compulsory pilotage in the area reduces the risk of collision with reefs.

On the national level, the Commonwealth Government developed a National Action Plan for Tourism in 1998. The Plan, which identifies conservation and careful management of the environment as essential to the long-term viability of the tourism industry, makes a commitment to ecologically sustainable tourism development and recognises that environmental considerations should be an integral part of economic decisions.

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IX-21 Southeast Australian Shelf LME

M.C. Aquarone, S. Adams, S. Frusher, and I.M. Suthers

The Southeast Australian Shelf LME extends from Cape Howe, at the southern end of the State of New South Wales, to the estuary of the Murray-Darling river system in the State of South Australia. It borders the Southern Ocean and the western boundary currents flowing into the West Wind Drift, which circulates around the continent of Antarctica. The LME has a surface area of about 1.2 million km^2, of which 0.17% is protected (Sea Around Us 2007), and contains the island of Tasmania and the Bass Strait, which separates the island from the mainland state of Victoria. There are over 50 islands in Bass Strait, the largest and inhabited ones being Kings Island and Flinders Island. The Murray-Darling river system has a large catchment area, and it used to transport nutrients and sediments from the land into the coastal waters, but the river is heavily exploited and river flow is minimal. A book chapter on this LME has been published by Morgan (1989).

The region is characterised by sub-tropical species with southern Tasmania being Australia's main temperate region. The area has a large and variable marine flora and fauna including a large number of endemic species and is of high conservation value (Hoese et al. 2006).

The southeast region is the meeting place of two of Australia's main currents. The East Australian current (see Eastern Australian LME) brings low nutrient waters into south eastern Australia before heading offshore off eastern Tasmania. The Leeuwin Current (see Western Australian LME) brings low nutrient waters into southern Australia and down the western region of Tasmania. Off western Tasmania this current is often referred to as the Zeehan Current (Baines et al. 1983). Higher nutrient waters are brought to southern Tasmania from the sub-Antarctic waters. The Flinders Current is a westward flow along the 600 m isobath, from western Bass Strait to Kangaroo Island (Middleton and Bye 2007). An upwelling system off the Bonney Coast between southeastern South Australia and Victoria also brings nutrients to the surface.

I. Productivity

The Southeast Australian Shelf LME has a diversity of habitats such as seagrass beds, mud flats, intertidal and sub-tidal rocky reefs, kelp forests and pelagic systems. It is considered a Class III, low productive ecosystem (<150 $gCm^{-2}yr^{-1}$). Estimates of the mean annual primary productivity from 1998-2006 of the southeast Australian continental shelf vary between 68 and 251 $gCm^{-2}d^{-1}$ (www.science.oregonstate.edu/ocean.productivity/) depending whether the estimate is based on chlorophyll or particulate carbon concentration, and if a temperature correction is applied. The Sea Around Us project estimates mean primary productivity at 187 g C m^{-2} d^{-1}. The large range of values may result from the atypically low nutrient concentrations for a shelf system at this latitude - a result of low continental discharge and poleward flowing boundary currents.
It is a temperate marine environment inhabited by communities rich in species, many of which are endemic to Australia. Investigations in Bass Strait and the south-eastern slope have revealed soft-bottom benthic communities more diverse than anywhere else in the world. For example, of the 638 species of fish recorded for Tasmania, 38 (6%) are endemic to Tasmania and 273 (43%) are endemic to Australia (Hoese et al. 2006).

Near the island of Tasmania, seasonal storm events accelerate the mixing of nutrients onto the shelf. Runoff from the Murray-Darling river system was a regional contributor to shelf nutrient processes and fluxes. For a general understanding of oceanographic processes affecting the nutrient dynamics and productivity of Australian marine ecosystems, see Australia's State of the Environment (SOE) Report 2006 (www.deh.gov.au/soe/index.html). Reports by States and Territories and National environment audits are available from this index. For more information on productivity, nutrient dynamics and land-sea interactions, see Furnas (1995) and UNEP (2003).

In the southwest of this LME strong westerly winds drive colder nutrient rich sub-Antarctic waters up the east coast of Tasmania. These waters are characterised by high nitrate and dissolved organic nitrogen concentrations in surface waters. These cooler windy periods result in less oligotrophic conditions with the phytoplankton dominated by large diatoms and the zooplankton by larger species such as krill. In years of strong westerlies the phytoplankton biomass and productivity increase and the spring bloom lasts longer. In such years, the zooplankton biomass increased 10 fold in late spring. In contrast, the surface waters in the summer and autumn period (January to July) reflect the intrusion of sub-tropical water which can be detected by increased salinities and very low dissolved inorganic phosphorus. This period coincides with a reduction in the westerly wind stress. These calmer warmer periods result in more oligotrophic conditions when the phytoplankton is dominated by small dinoflagellates and the zooplankton by small copepods (Harris et al., 1988; Harris et al., 1991; Clementson et al., 1989).

Productivity in the northwest of the LME is dominated by summer upwelling events. The largest of these is the Bonney upwelling in southeastern South Australia adjacent to the Victorian border. During winter the Leeuwin Current moves eastwards along the south Australian coast to the southern tip of Tasmania (Cirano and Middleton 2004; Cresswell and Peterson 1993; Godfrey et al. 1986). In the summer, the coastal wind reverses and changes to induce upwelling producing a westward flow at the coastal boundary (Middleton and Platov 2005). Sub-surface upwelling extends in an almost continuous band from the Bonney Coast to western Tasmania. Extensive areas of krill have been observed along this shelf margin, Hunter group of islands and King Island and the region has high conservation values, including the pygmy blue whale (Butler et al. 2002). La Nina years are associated with a weaker influence of the East Australian Current in Eastern Bass Strait and the Leeuwin Current in western Bass Strait. During this time cooler waters enter Bass Strait from the Bonney upwelling and the Flinders Current.

Oceanic fronts: The East Australian Current (EAC) carries tropical waters from the East-Central Australian Shelf LME into the Southeast Australian Shelf LME to feed a southward EAC and mesoscale eddies off eastern Tasmania (Figure IX-21.1). The Zeehan Current is the final extension of the Leeuwen Current along western Tasmania. East of Kangaroo Island the Flinders Current is probably responsible for intermittent upwelling in the deep canyon systems off the western Victorian Shelf. The Kangaroo Island Front (KIF) develops seasonally southeast of Kangaroo Island caused by wind-driven coastal upwelling (Belkin & Cornillon 2003, Belkin *et al*. 2009).

Southeast Australian Shelf LME SST (after Belkin 2009)
Linear SST trend since 1957: 0.53°C.
Linear SST trend since 1982: 0.20°C.

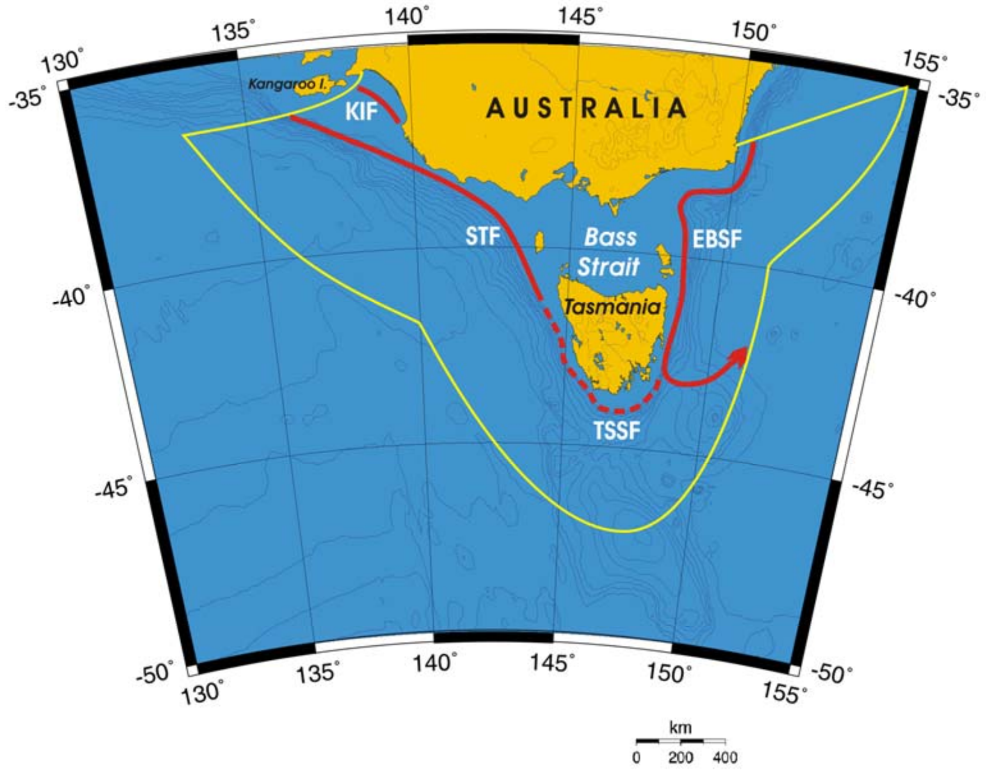


Figure IX-21.1. Fronts of the Southeast Australian Shelf LME. EBSF, East Bass Strait Front; STF, Subtropical Front; TSSF, Tasmania Shelf-Slope Front (most probable location). Yellow line, LME boundary. (after Belkin et al. 2009)

The thermal history of this LME features a long-term ascending trend, although this warming was quite erratic, including major reversals. Some peculiarities of this LME's thermal history are likely caused by its location as the southernmost Australian LME. Therefore this LME is affected by the Subantarctic and Antarctic (via atmospheric teleconnections) more strongly than are other Australian LMEs. The East Australian Current is a dominant warm current and its role increased over the last half-century as this current penetrated farther south by ~350 km over the 1944–2002 period, thus effectively warming up the East Tasmanian waters at a rate of 2.28°C/century (Ridgway, 2007).

The most striking difference between this LME and other Australian LMEs is the absence of a major peak in 1998 that could have been a manifestation of the 1997-98 El Niño, as observed elsewhere. Instead, SST peaked in 2001, possibly a delayed response to the El Niño 1997-98. A similar warm event peaked in 2000 in the adjacent Southwest Australian Shelf LME. The all-time maximum of 1989 can be tentatively correlated with the peak of 1988 in the Sulu-Celebes Sea LME, North Australian Shelf LME, West-Central Australian Shelf LME, and lesser peaks of 1989 in the Southwest Australian Shelf LME and of 1988 in the Northwest Australian Shelf LME. The peak of 1961 occurred simultaneously in the adjacent Southwest Australian Shelf LME. The cold events of 1964 and 1996 cannot be readily linked to similar events elsewhere. This asymmetry between warm and cold events suggests a weaker correlation between cold events versus a stronger correlation between warm events.

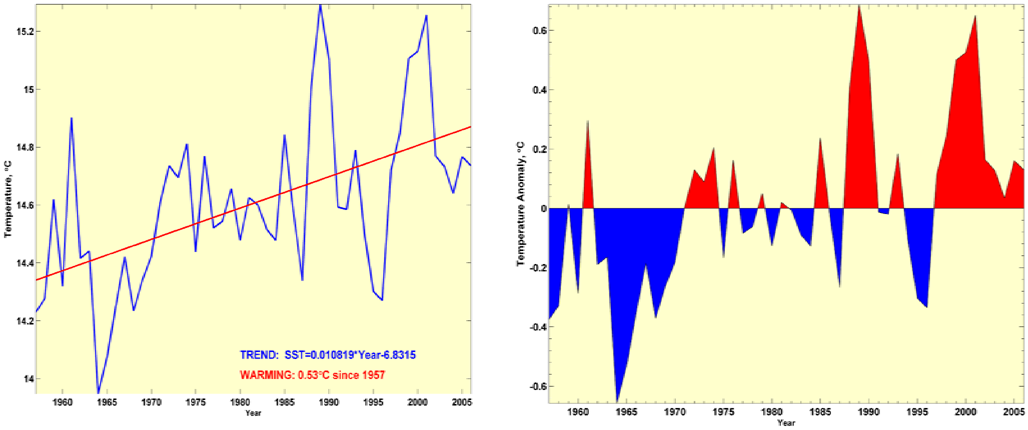


Figure IX-21.2. SE Australian Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology (after Belkin 2009).

***Southeast Australian Shelf LME, Chlorophyll and Primary Productivity*:** The Southeast Australian Shelf is considered a Class III, low productive ecosystem (<150 gCm^{-2}yr^{-1}).

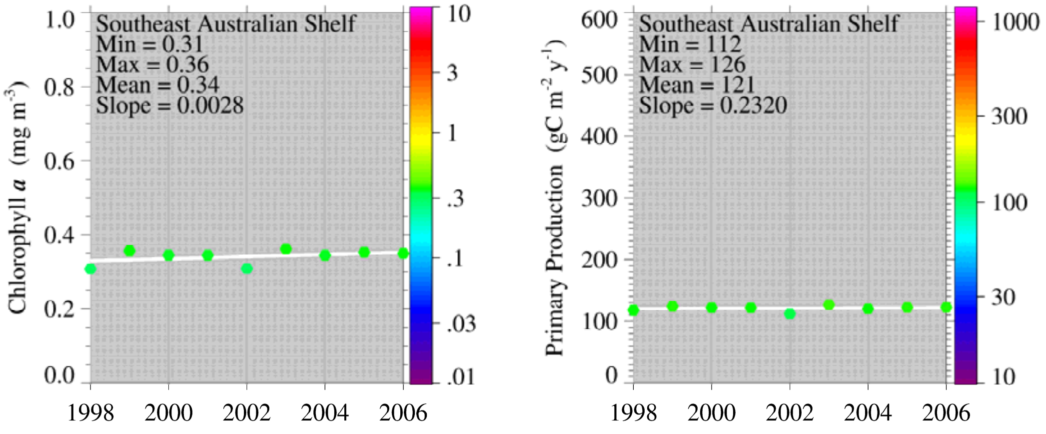


Figure IX-21.3. Southeast Australian Shelf LME trends in chlorophyll a and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Fig. IX-21.4 and IX-21.5 present the estimates of the Sea Around Us Project for the capture fisheries landings in this LME, and their ex-vessel value. Australian sources suggest that the combined capture fisheries and aquaculture production in the southeastern Australian LME is 121.5 thousand tonnes, valued at $1.05 billion Australian dollars, with the wild fish sector accounts for 60% of the weight and 50% of the value of production in this region, suggesting that the Sea Around Us figures are underestimates. The main groups fished include lobster, abalone, scallops, crabs, prawns, snapper, sardines, blue grenadier and flathead. The aquaculture sector includes Atlantic salmon, southern bluefin tuna, oysters and mussels. ABARE provides additional information on the characteristics of Australia’s fishing industry (www.abare.gov.au).

The region is a mix of high valued export fisheries, which includes nearly 50% of the global wild caught abalone production, and the bulk of the domestic fish market in Sydney and Melbourne. The small pelagics fishery has undergone substantial fluctuations over the decades with large catches of jack mackerel (*Trachurus declivis)* dramatically declining in eastern and southern Tasmania. Recently there has been an increase in redbait (*Emmelichthys nitidus*) (Anon. 2008a) In addition to the small pelagics fishery, dramatic fluctuations in recruitment of scallops and striped trumpeter (*Latris lineata*) reflect the dynamics of the physical environment (Anon. 2008b).

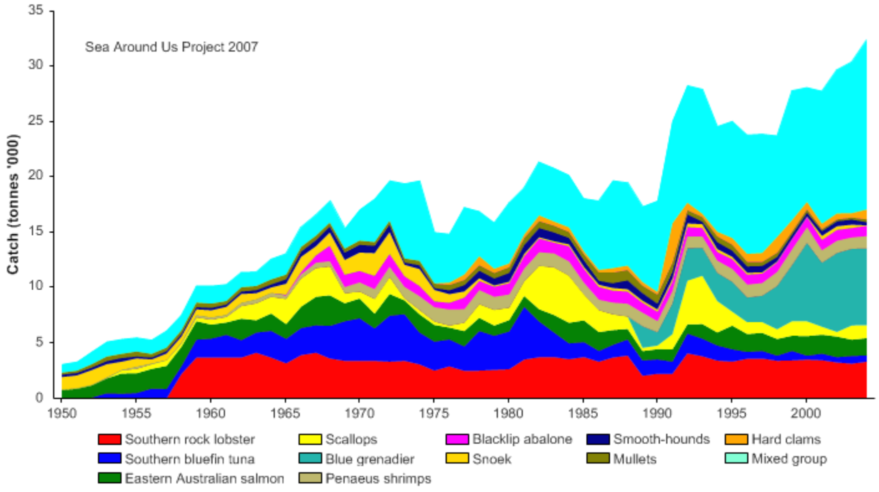


Figure IX-21.4. Total reported landings in the Southeast Australian Shelf LME by species (Sea Around Us 2007).

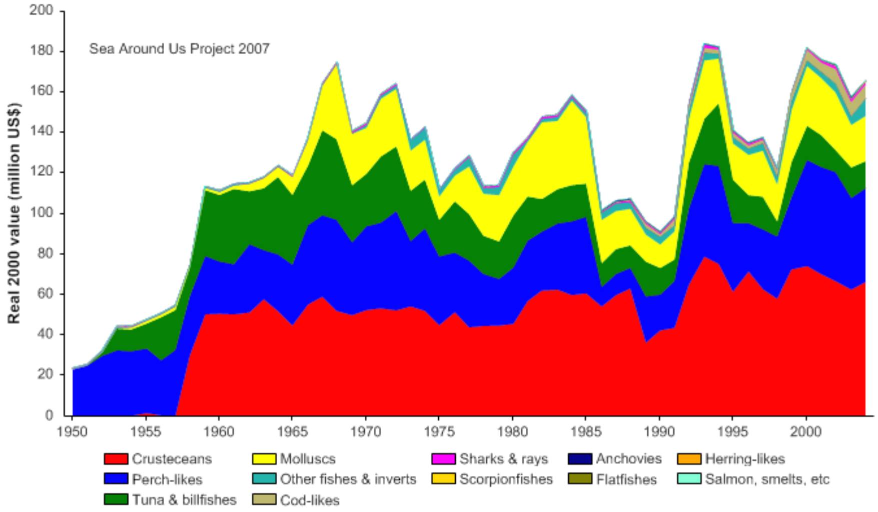


Figure IX-21.5. Value of reported landings in the Southeast Australian Shelf LME by commercial groups (Sea Around Us 2007).

ABARE estimates for 2006/2007 (including aquaculture) for fisheries production in Victoria was 8,243 t valued at $93.934 millions $AUD; South Australia production was 60,548 tonnes at a value in millions of $AUD of $426,499; Tasmania fisheries production in totalled 36,413 tonnes at a value in millions of $AUD $475,429 and Commonwealth managed fisheries harvested 16,328 tonnes at a value in millions of $AUD $54.539. (www.abare.gov.au). Quota management has been introduced into many of the more valuable fisheries over the last 20 years. This has resulted in substantial rebuilding of the biomass in several fisheries such as rock lobster (Haddon and Gardner 2008). The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is currently below 2.5% with Australia accounting for the largest share of the ecological footprint (Figure IX-21.6).

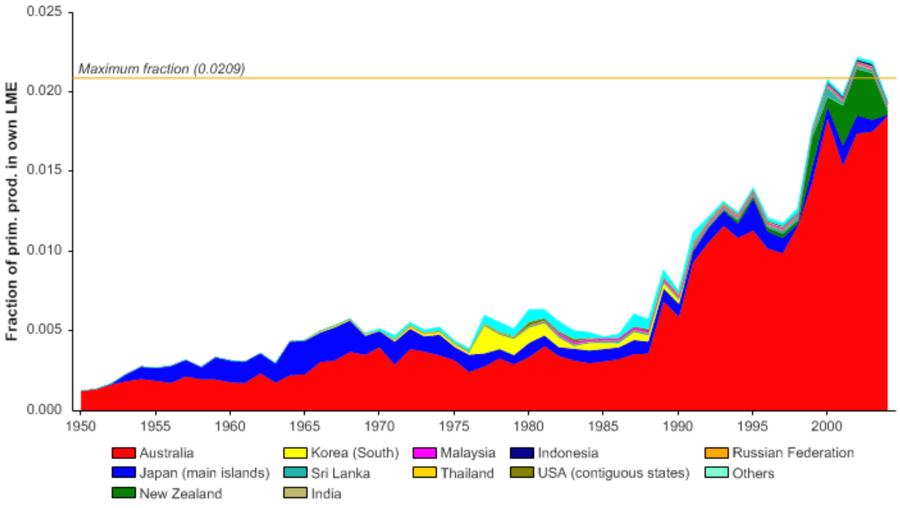


Figure IX-21.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Southeast Australian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Over the past twenty years, both the mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) and the FiB index have increased in the LME, indicating a development of new offshore fisheries from the late 1980s to the 1990s.

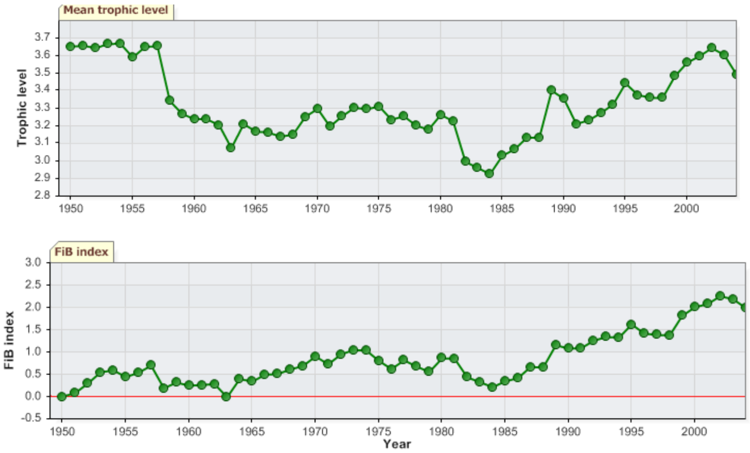
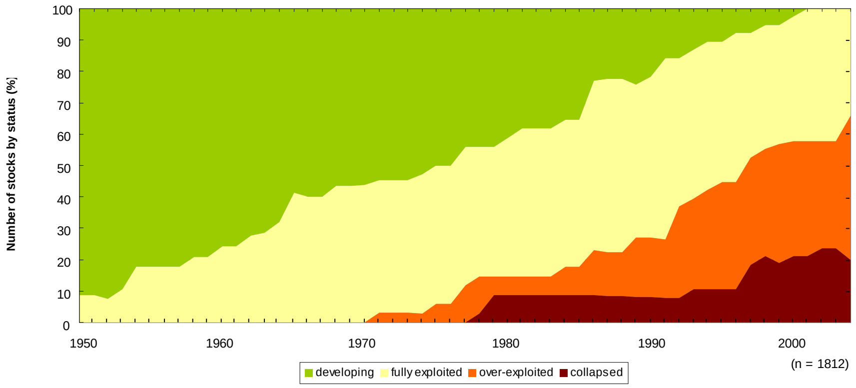


Figure IX-21.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Southeast Australian Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots suggest that while a sizeable fraction of the stocks in this LME may have been overexploited (Figure IX-21.8, top), about half of the catch biomass originates from stocks that are fully exploited (Figure IX-21.8, bottom). Moreover, changes to gear, management, fleet dynamics/fisher behaviour, market forces, as well as discarding, unstandardised catch data and climate (e.g. the jack mackerel fishery) prevent further interpretation. There is limited or no fishery independent data for many species, and recruitment records are unknown. Recent changes to management have improved the stock status of many fisheries.



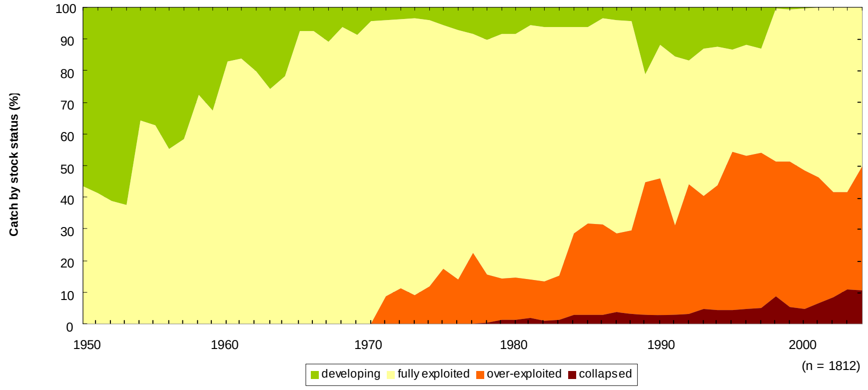


Figure IX-21.8. Stock-Catch Status Plots for the Southeast Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

Land use impacts within the Murray Darling Basin, nutrient loading from diffuse and point sources, soil erosion, soil salinisation, and dry climate with intermittent flows and natural salt stores in the landscape have resulted in significant or major nitrogen exceedances in the Lower Murray, Myponga, Fleurieu Peninsula and Willochra Creek River basis. In several of these river basins, guidelines for salinity, phosphorus and for turbidity have also been exceeded (http://audit.ea.gov.au/ ANRA/water/quality/). A major problem in this LME is the introduction of exotic marine organisms from the hulls of ships or as a consequence of discharging ballast water. A recent inventory of introduced marine pests found 57 species in Victoria, 45 in Tasmania and 43 in South Australia (www.marine.csiro.au/crimp/nimpis). These introduced marine species threaten native marine flora and fauna and local marine diversity as well as fishing and aquaculture.

Introduced species in this LME include the North Pacific sea star (*Asterias amurensis*), Japanese kelp (*Undaria pinnatifida)*, the New Zealand screw shell (*Maoricolpus roseus*), European fan worm (*Sabella spallanzanii*) and the toxic dinoflagellate (*Gymnodinium catenatum*). The North Pacific sea star native to northern China, Korea, Russia and Japan, was first found in Tasmania in 1986, but was misidentified as a native species until 1992. The sea star has since spread to Victoria. At present, its distribution in Australia appears to be limited to these two States. However, suitable conditions exist for its survival and reproduction in the West-Central Australian Shelf LME. The sea star is a voracious predator of shellfish, thus posing a serious threat to mariculture and wild shellfish fisheries. While significant research is being undertaken on the potential impacts of the sea star in Australia, the available data are still not adequate to conclusively determine if it is having an impact on Australian fisheries. Japanese kelp has appeared in near-shore habitats along the east coast of Tasmania and is spreading fast with the potential to invade the entire southern coastline. For more information on pollution issues see www.deh.gov.au/coasts/pollution/index.html, the State of the Environment Reports at www.deh.gov.au/soe and CSIRO's Center for Introduced Marine Pests at www.marine.csiro.au/crimp/. Climate change is also impacting on the distribution of species in southeastern Australia. The magnitude and poleward distribution of the East Australian Current (EAC) has increased over the last 60 years (Ridgway, 2007) and is expected to increase due to climate change with predictions that southeastern Australian marine waters will be the fastest warming in the southern hemisphere. With the increased penetration of the East Australian Current there has been an increase in the number and southerly distribution of sub-tropical species into Tasmania. The most notable of these is the long-spined sea urchin, which forms extensive barrens habitat (Johnson et al., 2005). These barrens habitats lead to substantial changes in productivity and biodiversity (Ling, 2008) with flow on impacts on fisheries. Initially, range expansion was by way of larval transport from NSW via the EAC. With increasing warmer waters, the conditions for *C. rodgersii* to complete it larval cycle *in-situ* in eastern and southern Tasmanian become more favourable (Ling et al., 2008). The dinoflagellate *Noctiluca scintillans* has also dramatically increased with summer blooms impacting on coastal salmon farms (www.tafi.org.au/zooplankton).

In the northwestern region of the LME, climate change is expected to increase the strength and duration of upwelling winds (Bakun 1990). This is expected to result in a stronger Bonney upwelling and for increased sub-surface upwelling events that extend from western Victoria to western Tasmania. An increase in these upwelling events at the beginning of summer accelerates primary and secondary productivity.

Climate change simulations are currently being improved for the Australian region at CSIRO, particularly in modeling the Southern Ocean, developing a more realistic Antarctic Circumpolar Current, and modeling the transport of surface water into the deep ocean. The latter process is particularly important in the sequestering of heat and carbon into the deep ocean, which influences the rate and pattern of warming globally.

IV. Socioeconomic Conditions

In the Southeast Australian Shelf LME, the population is 1,465,200 persons and between 5% and 10% of the total employment is in the fish industry--fisheries, aquaculture and processing sectors. The region is socially diverse, with some small, isolated communities and some major metropolitan centres, with the population growth highest in coastal metropolitan areas and large coastal regional centres (especially Melbourne). The two main industries for the LME are marine tourism and oil and gas. Bass Strait accounts for about 20% of the nation's oil and gas (Love 2004). In the Atlas of Australian Marine Fishing and Coastal Communities, (http://adl.brs.gov.au/), the region is characterised by a lower proportion of Indigenous persons, by younger median ages in coastal metropolitan areas and large coastal regional centres, by higher child dependency in many regional areas, and by higher socio-economic disadvantage in many non-metropolitan areas of coastal Tasmania with strong links to the fish industry. The southern rock lobster fishery is the most valuable in this region and was estimated in 2003 to provide 3,381 employment opportunities either directly or indirectly with a total economic impact of almost 0.5 billion dollars into regional economies. A record low catch rate in the South East coast is being reported for rock lobster in October, 2008 according to John Ashby, president of the Port MacDonnell Fishermen's Association (http://fis.com/fis/worldnews 16 October 2008). The South East Fishery, which includes both the trawl and gillnet, trap and line fisheries, is a major fish industry with landings in 2006/7 being 20,578 tonnes worth an estimated $AUD 78 million. Salmon aquaculture is carried out in Tasmania and its production was valued at $271 million in 2006/7 (www.abare.gov.au). Recreational fishing is an important pastime in this region with approximately 1 million people participating in the 12 months prior to May 2000. Participation rates were estimated at 29.3%, 24.1% and 12.7% in Tasmania, South Australia and Victoria respectively (Henry and Lyle 2003). The Southeast Australian Shelf LME contains a number of cities and ports, including Melbourne. Industry, shipping and tourism are major economic activities. There is offshore oil and gas off the Victoria coast. Marine and coastal-based tourism is important in this LME, both in terms of domestic and international tourism.

V. Governance

The Southeast Australian Shelf LME lies off the coast of four Australian States: New South Wales, Victoria, Tasmania and South Australia. The main governance issues of this LME pertain to industrial and agricultural degradation of the water quality, fisheries management and to the establishment of marine reserves. Fisheries are managed by either State or Commonwealth agencies. Most of the states manage the fisheries out to 5.5 km offshore and the Commonwealth manages fisheries beyond this zone. Several fisheries that are within the 5.5 km zone are managed by the Commonwealth (e.g. small pelagics) and other outside this limit by the State (eg. giant crab). Some fisheries have both Commonwealth and State zones (e.g. scallops). Most of the valuable fisheries in the region are managed under output controls and many have seen substantial rebuilding of legal sized biomass since the introduction of quota management systems. The less valuable fisheries tend to be managed through input controls that restrict effort. These include gear limits and seasonal and regional closures. Both State and Commonwealth fishers have established management advisory committees that usually involve industry, managers and research providers in the co-management of the resource. See the North Australian Shelf LME (Chapter VIII) for more information on fisheries management. Coastal marine reserves are managed by Conservation agencies in most States whereas offshore marine reserves are managed by the Australian Department of Environment, Water and Heritage.

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ANRDL. Australian Natural Resources Data Library [and the Bureau of Rural Sciences] at http://asdd.ga.gov.au/tech/node/brs-4.html

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X NORTH WEST PACIFIC

X-22 East China Sea LME
X-23 Kuroshio Current LME
X-24 Oyashio Current LME
X-25 Sea of Japan/East Sea LME
X-26 Okhotsk Sea LME
X-27 West Bering Sea LME
X-28 Yellow Sea LME

X-22 East China Sea LME

S. Heileman and Q. Tang

The East China Sea LME is bordered by the China mainland, northern coast of Taiwan, Japanese Archipelago, and southern coast of the Korean Peninsula. It has a surface area of about 775,000 km^2, of which 0.09% is protected, and contains 0.34% and 0.02 % of the world's coral reefs and sea mounts, respectively, and 8 major estuaries (Sea Around Us 2007). A monsoonal climate with alternating winter and summer monsoons and the occurrence of typhoons and cyclones characterise the LME. The main currents are the Kuroshio Current along the shelf break, Taiwan Warm Current on the continental shelf and the East China Sea Coastal Current in the coastal zone (Su 1998). The latter is formed by the coastal current from the Yellow Sea and the combined waters of the several large rivers. Its hydrology is strongly influenced by the above mentioned currents, freshwater and terrigenous sediment inputs, notably from the Changjiang (Yangtze River), Qiantangjiang and Mingjiang. A book chapter and a report pertaining to this LME are by Chen & Shen (1999) and UNEP (2005).

I. Productivity

The East China Sea LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}), based on satellite data used throughout this report. However, from Chinese surveys' in situ data, it appears that the East China Sea is a Class II, moderately productive ecosystem (between 150 and 300 gCm^{-2}y^{-1})(Q.Tang, personal communication, 2008). Indeed, based on Chinese survey data, primary production was 143 gCm^{-2}y^{-1} in 1997-2000 (Tang 2006); 220 gCm^{-2}y^{-1} in 1984-1985(Chen & Shen 1999); based on remote sensing and survey data, average primary production was 182gCm^{-2}y^{-1} in 1984-2007 (unpublished data by Q.Tang, personal communication, 2008).

The Kuroshio Current has a significant impact on the LME's nutrient budget. The Kuroshio Subsurface Waters have higher phosphorus/nitrogen and silica/nitrogen ratios than terrigenous discharge, which provides a signature of its upwelling over the continental slope. This high nutrient content results in high primary productivity in the water column. Phytoplankton abundance shows two peaks, with the higher peak from July to September and a secondary peak in April. Chen & Shen (1999) reported the identification of 209 species of phytoplankton, with key species including *Nitzchia* spp., *Coscinodiscus* spp. and *Skeletonema costatum*, and six species of zooplankton, with *Calanus sinicus* being one of the main species. Zooplankton biomass increases sharply after March with increasing water temperature and runoff, and is highest where coastal waters converge with the Yellow Sea and Kuroshio Currents. Fishing is the primary driving force, and climatic and environmental variation the secondary driving force of biomass change in this LME.

Oceanic fronts (Belkin et al. (2009): The East China Sea LME features diverse fronts (Hickox *et al*. 2000, Belkin & Cornillon 2003) (Figure X-22.1). In the north, the Yangtze Bank Ring Front (YBRF) surrounds the Yangtze Bank (Shoal). This front is caused by the huge fresh discharge of the Yangtze River and is maintained by tidal rectification that results in a clockwise current (and a closed quasi-circular front) around the Bank. A coastal front (FZF) exists along the Fujian-Zhejiang Coast between warm, saline waters of the Taiwan Warm Current flowing northward and the cold, fresh waters flowing southward along the coast. The Kuroshio Front (KF) invades the shelf north of Taiwan. These excursions are important for the cross-shelf exchange of heat, salt and nutrients. Sharp fronts exist between warm, saline waters of the Kuroshio and continental shelf water along the shelf break. Two distinct fronts exist west and east of Cheju Island (WCF and ECF respectively) that separate warm, salty waters carried by the Taiwan-Tsushima Current from colder, fresher resident inshore waters.

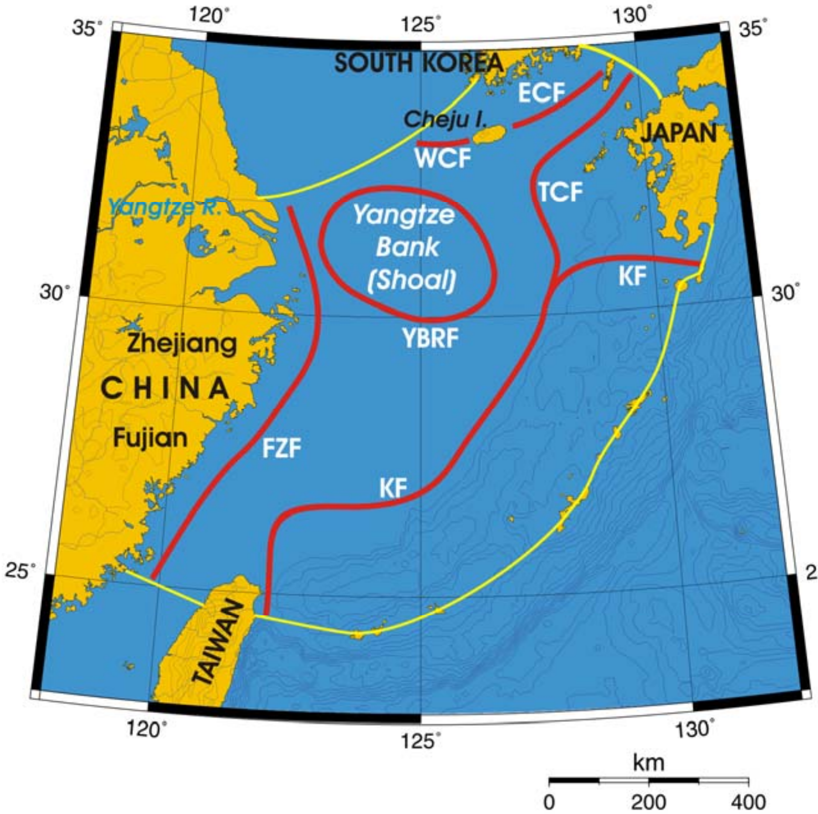

Figure X-22.1. Fronts of the East China Sea LME. ECF, East Cheju Front; FZF, Fujian-Zhejiang Front; KF, Kuroshio Front; TCF, Tsushima Current Front; WCF, West Cheju Front; YBRF, Yangtze Bank Ring Front. Yellow line, LME boundary. After Belkin et al. (2009).

East China Sea SST (after Belkin, 2009)
Linear SST trend since 1957: 1.55°C.
Linear SST trend since 1982: 1.22°C.

The East China Sea has experienced a dramatic 2°C warming since 1982 (Figure X-22.2). During 1957-1981, the SST was relatively stable. Then, SST increased from 20.6°C to 22.9°C at a rate of 0.13°C per year. A recent study of the ERA-40 reanalysis and other data sets, including HadISST and SODA (Simple Ocean Data Assimilation), has shown that climate warming caused weakening of the winter and summer monsoons over the East China and Yellow Seas after 1976, hence a weakening of wind stresses, particularly over the East China Sea, leading to the observed SST increase (Cai et al., 2006). The East China Sea warming was not spatially uniform (Wang, 2006). In summer, SSTs rose in most parts of the sea, including the Kuroshio and Taiwan Warm Current, but cooled in the north. The coastal zone warmed at a rate of >0.02°C/a, whereas the Kuroshio rate was <0.02°C/a. In winter, the fastest SST warming rate of >0.08°C/a was in the west, in the Taiwan Warm Current, suggesting rapid warming of its source, the Kuroshio. The recent warming could be partly offset in the future by a decrease of the Yangtze River runoff caused by the Three Gorges Dam (Yang et al., 2002, 2003). The runoff decrease leads to a salinity increase of the upper mixed layer, hence stability decrease and enhanced winter cooling and convective mixing. On the other hand, a decrease in the Yangtze River sediment transport increases water transparency and enhances radiative warming of water column.

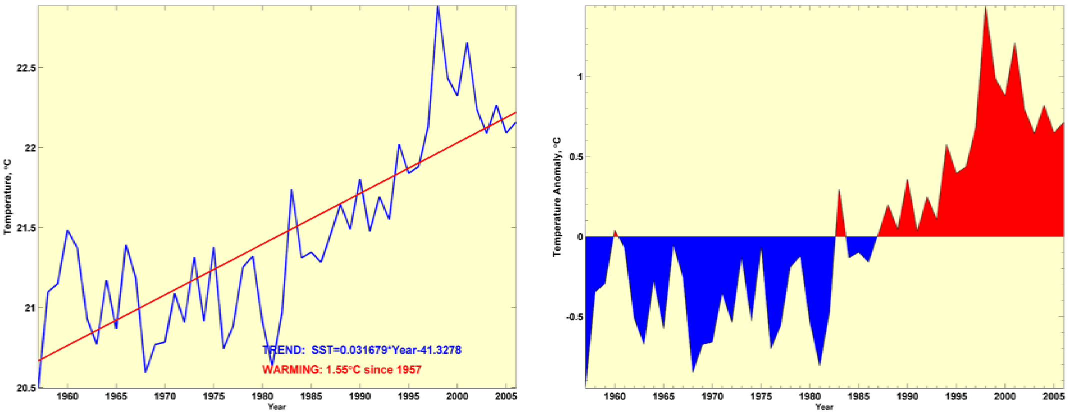

Figure X-22.2. East China Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

East China Sea LME Chlorophyll and Primary Productivity: The East China Sea LME is a Class I, highly productive ecosystem (>300 $gCm^{-2}y^{-1}$), based on source data used throughout this report.

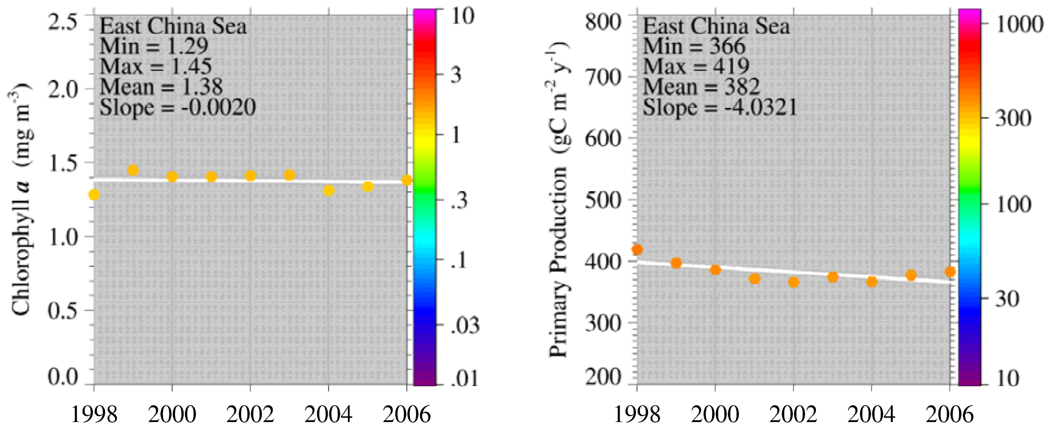

Figure X-22-3. East China Sea trends in chlorophyll *a* and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Fish and other living resources are heavily exploited in the East China Sea LME, with about 200 species of fish and invertebrates commercially fished. Total reported landings have increased to about 4.5 million tonnes in 2000, and recorded at a level of 4 million tonnes in 2004 (Figure X-22.4), though there is a serious concern as to the validity of the underlying reported landings statistics (see Watson & Pauly 2001). Significant changes in fish biomass and catch composition have occurred in the region, and are attributed to overexploitation and pollution (Chen & Shen 1999). Over the past three decades, the value of the annual catch ranged between US$8 billion and US$5 billion (in 2000 US dollars) except in 1977 and 1979 when extremely high values of US$9.7 billion and US$10 billion were recorded, respectively (Figure X-22.5).

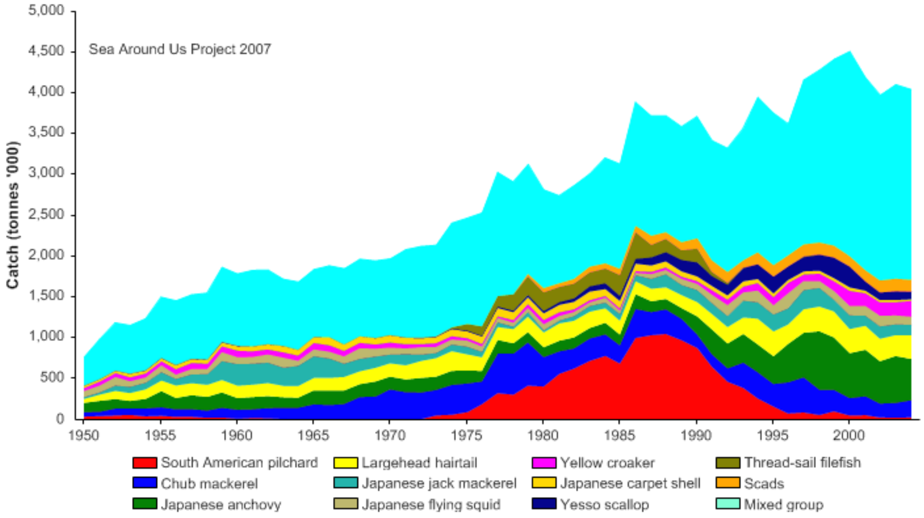

Figure X-22.4. Total reported landings in the East China Sea LME by species (Sea Around Us 2007).

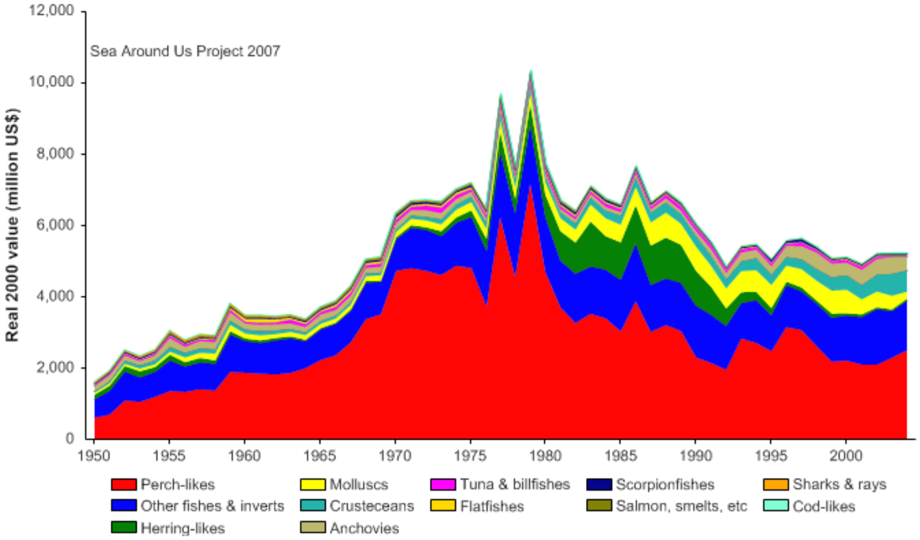

Figure X-22.5. Value of reported landings in the East China Sea LME by commercial groups (Sea Around Us 2007).

In recent years, the primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME has exceeded the observed primary production (Figure X-22.6), which indicates serious problems either with the methodology, assumptions and primary productivity data used by Pauly & Christensen (1995) or with the underlying reported landings statistics. In this particular case, the unrealistic PPR may have been a result of either the primary production values derived from satellite images are under-estimating the true primary production (with the high coastal turbidity of the LME, this is a distinct possibility) or the landings reported in the underlying statistics are exaggerated by including catches made outside the LME.

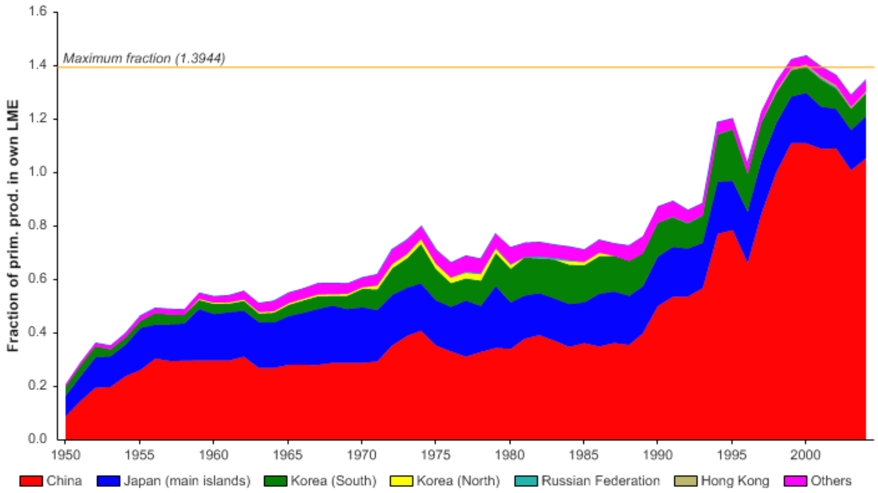

Figure X-22.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the East China Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

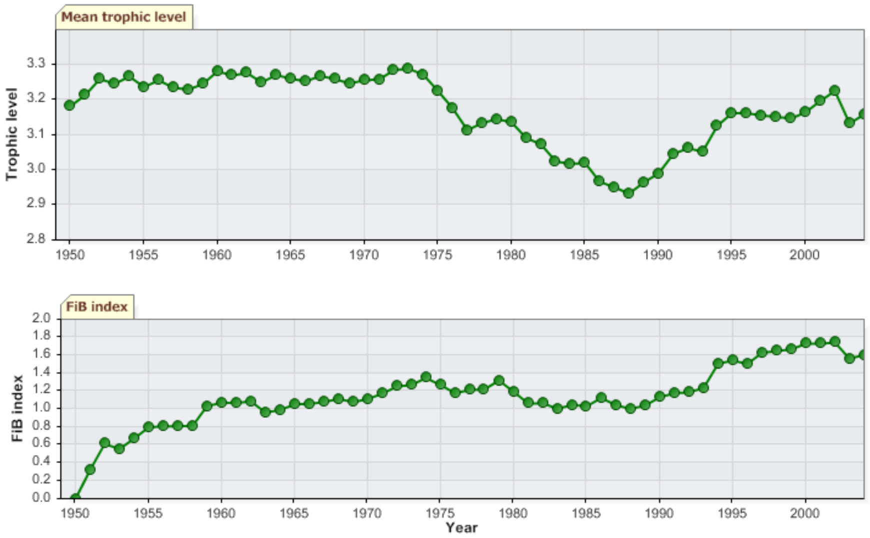

Figure X-22.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the East China Sea LME (Sea Around Us 2007)

The concerns over the quality of the underlying landings statistics are also highlighted in the long-term trends of the mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005; Figure X-22.7, top) and the FiB index (Figure X-22.7, bottom). Both indices show a familiar pattern of overexploitation in the region up to the late 1980s, with a slow expansion of the fisheries implied by the increase in the FiB index, followed by a period of a decline in the mean trophic level or a ‘fishing down’ of the local food webs (Pauly *et al.* 1998). Yet, in the 1990s both indices show a significant increase. Since such increases can not be attributed to increased catches of tunas and other large pelagic fishes (recalculation of the indices without tunas and other large pelagic species resulted in similar long-term trends as Figure X-22.7), it is possible that the underlying landings statistics include a large amount of catches from outside of the LME. However, from Chinese in situ data it appears that the East China Sea’s trophic level is much higher. Indeed, based on Chinese survey data, trophic level in the East China Sea was estimated as 3.7 in 2000-2001 (Zhang and Tang 2004), higher than the corresponding data in Fig X-22.7 (Q.Tang, personal communication, 2008).

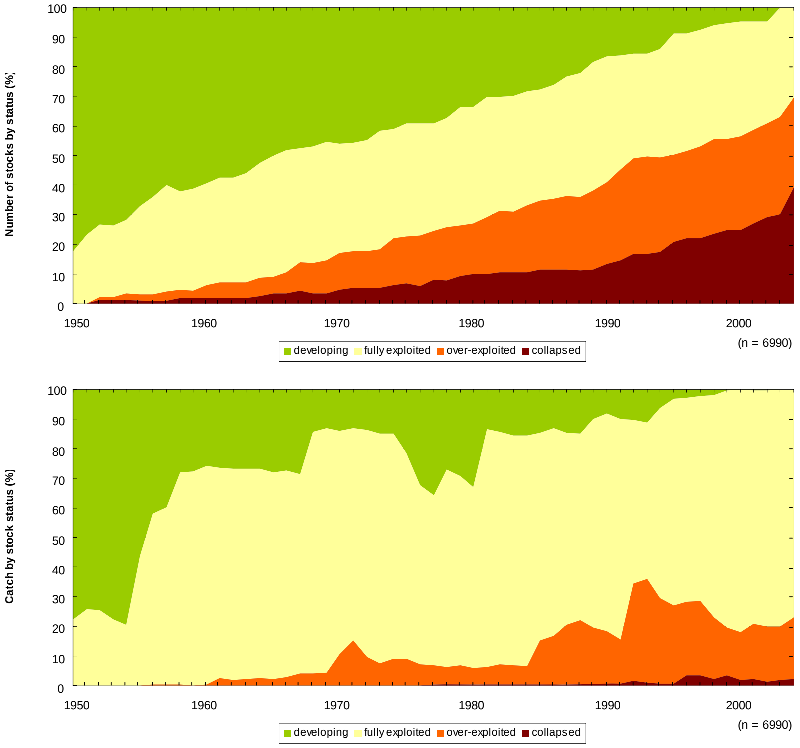

Figure X-22.8. Stock-Catch Status Plots for the East China Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stocks has been rapidly increasing, now accounting for over 60% of the commercially exploited stocks (Figure X-22.8, top), yet, with 80% of the reported landings biomass from fully exploited stocks (Figure X-22.8, bottom). Again, the quality of the underlying statistics must be questioned.

Overexploitation was found to be severe in this LME (UNEP 2005). Stocks of the major high-value demersal species such as croaker have decreased (Zhong & Power 1997) and catch per unit effort has declined by more than 50%. Before the 1970s, the popular fishing method of boat-knocking[1] resulted in the reduction of large and small yellow croaker stocks after the mid-1970s and their subsequent economic extinction in the mid-1980s. Meanwhile, catches of some small-sized, low-value species such as filefish, crabs and cephalopods increased rapidly. Individual species are becoming sexually mature at an earlier age and showing smaller size and lower age in the catch (Chen & Shen 1999). This is particularly so for species such as hairtail and yellow croaker, despite efforts to control fishing of these resources.

In recognition of the severe overexploitation condition, fishing effort and intensity have been reduced for Chinese fishers with a suspension of fishing during the 3 months of summer initiated in 1995 to protect fisheries (Tang 2003)

III. Pollution and Ecosystem Health

Pollution: Rapid economic development and a growing population in eastern China have led to significant increases in the discharge of inadequately treated industrial and domestic wastewater and sewage into the LME. The main pollutants carried by the Changjiang, Mingjiang and Jiulongjiang include COD, nutrients, petroleum hydrocarbon and heavy metals, which have all shown increases in recent years **(**SOA 2000-2002)**.** Aquaculture has also become one of the primary sources of pollution in localised coastal areas. Sewage discharge has resulted in microbiological pollution in some coastal localities, for example, Shenjiamen, Wenzhou and Taizhou Bay, where the amount of faecal *Escherichia coli* in shellfish has exceeded the national biological quality standard by as much as 1.5 to 8 times (ZOFA 2001**)**. Excessive nitrogen input from sewage as well as runoff of chemical fertilisers is causing eutrophication and HABS, which are ubiquitous in coastal areas. Concentrations of chlorophyll *a* of up to 16 mg m^{-3} have been recorded in some areas.

Occurrences of major harmful algal blooms (HABs) with wide geographical distribution have increased in frequency, but are largely confined to the summer from June to October (Chen & Shen 1999). In 2003, there were 86 HAB events covering a total area of 12,990 km^2, a significant increase from 1993 (SOA 2003). HABs have occurred primarily off the Changjiang Estuary, which has accounted for 70% of the total number of HAB occurrences, as well as in the Xiamen, Xiangshan and Sanmen Bays. Extensive loss of cultivated shellfish caused by HABs has been reported.

Soil erosion, deforestation and intensive cultivation are the main sources of high levels of suspended solids in coastal waters. In the Changjiang drainage basin, for instance, the area affected by soil erosion increased from 304,200 km^2 in 1987 to 572,400 km^2 in 1992 (CNRD 2004), resulting in significant input of suspended solids to coastal areas. Other activities such as dredging of waterways, building of bridges and dams, sand mining and reclamation increase the concentration of suspended solids in the coastal areas.

Accidental oil spills, offshore oil fields and marine transportation, especially ballast water from oil tankers, are major sources coastal and marine area pollution, particularly in estuaries. In 2002 and 2003, the total amounts of oil pollutants discharged into the LME by the Changjiang, Mingjiang and Jiulongjiang were 119,500, 10,600 and 1,000 tonnes, respectively **(**SOA 2000-2002)**.** Other land-based pollutants include heavy metals, which have been increasing in recent years. In 2001, pollutant residues such as petroleum hydrocarbon and arsenic were high in some commercially produced mussels and oysters. DDT and PCBs were also detected, but were within the limit for human consumption (ZOFA 2001).

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[1] Boat knocking: fishing method in which the side of the boat is struck with heavy objects, generating sound which damage the auditory mechanism of fish, and thus renders them susceptible to capture.

Habitat and community modification: The LME's habitats are being degraded as a result of unprecedented rapid industrial development and population growth over the last decade. Reclamation has contributed to a dramatic reduction in mangrove wetland area in recent years. Since 1949, about 840 km^2 of coastal wetlands have been reclaimed in Shanghai, while 120 km^2 of coastal wetlands were converted to other uses from 1995 to 2000 (Jin 2004). China has planned to reclaim a further 45% of its mudflats. The combined effects of reclamation and reduced sediment input due to changes to the Changjiang will result in the further loss of intertidal areas. The development of ports, industries and tourist facilities has severely damaged areas of rocky coast, particularly in Zhejiang Province. Populations of some native species are threatened by the introduction of alien species (Ding & Xie 1996). Continued population and industrial growth, as well as agricultural expansion, will place further pressure on the LME's health. The heavy reliance of the bordering countries on marine resources demands continued efforts to reclaim the environmental sustainability of this LME and its resources.

IV. Socioeconomic Conditions

The Changjiang Delta, with an average urbanisation level of nearly 50%, is the most industrial and densely populated area in the East China Sea LME. The Changjiang watershed covers 20% of China's total area and is home to about 400 million people. The area also supports about 40% of China's total agricultural and industrial production. In the last few decades, the economy of China, particularly in most coastal cities and provinces including Shanghai, Zhejiang, Jiangsu and Fujian, has increased rapidly.

Aquaculture and tourism are becoming increasingly important in coastal regions in China. Marine fisheries are a major economic sector, with about 4% of the world's fishery production coming from this LME. The fisheries provide employment opportunities, income generation and food security, particularly for the coastal populations. Overexploitation has significant economic impacts in the bordering countries (UNEP 2005). Fisheries resources and aquaculture operations are affected by HABs, which also cause public health problems. For instance, HABs resulted in direct economic losses of US$3.6 million in the Changjiang Estuary and the coastal waters off the Zhejiang in 2000 (UNEP 2005).

V. Governance

An important governance initiative in this LME will be to take measures for the recovery of depleted fisheries resources and improve ecological and environmental conditions. Appropriate laws and regulations will need to be enacted in order to protect fishing grounds and fisheries resources. Regional cooperation and coordination are facilitated through the Action Plan for the Protection, Management and Development of the Marine and Coastal Environment of the Northwest Pacific (NOWPAP), under the UNEP North-West Pacific Regional Seas Programme. NOWPAP's goals are to: develop regional monitoring and assessment activities; develop public outreach and environmental education; implement and further develop a Regional Contingency Plan for Oil Spills, signed and adopted by NOWPAP members in November 2004; and prepare a regional Strategic Action Plan to Abate Pollution from Land-based Activities including the mitigation of marine and coastal litter. NOWPAP is comprised of 6 priority projects, implementation of which is supported by a network of Regional Activity Centres in China, Russian Federation, Republic of Korea and Japan. NOWPAP has not yet adopted a legally binding Convention.

The North Pacific Marine Science Organisation (PICES) is an intergovernmental scientific organisation established in 1992. Its present members are Canada, China, Japan, Republic of Korea, Russian Federation and the U.S. PICES' role is to promote and coordinate marine research in the northern North Pacific and adjacent seas; advance scientific knowledge about the ocean environment, global weather and climate change, living resources and their ecosystems, and the impacts of human activities; and to promote the collection and rapid exchange of scientific information on these issues.

GEF supported the Regional Programme for Marine Pollution Prevention and Management in the East Asian Seas region from 1994 to 1999. The PEMSEA project is the five-year follow-on phase (2000-2005) meant to develop stronger partnerships in addressing environmental management problems in the region (www.pemsea.org).

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X-23 Kuroshio Current LME

I. Belkin, M.C. Aquarone and S. Adams

The Kuroshio Current LME extends from the Philippines to the Japanese Archipelago's northernmost island, Hokkaido. It has a surface area of about 1.3 million km^2, of which 0.33% is protected, and contains 1.29% of the world's coral reefs, 0.99% of the sea mounts, and 9 major estuaries (Sea Around Us 2007). Among its other underwater features are the Japan Trench, Ryukyu Trench, and Okinawa Trough. The Kuroshio (Black Current in Japanese) is a warm (24° C, annual mean sea surface temperature) current about 100 km wide that flows in a north-easterly direction along Japan's east coast. Northeast of Taiwan, the Tsushima Current branches off towards the Sea of Japan/East Sea. A rich variety of marine habitats results from the LME's wide latitudinal expanse. The region has a generally mild, temperate climate. Natural hazards in this region are active volcanoes, frequent earthquakes, tsunamis and typhoons. One of the first multi-chapter volumes in English devoted to the Kuroshio was by Marr (1970). Terazaki (1989) presented a book chapter on this LME.

I. Productivity

Small-and meso-scale eddies have been observed in the coastal regions of the Kuroshio Front, which separates the Kuroshio Current from the East China Sea LME. There are indications that these eddies contribute to the retention and subsequent survival of fish larvae transported by the Kuroshio Current. The Kuroshio Current LME is considered a Class II, moderately high (150-300 gCm^{-2}y^{-1}) productivity ecosystem (Figure X-23.3). Plankton biomass fluctuates from year to year, and is usually highest in the eddy area of the Kuroshio's edge. In the outer area, plankton distribution is low. Of the 66 species in 15 genera of diatoms commonly distributed in Kuroshio waters, 12 species in 5 genera are purely neritic cold water forms (Terazaki, 1989). The spring zooplankton biomass is much greater than in winter (Kozasa 1985). The LME is an important spawning and nursery ground for many important pelagic fishes such as clupeoids, horse mackerel, scomber and saury. In the southern part of this LME, the Ryukyu Archipelago has a tropical environment characterised by coral reefs, mangrove swamps and many diverse marine organisms. Field studies of the ocean environment in relation to biological production in the Kuroshio/Oyashio transitional region have been conducted through GLOBEC (Global Ocean Ecosystems Dynamics) and JGOFS (Joint Global Ocean Flux Study). NOAA has a moored buoy in the Kuroshio Current, providing surface data on winds, air temperature, relative humidity, rain rate, downwelling solar and longwave radiation, SST and salinity. The data are used in studies of climate change effects on the mass transport of the Kuroshio Current LME. Seasonal variations in temperature and nutrients were measured in Sagami Bay in the northern section of this LME (Terazaki 1989).

Oceanic fronts (Belkin and Cornillon 2003; Belkin et al. 2009): The Kuroshio Current is associated with two parallel fronts, with the stronger front along the inshore boundary of the Kuroshio Current and the weaker front along the Kuroshio's offshore boundary (Figure X-23.1). This double Kuroshio Front (KF) forms a large meander that emerges and disappears quasi-periodically off Japan, downstream of Izu Ridge. Its emergence is linked to inter-annual fluctuations in the Kuroshio transport and is ultimately related to the Pacific Decadal Oscillation (PDO) and El-Niño-Southern Oscillation (ENSO). The Kuroshio Front leaves the coast of Japan off Cape Inubo where it forms two quasi-stationary meanders, the so-called First and Second Meanders of the Kuroshio. These meanders often spawn extremely energetic anticyclonic warm-core rings that exist for many months in a transition zone between the Kuroshio Front and the Oyashio Front (OF).

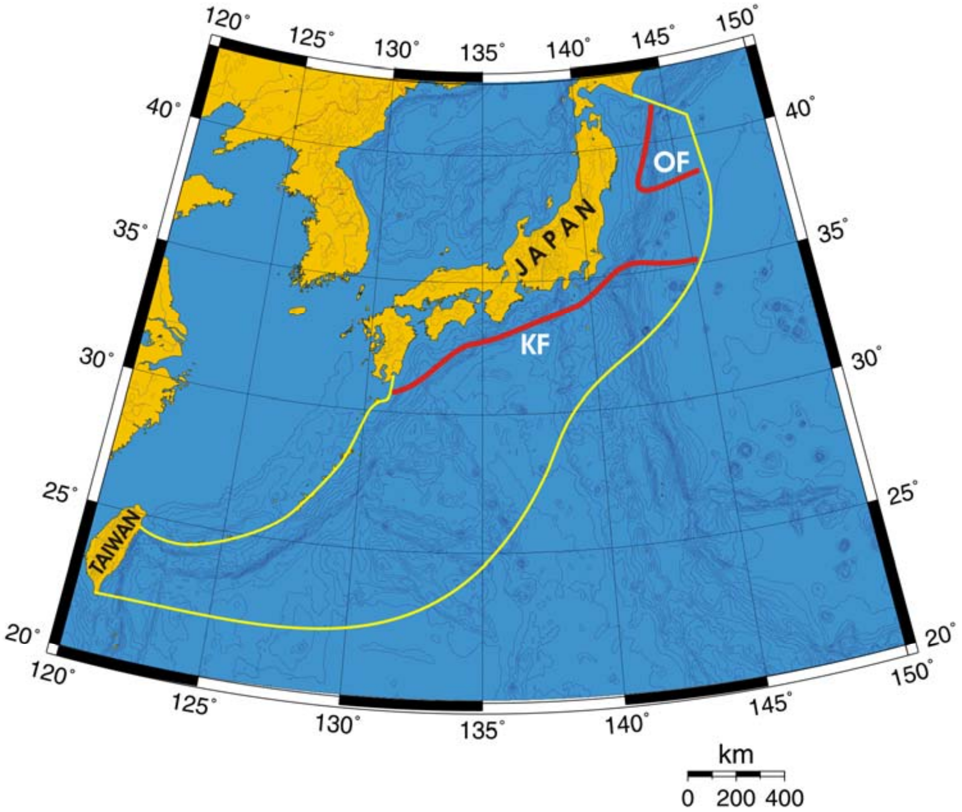

Figure X-23.1. Fronts of the Kuroshio Current LME. F, Oyashio Front; KF, Kuroshio Front. Yellow line, LME boundary. After Belkin et al. (2009).

Kuroshio Current SST (Belkin, 2009)(Figure X-23.2)
Linear SST trend since 1957: 0.65°C.
Linear SST trend since 1982: 0.75°C.

The Kuroshio Current thermal history is similar to the East China Sea LME. Since the Kuroshio flows over the East China Sea shelf, this current is likely affected by the East China Sea. During the 1950s-1970s, SST was rather stable, and then rose rapidly. After the all-time maximum of 1998 caused by the El Niño 1997-98, SST dropped to 23°C, still more than 0.5°C above the average level of the 1960s. Over the last 50 years, the North Pacific experienced several “regime shifts” that affected ocean stratification and all trophic levels (Chiba et al. 2008; Overland et al. 2008). These regime shifts have been shown to correlate with the Pacific Decadal Oscillation (PDO), El-Nino-Southern Oscillation (ENSO), Artic Oscillation (AO), North Pacific Index (NPI) and other atmospheric indices (Minobe 1997; Mantua et al. 1997; Mantua and Hare 2002). The North Pacific regime shift of 1976-77 (Mantua et al. 1997; Hare and Manthua 2000) did not transpire in the Kuroshio Current (although it affected the Oyashio Current). The Kuroshio Current LME shifted to warmer conditions after 1986, the last cold year on record, and experienced another shift to even warmer conditions, around 1997-1998. The shift of 1986-88 could be tentatively associated with the North Pacific regime shift of 1989 documented, among others, by Hare and Mantua (2000).

The shifts of 1987-88 and 1997-98 affected the abundance and biological indices of Pacific saury (Tian et al., 2004). The saury abundance and indices have been found to correlate with two wintertime parameters: SST in the NW Kuroshio waters and surface current velocity in the Kuroshio axis. As Tian et al. (2004, p. 235) pointed out: “These correlations suggest that winter oceanographic conditions in the Kuroshio region strongly affect the early survival process and determine the recruitment success of Pacific saury. The abundance of other major small pelagic species also changed greatly around 1989, suggesting that the regime shift in the late 1980s occurred in the pelagic ecosystem basin. We concluded that Pacific saury could be used as a bio-indicator of regime shifts in the northwestern subtropical Pacific.”

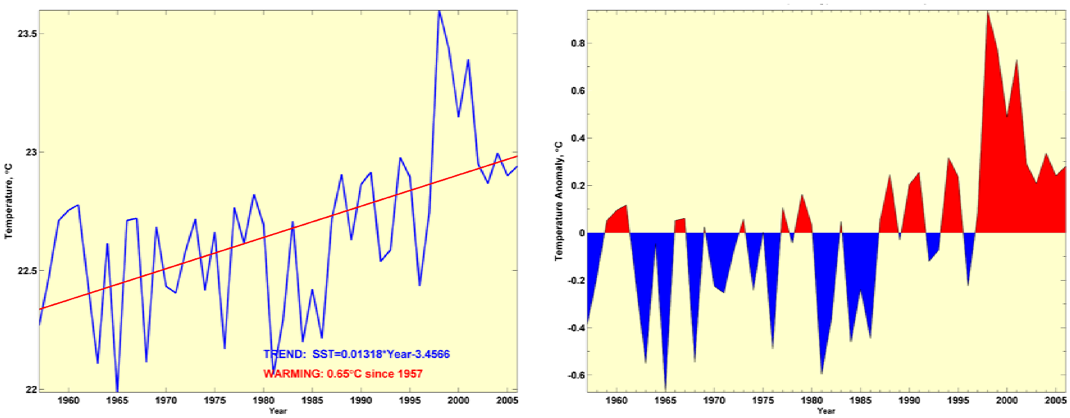

Figure X-23.2. Kuroshio Current LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Kuroshio Current LME Chlorophyll and Primary Productivity: The Kuroshio Current LME is considered a Class II, moderately high (150-300 gCm^{-2}y^{-1}) productivity ecosystem.

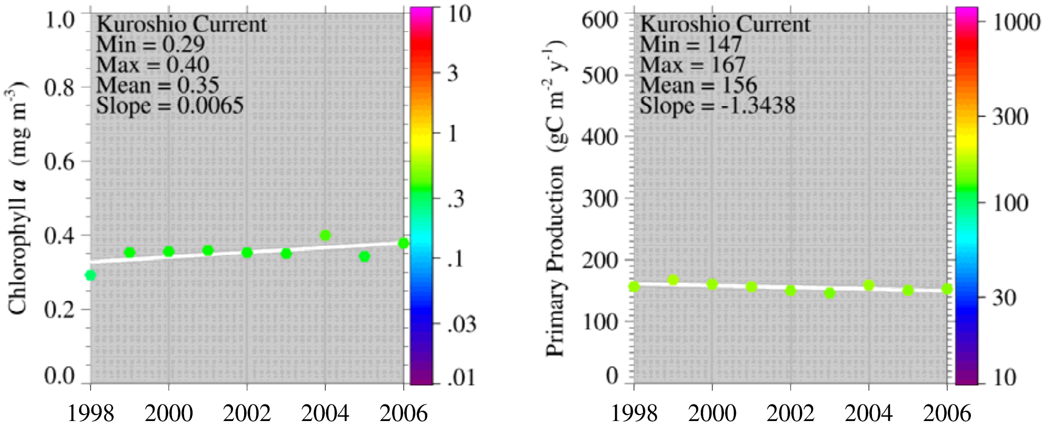

Figure X-23.3. Kuroshio Current LME trends in chlorophyll a (left) and primary productivity (right), 1998 – 2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O’Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Total reported landings in this LME reached 2.5 million tonnes in 1986, but the total has been on a decline following the collapse of the South American pilchard fisheries which dominated the landings in the 1980s (Figure X-23.4). The value of the reported landings peaked at nearly US$4.6 billion (in 2000 US dollars) in 1980 but has declined along with the reduced landings (Figure X-23.5).

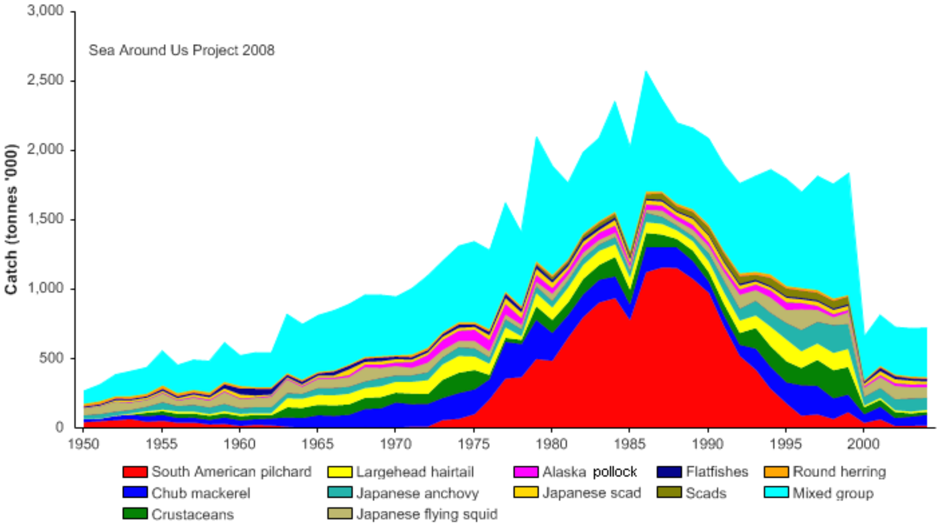

Figure X-23.4. Total reported landings in the Kuroshio Current LME by species (Sea Around Us 2007).

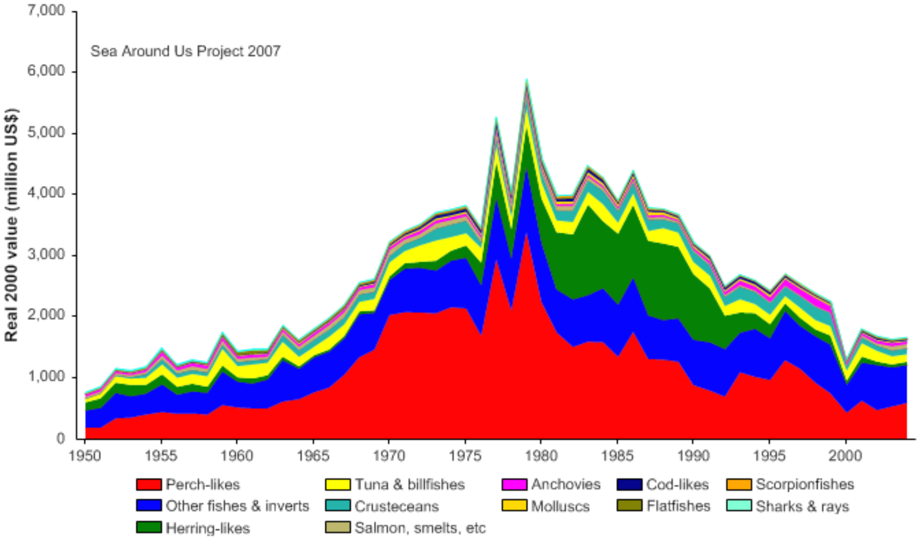

Figure X-23.5. Value of reported landings in the Kuroshio Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached 70% of the observed primary production in the late 1990s, (Figure X-23.6). Two likely explanations for the extremely high level of PPR recorded in the 1980s and 1990s are the over-reporting in the underlying landings statistics by China (Watson & Pauly 2001) and the shift in the distribution of South American pilchard beyond the LME boundary (Watanabe *et al.* 1996) which resulted in possible misreporting of some of the South American pilchard landings as being caught within the LME. Japan and China account for the largest share of the ecological footprint in the LME, though the extremely large size of the Chinese footprint must be questioned.

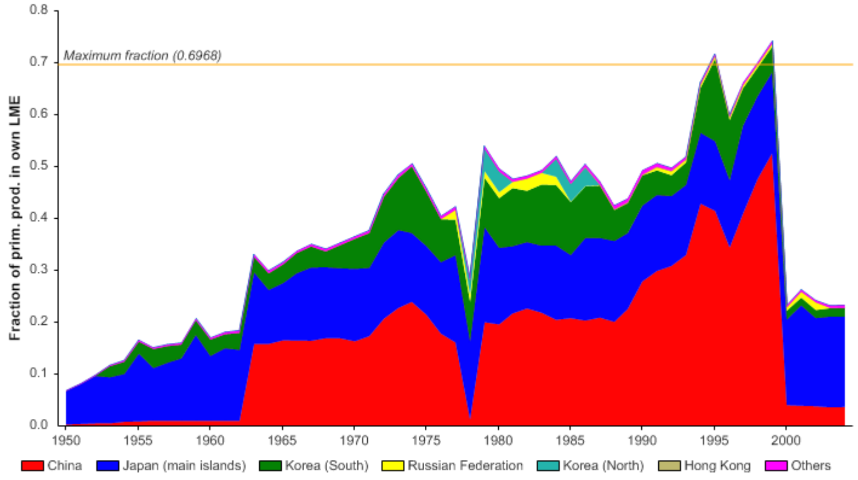

Figure X-23.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Kuroshio Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e. the MTI; Pauly & Watson 2005) shows a series of large fluctuations, reflecting the cyclic nature in the relative abundance, and hence the landings, of the low-trophic South American pilchard in the LME (Figure X-23.7 top). The FiB index shows a period of expansion in the 1950s and 1960s, after which the index levels off, indicating that the decrease in the mean trophic level resulting from the high proportion of South American pilchard catches in the 1980s was compensated for by its large landings (Figure X-23.7 bottom).

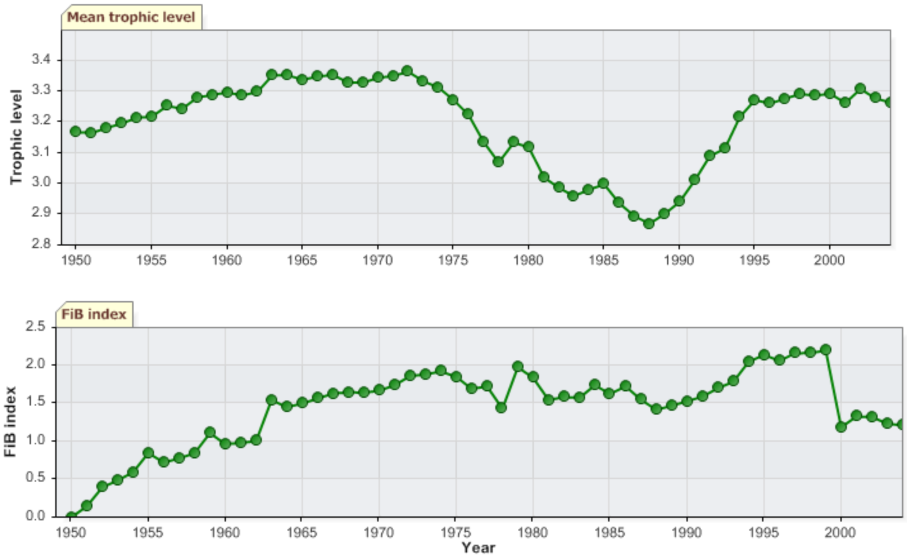

Figure X-23.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Kuroshio Current LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stock has been on a rise, accounting for 80% of the commercially exploited stocks by 2004 (Figure X-23.8, top) with only half of the reported landings supplied by fully exploited stocks (Figure X-23.8, bottom, and see Figure X-23.6). This is in line with the landings trends, which are declining since the mid-1980s (Figure X-23.4).

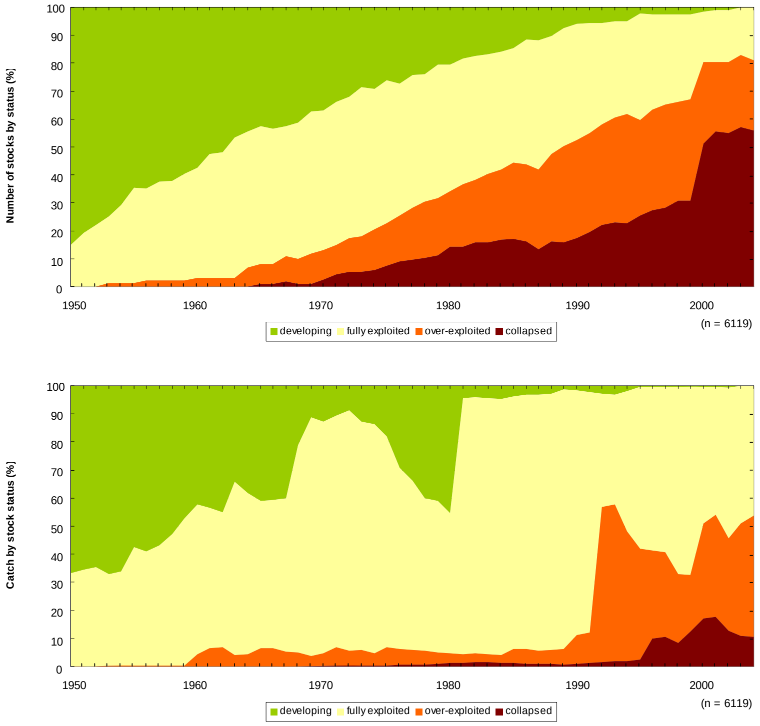

Figure X-23.8. Stock-Catch Status Plots for the Kuroshio LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The biomass of fish stocks depends on the biomass of lower trophic levels (prey), primary production, and also directly on oceanic and atmospheric conditions. The fish catches in the Kuroshio-Oyashio region strongly depend on two oceanographic patterns related to (1) Oyashio's southward intrusions (OSI) or meanders east of Honshu, and (2) Kuroshio's Large Meander (KLM) south of Honshu. Typically, there are two quasi-stationary southward meanders of the Oyashio east of Honshu (Qiu, 2001). Their southward limits SL01 and SL02 correlate with temperature and salinity in the Oyashio LME since the Oyashio meanders contain subarctic water that is markedly colder and fresher than resident water east of Honshu. The OSI strongly affect recruitment, biomass, and catch of such species as pollock, sardine and anchovy. The years when the OSI are well developed and protruded southward are cold years favorable for sardine because sardine uses these meanders as feeding grounds. The KLM development correlates with sardine recruitment and catch owing to the proximity of the KLM to the southern spawning and fishing grounds of sardine (Sakurai, 2007).

Various conceptual hypotheses have been put forth to relate ocean-atmosphere variability to fish catch. For example, Tian et al. (2003) related the abundance of Pacific saury to remote large-scale forcing originated as far away as the equatorial Pacific and the Arctic. Yatsu et al. (2008) linked stock fluctuations of the Pacific stock of Japanese sardine to the Aleutian Low intensification, Oyashio expansion, and mixed layer depth deepening and lower SST in the Kuroshio Extension - as well as less arrival of the two most important predators, skipjack tuna and common squid.

Multi-decadal fluctuations of, and strong correlation between, sardine and anchovy catches that fluctuate out-of-phase is well-known, although the mechanisms behind this phenomenon remain poorly understood (e.g. Chavez et al., 2003). The most recent results by Takasuka et al. (2008) shed a new light on this enigmatic pattern as they found that sardine and anchovy statistical distributions with regard to temperature are distinctly different. In the NW Pacific, they found anchovy to be warm and eurithermal, whereas sardine is cold and stenothermal. In the NE Pacific (California Current), this pattern is reversed.

III. Pollution and Ecosystem Health

Japan's rapid economic development after World War II impacted its marine environment. Rivers have been polluted. On the Pacific side there is air pollution from power plant emissions, resulting in acid rain. Lakes and reservoirs are acidified, resulting in a decrease in water quality and a threat to aquatic life. In the 1960s, heavy industries concentrated along the Japanese coast caused severe water pollution linked to red tides. Strict laws and standards established in the 1970s have improved the quality of coastal waters, although eutrophication in areas such as Tokyo Bay is still serious despite the development of sewage treatment systems. In the Tokyo/Yokosuka area, sewage pollution, habitat destruction and non-biodegradable pollution are considered the most serious problems. Further north, in the Hakodate/Otsuchi area, non-biodegradable pollution is also seen as the most serious problem, followed by sewage pollution and oil pollution. The numbers of reported marine pollution incidents for the coastal areas of Japan appear high. There have been oil spills and incidents caused by land-based activities. A marine environmental monitoring plan for coastal Japan is available online. Table 1-3-4 in the Report on the Environment in Japan (www.env.go.jp/en/focus/080704.html) indicates the number of marine pollution incidents caused by drifting oil and wastes, red tide, and blue tide (in Japanese: Aoshio; this phenomenon is caused by upwelling of blue-green oxygen-depleted turbid waters; observed in Tokyo Bay from early summer to autumn) in sea areas surrounding Japan in the past five years. In 2002, there were 516 occurrences, an increase of 30 occurrences over 2001. Oil spills from ships accounted for the majority of marine pollution, with 231 incidents reported in 2002.

IV. Socioeconomic Conditions

The wide latitudinal extension of the Kuroshio Current LME helps sustain regions varied in culture and economic development. The Japanese Archipelago is comprised of 4 main islands and 200 smaller islands, including those of the Amami, Okinawa, and Sakishima chains of the Ryukyu Islands, all linked by an efficient transport system. Fisheries are a major economic activity in Japan, which relies on the sea for its supply of fish, seaweed and other marine resources. Japan maintains one of the world's largest fishing fleets and accounts for nearly 15% of the global catch. According to the Japan Fisheries Agency report of 1997 (http://www.jfa.maff.go.jp/jfapanf/english/index.htm), Japan produced 7.4 million tons of fishing products in 1996. By 2007, fisheries production is reported at 5.70 million tons (www.stat.go.jp/english/data/handbook/c05cont.htm). The Japan Fisheries Market Report, issued by the Commercial Section of the Canadian Embassy, Tokyo for May 2002 states that Japan’s imports of fish and fisheries products recorded a high in

2001 of 3.823 million metric tons then valued at US$14.21 billion. Of Japan's 2,944 fishing ports, the main Pacific ports are Hachinohe, Shimizu, Tokyo and Tomakomai.

V. Governance

Japan is involved in the governance of this LME. As a country with major interests in fisheries, Japan has formulated and implemented conservation and management measures. In 1971, it established an Environment Agency. Since 1975, the Agency has been conducting annual surveys of marine pollution in LMEs adjacent to Japan including this LME. Another marine research programme, initiated in 1995, evaluates the effects of pollution on marine organisms and of air pollution on the marine environment. Internationally, Japan plays a central role supporting high seas fisheries for salmon, tuna, and bill fish. In order to cope with the changing economical and social situation, in 1997 the Fisheries Agency was reorganized into a four-department system; Fisheries Policy Planning Department, Resources Management Department, Resources Development Department, and Fishing Port Department (www.jfa.maff.go.jp/). The Fisheries Agency attempts to ensure a stable supply of marine products to the people and promotion of the marine products industry in Japan.

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X-24 Oyashio Current LME

S. Heileman and I. Belkin

The Oyashio Current LME is located in the northwest Pacific Ocean and is bordered by Russia (the Kamchatka Peninsula and Kuril Islands) and the Japanese island of Hokkaido. It covers an area of about 530,000 km^2, of which 0.19% is protected, and contains 0.09% of the world's sea mounts (Sea Around Us 2007). A sub-arctic climate characterises this LME, which is based on the distinctive cold Oyashio Current (or the Kuril Current) with its strong interannual variations in strength (Minoda 1989). The geographic remoteness and inaccessibility of the Kuril Islands, combined with the extreme environmental conditions have discouraged human settlement and contributed to making the Kuril Archipelago one of the least known regions of the world. The 2,000 km Kuril-Kamchatka island arc is part of the 'Ring of Fire', a chain of volcanoes encircling the Pacific Ocean (Simkin & Siebert 1994). Accounts pertaining to this LME include Minoda (1989) and UNEP (2006).

I. Productivity

The Oyashio Current LME is a Class II, moderately productive (150-300 gCm^{-2}y^{-1}) ecosystem (Figure X-24.3). The confluence zone of the cold Oyashio Current and the warm Kuroshio Current off northern Japan gives rise to some of the most productive marine areas of East Asia, with many species of fauna and flora and rich fishing grounds. The phytoplankton has 'traditional' spring bloom dynamics (Kasai *et al*. 1997) leading to a typical phytoplankton-macrozooplankton-fish food web. It is believed that the high zooplankton biomass depends on the cold waters of the Oyashio Current below the thermocline (Minoda 1989). The observed large fluctuations in the biomass and timing of zooplankton recruitment suggest that zooplankton grazing is an important factor in controlling the magnitude and the duration of the spring bloom (Saito *et al*. 2002).

Kamchatka and the Kuril Islands are of global importance. In 1996 five specially protected natural areas ('Kamchatka Volcanoes') were included among the UNESCO World Cultural and Natural Heritage Sites. The system of specially protected natural areas includes three reserves, three natural parks of regional importance, 25 protected areas, and 89 state nature monuments. The waters around Kamchatka are inhabited by the rare grey whale and several other species of marine mammals such as sea lions and otters.

Oceanic fronts (Belkin and Cornillon 2003; Belkin et al. 2009): The Oyashio Current Front originates at the western periphery of the Western Subarctic Gyre (Figure X-24.1). The upstream part of the Oyashio Current/Front is also called the East Kamchatka Current/Front and Kuril Current/Front. The Oyashio Current carries cold and fresh waters southwestward where they meet the warm and salty waters of the Kuroshio. As it flows southwestward, the Oyashio Current forms energetic eddies, up to 50-100 km in diameter, branches into the Okhotsk Sea via the Kuril Straits and undergoes water mass transformation owing to extremely intense tidal mixing in the Kuril Straits. A major permanent branch of the Oyashio Current penetrates into the Okhotsk Sea to form the West Kamchatka Current.

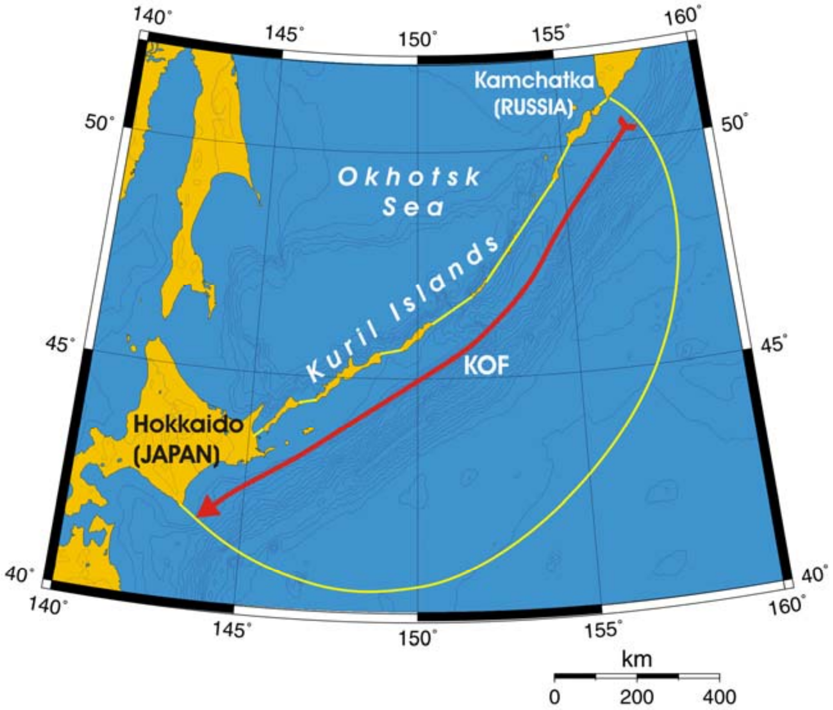

Figure X-24.1. Fronts of the Oyashio Current LME. KOF, Kuril-Oyashio Front. Yellow line, LME boundary. After Belkin et al. (2009).

Oyashio Current SST (Belkin 2009)(Figure X-24.2)
Linear SST trend since 1957: 0.48°C.
Linear SST trend since 1982: 0.60°C.

Over the last 50 years, the North Pacific experienced several "regime shifts" that affected ocean stratification and all trophic levels (Chiba et al. 2008; Overland et al. 2008). These regime shifts have been shown to correlate with the Pacific Decadal Oscillation (PDO), El-Nino-Southern Oscillation (ENSO), Artic Oscillation (AO), North Pacific Index (NPI) and other atmospheric indices (Minobe 1997; Mantua et al. 1997; Mantua and Hare 2002). The North Pacific regime shift of 1976-77 (Mantua et al. 1997; Hare and Manthua 2000) transpired in the Oyashio Current (but not in the Kuroshio Current). The Oyashio Current experienced a regime shift in the late 1980s from a cold epoch to a warm one, when SST rose by 1°C in just two years, a dramatic regional manifestation of the trans-Pacific regime shift of 1988-89 (Mantua et al., 1997; Hare and Mantua, 2000). The Oyashio Current is rather strongly correlated with the Okhotsk Sea LME, sometimes lagging 1 to 2 years behind the latter, suggestive of the Okhotsk Sea influence on the Oyashio Current. Another interesting feature of the Oyashio Current is a distinct 3- to 5-year periodicity.

According to Megrey et al. (2007), all three main groups of zooplankton increased during SST decrease; a similar correlation was observed in the subarctic sub-region of California, thus confirming a general tendency of negative correlation between zooplankton density and temperature. A caveat: the Oyashio sub-region at 42N, 155E in Megrey et al. (2007) is south of the LME, albeit still within the Oyashio Extension associated with the Polar Front (Belkin et al., 2002).

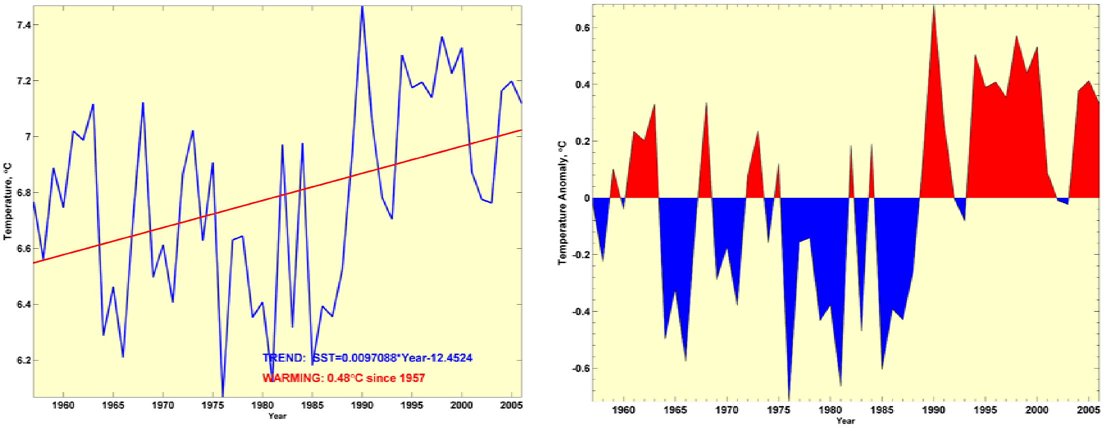

Figure X-24.2. Oyashio Current LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

***Oyashio Current LME Chlorophyll and Primary Productivity*:** The Oyashio Current LME is considered a Class II, moderately productive (150-300 gCm^{-2}y^{-1}) ecosystem.

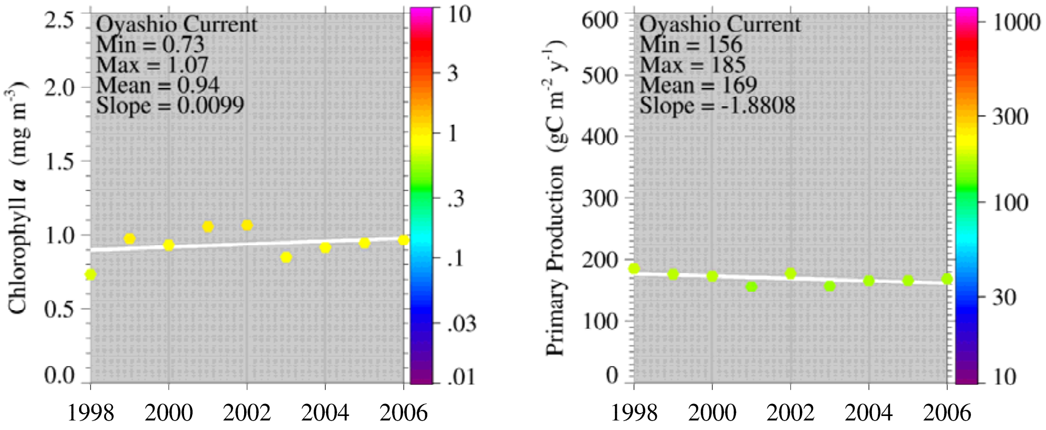

Figure X-24.3. Oyashio Current LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Oyashio Current flows off the Pacific coast of the Kuril Islands, an important fishing ground for the Russian Federation. In addition to the capture fisheries, a large number of kelp, scallop, abalone and algae are cultured in the region.

Total reported landings in the LME exceeded 900,000 tonnes in 1984-1985, with large catches of Alaska pollock and South American pilchard, but recorded around 300,000 tonnes in 2004 (Figure X-24.4). From 1970 to 1989 the total reported landings was valued at over US$1 billion (in 2000 US dollars) with a peak of US$1.5 billion recorded in 1980-1985 (Figure X-24.5).

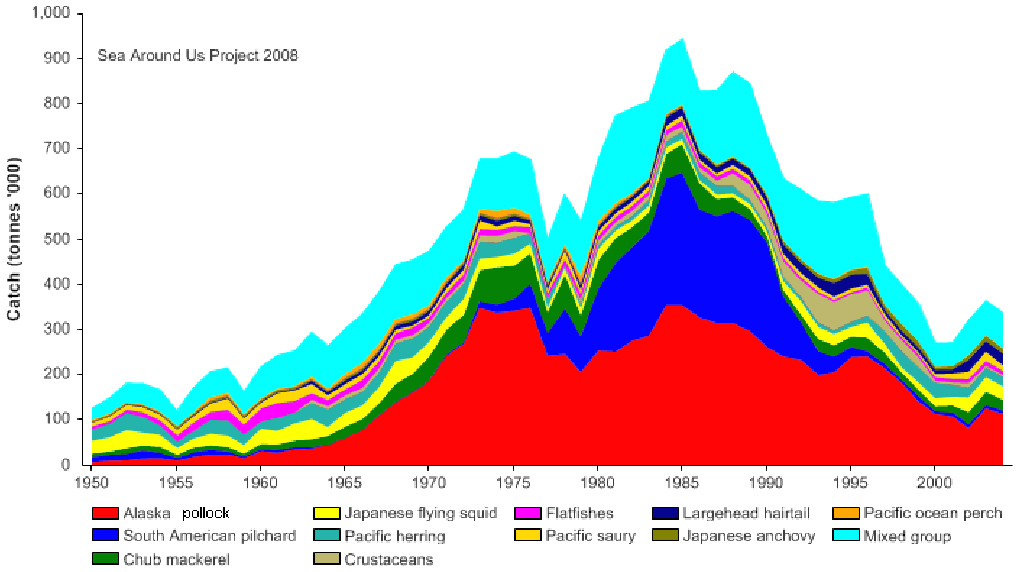

Figure X-24.4. Total reported landings in the Oyashio Current LME by species (Sea Around Us 2007).

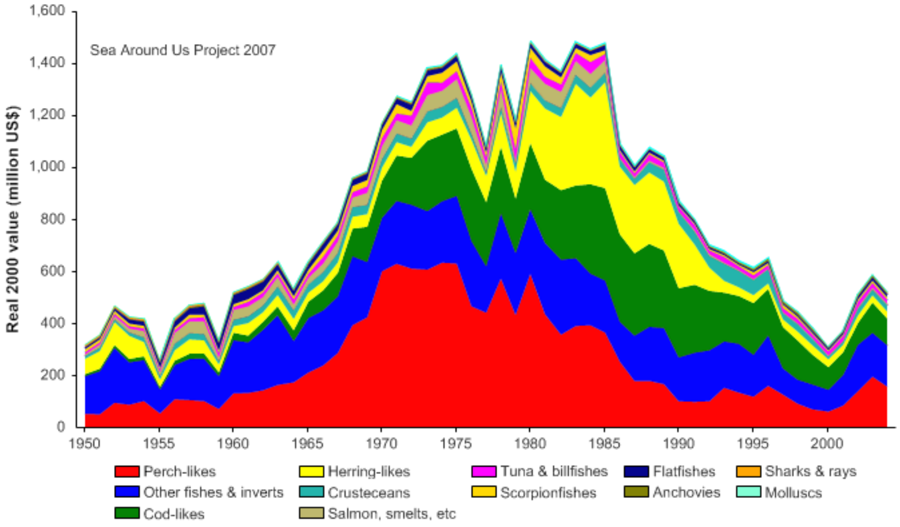

Figure X-24.5. Value of reported landings in the Oyashio Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 25% of the observed primary production in the mid 1980s and in 1995 but has not reached such level since (Figure X-24.6). Japan and Russia have the largest footprint in this LME. With Russia selling the rights to fish inside its EEZ, a large number of foreign fleets, mainly those from China and South Korea, as well as a number of flag-of-convenience ships, operate within the LME. Illegal fishing is also of concern, although its extent in Russian territorial waters is not known with any certainty.

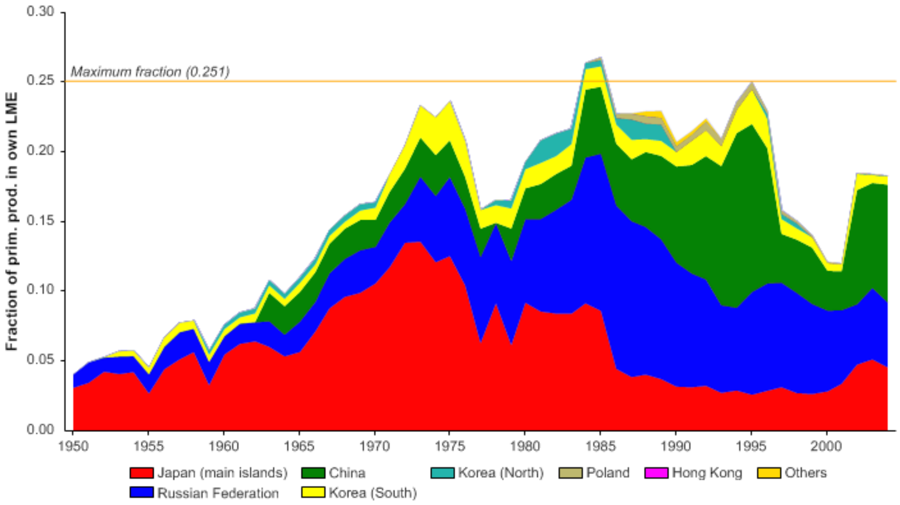

Figure X-24.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Oyashio Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e. the MTI; Pauly & Watson 2005) shows large fluctuations, reflecting the cyclic nature in the relative abundance, and hence the landings, of the low-trophic South American pilchard in the LME (Figure X-24.7 top); The FiB index shows a period of expansion in the 1950s and 1960s, after which the index levels off, indicating that the decrease in the mean trophic level resulting from the high proportion of South American pilchard in the reported landings in the 1980s was compensated for by its large landings (Figure X-24.7, bottom).

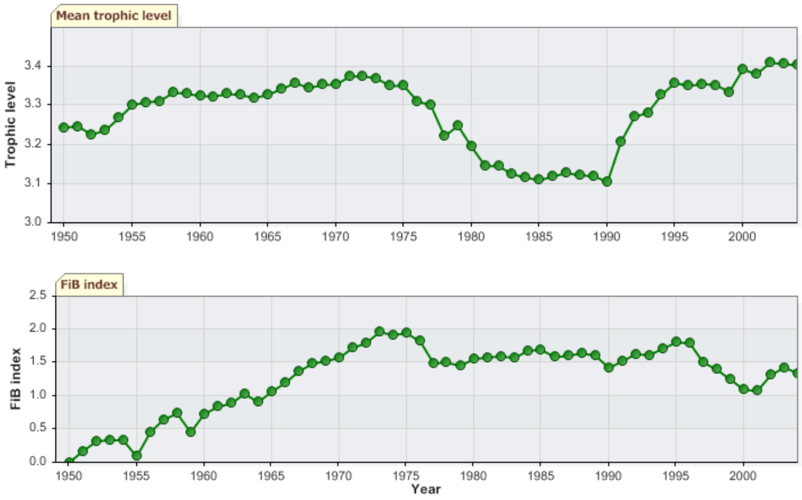

Figure X-24.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Oyashio Current LME (Sea Around Us 2007)

The Stock-Catch Status Plots indicate that the number of collapsed stocks have been rapidly increasing, accounting for 50% of the commercially exploited stocks in 2004, with an additional 30% of the stocks being overexploited (Figure X-24.8, top). Overexploited stocks contributed 80% of the catch biomass in 2004 (Figure X-24.8, bottom).

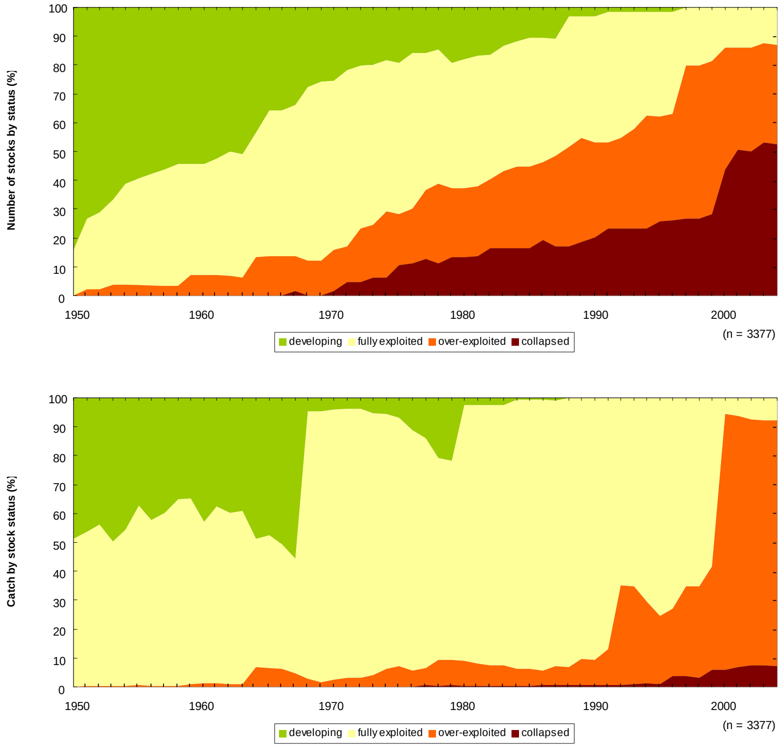

Figure X-24.8. Stock-Catch Status Plots for the Oyashio Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Overcapacity of the fishing fleet is a problem and the decrease in demersal shrimp and fish landings has been attributed to intense exploitation. Chub mackerel decreased in 1976, and by 1979 the fishery had disappeared in Hokkaido (Minoda 1989). The salmon catch decreased in 1977 but subsequently stabilised (Minoda 1989). Japanese efforts to breed and release salmon have led to an increase in chum salmon. The collapse of the populations of certain species (particularly red king crab) in the past has not been attributed to any one cause such as overfishing. Drift netting is an important pelagic fishing method in the Oyashio Current LME. Other methods include beam trawling for demersal species (UNEP 2006).

The effects of climate regime shift on ENSO events, western boundary currents and upper-ocean stratification and their biological consequences are reviewed by Sugimoto *et al*. (2001). The fisheries resources in this LME are also affected by climate variability. For instance, a significant weakening of the southward intrusion of the Oyashio Current off the east coast of Japan during 1988-1991 resulted in a decrease in chlorophyll concentrations and mesozooplankton biomass in late spring-early summer in the Kuroshio-Oyashio transition region. Changes occurred in the dominant species of small pelagic fish, through successive recruitment failures of Japanese pilchard. In addition, the southern edge of salmon habitats is expected to shift northwards as a result of global warming. The stands of cold-water seaweed may also decline, which may lead to a reduction of populations of abalone, sea urchins and other invertebrates that feed on this type of seaweed (UNEP 2006).

The biomass of fish stocks depends on the biomass of lower trophic levels (prey), primary production, and also directly on oceanic and atmospheric conditions. The fish catches in the Kuroshio-Oyashio region strongly depend on two oceanographic patterns related to (1) Oyashio's southward intrusions (OSI) or meanders east of Honshu, and (2) Kuroshio's Large Meander (KLM) south of Honshu. Typically, there are two quasi-stationary southward meanders of the Oyashio east of Honshu (Qiu, 2001). Their southward limits SL01 and SL02 correlate with SST and SSS in the Oyashio LME since the Oyashio meanders contain subarctic water that is markedly colder and fresher than resident water east of Honshu. The OSI strongly affect recruitment, biomass, and catch of such species as pollock, sardine and anchovy. The years when the OSI are well developed and protruded southward are cold years favorable for sardine because sardine uses these meanders as feeding grounds. The KLM development correlates with sardine recruitment and catch owing to the proximity of the KLM to the southern spawning and fishing grounds of sardine (Sakurai, 2007).

Various conceptual hypotheses have been put forth to relate ocean-atmosphere variability to fish catch. For example, Tian et al. (2003) related the abundance of Pacific saury to remote large-scale forcing originating as far away as the equatorial Pacific and the Arctic. Yatsu et al. (2008) linked stock fluctuations of the Pacific stock of Japanese sardine to the Aleutian Low intensification, Oyashio expansion, and mixed layer depth deepening and lower SST in the Kuroshio Extension - as well as less arrival of the two most important predators, skipjack tuna and common squid.

Multi-decadal fluctuations of, and strong correlation between, sardine and anchovy catches that fluctuate out-of-phase are well-known, although the mechanisms behind these phenomena remain poorly understood (e.g. Chavez et al., 2003). The most recent results by Takasuka et al. (2008) shed new light on these fluctuation patterns, as they found that sardine and anchovy statistical distributions with regard to temperature are distinctly different. In the NW Pacific, they found anchovy to be warm and eurithermal, and sardine to be cold and stenothermal. In the NE Pacific (California Current), this pattern is reversed.

III. Pollution and Ecosystem Health

Pollution: Since the greater part of the Oyashio Current LME is located far from the coastal areas of Japan and Russia, it is less affected by river and air pollution resulting from rapid economic growth and industrial production. Overall, pollution was found to be negligible (UNEP 2006), although solid waste is of concern in areas close to human settlements, including seasonal camps. Numerous navigation routes used by thousands of vessels all year round increase the potential for oil pollution in this LME. Up to five spills per year occur on average, especially on the Kuril route. Oil pollution is expected to increase with the development of new oil deposits and increased oil transport by tankers from Sakhalin. There is some concern over radioactive contamination from old, decommissioned nuclear submarines and other sources in this LME.

Habitat and community modification: The main cause of habitat modification is coastal development (e.g., port construction and operation), but this is relatively small-scale and not thought to lead to habitat loss. The release of chum salmon fry from hatcheries may lead to competition with other fish larvae for food, resulting in community modification. Global climate change is expected to influence the ENSO phenomenon, winter monsoon, western boundary currents, and upper ocean stratification, with biological consequences on coastal and marine habitats.

IV. Socioeconomic Conditions

The population of the east coast of Kamchatka and Kuril Islands is about 300,000, with a relatively low population density of about 2 inhabitants/km^2. In the north of the peninsula, the indigenous people of Kamchatka, the Koryaks, the Itelmen, the Chukchies and the Evenks have maintained their traditional way of life. The LME is rich in natural resources, including fish, minerals and potentially large oil and gas reserves. Fishing and fish processing, fuel and energy (e.g., geothermal, wind-driven, and hydroelectric power plants), ship repair, and tourism are the major economic activities of the Kamchatka region. At present, fisheries make up 80% of the industrial and economic activities of Kamchatka and the Kuril Islands, while aquaculture (of fish and other marine organisms) is of major interest in Hokkaido. The socioeconomic impacts of illegal fishing by foreign boats and the possibility of fish stock collapse along with temporary bans on salmon fishing as a result of weak salmon runs are of concern in the region.

V. Governance

The long-term dispute between Russia and Japan over sovereignty of the South Kuril Islands resulted in a dispute over fishing rights in the Oyashio Current LME, which is under a serious environmental threat, especially the southern Kuril Islands where the biota is considerably more diverse than the central and northern islands. Action is needed to explore, document and protect the unique and delicate flora and fauna of these islands. At present, the south Kuril Islands are governed by Russian administration as part of Russia's Sakhalin oblast' (district). Japan claims these four islands – Iturup, Kunashir, Shikotan, and the Habomai Rocks - and refers to them as the "Northern Territories". In 2000, Russia and Japan signed a programme for joint economic development of South Kurils.

Until 1993, the International North Pacific Fisheries Commission, composed of Canada, Japan and the U.S., was a regulatory agency for fisheries in the Oyashio Current LME. This Commission was dissolved with the entry into force of the Convention for the Conservation of Anadromous Stocks in the North Pacific Ocean.

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X-25 Sea of Japan / East Sea LME

S. Heileman and I. Belkin

The Sea of Japan/East Sea LME is bordered by China, Japan, North Korea, South Korea and the Russian Far East. This LME has a mean depth of 1,350 m, a surface area of about 984,000 km^2, of which 0.40% is protected, and contains 0.25% of the world's sea mounts and 10 major estuaries (Sea Around Us 2007). Narrow straits connect the LME to the Sea of Okhotsk, the North Pacific and the East China Sea, with the Korean Strait accounting for 97% of the total annual water exchange (Baklanov *et al*. 2002). Flowing southwest along the Far East's coast of Russia is the cold Primorskii (Liman) Current (Dobrovol'sky & Zalogin 1982). This LME spans both subtropical and temperate climatic zones and climate is the primary driving force of biomass change. Monsoon atmospheric circulation mainly determines the sea climate. A book chapter and report on this LME have been published by Terazaki (1999) and made available electronically by UNEP (2006).

I. Productivity

The Sea of Japan/ East Sea LME is a Class II, moderate productive ecosystem (150-300 gCm^{-2}y^{-1}). Considerable variation in the composition, distribution and abundance of the plankton community has been recorded and associated with environmental variability (Terazaki 1999). Diatom blooms occur primarily in the spring and a subsurface chlorophyll maximum is sometimes found in the deeper layers, particularly in spring and winter. The zooplankton community has low diversity in terms of number of taxonomic groups and species, with five zooplankton groups accounting for over 99% of the biomass: copepods, which are the most abundant, euphausiids, chaetognaths, amphipods and mysids. At a depth of 0-5 m in open and semi-closed bays there are widespread communities of species such as blade kelp (*Laminaria hyperborean*) and Irish moss (*Chondrus crispus)*, with biomass up to 12 kgm^{-2}. Tropical, sub-tropical and arctic animals occur in the LME, with the coastal fauna and flora consisting of a higher percentage of sub-tropical species.

Oceanic fronts (Belkin et al. 2009; Belkin and Cornillon, 2003): The Subarctic (Subpolar) Front (SAF) crosses the Japan (East) Sea zonally from west to east and then extends meridionally northward into the Gulf of Tartar (Tatarskiy Zaliv) (Figure X-25.1). From satellite data, three tributaries of this front have been identified in the western part of the sea. This major front divides the Japan Sea/East Sea LME into two parts, northern and southern, with different oceanographic regimes. The Liman Current Front (LCF) extends along the coast of the Russian province, Primorskii Krai, in the northwestern part of the Japan/East Sea. Small and meso-scale fronts are generated near Laperouse Strait and in the southern part of the Gulf of Tartar owing to vigorous tidal mixing and the influx of Okhotsk Sea waters.

Sea of Japan / East Sea LME SST (Belkin 2009)
Linear SST trend since 1957: 0.82°C.
Linear SST trend since 1982: 1.09°C.

Since 1957, the Japan Sea/ East Sea LME experienced at least one regime shift, between 1986 and 1990 (Figure X-25.2). The last cold year of 1986 saw the all-time minimum SST of 12.0°C. Then, SST rose by >1.5°C in 4 years, a regional manifestation

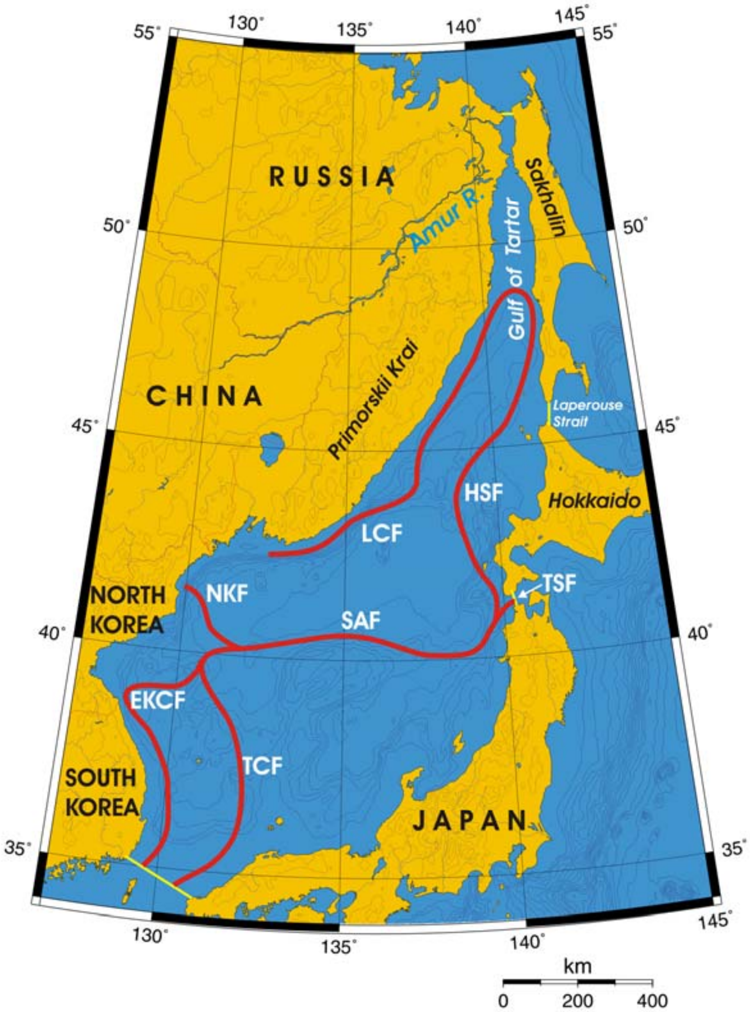

Figure X-25.1. Fronts of the Sea of Japan/ East Sea LME. EKCF, East Korea Current Front; HSF, Hokkaido-Sakhalin Front; LCF, Liman Current Front; NKF, North Korea Front; SAF, Subarctic (Subpolar) Front; TCF, Tsushima Current Front; TSF, Tsugaru Strait Front. Yellow line, LME boundary. After Belkin et al.(2009) and Belkin and Cornillon (2003).

of the trans-Pacific regime shift of the late 1980s (Hare and Mantua, 2000) that profoundly affected the Japan Sea/East Sea ecosystem (e.g. Zhang et al., 2007). The all-time maximum of 1998 caused by the El Niño 1997-98 saw SST>14°C, which was >2°C above the all-time minimum of 1986. Interannual variability in the Japan Sea is substantial, with a magnitude of 1°C. Thermal histories of the Japan Sea/ East Sea and Kuroshio are similar since the Kuroshio's main branch, Tsushima Current, flows across the Japan Sea.

Using 1°×1° resolution SST data from 1950-1998 compiled by the Japan Meteorological Agency, Hong et al. (2001) found a strong correlation between SST and ENSO (El Niño Southern Oscillation) events and showed that SST anomalies in the Japan Sea occurred simultaneously with development of ENSO events in the Tropical Pacific. From a similar time period of 1951-1996, Park and Oh (2000) found SSTs in the East Asian Marginal Seas (EAMS) lagging ENSO events in the eastern Equatorial Pacific. The phase lag between SST anomalies in the EAMS and ENSO was found to depend on the variability scale: 5-9 months for 2- to 3-year periods, and 18-22 months for 6-year oscillations.

Significant spatial contrasts were found between the northern and southern parts of the Japan Sea/ East Sea: a cooling in 1965-66 was confined to the southern part, whereas its northern part experienced a sudden warming (Park and Oh, 2000). These contrasts can be explained by the existence of a major front that separates the northern and southern part of the Japan Sea/ East Sea (e.g. Belkin and Cornillon, 2003).

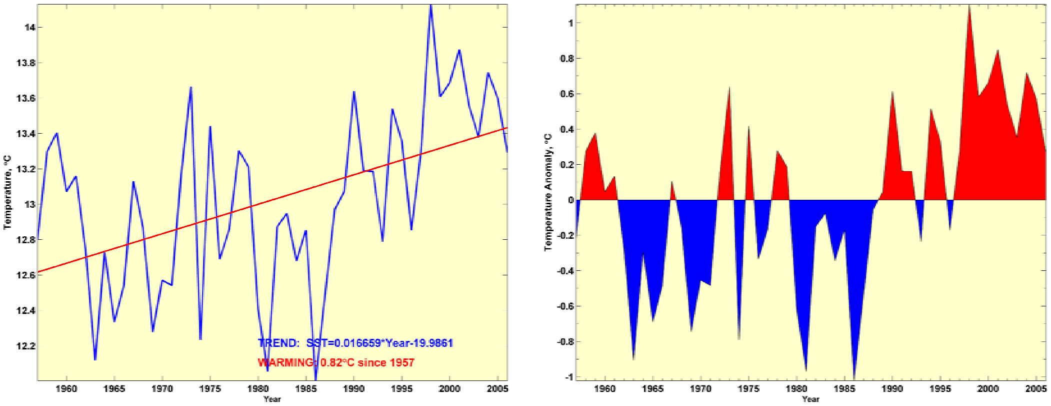

Figure X-25.2. Sea of Japan/ East Sea LME annual mean SST (left) and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Sea of Japan/ East Sea LME Chlorophyll and Primary Productivity: The Sea of Japan/ East Sea LME is a Class II, moderately productive ecosystem (150-300 gCm^{-2}y^{-1}).

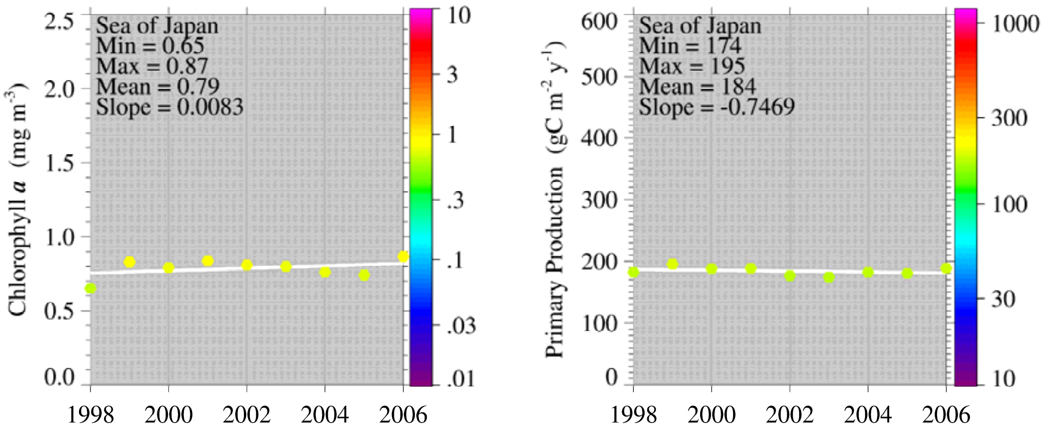

Figure X-25.3. Sea of Japan/ East Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Marine fisheries are an important economic sector for the countries bordering the Sea of Japan/East Sea LME. Both cold and warm-water fish occur in the LME, with salmon, Alaska pollock, sea urchin, sea cucumber, crab and shrimp being the most valuable species. There is a strong correlation between high catches of some species, such as mackerel and the meandering of the Tsushima Current (Terazaki 1999). Long-term fluctuations of South American pilchard *Sardinops sagax*, accompanied by noticeable geographic shifts in its spawning and nursery grounds have been observed, but no relationship has been found between high pilchard catches and the Tsushima Current. Catches of anchovy, round herring, yellowtail, scad and squid have also fluctuated over the past few decades. Total reported landings in the LME reached 2.2 million tonnes in 1984 but have since declined to around 1 million tonnes in 2004 (Figure X-25.4). The fluctuation in the landings can be attributed mainly to the high reported landings of South American pilchard, which accounted for 30% of the total landings in the mid to late 1980s. The value of the reported landings also rose steadily to over US$4.6 billion (in 2000 US dollars) in 1979, due to the high value commanded by chub mackerel (Figure X-25.5).

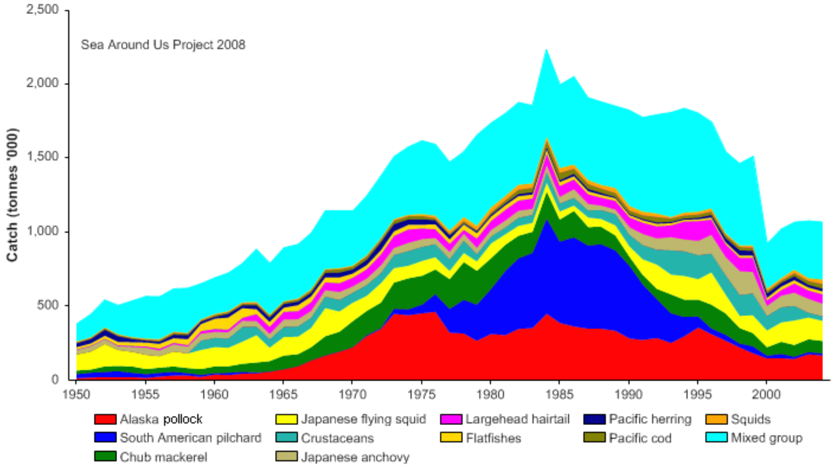

Figure X-25.4. Total reported landings in the Sea of Japan LME by species (Sea Around Us 2007)

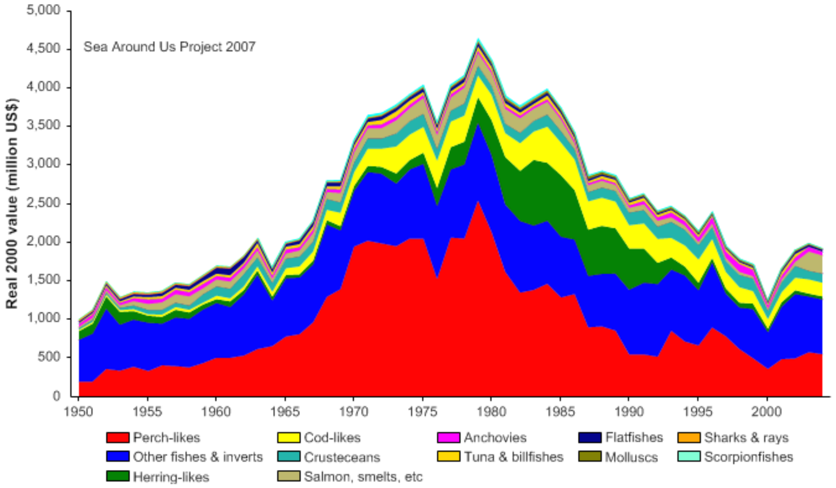

Figure X-25.5. Value of reported landings in the Sea of Japan LME by commercial groups (Sea Around Us 2007)

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 50% of the observed primary production in the 1990s but has since declined in recent years (Figure X-25.6). This extremely high PPR may be a result of over-reporting by China in its landings statistics (Watson & Pauly 2001). China, Japan and Russia account for the largest share of the ecological footprint in the LME, though the size of the Chinese footprint must be questioned.

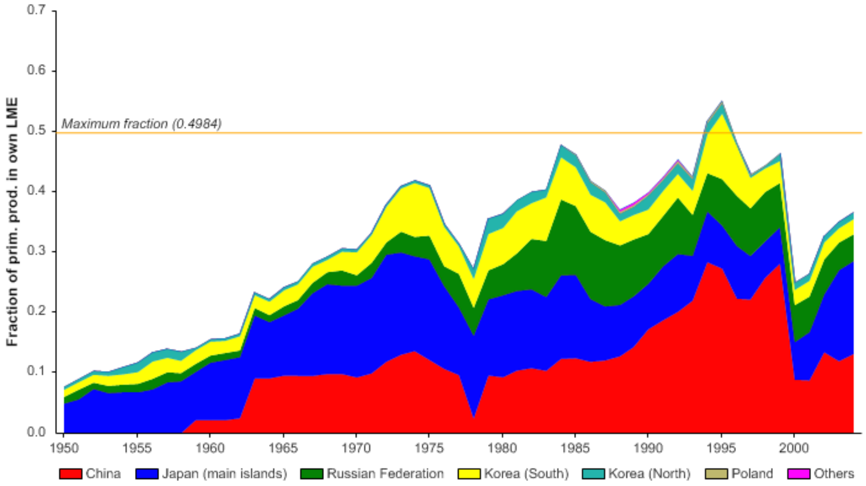

Figure X-25.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Sea of Japan /East Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e. the MTI; Pauly & Watson 2005) shows a large fluctuation, reflecting the cyclic nature in the relative abundance, and hence the landings, of the low-trophic South American pilchard in the LME (Figure X-25.7 top); the FiB index shows a period of expansion in the 1950s and 1960s, after which the index levels off, indicating that the decrease in the mean trophic level resulting from the high proportion of reported landings of South American pilchard in the 1980s was compensated for by its large volume of landings (Figure X-25.7 bottom).

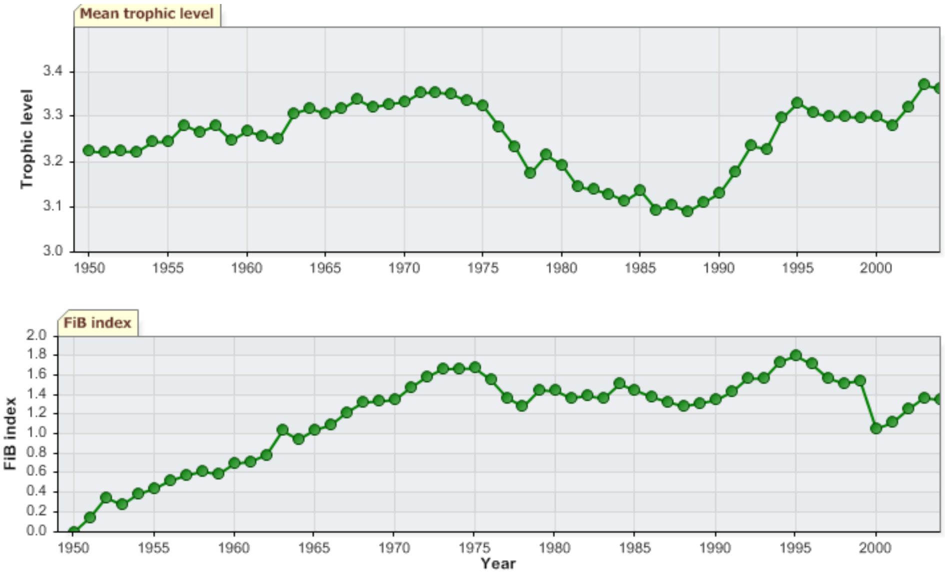

Figure X-25.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Sea of Japan LME/ East Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plot indicates that the number of collapsed and overexploited stocks in the LME has been rapidly increasing, to 80% of the commercially exploited stocks (Figure X-25.8, top), with almost half of the reported landings still supplied by fully exploited stocks (Figure X-25.8, bottom).

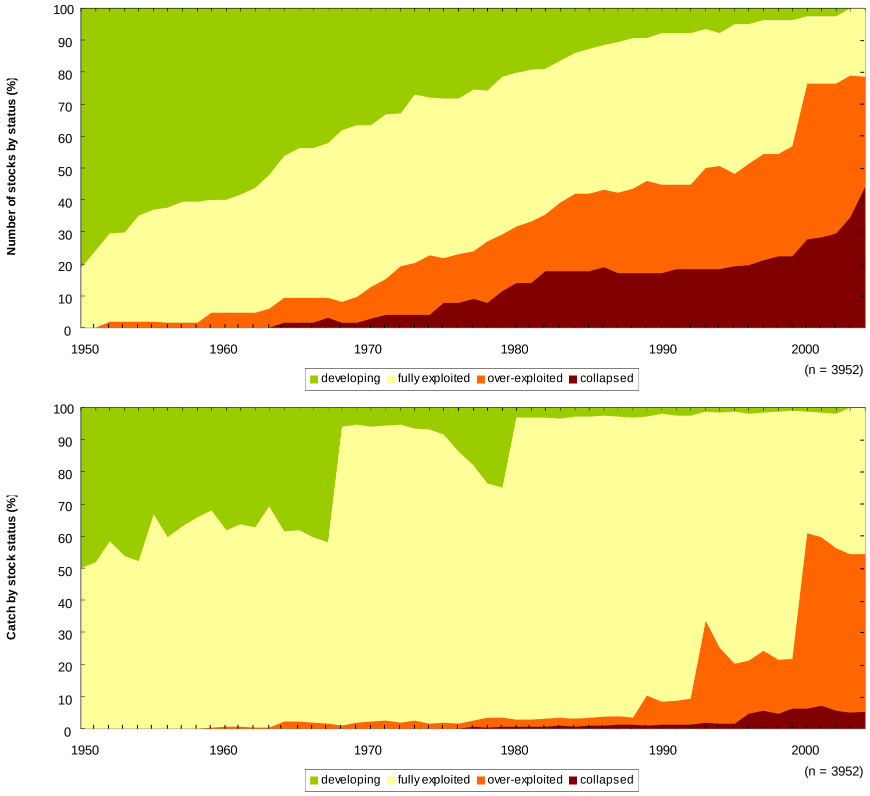

Figure X-25.8. Stock-Catch Status Plots for the Sea of Japan/ East Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Catches of fish and invertebrates beyond MSY have resulted in severe overexploitation of several of the major species in this LME (UNEP 2006). For instance, overfishing of the Pacific herring in Peter the Great Bay (Zaliv Petra Velikogo in Russian; off Vladivostok) led to the closure of this fishery. Illegal and unreported fishing is a major concern, and leads to uncertainties in the status of the fish stocks. In addition, hundreds of Russian, Japanese, Chinese and Taiwanese unregistered fishing vessels as well as flag of convenience ships operate in this LME. Current ongoing efforts to modernise the fishing industry in the Russian Far East and ambitious regional and national government programmes to increase Russian fish harvests over the next decade will put increased pressure on the fish stocks (UNEP 2006). These efforts, coupled with inadequate monitoring and enforcement due to funding shortfalls, could result in overfishing of some other species such as pollock (Baklanov *et al*. 2003). In recent years, the fishing industry has been working on ways to switch from a "fish-catching" to a mariculture mode. Facilities such as the Toyama Prefectural Fish Breeding Centre and others are conducting research on the growing and releasing of juvenile prawns, red seabream, flounder and other fish.

III. Pollution and Ecosystem Health

Pollution: Pollution standards have improved the quality of coastal waters (UNEP 2006). Pollution is mainly due to effluents from industries as well as human settlements, run-off from land (including agricultural areas) and atmospheric fallout. Microbiological pollution is often a problem arising from inadequate treatment of the large volume of wastewater generated by human populations. Eutrophication and harmful algal blooms are a serious problem in some parts of the LME, particularly because of their harmful effects on fisheries (Taylor & Trainer 2002).

Chemical pollution is of concern in industrial areas, with heavy metal pollution being prevalent. In cities and settlements in the Russian Far East, the maximum permitted concentrations of lead were exceeded in several places such as in Rudnaya Pristan' (literally Ore Wharf; 514 km north of Vladivostok, on the coast), where the annual average level of lead is twice as high as in other areas (Kachur & Tkalin 2000). Rudnaya Pristan' was cited by the Blacksmith Institute as one of the most polluted places in the world. The concentrations of detergents, petroleum hydrocarbons and heavy metals are high in coastal lagoons. In the northern region from the Zolotoy Cape to Povorotny Cape (on the Russian Far East's coast of the Sea of Japan/East Sea) there are several local sources of pollution in coastal waters, largely from ore-mining and ore-chemical production. Pollutants include large quantities of lead, copper, zinc, cadmium, arsenic and boron in dissolved as well as suspended forms (UNEP 2006). Some coastal lagoons in the southern areas of the LME show relatively high turbidity as a result of increased coastal erosion. Solid waste often litters beaches and damage fishing nets. The proportion of plastic material in solid waste has increased sharply in recent times, accounting for more than 80% of the total waste volume (UNEP 2006). Oil pollution is a significant problem along the major shipping routes. Increasing numbers of accidents have occurred in recent years and spills have caused high mortality of sea birds and contamination of seashores. Oil from open ocean sources constitutes only 10% - 20% of all oceanic oil pollution, while coastal and land-based pollution constitutes 80% - 90%.

Habitat and community modification: Overall, habitat and community modification are found to be slight, although there has been moderate loss of certain habitats and severe modification in the littoral belts in the southern areas (UNEP 2006). Excessive land reclamation and coastal development have led to the destruction of some mangrove areas and have harmed coral reefs in the southern Sea of Japan/East Sea LME. Increased volumes of industrial and sanitary wastewater in the coastal zone as well as run-off from agricultural lands have caused the modification of some benthic communities. In the last decade, the bottom communities in the Peter the Great Gulf have shown visible changes. For instance, there has been a progressive reduction of some species of benthos as well as plankton and an increase in populations of some species of polychaetes, sea-lettuce and other organisms that are pollution indicators. Degradation of seagrass beds in Amur Bay has led to shrinkage of the spawning grounds of the Pacific herring (UNEP 2006). In the last 25 years there has been a reduction in the density of macrobenthos, notably autotrophic species, with a growing quantity of heterotrophic species. Areas occupied by bivalves resistant to pollution and silting are expanding as a result of the industrial development of this bay.

The environmental and ecological disturbances resulting from growing economic development will continue to threaten the health of the Sea of Japan LME (UNEP 2006). On the other hand, improvements in waste treatment and construction of new and efficient treatment facilities will help to reduce some of the negative impacts of economic growth.

IV. Socioeconomic Conditions

The Sea of Japan/East Sea LME region has an increasingly urban coastal population. The people are particularly dependent on the sea for their food and livelihoods. Important economic activities in the coastal and marine areas include port operations, shipping, fisheries, seafood processing and mining.

The overexploitation of fish and other living resources has resulted in reduced economic returns and loss of employment (UNEP 2006). Downstream fisheries and coastal communities, which are highly dependent on fisheries, are also seriously affected by overexploitation. Eutrophication, chemical pollution and spills have severe effects on local fisheries, aquaculture and recreation. Heavy metals, nitrogen compounds and other hazardous substances cause allergies, poisoning, chronic inflammations as well as infectious diseases. In some local areas in these coastal waters cannot be used for recreation due to the large volume of wastewater discharge.

V. Governance

The countries bordering the Sea of Japan/ East Sea LME are involved in several regional programmes such as NOWPAP (see the East China Sea LME) and organisations such as PICES (see the East China Sea LME). All countries are members of the 10-nation Working Group for the Western Pacific, which was established by UNESCO to plan and coordinate multilateral ocean science programmes. China, Japan and South Korea have ratified the 1982 UN Law of the Sea Convention (UNCLOS) and proclaimed their respective EEZs in the late 1990s. All the countries are members of the International Maritime Organisation (IMO) and have acceded to MARPOL. China, Japan and Russia are parties to the 1972 London Dumping Convention.

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X-26 Sea of Okhotsk LME

S. Heileman and I. Belkin

The Sea of Okhotsk LME is bordered by Russia and northern Japan, with an extensive area of 1.6 million km^2, of which 0.09% is protected, and which contains 0.04% of the world's sea mounts (Sea Around Us 2007). The entire sea is located in the cold temperate zone, with intense ice formation in almost all areas of the sea. There are marked differences in climate, hydrography and biology between its northern and southern parts. Variations in climate and hydrography are related to atmospheric processes over the northwest Pacific. The current system is complex and characterised by three large cyclonic gyres (Baklanov *et al*. 2003). The straits connecting the Sea of Okhotsk LME to the Sea of Japan/East Sea and the Pacific Ocean allow water exchange between the basins, which has a pronounced effect on the distribution of the hydrological characteristics of the LME. A book chapter and report pertaining to this LME are by Kuznetsov *et al*. (1993) and UNEP (2006).

I. Productivity

The Sea of Okhotsk LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}y^{-1}). The total annual production of zooplankton has been estimated at 3 billion tonnes and benthic production at 3.4 billion tonnes (Kuznetsov *et al*.1993). Plankton and benthic species are unevenly distributed throughout the LME as a result of the complex circulation patterns. The most productive zones are in the upwelling areas and waters off Kamchatka, and the northern and western areas are especially rich in plankton, while the central deep area is relatively poor (Markina & Chernyavsky 1984). High plankton concentrations in the areas of downwelling are also observed and primarily attributed to mechanical accumulation.

Overfishing followed by climatic variability are primary forces driving biomass change in the Sea of Okhotsk (Sherman 2003). High interannual variability in the climate and hydrography affects the reproductive conditions and trophic relationships of the marine organisms (Shuntov 2001). The productivity dynamics in this LME are characterised by the relatively small role of herbivorous zooplankton, the substantial role of carnivorous zooplankton and the large portion of production by herbivorous plankton and demersal organisms that is converted to detritus.

At least 16 species of marine mammals inhabit the LME seasonally or year round and include grey, humpback and killer whales, as well as eared, fur and ribbon seals. The grey, bowhead, northern fin and humpback whales are listed as endangered in the Russian Red Book.

Oceanic fronts (Belkin et al. 2009): This LME is characterised by a very energetic tidal regime and intense water mass exchange with the open Pacific Ocean; as a result, several fronts (Figure X-26.1) of various physical natures exist here (Belkin and Cornillon 2003, 2004). A branch of the Kamchatka Current penetrates into the Okhotsk Sea via the First Kuril Strait to form the West Kamchatka Current associated with a water mass front (WKCF). Robust tidal mixing fronts develop over the western and northern shelves (WSF and NSF, respectively), especially off Magadan (MSF) and within Shelikhov Gulf (SGF), where the tidal magnitude peaks at 12 to 13 m. Very sharp tidal mixing fronts surround Kashevarov Bank (KBF) and Shantarsky Islands. An estuarine front bounds the Amur

River plume; this front continues southward along the east coast of Sakhalin as the East Sakhalin Current Front (ESCF) (Belkin and Cornillon 2003; Belkin et al. (2009)).

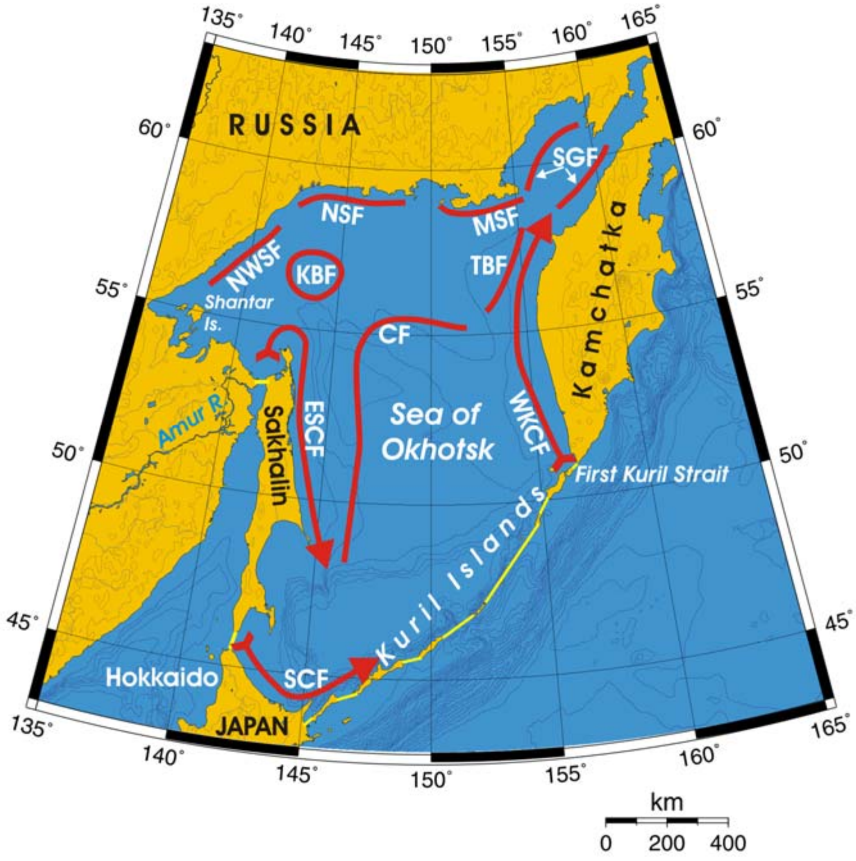

Figure X-26.1. Fronts of the Sea of Okhotsk LME. CF, Central Front; ESCF, East Sakhalin Current Front; KBF, Kashevarov Bank Front; MSF, Magadan Shelf Front; NSF, North Shelf Front; NWSF, Northwest Shelf Front; SCF, Soya Current Front; SGF, Shelikhov Gulf fronts; TBF, TINRO Basin Front; WKCF, West Kamchatka Current Front. Yellow line, LME boundary. After Belkin and Cornillon (2004) and Belkin et al. (2009).

Sea of Okhotsk LME SST (after Belkin, 2009)
Linear SST trend since 1957: 0.49°C.
Linear SST trend since 1982: 0.31°C.

The thermal history of the Sea of Okhotsk is strongly correlated with the Oyashio Current LME. In both LMEs, a major regime shift occurred in the late 1980s (Mantua et al., 1977; Hare and Mantua, 2000). The last cold year was 1987 (cf. 1988 in the Oyashio). The all-time maximum of 1990 was synchronous with the Oyashio. Both cold events, of 1992 and 2001, occurred approximately one year before similar cold events of 1992-93 and 2002-03 in Oyashio. The above one-year time lag between Okhotsk and Oyashio events suggests advective influence of the Okhotsk Sea on the Oyashio Current.

Using EOF analysis of the most recent satellite SST data, 1997-2006, Novinenko and Shevchenko (2007) found maxima in 1999 and 2006 and minimum in 2002; the last two extrema likely correspond to the 2005 maximum and 2001 minimum respectively, albeit with a one-year time lag.

Even though the pan-Pacific regime shift of 1976-1977 has not transpired in the Okhotsk Sea SST, it has caused substantial phenological changes across western subarctic North Pacific (Chiba et al., 2006, p. 907): “After the regime shift, the timing of the peak abundance was delayed one month, from March–April to April–May, in the spring community, whereas it peaked earlier, from June–July to May–June, in the spring–summer community, resulting in an overlap of the high productivity period for the two communities in May. Wintertime cooling, followed by rapid summertime warming, was considered to be responsible for delayed initiation and early termination of the productive season after the mid-1970s.” Chiba et al. (2006, p.207) have drawn a distinction between the regime shift of 1970s and the one of the 1990s: “Another phenological shift, quite different from the previous decade, was observed in the mid-1990s, when warm winters followed by cool summers lengthened the productive season.”

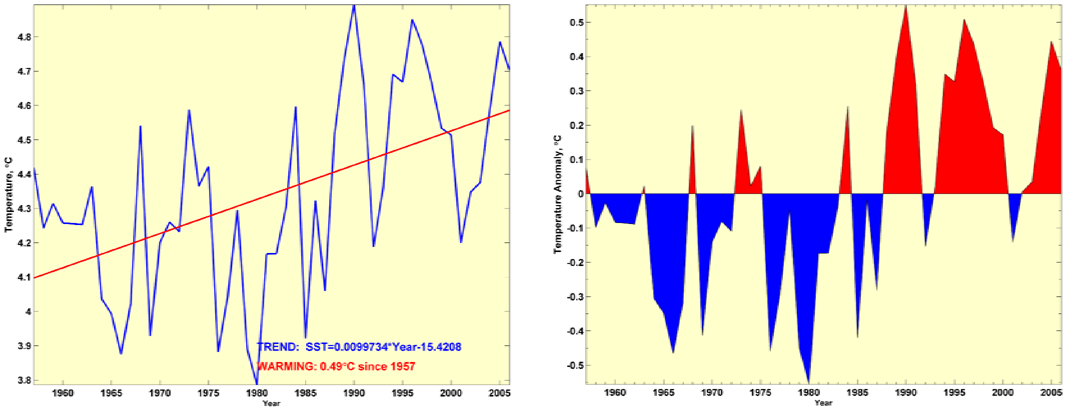

Figure X-26.2. Sea of Okhotsk LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Sea of Okhotsk LME Chlorophyll and Primary Productivity: The Sea of Okhotsk LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}y^{-1}).

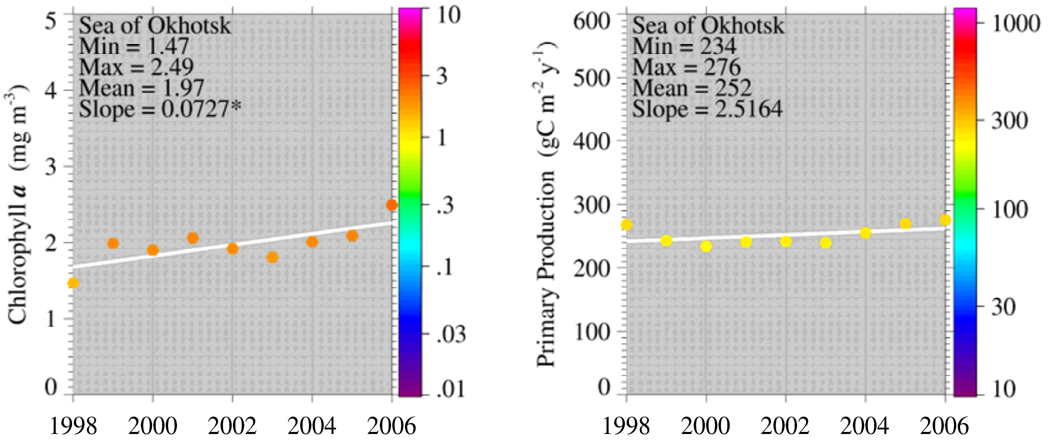

Figure X-26.3. Sea of Okhotsk LME, trends in chlorophyll a (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O’Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Sea of Okhotsk LME is rich in fisheries resources, with approximately 300 commercially exploited species. Within the Russian EEZ, the fish stocks have been estimated at 26 million tonnes including 16 million tonnes of gadoids (Project SEA 1998). Species of commercial importance include Alaska pollock (*Theragra chalcogramma*), Pacific herring (*Clupea pallasii*), Pacific saury (*Cololabis saira*), flounders (e.g., *Atheresthes evermanni*, *Hippoglossoides robustus*, *Limanda punctatissimus*, *Liopsetta glacialis*), Pacific salmon (*Oncorhynchus tshawytscha*), halibut (e.g., *Hippoglossus stenolepis, Paralichthys olivaceus*), cod (*Gadus macrocephalus*), capelin (*Mallotus villosus*), South American pilchard (*Sardinops sagax*; a.k.a sardine), king crab (*Paralithodes* sp.) and shrimp. Fluctuations in the abundance of some fish stocks (e.g., pollock, herring) have been attributed primarily to overfishing and secondarily to climatic and oceanographic factors, in particular fluctuations in warm and cold years (Kuznetzov *et al*. 1993).

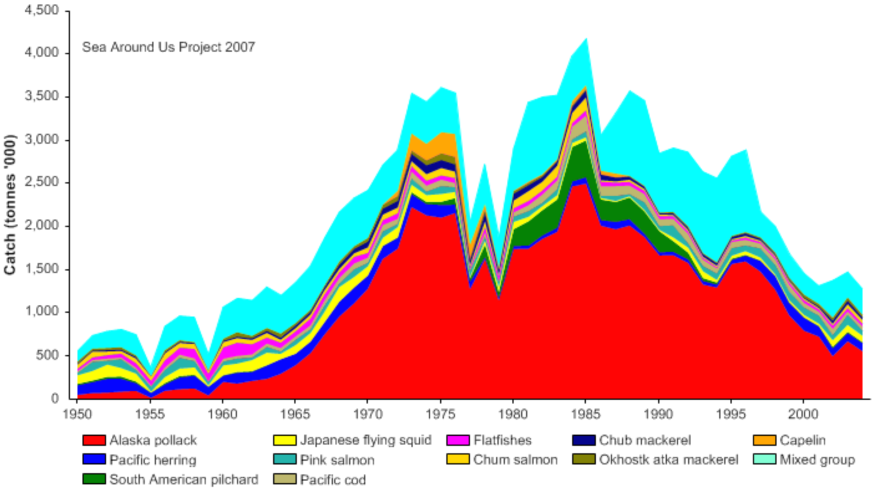

Figure X-26.4. Total reported landings in the Sea of Okhotsk LME by species (Sea Around Us 2007).

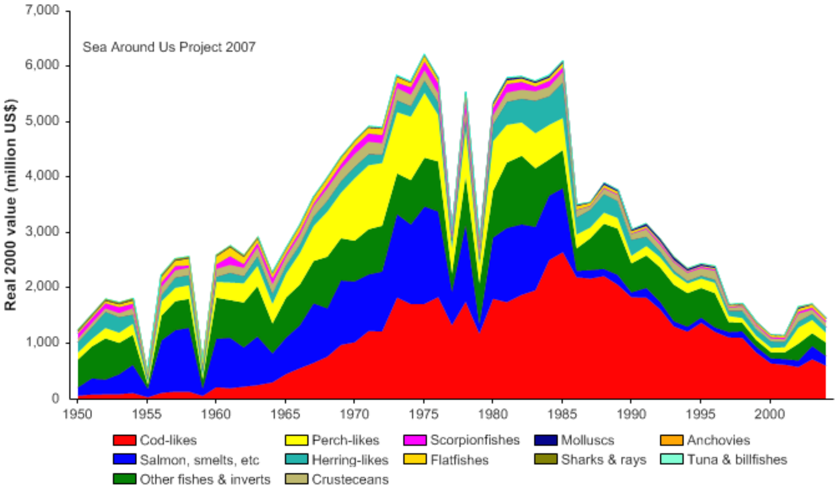

Figure X-26.5. Value of reported landings in the Sea of Okhotsk LME by commercial groups (Sea Around Us 2007).

Total reported landings showed two peaks with 3.6 million tonnes in 1975 and 4.1 million tonnes in 1985 (Figure X-26.4). Alaska pollock accounted for almost two-thirds of the total landings in the mid 1980s. The reported landings were valued at over US$5 billion (in 2000) during the peak landings of the mid 1970s and the early 1980s (Figure X-26.5). The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached 50% of the observed primary production in the mid 1980s, but has declined in recent years (Figure X-26.6). Russia has the largest share of the ecological footprint in this LME, but Japan accounted for the largest footprint in the 1960s and 1970s.

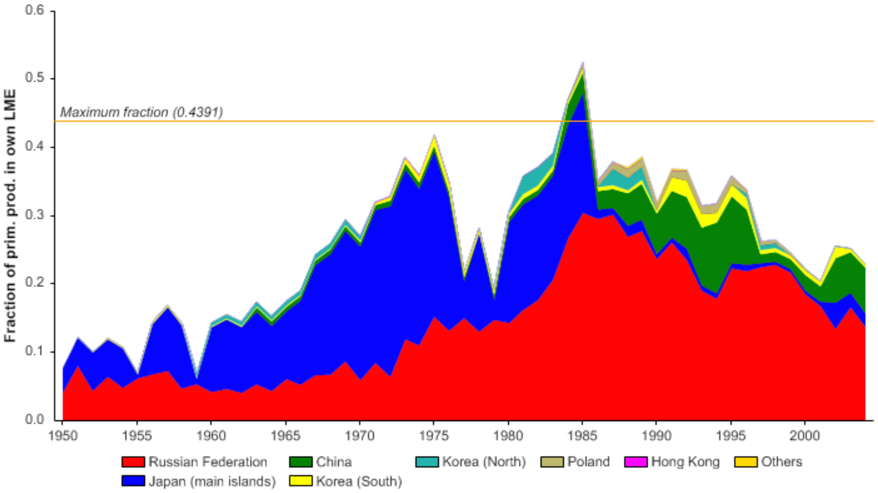

Figure X-26.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Sea of Okhotsk LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic levels of the reported landings (i.e., the MTI; Pauly & Watson 2005) underwent a steady decline to the late 1980s (Figure X-26.7 top), suggesting a 'fishing down' of the local food webs (Pauly *et al.* 1998), despite the expansion of fisheries in the region over the same period as evident by the increase in the FiB index, which levelled off in the early 1990s (Figure X-26.7 bottom). Yet, as the landings in the LME became predominantly that of Alaska pollock, a high trophic species, in the 1990s, the mean trophic level began to increase despite the decline in the total landings.

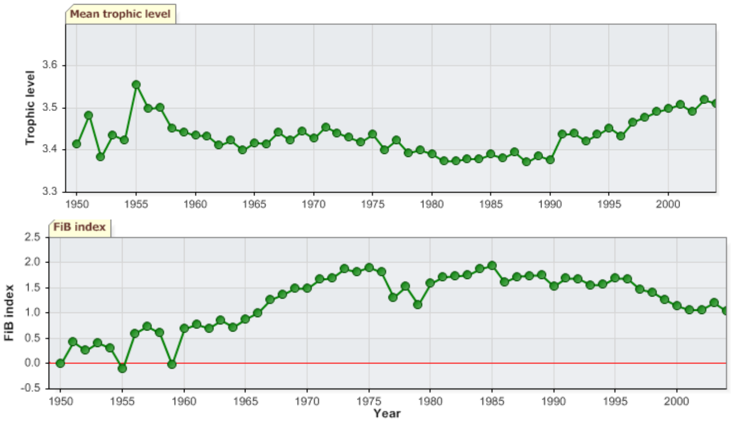

Figure X-26.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Sea of Okhotsk LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stocks in the LME have been increasing, to about 90% of the commercially exploited stocks (Figure X-26.8, top) and these stocks account for the majority of the catch (Figure X-26.8, bottom).

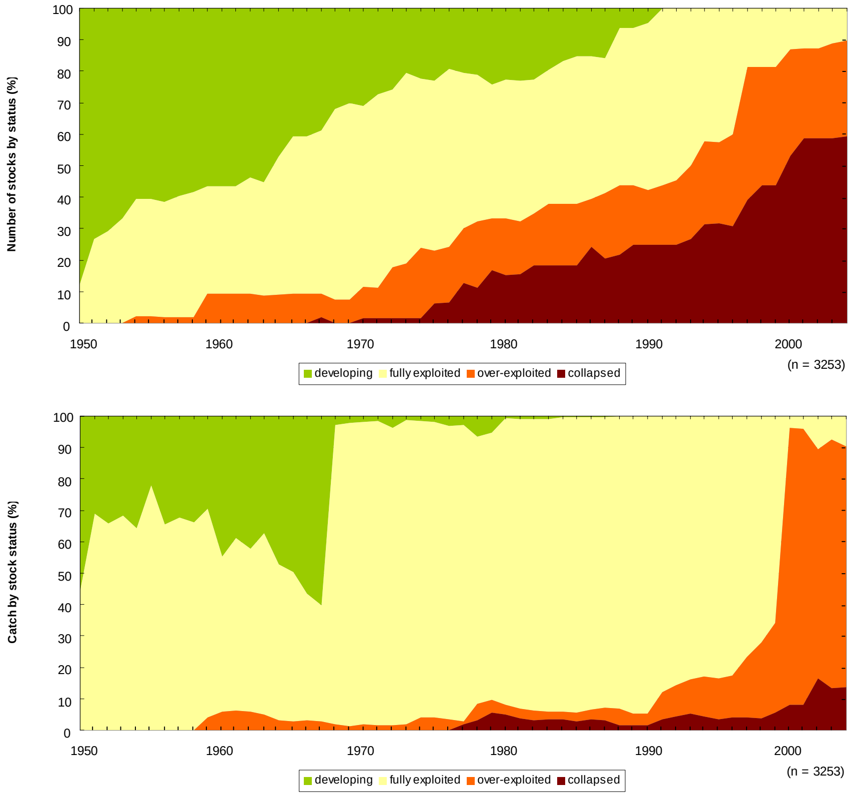

Figure X-26.8. Stock-Catch Status Plots for the Sea of Okhotsk LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Despite fisheries regulations and control measures, most of the major fish stocks in the Okhotsk Sea LME are severely overexploited (UNEP 2006). Historical records show changes in the status of the living resources because of fishing. The high catch and discarding of young pollock in the 1990s have contributed to reducing the adult stock biomass. Flounder stocks were depleted after intensive exploitation in the late 1960s and herring catches declined in the mid-1970s. Several species such as grenadier (*Coryphaenoides* sp.), eel pout (*Bothrocara brunneum*) and skate (e.g., *Bathyraja* sp.) are caught as bycatch in the halibut fishery. The reduction of fish stocks through high fishing pressure increases their vulnerability to unfavourable environmental conditions. Increasing the catches to the maximum sustainable yield may create overall instability in the populations, leading to further stock decline. On the other hand, under relatively stable climatic and oceanographic conditions and at moderate fishing intensity, relatively high stock levels of species such as pollock can be maintained (Kuznetsov *et al*. 1993). Therefore, environmental variability must be taken into account in the management of the LME's fisheries.

III. Pollution and Ecosystem Health

Pollution: Pollution was assessed as slight, although chemical pollution and oil spills are of some concern (UNEP 2006). The exploitation of oil and natural gas off Sakhalin's east coast and shelf and throughout the LME increases the risk of pollution. Contrary to prohibitions under Russian laws, the toxic waste products of drilling and oil production on the Sakhalin shelf are discharged into the sea. The quantity of these wastes is expected to exceed many million tonnes with the further development of oil fields in the region. In the area of drilling operations, discharges of mud and toxic drilling fluids cause changes in the structure of the benthic communities (Shuntov 2001). In North Sakhalin the deterioration of ecological conditions from oil and gas exploitation has already disturbed about 40% of salmon spawning grounds, including the loss of 130 small rivers (Moiseychenko & Abramov 1994). Tanker traffic and extreme weather conditions in the LME increase the risk of oil spills and vessel collisions on the Northern Sea Route. Since the 1990s, about 3,800 tonnes of oil products have been spilled as a result of three major accidents at sea. The coastal currents of Sakhalin Island could propagate oil pollution to the southern Kuriles and to the Japan coast.

Habitat and community modification: There are no records of serious habitat modification in the Okhotsk Sea LME, although some habitats show slight degradation (UNEP 2006). Oil and gas prospecting, drilling, navigation, and oil spills are a potential danger for marine mammals, particularly the endangered grey whale, whose feeding and reproduction are disturbed by these activities. Massive oil and gas development in the waters off Sakhalin Island, an important breeding site for the spotted seal, could also affect the population of this marine mammal.

Drilling and excavating, in combination with the possible impact of oil or chemicals spills on the benthic communities of the Okhotsk Sea LME, are also of concern. Studies in the vicinity of drilling platforms on the Sakhalin shelf showed that the plankton community has been subjected to considerable pressure from the waste of drilling operations. Increased oil transport through the LME is a serious potential threat.

IV. Socioeconomic Conditions

The coastal zone of the Sea of Okhotsk LME is inhabited by about 700,000 people. Beginning in 1992, Russia experienced a population decline due to death and migration. Major industries include fisheries, oil and gas extraction, coal mining, sea transport and ship repair. Oil and natural gas deposits were recently discovered off Kamchatka's west coast and the peninsula is also rich in deposits of gold, silver, copper and coal. However, the remoteness of this area and its lack of infrastructure hinder regional development.

Marine fisheries, including fish processing, provide an important economic basis for the lucrative Sakhalin fishing industry as well as for fishing companies based in Kamchatka and Japan. Employment in the fishing industry is about 48% in the Kamchatka region and 16.6% in the Far-Eastern region as a whole (Baklanov *et al*. 2003). However, the reduction in fish catches due to overexploitation has led to an increase in the number of unprofitable enterprises and conflicts among fishers for larger quotas throughout the region, with economic losses in 2000 exceeding US$100 million.

V. Governance

The LME is governed by Russia, although the issue of sovereignty over the south Kuril Islands involves Japan. Because of its great natural resource wealth (petroleum, gas and fish), the LME is of geo-political interest to a number of countries, including the USA and Japan. National regulations on the protection of living aquatic resources (including fisheries resources) adopted in accordance with UNCLOS are the Federal Law of the Continental Shelf of the Russian Federation, the Federal Law of the Exclusive Economic Zone of the Russian Federation and the Law of the Protection and Exploitation of Marine Living Resources of the Russian Federation aimed at establishing the principles of sustainable fishing.

Legislative frameworks related to oil spills include international conventions such as MARPOL. At the national level, measures to control oil spill accidents are regulated by the Russian Federal Law of Environmental Protection. Russian authorities and international companies are perceived as being more interested in developing Sakhalin Island's oil and gas fields than in improving the island's capacity to prevent and respond to oil spills. Two environmental organisations (Sakhalin Environment Watch and the California-based Pacific Environment and Resources Centre) invited a team of independent experts to the island to review local spill prevention and response measures. The investigation resulted in 78 detailed recommendations. While some of these recommendations, including the conduct of a comprehensive vessel traffic risk assessment of the Sakhalin coast, were implemented by the Russian government, there is still major international concern over this issue.

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X-27 West Bering Sea LME

M.C. Aquarone, I. Belkin and S. Adams

The West Bering Sea LME lies off Russia's northeast coast and borders the Aleutian Trench. The LME has a surface area of nearly 2 million km^2, of which 2.90% is protected, and contains 0.51% of the world's sea mounts (Sea Around Us 2007). The bottom topography includes the deep Aleutian Basin, Kamchatka Basin and Bowers Basin. LME book chapters and articles pertaining to this LME are by Morgan (1989) and Ray & Hayden (1993).

I. Productivity

The LME is considered a Class II, moderately high productivity ecosystem (150-300 gCm^{-2}y^{-1}). The LME contains a variety of biological resources adapted to sea ice, including 450 species of fish, crustaceans and molluscs, and 25 species of marine mammals such as polar bears, whales, walruses and sea lions. The Bering Sea provides an important habitat for grey whales, endangered Steller sea lions and a variety of seabirds. The National Academy Press has produced a volume on the Bering Sea (available online), which provides additional information from an ecosystems perspective (National Academy Press 1996). The Pacific Oceanological Institute in Vladivostok provides on-line information about the LME's oceanography (www.pacificinfo.ru/en/). Over the past century, the extent of the winter pack ice has decreased. In the winter of 2001, the Bering Sea was effectively ice free.

Oceanic fronts (after Belkin and Cornillon 2003, Belkin and Cornillon 2005, and Belkin et al. (2009): A major northwestward current of the Eastern and Western Bering Sea shelves bifurcates upstream of Cape Navarin (Figure X-27.1). The northward branch flows toward the Bering Strait as the Anadyr-Chukotka Current associated with the Gulf of Anadyr Front (GAF). The southward branch flows first along the Koryak Coast, then along Kamchatka Peninsula, and is associated respectively with the Koryak Coast Current Front (KCCF) and the East Kamchatka Current Front (EKCF). The KCCF is very stable, apparently owing to a very steep upper continental slope and well defined sharp shelf break off the Koryak Coast that together steer this front. The East Kamchatka Current is by far the most important flow out of the West Bering Sea LME, exporting over 10^7 m^{3}s^{-1} of cold, low-salinity water.

West Bering Sea LME SST (after Belkin 2009)
Linear SST trend since 1957: 0.48°C.
Linear SST trend since 1982: 0.39°C.

The long-term cooling of the late 1950s-early 1970s culminated in the all-time minimum of 4.2°C in 1976. The North Pacific regime shift of 1976-77 (Mantua et al., 1997; Hare and Mantua, 2000) has transpired in the West Bering Sea with the utmost clarity and was extremely abrupt. It started as a 0.6°C SST rise in 1977, followed by a steady SST increase until present. Thus the regime shift of 1976-77 was a switch from a long-term cooling to a long-term warming, separated by a step-like SST increase. The all-time maximum of 1996 is bizarre since it occurred before the El Niño 1997-98 and before a similar warm event in the East Bering Sea. The cold event of 1999 occurred simultaneously across the entire Bering Sea. Most regime shifts are thought to be linked to the Pacific Decadal Oscillations, PDO. The SST regime shift of 1976-77 occurred simultaneously with a shift from negative PDO index to a positive PDO index.

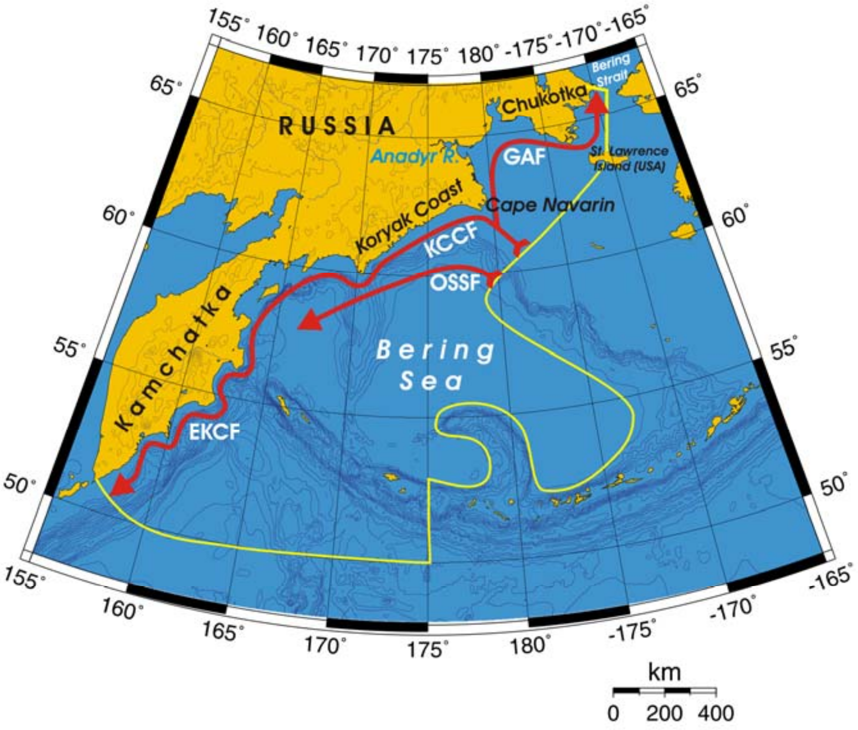

Figure X-27.1. Fronts of the West Bering Sea LME. EKCF, East Kamchatka Current Front; GAF, Gulf of Anadyr Front; KCCF, Koryak Coast Current Front; OSSF, Outer Shelf-Slope Front. Yellow line, LME boundary. After Belkin et al. (2009).

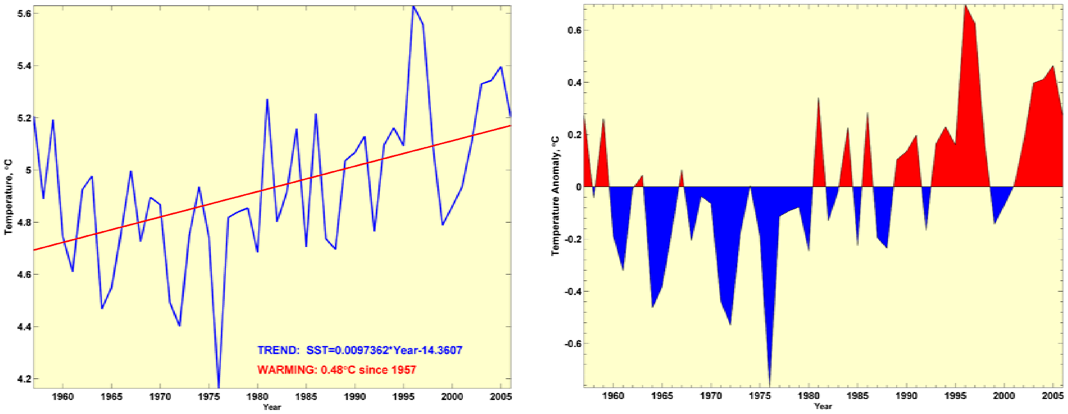

Figure X-27.2. West Bering Sea LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

***West Bering Sea LME Chlorophyll and Primary Productivity*:** The LME is considered a Class II, moderately high productivity ecosystem (150-300 gCm^{-2}y^{-1}).

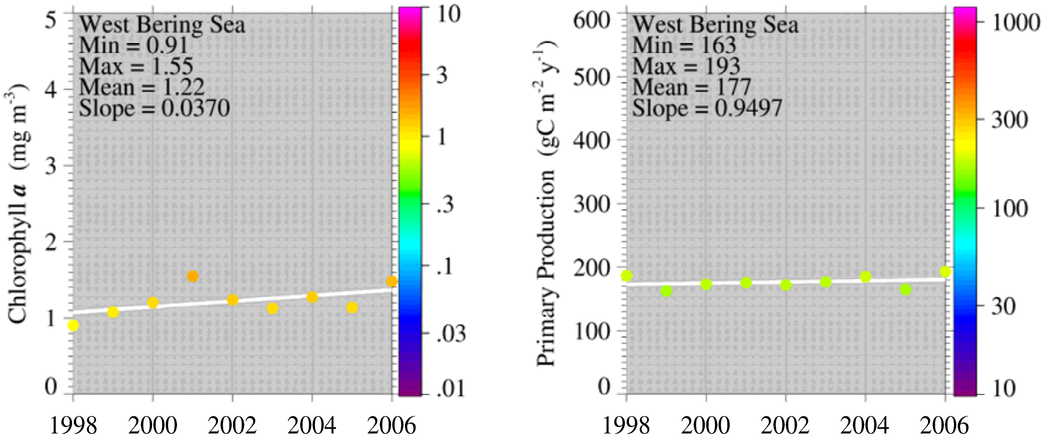

Figure X-27.3. West Bering Sea LME trends in chlorophyll *a* and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The West Bering Sea LME has the largest biomass of cod-like fishes in the world. Other species fished include Alaskan pollock, Pacific saury, salmon, flatfish, rockfish, halibut, flounder, herring, squid and a variety of crab species and other crustaceans. There have been large and sudden population fluctuations in the stocks of these species. The Pacific Rim Fisheries Program of the Alaska Pacific University lists commercial fisheries quotas for the Russian Far East including the Bering Sea. Salmon and trout catches are declining. A major problem is unreported fishing in the West Bering Sea and in the 'Donut Hole', a high seas area that does not come under the jurisdiction of either Russia or the USA (Alaska). Catches have been illegally transferred to Russian carrier vessels bound for ports in Japan, South Korea, China, the U.S and Canada. There is evidence of fishing in prohibited areas. The rise of industrial fishing has also had a major impact. The Bering Sea Ecosystem volume (National Academy of Science 1996) has sections on higher trophic levels, fisheries and human use.

Total reported landings[1] recorded 960,000 tonnes in 1985 and 950,000 tonnes in 1988 but have since declined by more than half, with only 430,000 tonnes reported in the most recent year. (Figure X-27.4)[2].

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[1] Due to a recent adjustment to the boundaries of the West Bering Sea LME, the landings data presented here are based on the 1950-2003 data, computed using the boundaries defined in Figure X-27.1. Data for 1950-2004, based on the new LME boundaries, will be available online at www.seaaroundus.org.

[2] Information on the value of reported landings cannot be provided at this stage, due to the recent adjustments in LME boundaries (see note 1 above). Data for values using the newly adjusted boundaries will be available at www.seaaroundus.org.

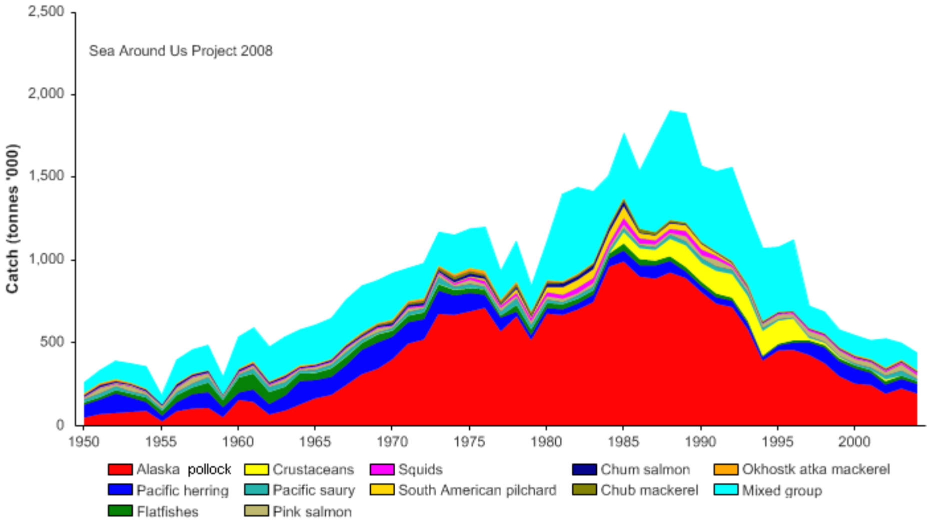

Figure X-27.4. Total reported landings in the West Bering Sea LME by species (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 12% of observed primary production in the late 1980s, but has declined in recent years (Figure X-27.5). Russia has the largest share of the ecological footprint in the LME.

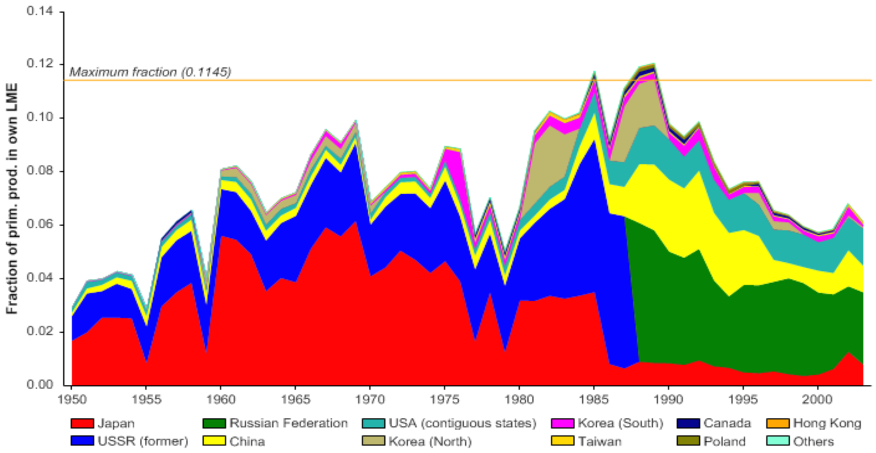

Figure X-27.5. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the West Bering Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has declined from the early 1960s to the mid 1980s, suggesting a 'fishing down' of the food webs in the LME (Pauly *et al*. 1998; Figure X-27.6 top), though the decline in the mean trophic level appears to have been compensated for by the increased landings as evident in the positive trend of the FiB index (Figure X-27.6 bottom). Yet, as Alaska pollock, a high trophic species, increasingly dominated the landings in the LME in the 1990s, the mean trophic level began to increase despite the decline in the total landings, as indicated by the decline FiB index (Figure X-27.6 bottom).

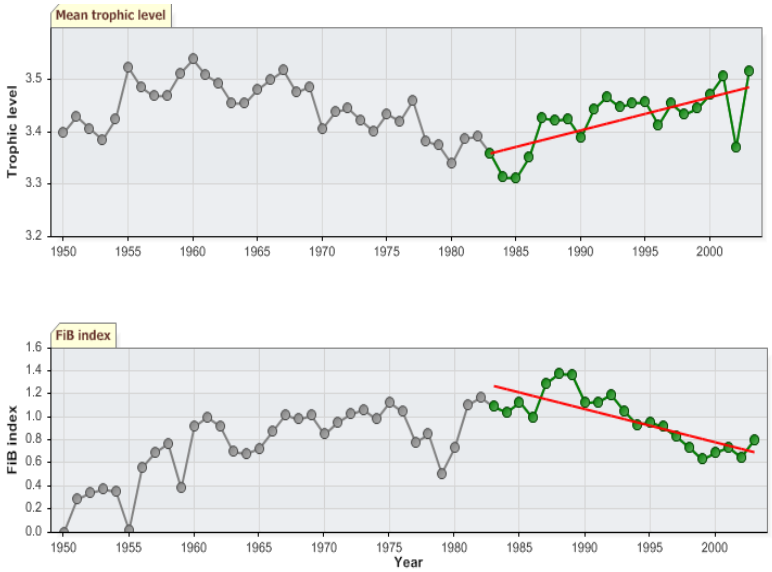

Figure X-27.6. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the West Bering Sea LME (Sea Around Us 2007)

The Stock-Catch Status Plots indicate that more than 60% of the exploited stocks in the LME have collapsed, with another 30% overexploited (Figure X-27.7 top). The reported landings in the region are mostly supplied by overexploited stocks with 20% from the collapsed stocks (Figure X-27.7 bottom).

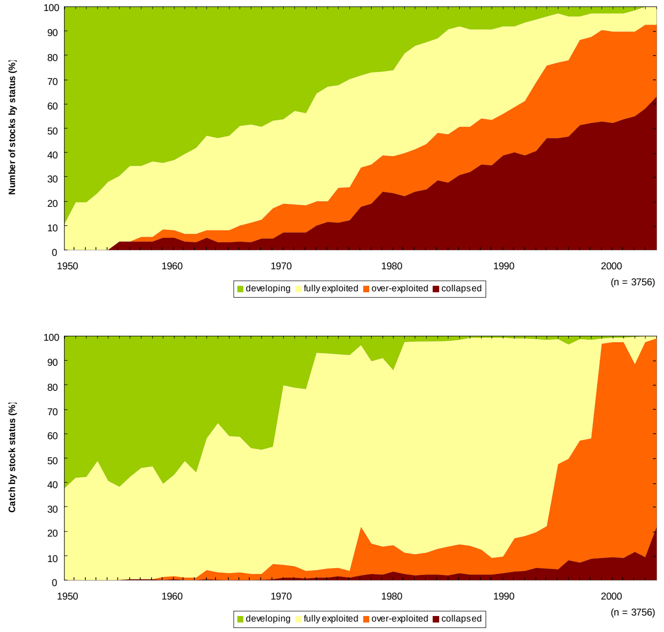

Figure X-27.7. Stock-Catch Status Plots for the West Bering Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

Signs of ecosystem stress include the decline of the pollock catch and in numbers of the Steller sea lion and sea otter populations. The poaching of sockeye salmon for their eggs is preventing the salmon from reaching their spawning grounds in the Pacific. Petroleum and other contaminants have been found in marine mammals, a result of the growing industrialisation of the region. The West Bering Sea LME has low levels of toxic contaminants, but these have been rising over the last 50 years due to increased human activities (mining, fishing and oil exploration). This increase is linked to the long-range transport of contaminants through the ocean and atmosphere from other regions. Cold region ecosystems such as this are more sensitive to the threat of contaminants because of their slow breakdown in colder areas. Also, animals high in the food web with relatively large amounts of fat tend to have high concentrations of organic contaminants such as pesticides and PCBs. Today, Russia is faced with many environmental problems inherited from the Soviet Union. Russian regional authorities and multi-national oil companies are pushing for further oil exploration and development in these fragile ecosystems. However, the Russian Supreme Court has invalidated a governmental decree that would have allowed the marine discharge of toxic wastes from oil drilling off Russia's Far East coast.

IV. Socioeconomic Conditions

Fish and game have supported the lives of people of the West Bering Sea LME for many centuries. Marine mammal hunting has been a part of the traditional economy of the indigenous coastal populations. They are provided with an annual quota to harvest whales, ringed seals, and walruses. Marine mammals are used for food, skins and fat. In recent years, people have begun to migrate away from this region. Most of the area’s population are immigrants from Russia and Ukraine. In more recent times, Russian and Ukrainian immigrants were attracted to the LME’s coastal areas because of high incomes and the prospects of oil profits. Today, in the context of the new Russian economy, incomes are not higher than in other regions of Russia. With the decline of fish stocks and onshore fish processing in Kamchatka, local fishermen were losing their jobs and their profits.

Three Russian areas comprise the coastline of this LME—the Kamchatka Peninsula, the Koryak Autonomous Area and the Chukotka Autonomous Area. In October 2006, the *New York Times* reported that Kamchatka had selected protection zones for rivers “because fish runs are the best foundation for the peninsula’s economy.” The salmon fisheries’ annual value is US$600 million. The Kol River has as many as five million returning salmon each year and will now be protected. Other areas now protected are the Oblukovina, Krutogorova, Kolpakova, Opala and Zhupanova rivers. The watersheds will be protected from habitat disruption while allowing traditional uses such as sport fishing, trapping and hunting. Each river will have a biological station to study the ecology of the river and the fish. All the rivers except the Zhupanova are to be designated as protected areas. In July 2007 a merger united the Russian Federation's constituent parts on the Kamchatka Peninsula.

V. Governance

The West Bering Sea LME is bordered by Russia. Other users of the marine environment such as the U.S. and Japan also impact the rich biological resources of the LME. Issues that are being addressed are conservation strategies, legal issues, fisheries economics and scientific monitoring. Coordination is critical for the sustainable use of the fisheries.

Attempts on the Russian side to deal with management issues and the poaching problem have failed due to a lack of appropriate legislation and weak enforcement. Stakeholders, who include fishermen, industry leaders, anti-oil activists and fisheries conservationists, must find collaborative solutions to some of these problems. There is a lack of transparency in fisheries policy decision-making, with the quota discussion remaining secret. Local environmental groups are opposing further oil exploration in the Bering Sea, fearing that oil exploitation would adversely impact Russia's vital fisheries economy, which supports many local communities. They also maintain that oil exploitation presents an environmental threat. More information is available on the 2001 Bering Sea Fisheries Conference with the U.S. and Russian organisations at www.pacificenvironment.org/.

The International Bering Sea Forum met in Kamchatka in 2006 and adopted the following resolutions:

- A resolution calling for a comprehensive network of Marine Protected Areas in the Bering Sea, based upon the best available science and local traditional knowledge;
- A resolution to defend Bristol Bay from threats presented by proposed offshore oil and gas development and the development of North America’s largest gold and copper open pit mine; and
- A resolution calling for the reform of shipping safety standards in the Bering Sea.

Details of the meeting are available at www.beringseaforum.org/ 2006 meeting.html.

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X-28 Yellow Sea LME

S. Heileman and Y. Jiang

The Yellow Sea LME is bordered by China and the Korean Peninsula. It is one of the largest shallow continental shelf areas in the world, covering an area of about 437,000 km^2, of which 1.75% is protected (Sea Around Us 2007) and with an average depth of 44 m and maximum depth about 100 m (Tang 2003). The Kuroshio Current is the major driver of the shelf water circulation. There are 10 major estuaries (Sea Around Us 2007), and some of the rivers discharging directly into the Yellow Sea include the Han, Yangtze and Huanghe. River discharges peak in the summer and have important effects on the LME's salinity and hydrography. In addition to river runoff, other major potential sources of nutrient input into the Yellow Sea LME are the atmosphere and intrusion of oceanic water from the Kuroshio Current (Zhang *et al*. 1995). A monsoon climate regime prevails in this region. Book chapters and reports pertaining to this LME are by She (1999), Tang (1989, 2003), Tang & Jin (1999), Tang *et al*. (2000), Zhang & Kim (1999) and UNEP (2005).

I. Productivity

The Yellow Sea LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}). Spring and autumn peaks in the production cycle have been observed. Neritic diatoms, dominated by species such as *Skeletonema costatum*, *Coscinodiscus* sp., *Melosira sulcata* and *Chaetoceros* sp., are the major constituents of the phytoplankton. Zooplankton biomass increases from north (5-50 mgm^{-3}) to south (50-1,000 mgm^{-3}), with the dominant zooplankton species being *Sagitta crassa*, *Calanus sinicus*, *Euphausia pacifica* and *Themisto gracilipes* (Tang 2003).

The LME supports substantial populations of fish, invertebrates, marine mammals and seabirds. Its fauna is recognised as a sub-East Asia province of the North Pacific Temperate Zone (Zhao 1990). Thirty-one marine mammal species are found in the LME (Sea Around Us 2007). All the living components of the ecosystem show marked seasonal variations (Tang 2003). There is evidence of change in the composition of both phytoplankton and zooplankton communities in the Yellow Sea (GEF/UNDP 2007). Climatic variability is a secondary driving force of biomass change in this LME, following overfishing (Sherman 2003).

Oceanic fronts (after Belkin et al. 2009): Several tidal mixing fronts (Figure X-28.1) exist within this LME, which includes the Yellow Sea and Bohai Sea (Hickox *et al*. 2000, Belkin & Cornillon 2003). The most conspicuous fronts are observed around Shandong Peninsula (between Yellow Sea and Bohai Sea), off Jiangsu Shoal, and off two major bays west of the Korean Peninsula. A new front identified in Bohai Sea (Hickox *et al*. 2000) is likely a water mass front between waters that flow in and out of the Bohai Sea. The freshwater discharge of the Yellow River plays a minor role in maintaining the Yellow Sea fronts compared with the Yangtze River discharge's role in maintaining the East China Sea LME fronts. A subsurface front in the central part of the Yellow Sea surrounds a cold water mass formed by wintertime cold air outbreaks (Belkin *et al*. 2003).

Yellow Sea LME SST (after Belkin 2009) (Fig. X-28.2)
Linear SST trend since 1957: 0.97°C.
Linear SST trend since 1982: 0.67°C.

The Yellow Sea experienced long-term fast warming superimposed over a regime shift in the late 1970s-early 1980s. The regime shift was accentuated by two cold events that peaked in 1977 (when SST dropped by >3°C, from 15.5°C in 1975 to 12.4°C in 1977) and in 1981. These cold spells were barely noticeable in the adjacent East China Sea LME. However, the year of 1981 was anomalously cold in the Kuroshio Current LME, Sea of Japan/ East Sea LME, and Oyashio Current LME. Therefore the event of 1981 was of a large scale. The cold peak of 1977 was confined to the Yellow Sea. The previous year of 1976, with a 2°C drop in just two years, was relatively cold in the adjacent East China Sea LME. This extreme event was likely caused by cold air outbreaks from Siberia.

A recent study of the ERA-40 reanalysis and other data sets, including HadISST and SODA (Simple Ocean Data Assimilation), has shown the observed warming of the Yellow Sea to have likely been a result of global climate warming, which caused a weakening of the winter and summer monsoons over the Yellow Sea after 1976, hence a weakening of wind stresses (Cai et al. 2006).

The East China Sea warming was not spatially uniform (Wang, 2006). In summer, the SST warmed in the north and cooled in the south. Warming rates exceeded 0.02°C per year in the coastal zones of the northern Yellow Sea, whereas cooling rates exceeded -0.02°C/a in the south. In winter, the SST warmed at a rate of >0.04°C per year in the Yellow Sea Warm Current contained within the central Yellow Sea, suggesting rapid warming of its source, the Kuroshio Current.

Figure X-28.1. Fronts of the Yellow Sea LME. BSF, Bohai Sea Front; JF, Jiangsu Shoal Front; KyBF, Kyunggi (Kyonggi) Bay Front; SPF, Shandong Peninsula Front; WKoBF, West Korea Bay Front. Yellow line, LME boundary. (After Belkin et al. 2009).

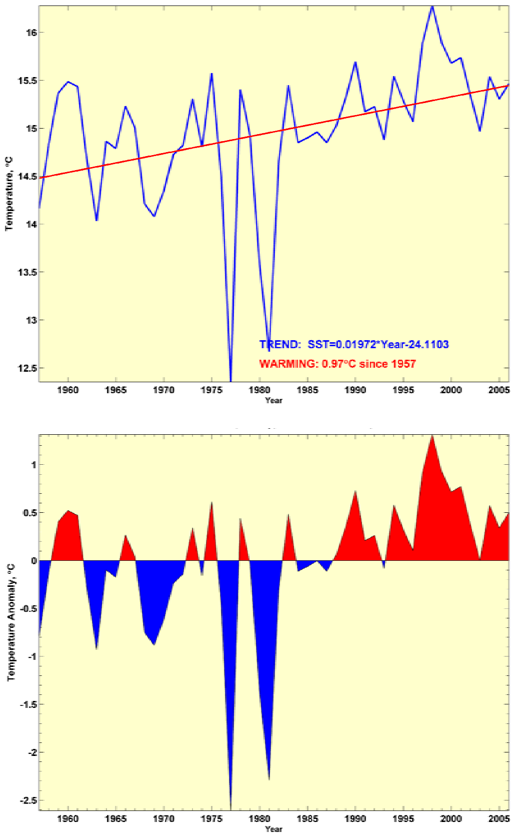

Figure X-28.2. Yellow Sea LME annual mean SST (top) and SST anomalies (bottom), 1957-2006, based on Hadley climatology. After Belkin (2009).

Yellow Sea LME Chlorophyll and Primary Productivity: The Yellow Sea LME is a Class I, highly productive ecosystem (>300 gCm^{-2}y^{-1}).

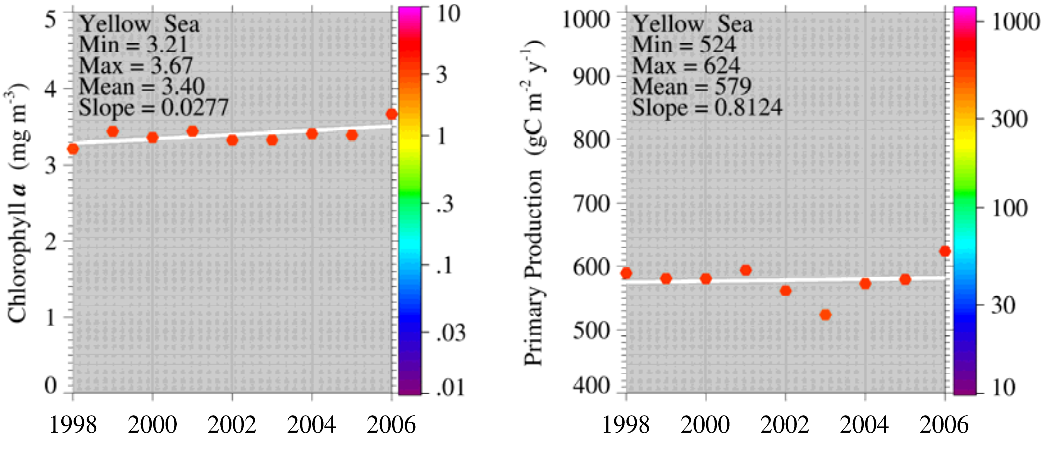

Figure X-28.3. Yellow Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Yellow Sea LME has well-developed multispecies and multinational fisheries. The fish communities are diverse, ranging from warm water species to cold temperate species (Tang 2003). About 100 species of fish, squid and crustaceans are commercially fished, among which are Pacific saury (*Cololabis saira*), chub mackerel (*Scomber japonicus*), hairtail (*Trichiurus lepturus*), Japanese anchovy (*Engraulis japonicus*), yellow croaker (*Pseudosciaena polyactis*) and Japanese flying squid (*Todarodes pacificus*). In addition to the capture fisheries, the culture of seaweeds and shellfish is an important economic activity, particularly in China. The growth rate of sea farming and ranching production is greater than the growth rate of marine capture fisheries in China.

Total reported landings in the LME have been on the rise, recording 3.3 million tonnes in 2000 and 3 million tonnes in 2004 (Figure X-28.4). The value of the reported landings peaked at 6.8 billion US$ (in 2000 real US$) in 1977 (Figure X-28.5).

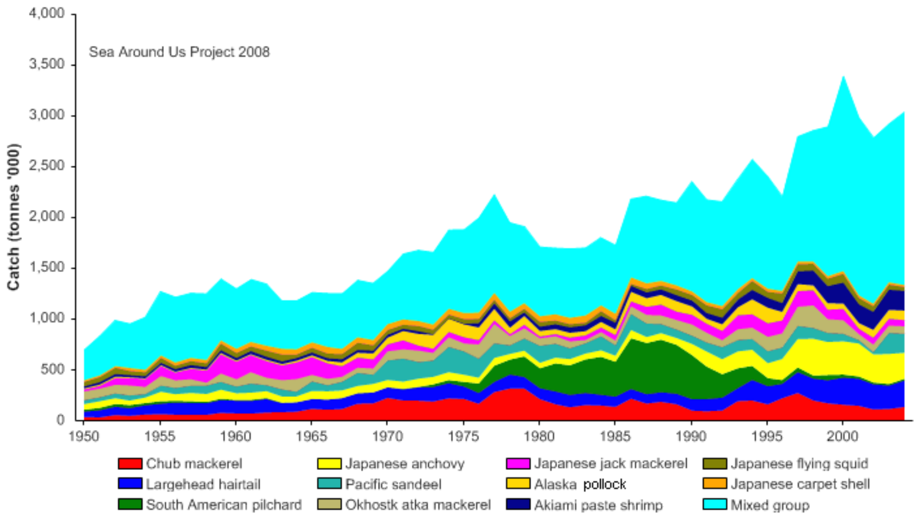

Figure X-28.4. Total reported landings in the Yellow Sea LME by species (Sea Around Us 2007).

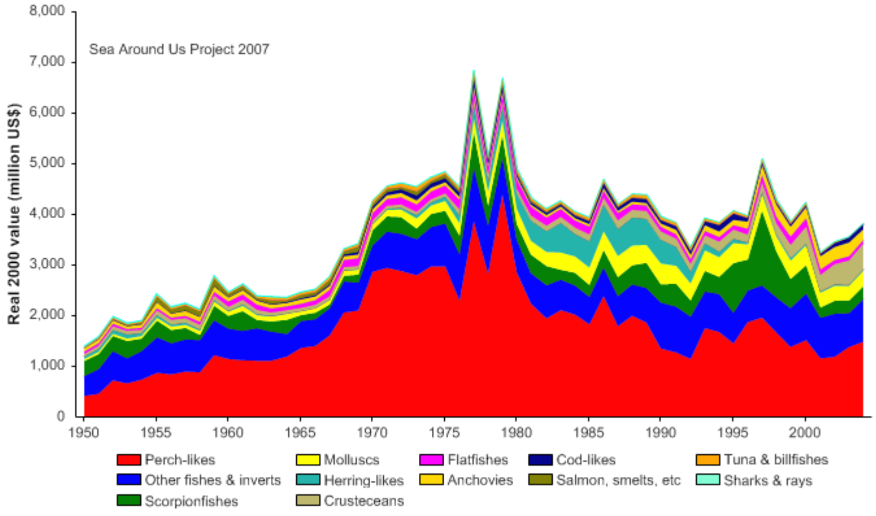

Figure X-28.5. Value of reported landings in the Yellow Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR) (Pauly & Christensen 1995) to sustain the reported landings in this LME reached 90% of the observed primary production in the late 1990s, a level far too high to be realistic (Figure X-28.6). Such PPR is likely a result of an over-reporting of catches in the underlying statistics by misreporting of catches outside the LME as local catch, or an under-estimate of primary productivity in the region, or both. The dominance of China in this ecosystem, however, is not likely to be an artefact of the estimation errors.

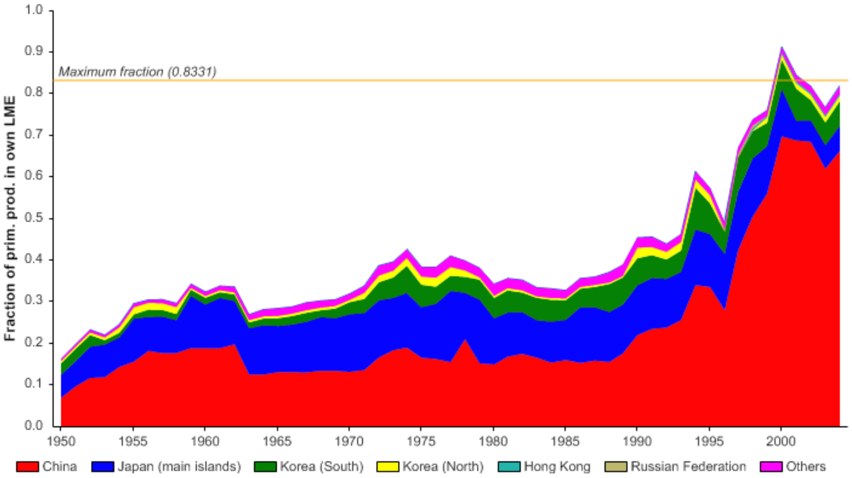

Figure X-28.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Yellow Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (Pauly & Watson 2005; Figure X-28.7 top) and the Fishing-in-Balance index (FiB) (Figure X-28.7) are difficult to interpret, likely due to the possible misreporting in the underlying catch statistics (see above).

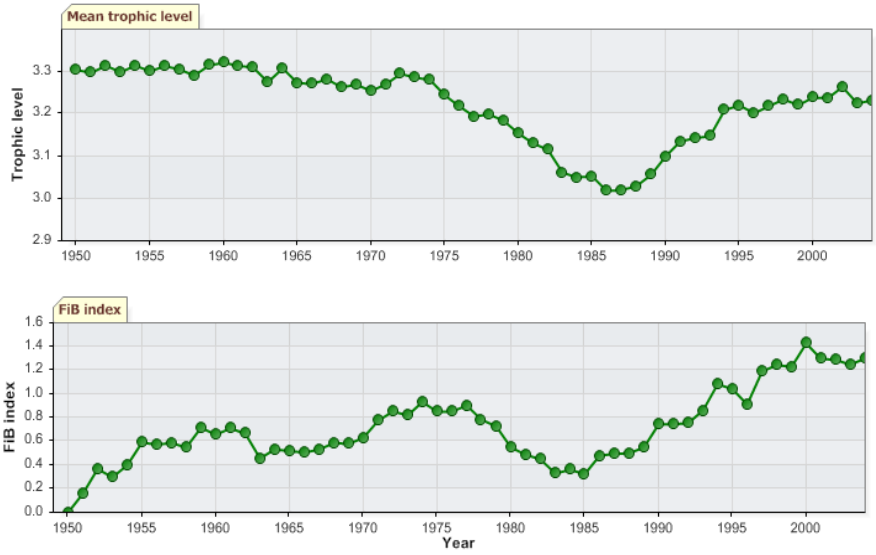

Figure X-28.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Yellow Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stocks have been increasing, accounting for 60% of the commercially exploited stocks in the LME (Figure X-28.8, top). However, 70% of the catch is still supplied by fully exploited stocks (Figure X-28.8, bottom). Again, the quality of the underlying catch data must be questioned.

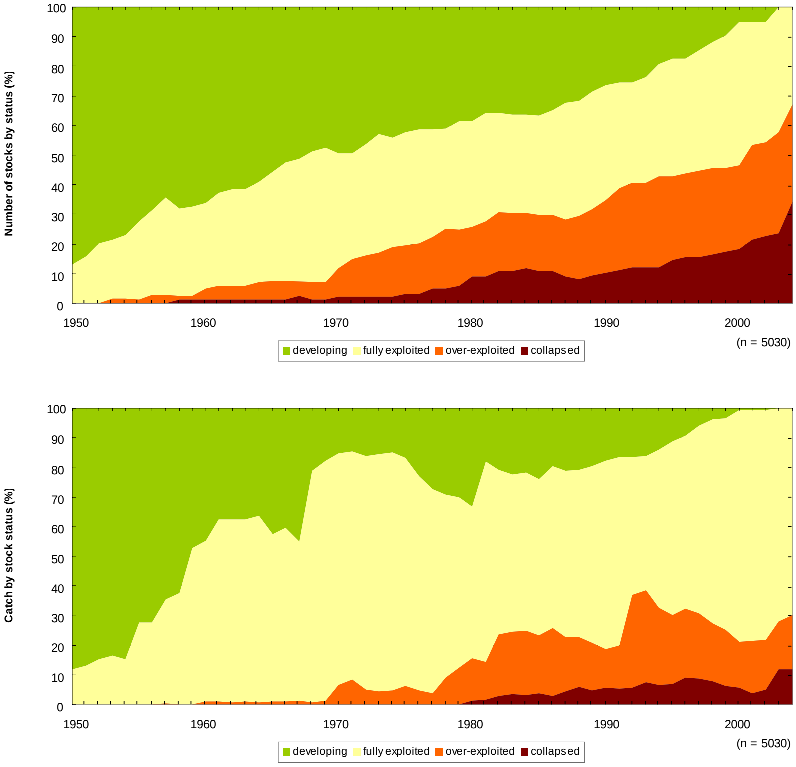

Figure X-28.8. Stock-Catch Status Plots for the Yellow Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level. Higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The Yellow Sea LME Transboundary Diagnostic Analysis (TDA) (GEF/UNDP 2000) for the Yellow Sea LME Project funded by the Global Environment Facility (GEF), has identified the decline in commercial fisheries as one of the major transboundary concerns in the LME. The 2007 TDA on reducing environmental stress in the Yellow Sea Large Marine Ecosystem (GEF/UNDP 2007) identifies over-exploitation of target wild fish species and the impact of climate change, the decline in landings of many traditional commercially important species, increased landings of low value species, overcapacity of the fishing sector, and unsustainable mariculture as the issues of greatest concern. It notes the dominance of the overall fisheries catch by China for all species, the apparent decline of the Pacific herring, the rapid growth of the anchovy fishery in China to a level of 0.6 million tons in 1996, and the recovery of small yellow croakers, a species that is economically important in the Yellow Sea LME. The increased presence of jellyfish is a reflection of changes in primary and secondary productivity in the system and alterations to the food web of the Yellow Sea (GEF/UNDP 2007). Despite the increase in annual catch, overexploitation was found to be severe in this LME (UNEP 2005), one of the most intensively exploited areas in the world. Changes in the dominant species are believed to reflect a response to overexploitation of the dominant stocks as a result of increased fishing effort (GEF/UNDP 2007). While natural environmental perturbations might have contributed to an increase in the abundance of small pelagic species (Tang & Jin 1999), intensive fishing is the primary driving force of biomass changes in this LME (Sherman 2003, Tang 2003). Many stocks became intensively exploited by Chinese, Korean and Japanese fishers following the introduction of bottom trawlers in the early 20th Century. The increase in fishing effort and its expansion to the entire LME resulted in almost all major stocks being fully fished by the mid-1970s and overfished by the 1980s (Zhang & Kim 1999, Tang 2003). Dramatic declines in CPUE of the Korean fleet occurred in the late 1970s and the average CPUE in the 1990s was less than one tenth of the highest CPUE in the mid-1970s (GEF/UNDP 2000). Similarly, catches of major fish species on the Chinese side of the LME also showed a dramatic decline, particularly yellow croakers.

Overexploitation of the major stocks has had a significant impact on the ecosystem as a whole, as reflected by major biomass flips (Sherman 1989, Tang 2003). In the 1950s-1980s, the larger demersal and predatory pelagic species with a higher commercial value were replaced by low value species, primarily small pelagic fish such as chub mackerel, black scraper (*Navodon modestus*) and Japanese anchovy. Accompanying the changes in species composition were changes in the size structure of the fish populations. In 1986, about 70% of the biomass consisted of fish and invertebrates with a mean standard length of 11 cm and a mean weight of 20 g. In contrast, the mean body length in the 1950s and 1960s exceeded 20 cm. The mean trophic level of the catch also declined between the 1950s and 1980s.

Overexploitation has transboundary implications because many fish species in this LME migrate among the common fishing grounds of China, Korea and Japan. Destructive fishing practices, such as indiscriminate trawling in coastal waters and the use of explosives and chemicals, are of transboundary importance as these practices have a detrimental impact on the spawning and breeding grounds of the shared fish stocks. Up to 30% of all the catch from the Chinese and Korean sides consists of bycatch, which occasionally includes seals (Jin 2003). In recognition of the severe overexploitation condition, fishing effort has been reduced for Chinese fishers with a suspension of fishing during the 3 months of summer initiated in 1995 to protect juveniles (Tang 2003).

III. Pollution and Ecosystem Health

Pollution: In general, pollution was found to be severe in localised hotspots (UNEP 2005). The rivers that discharge into coastal areas and harbours are the most serious sources of pollution (She 1999; Chua 1999). Major pollutants include organic material, oil, heavy metals and pesticides that come mainly from industrial wastewater, domestic sewage, coastal cities, agriculture and mariculture areas (Zhou *et al*. 1995, She 1999). More than 100 million tonnes of domestic sewage and about 530 million tonnes of industrial wastewater from coastal urban and rural areas are discharged into the nearshore areas of the Yellow Sea each year (GEF/UNDP 2000). Some improvements may be expected in the future through efforts by both the Chinese and Korean governments to improve capacity in treating industrial wastes and domestic sewage.

Eutrophication is severe in this LME (UNEP 2005), with an increase in the frequency, extent and duration of HABs since the early 1970s, mainly on the Chinese side, as a result of increasing nutrient inputs, mariculture and weather anomalies (She 1999). HAB organisms may be introduced by shipping traffic and the huge discharge from the Changjiang River during the summer monsoon. China’s State of the Environment for 2007 reports, for 2005, 82 cases of red tides with “large-scale red tides concentrated in the middle Zhejiang Province, outer Yangtze River Mouth, Bohai Bay, Meizhou Bay”

(SEPA 2007). This results in reduced diversity among algal and zooplankton species and is harmful to higher organisms such as fish (GEF/UNDP 2007). There has been a significant increase in the abundance of jellyfish and jellyfish blooms in the Yellow Sea LME (GEF/UNDP 2007). Jellyfish cause interference with fishing activities and pose threats of stinging to sea bathers.

The concentration of metals, pesticides and petrogenic hydrocarbons in marine organisms is gradually increasing, sometimes to levels exceeding those allowable for consumption (She 1999). Pollution by suspended solids is localised in coastal areas (SEPA 2004). Indiscriminate discharge of garbage and other solid wastes from mariculture, urban centres and tourism has greatly increased the amount of floating solid wastes in rivers and coastal waters (UNEP-RRC.AP 2003, SEPA 2004). Existing sanitary landfills are not sufficient to effectively handle the solid wastes, particularly on the Chinese side. Although the impacts are largely localised, solid wastes may have transboundary impacts since they can be carried across national borders by ocean currents.

Effective enforcement by both the Chinese and Korean governments in recent years has helped to control oil spills from maritime activities (SEPA 2004). Nevertheless, oil spill incidents on the Chinese side of the Yellow Sea LME have increased substantially over the years, and are expected to rise with increasing oil and natural gas exploration and exploitation activities. Furthermore, increasing economic development in the region is expected to triple the shipping traffic over the next 25 years, increasing the likelihood of oil spills (GEF/UNDP 2000).

Habitat and community modification: The main cause of habitat loss has been land reclamation, especially in estuaries and shallow bays (GEF/UNDP 2007). Coastal habitats, especially estuaries and shallow bays, are threatened by intensive coastal development and land filling that destroys wetlands, resulting in severe overall habitat and community modification (UNEP 2005). More than 30% of the mud bottom habitat was lost over the past 30 years due to agriculture, increased mariculture activities, and the opening up of salt-pans (GEF/UNDP 2007). Effluents from industrial complexes, coastal cities, tourism and recreational activities also contribute to the degradation of coastal habitats. Heavy erosion has occurred in about 30% of the sandy foreshore on the Chinese side, mainly from beach sand mining, road construction and recreational activities along the coastal plains (SEPA 2001). China’s State of the Environment for 2005 (SEPA 2007) reports good coastal seawater quality in Hainan, Guangxi, Shandong and Guangdong, while Shanghai and Shejiang suffered from bad coastal seawater quality.

Habitat modification has resulted in changes in biodiversity, species composition and community structure in some areas. Many commercial species of shrimp, crab and shellfish, especially in nursery and spawning areas, as well as benthic communities, have been seriously affected or have disappeared as a result of pollution and high sediment loads (She 1999). For example, species from the family *Nereidae* and lancelets (*Amphioxus*) have become rare and biodiversity has been significantly reduced in sandy foreshore areas. Substantial changes in the biodiversity of benthic organisms in the muddy foreshore of the region have also occurred. For instance, in the 1950s, the benthos in some areas contained about 170 species, which were reduced to some 70 species in the 1980s and to only a few pollution-resistant species in the 1990s (NEPA 1997). The number of economically important species has been reduced in estuaries and the ecological function of these habitats as spawning and nursery grounds for fish and shrimps has been impaired. The decline of vulnerable species is attributed to loss of habitat along with overexploitation of fisheries and destructive fishing practices, climatic change, rapid economic development, the increased demand for seafood, and engineering works on watercourses (GEF/UNDP 2007).

IV. Socioeconomic Conditions

The areas that drain into the Yellow Sea LME are inhabited by about 600 million people or 10% of the world's population (GEF/UNDP 2000). The inhabitants of large coastal cities such as Qingdao, Tianjin, Shanghai and Pyongyang are dependent on the LME as a source of food, economic development, recreation and tourism. Petroleum exploration and exploitation form an important economic sector in the Chinese and North Korean parts of the Yellow Sea. In addition, the sea is becoming increasingly important to shipping, with a growth in international trade in the region.

Fishing and mariculture constitute an important source of food, employment and foreign exchange to the bordering countries. Overfishing has reduced the available food supply for local communities. Poor catches have reduced business activities in the seafood processing industry by around 10%, with obvious economic implications (Pauly et al. 1998; UNEP 2005). The decline in capture fisheries has promoted the development of mariculture in China. Mariculture for shellfish and seaweeds has a long history in the region. The combined production of mariculture and aquaculture has grown to a level of 6 million tons in 2004 (GEF/UNDP 2007).

Over the past decades, increased pollution has had severe socioeconomic impacts (UNEP 2005). Pollution of localised near-shore areas, bays, and coastal habitats from land-based sources is affecting the livelihoods of the local population. There has been a loss of 30-50% of the development potential of the coastal areas for recreational activities (SEPA 2004), and drastic declines in fisheries and the production of penaeid shrimp and scallop in some areas (Jin 2003). The high concentrations of heavy metals and pesticides in some species have reduced the commercial value of these products (She 1999). SEPA 2007 reports that direct economic losses caused by red tides exceeded 69 million yuan in 2005. Pollution has also affected human health, with an increase in the incidence of diseases, seafood poisoning and death from the consumption of contaminated seafood. Habitat degradation has affected not only the value and ecological functions of habitats, but also the livelihoods of coastal communities (Xie & Wang 2003). Improved governance mechanisms are needed to better balance socioeconomic development and environmental protection.

V. Governance

Governance of the LME is shared by China, North Korea and South Korea. While the three countries have different governmental structures and national laws in place relating to the management of aquatic resources and environmental protection, they are parties to international conventions such as UNCLOS, MARPOL, the Convention on Biodiversity (CBD), Ramsar, the Basel Convention, and the FAO Code of Conduct for Responsible Fisheries, and to bilateral treaties. Regional and international programmes, organisations with water-related activities such as NOWPAP and PICES (see the East China Sea LME for information on NOWPAP and PICES), and the UN Economic and Social Commission for Asia and the Pacific form a strong institutional framework for the marine environment. The transboundary issues of concern in the LME are the management of living marine resources, industrial pollution and ecosystem health (GEF/UNDP 2000 and 2007). To aid the recovery of depleted fish stocks, China has started to close the Yellow Sea LME to Chinese fishers for 2 -3 months in the summer to protect juvenile stages of fish (Tang 2003). Marine protected areas were established in 2005 in Ximen Island off Leqing City and in the Ma'an Islands of Shengsi County, Zhejiang Province to protect marine species resources, terrestrial features and intertidal wetlands.

Progress is being made in the introduction of ecosystem-based management in this LME (Zhang & Kim 1999). GEF supported a Regional Programme for Marine Pollution Prevention and Management in the East Asian Seas region from 1994 to 1999. At present, China and South Korea are partnering in the GEF-supported project 'Reducing Environmental Stress in the Yellow Sea Large Marine Ecosystem'. The long-term objective of this project is to ensure environmentally sustainable management and use of the LME and its watershed by reducing stress and promoting the sustainable development of the LME. This project has prepared a Preliminary TDA (GEF/UNDP 2000) which was updated in 2007 (GEF/UNDP 2007), along with National Yellow Sea Action Plans and a regional SAP, to be implemented by the Yellow Sea LME project. The TDA has identified governance and capacity building as major transboundary issues to be addressed. This LME is also included in the PEMSEA project (see the Gulf of Thailand LME, Chapter VIII). To strengthen regulations pertaining to environmental protection and resolve issues effectively in the Yellow Sea LME, a governance commission is being developed as a non-legally binding cooperative institution run by the participating governments to carry out joint scientific research projects and improve legal institutions and partnerships for the protection of the Yellow Sea marine environment.

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XI THE ARCTIC

- XI-29 Arctic Ocean LME
- XI-30 Beaufort Sea LME
- XI-31 Chukchi Sea LME
- XI-32 East Siberian Sea LME
- XI-33 Kara Sea LME
- XI-34 Laptev Sea LME

XI-29 Arctic Ocean LME

I. Belkin, M.C. Aquarone and S. Adams

The Arctic Ocean LME is centred on the North Pole and is bordered by the landmasses of Eurasia, North America and Greenland, or more precisely, by the LMEs adjacent to these landmasses (except for the Canadian Arctic Archipelago, see Figure XI-29.1). It covers over 6 million km^2, of which 2% is protected, and contains 0.2% of the world's sea mounts (Sea Around Us 2007). Three prominent ridges (Alpha Mendeleev Ridge, Lomonossov Ridge and Gakkel Ridge) divide the Arctic basin into four sub-basins. The LME lies within the domain of the North Atlantic Oscillation. It has a perennial ice cover that extends seasonally between 60° N and 75° N latitude. Ice cover reduces energy exchange with the atmosphere, which results in reduced precipitation and cold temperatures. The LME is subject to rapid climate change with the ice cover shrinking in thickness and extent. The National Aeronautics and Space Administration (NASA) reported on 13 September 2006 that, in 2005-2006, the winter ice maximum was about 6% smaller than the average amount over the past 26 years (NASA 2006). The sea ice extent in September 2007 was about 20-25% below the long-term mean. Additional reports pertaining to the Arctic Ocean LME are found in UNEP (2004,2005).

I. Productivity

The continental shelf is 100-200 km wide north of Alaska. In Siberia, it can extend to over 1,600 km in some areas. In winter, the ice pack more than doubles in size, extending to the encircling landmasses. Water masses typically circulate cyclonically but the circulation patterns are complex and variable. For more information concerning the movement of sea ice in this LME, see NASA (1992). NOAA's State of the Arctic Report is available in PDF format at www.pmel.noaa.gov/. Low temperatures, ice cover and extreme seasonal variations in light conditions are some of the physical characteristics that slow down biological processes, limit the productivity of Arctic ecosystems and make them more vulnerable to contaminants.

The Arctic Ocean primary production strongly depends on the ocean's sea ice cover (SIC). Over the last decade, the Arctic SIC extent and thickness decreased dramatically. The SIC area in 2007 and 2008 was 20-25% smaller than ever before. As the SIC shrinks, the open water area (OWA) increases, accompanied by increase in primary production. Since 1998, the Arctic OWA has increased at the rate of 0.07×10^6 km^2 year^{-1}, resulting in elevated rates of annual primary production in most recent years, with a 9-year peak in 2006 and the average pan-Arctic primary production of 419 ± 33 Tg C a^{-1} in 1998–2006 (Pabi et al., 2008). The observed interannual variability of the SIC is believed to be a major factor explaining year-to-year differences in primary production, whereas SST changes (related to the Arctic Oscillation) and incident irradiance are considered to be minor factors (Pabi et al., 2008). The total production for the deep central Arctic Ocean is estimated to exceed 50 Tg C a^{-1} (Sakshaug, 2003).

According to Bluhm and Gradinger (2008), the seven core marine mammals of the Arctic are: bowhead whale (*Balaena mysticetus*), beluga (belukha) whale (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), walrus (*Odobenus rosmarus*), bearded seal (*Erignathus barbatus*), ringed seal (*Phoca hispida*), and polar bear (*Ursus maritimus*) Fish fauna is not well studied partly because of the lack of commercial fishery. Among 60 fish species found in the Russian sector of the Arctic are Arctic cisco, European cisco, muksun (*Coregonus muksun*), Atlantic whitefish (*Coregonus huntsmani*), Arctic char, navaga (*Eleginus nawaga*) and sheefish (*Stenodus leucichthys*). Arctic cod are the main consumers of plankton in the Arctic seas. A bathymetric map is available at www.ngdc.noaa.gov/

Oceanic Fronts (Belkin et al. 2009)(Figure XI-29.1): Observations of fronts in the open Arctic Ocean are hampered by perennial ice cover that prevents satellite remote sensing of fronts in the Arctic Basin. Hydrographic surface and subsurface data collected from surface vessels, ice drifting stations and submarine revealed a major front in the central Arctic that separates Atlantic waters from Pacific waters. Until the mid-1990s, this front was located over the Lomonosov Ridge (LRF). Observations from the late 1990s and early 2000s have documented a major shift of this front that occurred around 1995. Since then, the front ran along Mendeleyev-Alpha Ridge (MARF). It is unclear yet if the front will shift back in the future and if such shifts occurred in the past. In the Nordic Seas, the water-mass Arctic Front (AF) separates the Greenland and Norwegian Seas, while the East Greenland Current Front (EGCF) is a shelf-slope front.

Figure XI-29.1. Fronts of the Arctic Ocean LME. Acronyms: AF, Arctic Front; LRF, Lomonosov Ridge Front; MARF, Mendeleyev-Alpha Ridge Front. Yellow line, LME boundary. After Belkin et al. (2009).

Arctic Ocean LME, Sea Surface Temperature:
Linear SST trend since 1957: NA°C.
Linear SST trend since 1982: NA°C.

This LME has been excluded from the analysis (after Belkin, 2009) since it is covered by sea ice almost year round, therefore SST data are deemed severely contaminated by the sea ice presence.

II. Fish and Fisheries

The Arctic Ocean LME, along with its surrounding LMEs is unique in that the melting and freezing of ice creates rich habitats close to the sunlit surface. The wide continental shelves provide large shallow areas, where freshwater from north-flowing rivers creates estuarine conditions. There is a limited number of true Arctic species of commercial importance. Arctic charr (*Salvelinus alpinus*) occurs throughout the Canadian Arctic, and have been sighted farther north than any other fish species. In the summer, many stocks of Arctic charr migrate to the sea, where they have a larger resource base to exploit and thus are able to grow faster. While at sea, they feed on crustaceans and small fish. Before winter, these migrants return to the rivers and lakes. Under extreme winter conditions, they hardly feed at all. Sea mammals abound and are still exploited. However, the Arctic LME does include waters seasonally ice-free and regularly commercially fished, both in the Northwest Atlantic (including Davis Strait and Baffin Bay) and in the Northeast Atlantic (waters north of Iceland and towards Svalbard). Thus, reported landings in the Arctic Sea LME (Figure XI-29.2) are dominated by catches taken in the Atlantic waters. These reported landings show a series of peaks and troughs (Figure XI-29.2). From the 1950s to early 1970s, the catch was dominated by ocean perch and thereafter by capelin. The highest catch of about half a million tonnes, consisting mainly of capelin, was obtained in 1996.

Only scattered reports are available for the coastal areas around the Arctic Archipelago off the coastline of Canada bordering the Arctic Sea LME. This coastal region of the Arctic Ocean has provisionally been designated as LME 65 (PAME 2007) in Figure XI-29.1. Booth & Watts (2007) have verified the catches from these areas, as reported by the Canadian Department of Fisheries and Oceans, from the bottom up, i.e., based on the size of the human populations in coastal communities, and their seafood consumption patterns. The resultant estimates of catches, which peaked at over 2,500 t in 1960 (driven by feed requirements for sled-dogs subsequently replaced by the snowmobile as the major form of transport) before declining to around 600-700 t per year in recent years, are small compared to the reported landings for the current Arctic LME. Nevertheless, these catches are significant in terms of true arctic fisheries, and will form the predominant catches for the anticipated new Arctic Archipelago LME. These data for the new Arctic Archipelago LME can be found at www.seaaroundus.org.

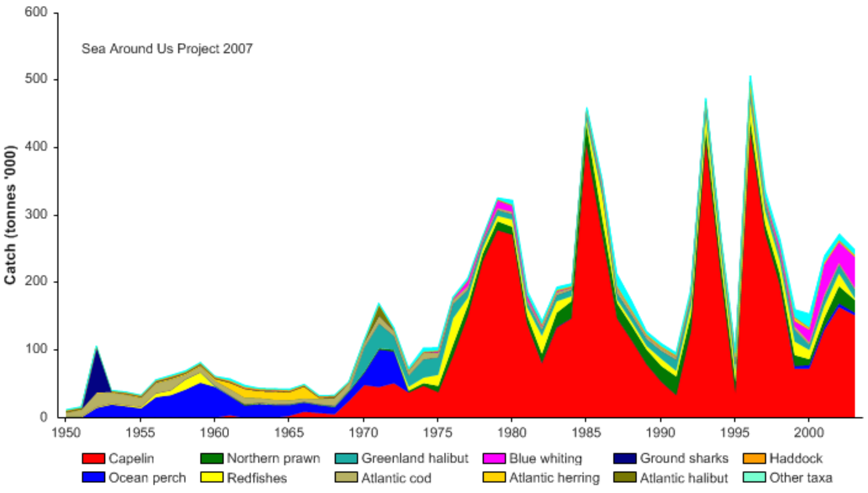

Figure XI-29.2. Total reported landings in the Arctic Ocean LME by species (Sea Around Us 2007).

III. Pollution and Ecosystem Health

Being away from immediate sources of pollution and shipping and fishing activities, the Arctic Ocean LME is relatively clean and has intact or slightly disturbed ecosystems (Lystsov 2006).

The Arctic Ocean is a sink for global pollution because of the flow of oceanic and atmospheric currents. It is a fragile ecosystem threatened by land-based sources of pollution, particularly POPs and heavy metals (Lystsov 2006), shipping, dumping and the exploitation of offshore hydrocarbon. The Alfred Wegener Institute for Polar and Marine Research observed in 2006, the highest air pollution on record since measurements began in 1991. The orange-brown 'Arctic Haze' over the west coast of Svalbard contained up to fifty micrograms aerosol per cubic metre air in Ny-Alesund—values usually measured during rush hour in cities and 2.5 times the concentrations measured there in spring 2000. Increased warming is expected and climatic variability has already had a significant impact on this LME (AWI 2006). A State of the Arctic Environment Report is available at www.amap.no /assess/soaer-cn.htm. Ocean currents transport contaminants into the Arctic Ocean. The main inflow of water is via the Norwegian Current into the Barents and Kara seas, and via the West Spitsbergen Current through Fram Strait into the Arctic Ocean. Persistent contaminants bioaccumulate in plants and animals and their food webs. Fat, or the ability to gather and store energy as a means of survival during the dark and cold winter, plays an important role in animal metabolism in the Arctic. Fat increases biomagnification of fat-soluble contaminants, which is accentuated in many Arctic animals by their long lives. Airborne pollutants can be deposited on sea ice, which then melts and releases its pollutant load to the ocean surface waters (see Pfirman *et al*. 1995 and 1999). Arctic deep water has an extremely long residence time. Part of the legacy of the Cold War is environmental contamination, mostly from nuclear tests at Novaya Zemlya but also from nuclear processing plants such as Windscale/Sellafield, with chemical and radioactive contaminants (such as iodine, caesium, plutonium and other radioactive isotopes) working their way into the Arctic food chain. People who rely on marine systems for food resources are at risk.

Endangered marine species include walruses and whales. Fragile Arctic ecosystems are slow to change and slow to recover from disruptions or a thinning polar icepack. On 15 May 2006 the *Guardian* reported record amounts of the Arctic ocean failed to freeze during the recent winter, and that the sea ice reached an all-time low in March, down some 300,000 square kilometres from 2005 and said that if the cycle continues, the recovery of ice in winter will no longer be sufficient to compensate for increased melting in the summer. The low-lying Arctic coasts of western Canada are particularly sensitive to sea-level rise. Coastal erosion and retreat as a result of the thawing of ice-rich permafrost are threatening communities, heritage sites, and oil and gas facilities.

IV. Socioeconomic Conditions

The Arctic Circle of 80° N Latitude encompasses parts of Sweden, Finland, Greenland, Canada, Russia, the USA (Alaska), the Sverdrup Islands and the Svalbard (Spitsbergen, Norway). Human settlement consists of small communities, nomadic groups of indigenous people, and larger communities residing around a harbour, a factory or a mineral resource. The Arctic coastal areas are among the most sparsely populated in the world. The region is facing huge socioeconomic challenges and change. All communities are dependent on the natural resources of this remote and harsh region. Hunting and fishing are traditional sources of livelihood. In former times, fur seals and whales were the object of a major trade. Indigenous groups number 1.5 million out of a total Arctic population of 10 million. These indigenous groups have shown resilience and an ability to survive changes in resource availability, but may be less well equipped to cope with the combined impacts of climate change and globalisation. Ice and fish are critical to the traditional lifestyle of the indigenous populations. As Achim Steiner, Executive Director of the UN Environment Programme (UNEP), recently said: “The costs of climate change are already being paid by the peoples and communities of the Arctic” (Science Daily, April 11, 2007).

The Arctic economy is a mixture of formal economies (commercial harvesting of fish, oil and natural gas and mineral extraction, forestry, and tourism) and informal subsistence economies (the harvesting of natural renewable resources such as seals and whales, with seals, for instance, providing food, heat, light and clothing). Increasingly, the overall economy is tied to distant markets. For example, in Alaska, gross income from tourism is US$1.4 billion. Technological advances and climatic change threaten the tradition of utilising the environment and its renewable resources for survival. The subsistence economy enters into conflict with the expanded use of natural resources such as oil, gas, metals and minerals. The growth of tourism will lead to new and more frequently used navigation routes.

V. Governance

Sweden, Finland, Greenland, Canada, Russia, the U.S. (Alaska), and Norway (Svalbard-Spitsbergen) border the Arctic Ocean LME. Russia has the longest coastline, encompassing five adjacent LMEs (Barents, Kara, Laptev, East Siberian and Chukchi Sea LMEs). Regional governance is important because of the unique character of this LME. While the Arctic is made up of several large seas, it is essentially a semi-enclosed ocean shared by the surrounding countries. The fragility of the Arctic Ocean calls for reinforced efforts among neighbouring states. The Arctic Region has an independent Regional Seas Programme that has not been established under UNEP, although it participates in the global meetings of the Regional Seas, shares experiences and exchanges policy advice and support to the developing Regional Seas Programmes.

In 1991, the Arctic countries adopted an Arctic Environmental Protection Strategy. In 1996, the Arctic Foreign Ministers agreed to the Ottawa Declaration. The Arctic Council was founded as an intergovernmental forum for cooperation among national governments and six Arctic indigenous organisations. In 2000, the Council agreed on a strategic framework for sustainable development and its economic, social and cultural aspects. The Arctic Monitoring and Assessment Programme (AMAP) presented a comprehensive report on the state of the Arctic environment in 1998 (www.amap.no/). The Programme for the Conservation of Arctic Flora and Fauna has finalised an overview report on biodiversity and conservation in the Arctic, including its marine areas. The Arctic Council is also engaged in work aimed at enhancing environmental safety in connection with the transportation of oil and gas. An expert group on Emergency, Prevention, Preparedness and Response (EPPR) has prepared a circumpolar map of resources at risk from oil spills in the Arctic. Also a Working Group of the Arctic Council, the Protection of the Arctic Marine Environment (PAME) has prepared a regional action plan for the control of land-based sources of Arctic marine pollution. Climate variability and change will pose challenges to the future prospects of humans and of nature in the Arctic. To help address these challenges, the Arctic Council has adopted a new project on Climate Impact Assessment in the Arctic (ACIA).

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XI-30 Beaufort Sea LME

I. Belkin, M.C. Aquarone and S. Adams

The Beaufort Sea LME is a high-latitude LME bordered by northern Alaska and Canada. It has a surface area of about 770,000 km^2, of which 0.02% is protected, and contains 0.1% of the world's sea mounts (Sea Around Us 2007). An Arctic climate and extreme environment characterise the LME, which is driven by major seasonal and annual changes in Arctic climate conditions and is ice-covered for most of the year. The anticyclonic Beaufort Gyre forms a clockwise drift pattern. Carleton Ray & Hayden (1993), describe marine biogeographic provinces of the Bering, Chukchi and Beaufort Seas.

I. Productivity

During much of the year light penetration is limited because of ice cover. Productivity is relatively high only in the summer when the ice melts. As a whole, the Beaufort Sea is considered oligotrophic. However, the coastal region supports a wide diversity of organisms, some of which are unique to this coast. The Beaufort Sea coastal areas provide habitat for ducks, geese, swans, shorebirds and marine birds. Many species of birds and fish rely on river deltas, estuaries, spits, lagoons and islands in the coastal waters for breeding, food, shelter and rearing their young. The Beaufort Sea LME is considered a Class II, Moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). An important question is how this productivity might change under an altered climatic regime. Melnikov et al. (2002) compared data from 1997-1998 with older data from 1979-1980 to find a drastically impoverished fauna of late. This change may have been associated with the high phase of the Arctic Oscillation in the early 1990s, accompanied by increased melting, runoff increase, and freshening of the upper layer. As a result, diatoms became scarce, replaced by freshwater green algae, while nematodes, copepods, amphipods and turbellarians all disappeared. It becomes clear that the biological community response to global change is most likely in the regions, where the sea ice retreat is rather remarkable, e.g., in the region of Beaufort Gyre. For data on selected invertebrates, fishes, birds and mammals, see Carleton Ray & Hayden (1993).

Oceanic fronts (Belkin et al. 2009): The Shelf Break/Shelf-Slope Front (SSF) is the most robust front within this LME (Figure XI-30.1). This front extends along the shelf break and upper continental slope. The front's stability is at maximum where the shelf break is best defined and where the upper slope is the steepest, e.g. off Cape Bathurst in the Canadian Beaufort Sea (Belkin *et al.*, 2003; Belkin *et al.*, 2009). This place is well known as the site of Cape Bathurst Polynya and also a "hot spot" of marine life where sea birds and marine mammals congregate. Transient fronts form at the dynamic boundary of the Mackenzie River plume and also within this plume (Belkin *et al*. 2009).

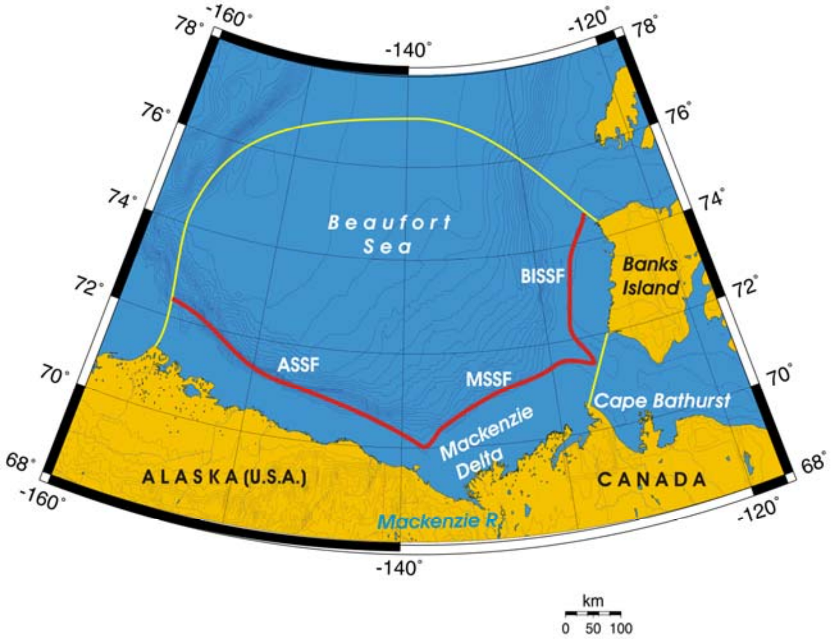

Figure XI-30.1. Fronts of the Beaufort Sea LME. ASSF, Alaskan Shelf-Slope Front; BISSF, Banks Island Shelf-Slope Front; MSSF, Mackenzie Shelf-Slope Front. Yellow line, LME boundary. After Belkin et al. (2009).

Beaufort Sea LME SST (after Belkin, 2009)
Linear SST trend since 1957: 0.17°C.
Linear SST trend since 1982: 0.34°C.

The Beaufort Sea warming was slow-to-moderate. Its annual variability was rather small, <0.5°C. The only significant event occurred in 1998, when SST peaked at -0.6°C, a whole degree above the all-time, 1974 minimum of -1.6°C. A comparison of the SST time series with the Arctic Oscillation (AO) index (Climate Prediction Center 2007) suggests a strong correlation between SST and the AO index, with negative SST anomalies corresponding to positive values of AO index.

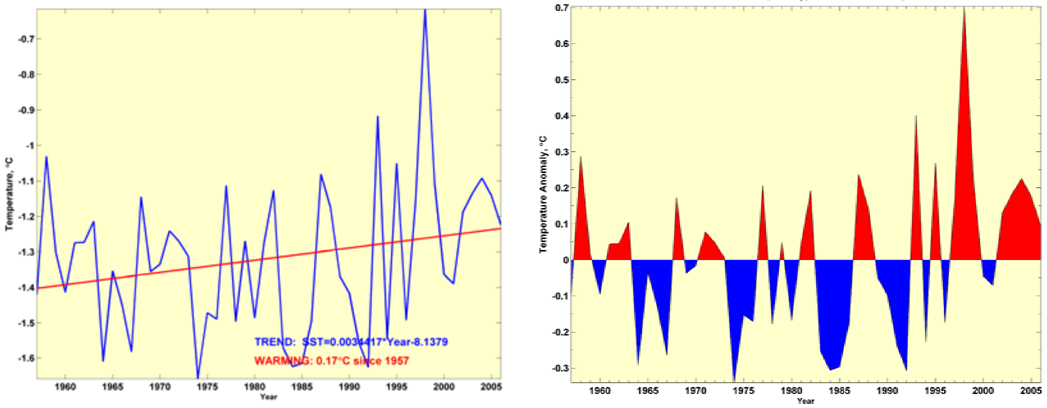

Figure XI-30.2a. Beaufort Sea LME Annual Mean Sea Surface Temperature (SST) (left) and Annual SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin. (2009).

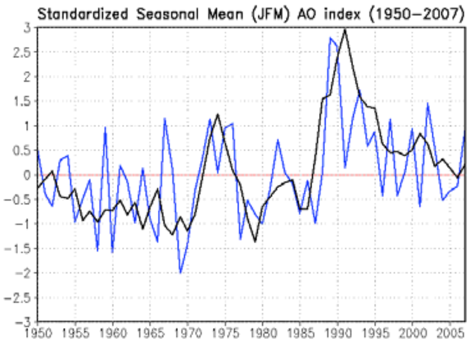

Figure XI-30.2b.The standardized seasonal mean Arctic Oscillation (AO) index during cold season (blue line) is constructed by averaging the daily AO index for January, February and March for each year. The black line denotes the standardized five-year running mean of the index. Both curves are standardized using 1950-2000 base period statistics (Climate Prediction Center, 2007).

Beaufort Sea LME Chlorophyll and Primary Productivity: The Beaufort Sea LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}).

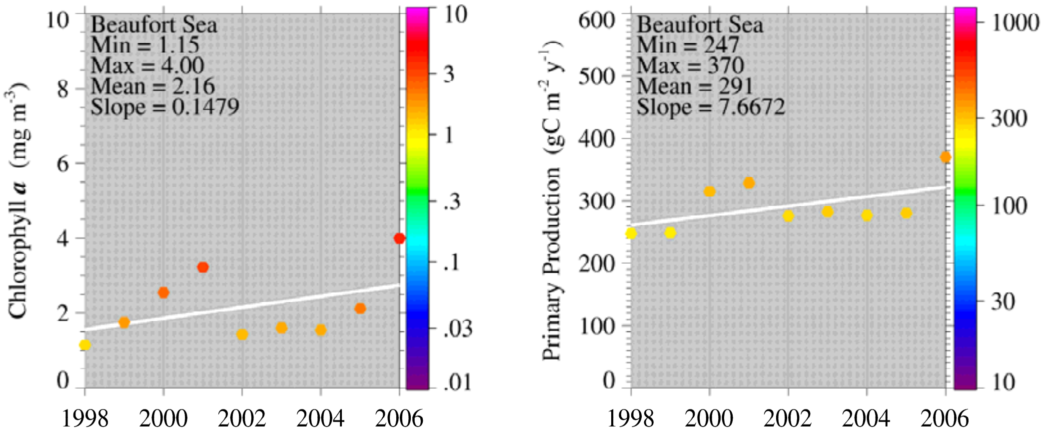

Figure XI-30.3. Beaufort Sea LME trends in chlorophyll a and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

NOAA statistics on Alaska in 'Our Living Oceans' apply to all of Alaska, without a specific statistical breakdown for the U.S. section of the Beaufort Sea LME. For statistics on the beluga and other marine mammals in the Beaufort Sea, see NOAA (1999). There are three coastal communities (Tuktoyaktuk, Sachs Harbour and Kaktovik) and two inland communites (Aklavik and Inuvik) that make use of the Beaufort Sea, largely for subsistence, but also some commercial fisheries occur in Canadian waters. Catches in 1950 were estimated to be approximately 167 tonnes before peaking in 1960 at approximately 255 tonnes and in 2001 catches were estimated at approximately 58 tonnes. Important species include Dolly varden (*Salvelinus malma*), whitefish (Coregonidae) and two other species, Inconnu (*Stenodus leucichthys*) and Pacific herring (*Clupea pallasii*), of lesser importance.

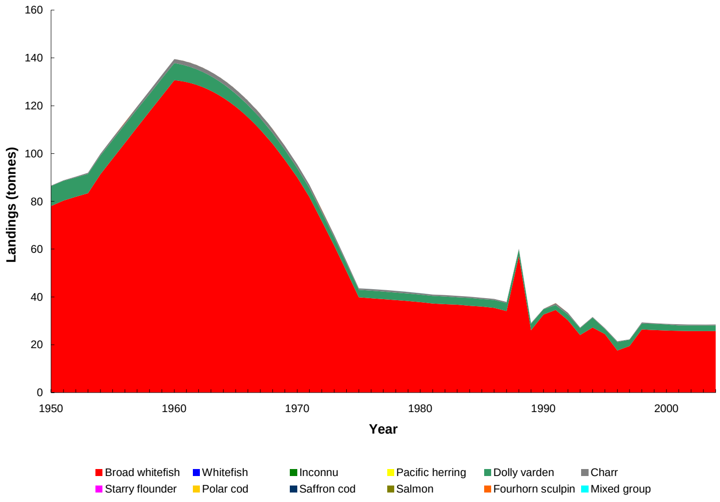

Figure XI-30.4. Total estimated catches (subsistence fisheries) in the Beaufort Sea LME (Sea Around Us 2007)

Due the tentative nature of these catch estimates, no indicators based on these data will be presented (but see Sea Around Us 2007)

The benthic offshore community includes Arctic cod, saffron cod, eelpouts and sculpins (Frost and Lowry 1983; Moulton and Tarbox 1987; Barber *et al* 1997; Jarvela and Thorsteinson 1999). Arctic cod is a particularly important component of the food web of the Beaufort Sea because they are prey for seals, seabirds and beluga whales (Bradstreet *et al.* 1986). Smelt are thought to be one of the most common pelagic marine fish in the Beaufort Sea and are prey for beluga whales, arctic cod and marine birds (Norton and Weller 1984). Large winter aggregations of Arctic cod have been recently discovered hydroacoustically under sea ice cover in Franklin Bay, SE Canadian Beaufort Sea (Benoit *et al.*, 2008). The estimated total biomass of cod would amply satisfy the requirements of predators, mostly seals. Thus, “dense accumulations of Arctic cod in embayments in winter likely play an important role in structuring the ecosystem of the Beaufort Sea.” (Benoit *et al.*, 2008).

III. Pollution and Ecosystem Health

Valette-Silver, M.J. Hameedi, D.W. Efurd and A. Robertson reported in 1999 that, “surficial sediments in the western Beaufort Sea contained generally high concentrations of arsenic (up to 58 ppm as corrected for grain size), very low amounts of organo-chlorine compounds and concentrations of total polycyclic aromatic hydrocarbons (PAHs) ranging from ~160 to 1100 ng/dry weight. Invertebrates contained higher concentrations of total PAHs than fish, with naphthalene being the largest contributor. “Diagnostic ratios of various PAH compounds in our samples do not suggest crude oil as the main source of PAHs.” Other sources of PAHs to the region include rivers outflow, coastline erosion, oil seeps, diagenesis, and long-range atmospheric transport. “Organochlorine contaminants were consistently found in our samples at concentrations generally lower than those found in other parts of the United States.” Cesium (Cs) was found in measurable amounts in all sediments and biota samples. Isotopic ratios showed that radionuclides originated most likely from global fallout. Compared to other coastal areas off Alaska, the Arctic, and the conterminous United States, Beaufort Sea contamination appears generally low.”

There is increasing global concern regarding the effect of changes in the Arctic climate on fish, marine mammals and associated wildlife, and regarding the socioeconomic impacts of these changes. Changes in water flow, the transport of nutrients through the Bering Strait and the loss of ice habitat caused by global warming will have an effect on all the living resources of this LME. Oil and gas exploration, extraction and transport, and new drilling projects targeting oil and gas in the Alaskan Beaufort Sea require constant monitoring. Recommended impact assessments include analyses of potential mortality in the event of spills, damage to food sources, production-related changes in marine mammal distribution, movement, and abundance, and additionally, the risks and effects of exposure of native people to contaminants in whales and other marine mammals from the oil industry. Pollution and acoustical disturbance from vessel traffic on the proposed Northern Sea Route are also concerns.

IV. Socioeconomic Condition

Economic activity is mostly concerned with the exploitation of natural resources (petroleum, natural gas, fish and seals). Fishing contributes to the economy and provides protein for the region’s native people. The Inupiat catch fish and bowhead whales, while the Inuvialuit catch several species of marine mammals. Ringed seals were once important to the local cash economy, but the market for seal pelts has largely disappeared. Whaling, however, continues to be a key subsistence activity. Oil has been discovered in Prudhoe Bay, but offshore oil production costs are higher in the Arctic than elsewhere. The Northstar Project targets oil in the Alaskan Beaufort Sea, but scientists recommend that it should consider native hunters and consumers of whales in the area. Whales and other marine mammals are vulnerable to contaminants from the oil industry. Protection of the region’s lifestyle is a major socioeconomic theme, as is the need to protect and preserve the Arctic wildlife, its environment and biological productivity.

V. Governance

The Beaufort Sea LME is bordered by Alaska (USA), the Yukon Territory, the Inuvik Region and part of the Northwest Territories (Canada). There are transboundary issues that need to be addressed by both countries. Fisheries governance in Alaska comes under the Alaska Department of Fish and Game. In Canada, self-government is being negotiated by two native groups, the Inuvialuit and Gwich'in, to ensure that they retain control over their inherent rights and preserve their cultural identity and values within a changing northern society. A Beaufort Sea Beluga Management Plan was developed in 1993 by the Fisheries Joint Management Committee. The goals of the plan were to maintain a thriving population of beluga whales and a sustainable harvest of beluga for the Inuvialuit people. In this volume, the Barents Sea LME (Chapter XIII-36) contains additional information on Arctic governance.

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XI-31 Chukchi Sea LME

S. Heileman and I. Belkin

The Chukchi Sea LME is a high-latitude system situated off Russia's East Siberian coast and the northwestern coast of Alaska. This LME is a relatively shallow marginal sea with a surface area of 776,643 km^2 , of which 5.4% is protected (Sea Around Us 2007), and an extensive continental shelf. According to the Atlas of the Oceans (USSR Navy, 1980), the Chukchi Sea alone has the surface area of 595,000 km^2, water volume of 42,000 km^3, and total water catchment area of 261,500 km^2. Total river runoff is less than 100 km^3. An arctic climate and major seasonal and annual changes in ocean climate, in particular the annual formation and deformation of sea ice, characterise this LME. The ice-free zone of the summer is about 150-200 km wide, the position of the ice edge being determined by northward flowing streams of Pacific water through the Bering Straits (Muench 1990). The ice cover of the Arctic Seas plays an important role in the Earth's climate formation. Additional descriptions of the Chukchi Sea LME are found in Carleton Ray & Hayden (1993) and UNEP (2005).

I. Productivity

Primary production from in situ data varies between 150-300 gCm^{-2}yr^{-1}, while maximum concentration of zooplankton can be as high as 1300 mg m^{-3} (Lukianova 2005; Vetrov and Romankevich 2004). Benthos biomass in this LME is higher than elsewhere in the Arctic, up to 500 g m^{-2} (Lukianova 2005). The total biomass of this LME is 120 million tonnes, while the annual production is 4.1 million tonnes of carbon (Vetrov and Romankevich 2004). Most of the nutrients come from the Pacific water, although upwelling of nutrient-rich bottom water, such as in Lancaster Sound, also creates favourable conditions for phytoplankton growth. The annual formation and melting of sea ice influence the productivity of this LME by releasing nutrients to the melt water. In addition, seasonal faunal shifts between winter and summer (e.g., salmon, migratory birds and mammals) have been described (Carleton Ray & Hayden 1993). In this volume, the Barents Sea LME chapter presents additional information on the biodiversity and food web Arctic Seas.

Oceanic fronts: Five fronts are found within this LME (Belkin *et al.* 2003; Belkin *et al*. 2009) (Figure XI-31.1). The Kotzebue Sound Front (KSF) bounds the northward Bering inflow. Low-salinity Bering Sea waters flow around Chukotka northwestward along the Chukotka Front (CF) toward Herald Valley. The Siberian Coastal Current/Front (SCCF) enters the Chukchi Sea through Long Strait, rounds Wrangel Island and continues northward via Herald Valley. The Herald Shoal Front (HSF) is situated over the steep southern slope of the namesake shoal. A stable front extends along Barrow Canyon (BCF).

Chukchi Sea LME SST (after Belkin 2009)(Figure XI-31.2)
Linear SST trend since 1957: 0.58°C.
Linear SST trend since 1982: 0.70°C.

The long-term warming of the Chukchi Sea over the last 50 years was modulated by strong interannual variability, with a magnitude of about 0.5-1.0°C, as well as decadal variability and at least one regime shift. Two regimes can be distinguished: (1) overall cooling until 1983; (2) overall warming since 1983. The long-term warming accelerated after the all-time minimum of -1.0°C in 1983, and by 2005 SST reached 0.3°C, a 1.3°C increase over 22 years. Even though the Chukchi Sea is affected by warm water influx from the Bering Sea through the Bering Strait, this influx apparently is not critical for the Chukchi Sea thermal regime. This is evidenced by the lack of Chukchi Sea manifestation of the 1976-77 North Pacific regime shift, which was quite abrupt in the Bering Sea, in both East and West Bering Sea LMEs. The impact of the Bering Sea inflow is two-fold, since this inflow consists of two components, eastern and western, with potentially different thermal signatures (Weingartner et al. 2005; Woodgate *et al.* 2006).

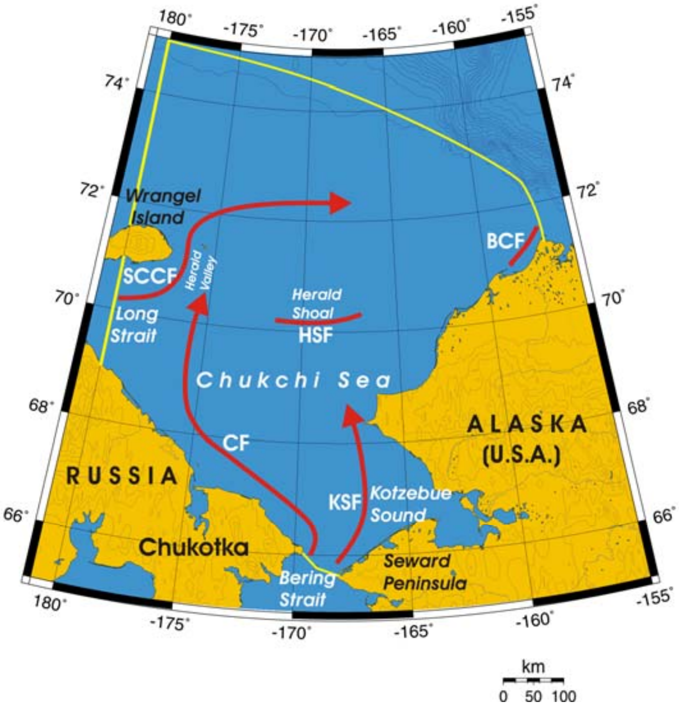

Figure XI-31.1. Fronts of the Chukchi Sea LME. BCF, Barrow Canyon Front; CF, Chukotka Front; HSF, Herald Shoal Front; KSF, Kotzebue Sound Front; SCCF, Siberian Coastal Current Front. Yellow line, LME boundary. After Belkin *et al.*, 2003; Belkin *et al.*, 2009).

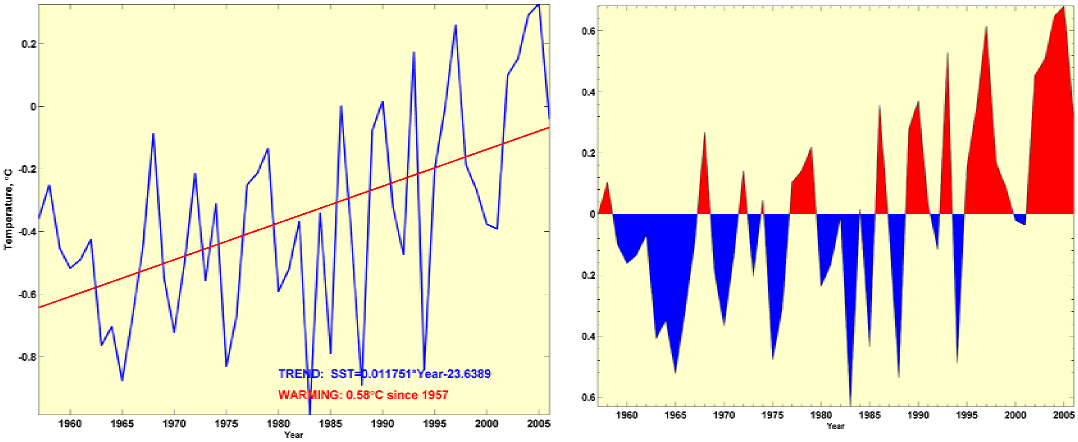

Figure XI-31.2. Chukchi Sea LME Mean Annual Sea Surface Temperature (SST; left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Chukchi Sea LME Chlorophyll and Primary Productivity: The Chukchi Sea LME is considered a Class II, moderately high productivity ecosystem (150-300 gCm^{-2}yr^{-1}).

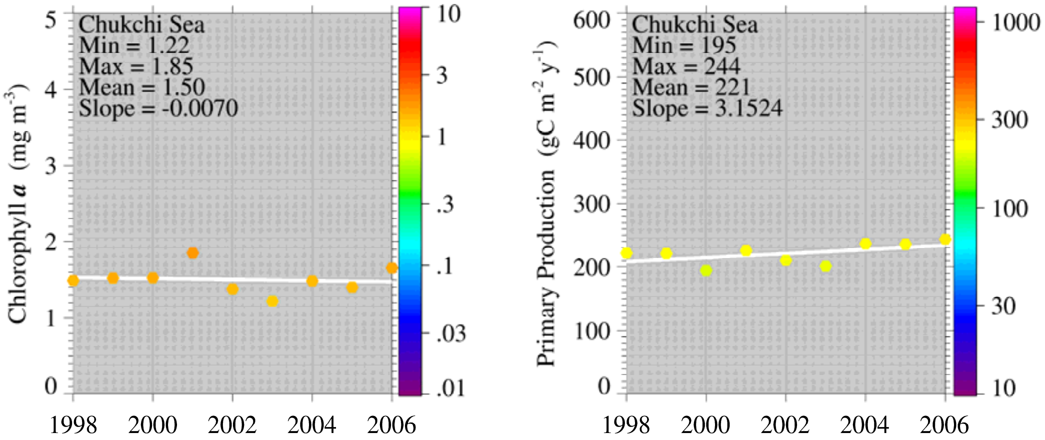

Figure XI-31.3. Chukchi Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Key marine species in this LME are salmon (*Oncorhynchus* spp.), herring (*Clupea pallasii pallasii*), walrus (*Odobenus rosmarus*), seals, whales (Greenland whale, blue whale, killer whale, beluga/belukha whale, and humpback whale being most common) and various species of waterfowl. Total annual catch shows dramatic oscillations on the scale of two-to-three years (Figure XI-31.4). Some of these oscillations are probably due to the impact of varying ice and weather regimes, whereas others may have been caused by the internal dynamics of this ecosystem. The key subsistence marine species are likely to undergo shifts in range and abundance due to climate change. The central and eastern Arctic Seas do not have a significant fishing industry, except near coastal areas. There is no evidence of overfishing in this LME (UNEP 2005).

As salmon extends its range into the Arctic, and walleye pollock into the northern Bering Sea, "the North Pacific Fishery Management Council has begun to develop an Arctic Fishery Management Plan that will provide a framework for future commercial fishing in the Chukchi Sea. Presently, the precautionary approach keeps the fishery closed while scientific data can be collected and assessed." (Alaska Climate Impact Assessment Commission 2008, p.21).

Very scarce data are available from the Russian part of the Chukchi Sea, which is only sparsely populated. Pauly & Swartz (2007) estimated a fish catch of 100 tonnes per year for the period 1950-2004, consisting overwhelmingly of salmonids. Catch figures are not transferred to FAO.

Salmonids also dominate the catches from the Alaskan part of the Chukchi Sea, i.e., taken north of Cape Prince of Wales on the Seward Peninsula, which are collected from commercial, subsistence and sport fisheries by Alaska's Department of Fish and Game.

The catches from the Alaskan Chukchi Sea were assembled by S. Booth and D. Zeller (Sea Around Us Project, unpublished data), and added to the catch estimate from the

Russian part of the Chukchi Sea. This resulted in Figure XI-31.4. As can be seen, the overall catch from the Chukchi Sea fluctuates between 500 tonnes and 3,000 tonnes and consists predominantly of salmonids.

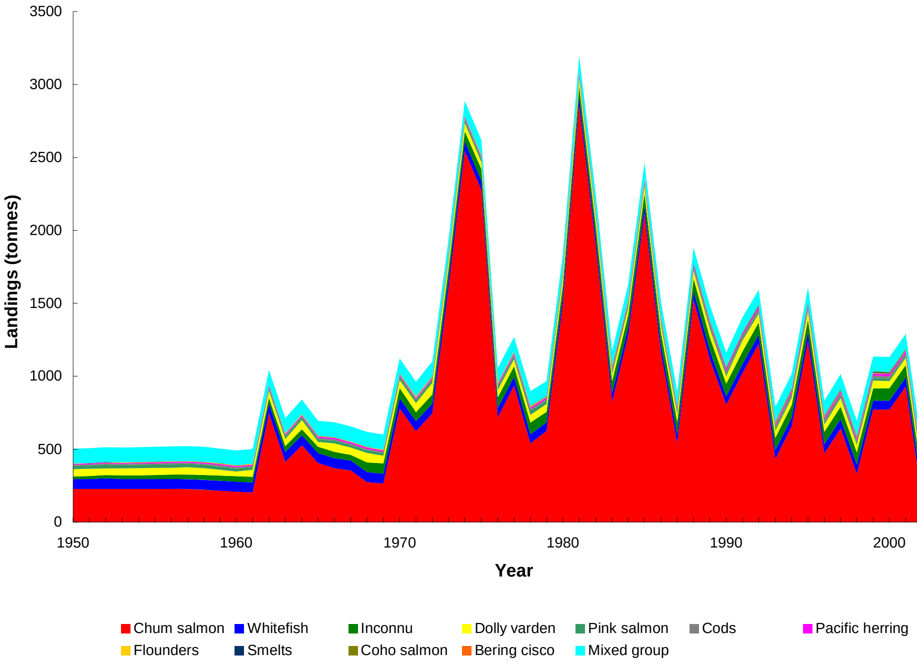

Figure XI-31.4. Total estimated catches (subsistence fisheries) in the Chukchi Sea LME (Sea Around us 2007)

Due the tentative nature of these catch estimates, no indicators based on these data will be presented (but see Sea Around Us 2007).

III. Pollution and Ecosystem Health

Pollution: Pollution in the Chukchi Sea LME is generally slight and attributed mainly to chemicals and oil spills (UNEP 2005). In spite of the considerable remoteness from major economic activities, heavy metals, aromatic and chlorinated hydrocarbons, as well as new contaminants (endosulfan, bromoform, dibromomethane, etc.) have been discovered over the last few years in the Chukchi Sea LME. According to the data of the Arctic Monitoring Regional Centre, a broad spectrum of trace metals was found in the surface waters of the Chukchi Sea (GOIN 1996a-d, Roshydromet 1997-2002).

The distribution of organic pollutants in this LME has become increasingly pronounced over the past decade (Izrael & Tsyban 1992, 2000, Tsyban 1999, Roshydromet 2001). Great concern is caused by pollution of the Chukchi shelf by PCBs. Although their atmospheric content decreased in 1993 compared to 1988, the concentrations of these toxicants in the LME waters remained unchanged. The PCB content of the bottom sediments has doubled between 1988 and 1993 (Hinckley *et al*. 1992, Izrael & Tsyban 2000). This fact is indicative of accumulations of organochlorines in the Chukchi Sea LME. It is noteworthy that the long residence times of these compounds (several decades) in the marine environment determines their active circulation along food webs and accumulation in hydrobionts, including trade organisms. At present, it is believed that hexachlorocyclohexanes (HCHs) rank among the most widespread chlorinated pesticides in the Arctic seas (Bidleman *et al*. 1995). For example, the HCH content of water samples from the Chukchi Sea LME exceeds that of other chlorinated hydrocarbons such as PCBs and DDT.

A serious concern arises from prospecting and production of oil and gas on the Chukchi shelf. Exploration and industrial drilling impact the pelagic and bottom systems in a number of ways, including the hazardous consequences of seismic prospecting and pollution of water and bottom sediments by drilling fluids and slurries, oil, copper and other metals pollution. In all the components of the Chukchi Sea ecosystem, benzo(a)pyrene, an indicator of carcinogenic PAHs, has been found. The coefficients of benzo(a)pyrene accumulation in particulate matter and in biota proved to be high (Izrael & Tsyban 1992, Tsyban 1999, Izrael & Tsyban 2000, Roshydromet 1997-2002). Contaminants are endangering marine mammals such as walruses and whales (Reynolds III *et al.* 2005).

Habitat and community modification: The coastal areas of the Chukchi Sea LME are thought to be in relatively pristine condition due to the sparse human population and the region's general remoteness. There are no records of serious habitat loss in the region, but there is evidence of localised degradation of some habitats. Habitat and community modification were assessed as slight and mainly attributed to pollution (UNEP 2005).

Climate change is expected to have a profound ecological impact in the Arctic LMEs. The Arctic climate is warming rapidly and much larger changes are expected (ACIA 2004). Species ranges are projected to shift northward on both land and sea, bringing new species into the Arctic while severely limiting some species currently present, leading to the possible extinction of some species. Salmon, herring, walrus, seals and whales are likely to undergo shifts in range and abundance. On the other hand, some arctic marine fisheries are likely to become more productive (ACIA 2004). A major issue is the thinning polar ice pack. Ice and climate records show climate warming occurring in the southern section of the LME. Climate change and receding sea ice are affecting the distribution, migration patterns and abundance of some wildlife species.

At present the transboundary waters of the Chukchi Sea LME are in relatively healthy condition (UNEP 2005). This may change, however, as a result of the rapid development of the oil and gas industry on the Arctic shelf, the increased volume of oil and gas transport as well as the accidental introduction of alien species with ship ballast water. Management and development of the Chukchi Sea LME must take account of the impacts of climate change.

IV. Socioeconomic Conditions

The coastal zone of the LME is mostly inhabited by indigenous peoples, most of whom live in rural areas. Economic activity focuses on fisheries and the exploitation of petroleum and natural gas. Contaminant levels in some Arctic indigenous groups can be 10 - 20 times higher than in most temperate regions (AMAP 1997). Heavy metals, PAHs and other persistent toxic substances have a strong mutation effect in humans. The potential impact of rapid climate change could put the native human communities at risk. The impact of recent climate warming is reflected in marine hunting data. This has improved conditions for native hunting of walrus but has adversely impacted other human activities (Mulvaney 1998). For instance, when sea ice is forming late, certain types of hunting are delayed or may not take place at all. On the other hand, when sea ice melts too quickly in the spring, it greatly decreases the length of the hunting season. There have been substantial shifts in native hunting practices, subsistence activities and the consumption of marine products on the Chukchi Peninsula during the last decade. The growth of poverty and unemployment in the coastal areas of the Russian Arctic seas is closely connected with the destruction of natural systems and the loss of traditional types of natural resource management.

V. Governance

The Chukchi Sea LME is bordered by Russia and the U.S. Any consultative framework to manage the marine resources of the Arctic LMEs requires attention to the culture and economy of indigenous peoples. Stakeholders in the Chukchi Sea LME include the Inuit Circumpolar Conference and the Council of Elders of the Chukchi of Arctic Russia. In September 1996, eight Arctic countries signed the Ottawa Declaration, under which the Arctic Council Board, an international forum of the Arctic countries, was created. This Board is an instrument for addressing Arctic pollution problems, in particular, those related to sustainable development and Arctic environment protection.

The protection of nature in the Arctic, including of the Chukchi Sea LME, is regulated by several international agreements and conventions. See the Barents Sea LME (Chapter XIII-36) for more information on Arctic governance. GEF is supporting two projects in the region. One project supports a National Plan of Action in the Russian Federation for the Protection of the Arctic Marine Environment from Anthropogenic Pollution (Phase 1). This project focuses on pre-investment studies of identified priority hot spots with known significant transboundary consequences, with additional activities to include necessary support through the development of legal, institutional and economic measures. The other project, ‘Integrated Ecosystem Approach to Enhance Biodiversity Conservation and Minimise Habitat Fragmentation in Three Selected Model Areas in the Russian Arctic’, will develop and implement integrated ecosystem management strategies in the Russian Arctic and strengthen stakeholder capacity in sustainable biodiversity management. Chapter XIII-36, Barents Sea LME, presents additional information on Arctic governance.

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XI-32 East Siberian Sea LME

S. Heileman and I. Belkin

The East Siberian Sea LME is a high-latitude Arctic LME off Northeast Russia. A topographical boundary with the Laptev Sea LME to the west is formed by the New Siberian Islands. This LME is a relatively shallow, marginal sea with an extensive continental shelf and a surface area of about 900,000 km^2, of which 3.4% is protected (Sea Around Us 2007). According to the Atlas of the Oceans (USSR Navy, 1980), the Eastern Siberian Sea has the surface area of 913,000 km^2, water volume of 49,000 km^3, and total water catchment area of 1,342,000 km^2. Climatic conditions are extremely severe, with major seasonal and interannual variation and ice cover for most of the year. The total river runoff exceeds 200 km^3/year, including Kolyma (135) and Indigirka (57) Rivers. A report pertaining to this LME is UNEP (2005).

I. Productivity

The East Siberian Sea is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}). In situ data on primary production are absent. The summer plankton bloom is short but intense. The total monthly production in August-September is 2.5 million tonnes, while the annual production is just 7 million tonnes owing to the very short vegetation season since this LME encompasses the most ice-covered shelf sea in the Arctic (Vetrov and Romankevich 2004). Coastal erosion and river discharges provide a major source of suspended matter and nutrients to this LME. However, the availability of light and nutrients has been restricted by seasonal ice cover for most of the year, limiting production to a brief period after the ice melts in summer. Climate is the primary force driving biomass changes in the LME. The formation and melting of ice complicate the thermal, chemical, sedimentological and biological processes. The zooplankton of the East Siberian Sea LME is dominated by Pacific species of copepods. The zooplankton production in winter is less than 10 mgCm^{-2}d^{-1}, whereas in summer it varies between 25 and 65 mgCm^{-2}d^{-1} (Vetrov and Romankevich 2004). Sea birds, ringed seal, walrus, beluga/belukha whale, Arctic fox and polar bear make up the varied and rich fauna at the edge of the drifting ice and on the shore. See the Barents Sea LME for additional information on the biodiversity and food web of Arctic Seas.

Oceanic fronts (Belkin et al. 2009)(Figure XI-32.1): The Siberian Coastal Current (SCC) is associated with a front (SCCF) that extends across the southern part of this LME (Figure XI-32.1). The front separates low-salinity coastal waters from offshore waters. The SCC carries huge amount of fresh water from great Siberian rivers such as Ob', Yenisey and Lena, and also Khatanga, Olenek, Indigirka, Yana, and Kolyma. The SCC transports these waters along the SCCF eastward through Long Strait into the Chukchi Sea. Estuarine fronts develop off the mouths of Indigirka and Kolyma, and also off Ayon Island.

East Siberian Sea LME SST (after Belkin 2009)(Figure XI-32.2)
Linear SST trend since 1957: 0.37°C.
Linear SST trend since 1982: 0.36°C.

The East Siberian Sea warming was moderate. Its interannual variability was very small, ~0.2-0.4°C. The only major event occurred in 1989-1990, when SST rose by 1°C in just two years, reaching -0.3°C in 1990, thus exceeding by 1.3°C the all-time minimum of -

1.6°C. This event nearly coincided with the largest increase of the Arctic Oscillation (AO) index on record since 1950 (Climate Prediction Center 2007).

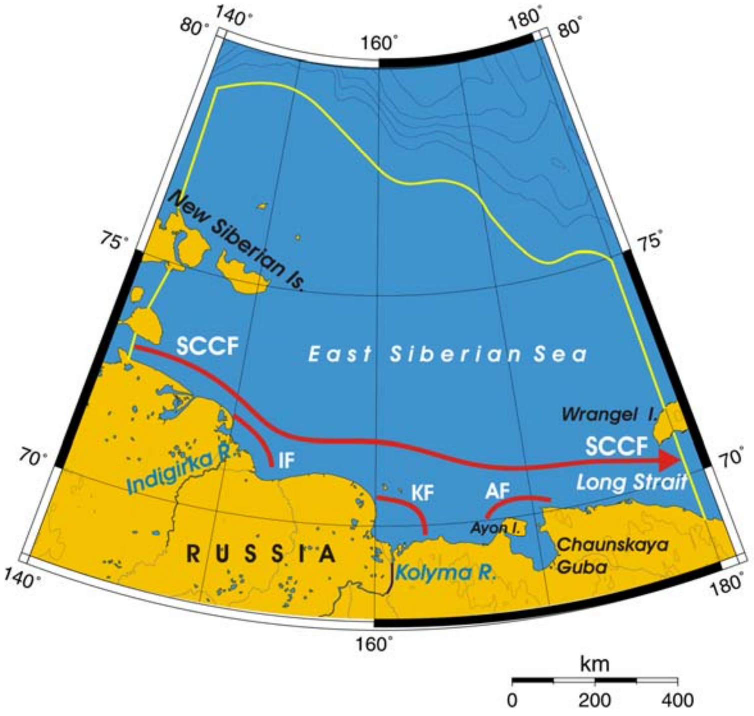

Figure XI-32.1. Fronts of the East Siberian Sea LME. AF, Ayon Front; IF, Indigirka Front; KF, Kolyma Front; SCCF, Siberian Coastal Current Front. Yellow line, LME boundary. After Belkin et al. (2009).

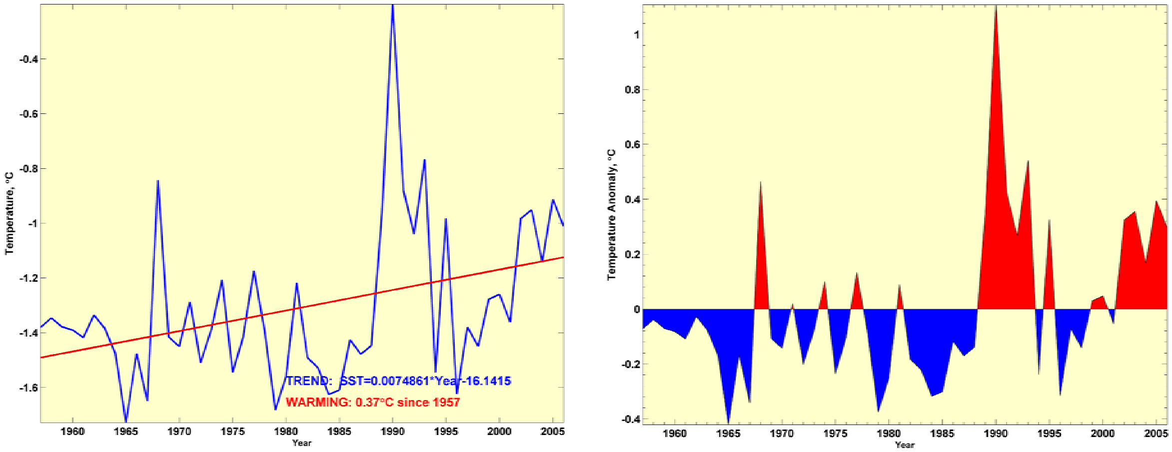

Figure XI-32.2. East Siberian Sea LME mean annual SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

East Siberian Sea LME Chlorophyll and Primary Productivity: The East Siberian Sea is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}).

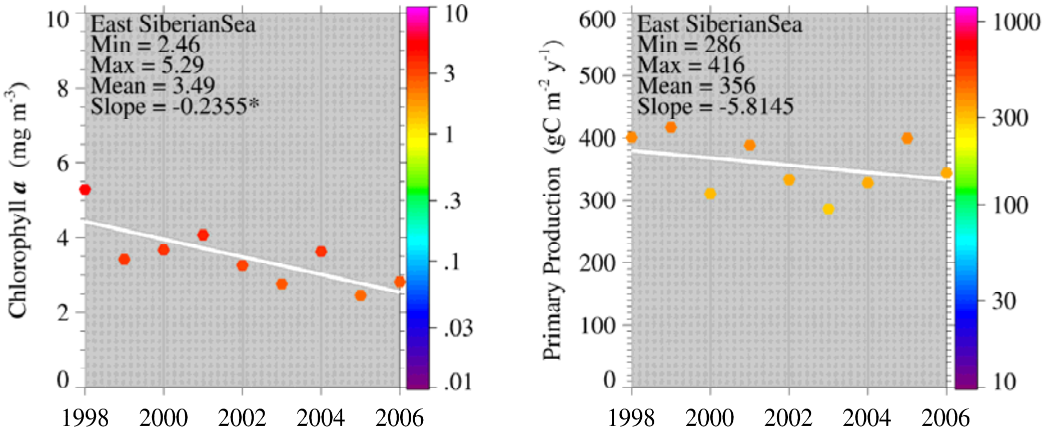

Figure XI-32.3. East Siberian Sea LME trends in chlorophyll *a* (left) and primary productivity (right) 1998 – 2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The number of species and stocks of biological resources in the East Siberian Sea LME is small. Several valuable fish species are found in this LME, but the largest stocks are generally concentrated in sub-estuarial zones. Much of the salmon catch is low-grade pink salmon that is canned and sold domestically. Valuable species such as pollock, halibut and crab are poised to play a more important commercial role. At present, overexploitation is not of concern in the LME (UNEP 2005).

As in the Kara and Laptev seas, whitefish species (genus *Coregonus*), called 'sig' in Russian, form the bulk of the fishery in this LME. However, detailed records are available only from the lower reaches of the Indigirka and Kolyma Rivers for the years from 1981 to 1990 (Larsen *et al.* 1996). These data, amounting to about 3,000 tonnes per year on average, do not show any consistent trend, unlike those from the Kara Sea. Pauly & Swartz (2007), in the absence of other data which may support an alternative estimation procedure, extrapolated backward to 1950 the mean catch of the first three years with data (1980-1982). Similarly, they extrapolated forward, from 1991 to 2004, the mean catch of the last three years with data. An additional 30% of 'other fish' was included, following Larsen *et al.* (1996). The time series of the estimated catches are presented in Figure XI-32.4.

Due the tentative nature of the East Siberian Sea LME catch estimates, no indicators based on these data will be presented (but see Sea Around Us 2007).

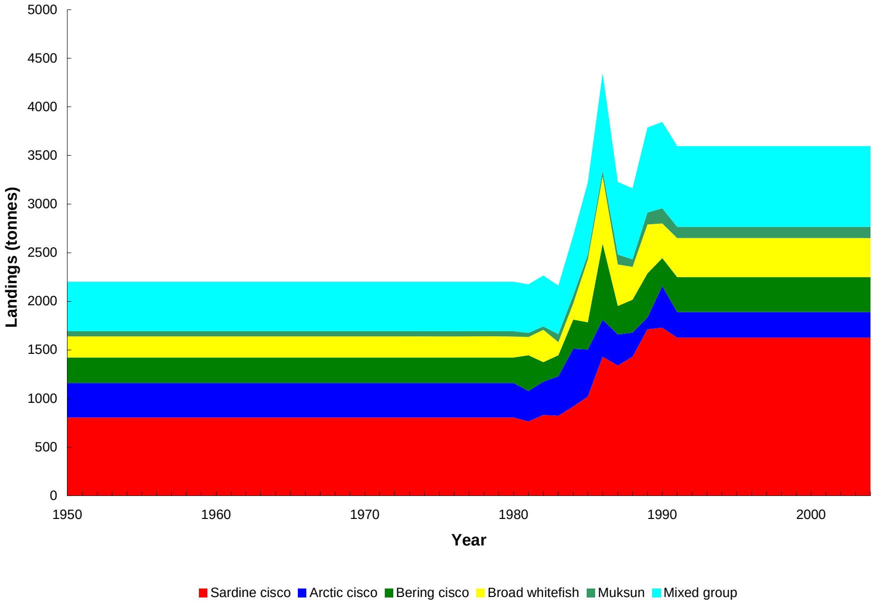

Figure XI-32.4. Total estimated catches (subsistence fisheries) in the East Siberian Sea LME (from Pauly & Swartz 2007)

III. Pollution and Ecosystem Health

Pollution: Runoff from industrial as well as agricultural areas in the Kolyma and Indigirka watersheds makes a significant contribution to pollution in this LME. However, overall, pollution is slight and attributed mainly to chemicals and spills, which are of greater concern in localised areas (UNEP 2005). According to chemical monitoring data of the Roshydromet network as well as the Arctic Monitoring Centre, several contaminants are found in the LME. A broad spectrum of trace metals was discovered in the water and bottom sediments. DDT, HCH and PCBs have been found in water samples, with maximum concentrations found in the areas of river discharge (GOIN 1996a-d, Roshydromet 1997-2002).

Particularly severe climatic and ice conditions increase the risk of pollution from shipping and spills. The maximum concentrations (up to 80 $\mu g l^{-1}$) of petroleum hydrocarbons were observed near the Novosibirsk Islands and Wrangel Island (GOIN 1996a). Some other hazardous contaminants (organochlorine compounds, heavy metals and radionuclides) can be found in snow, ice, seawater, sediments and marine organisms. The average concentrations of these contaminants are, however, very low. According to microbiological indices, the waters in some areas vary from relatively clean to lightly and moderately polluted (in localised zones in summer).

Habitat and community modification: Modification of habitats was assessed as slight (UNEP 2005). While there are no records of serious habitat loss in the region, there is evidence of localised degradation in some areas. Issues pertaining to the health of this LME are endangered marine species such as walruses and whales, the fragile marine ecosystem, which is slow to recover from disruptions or damage, and the thinning polar ice pack.

IV. Socioeconomic Conditions

A notable feature of this LME is the relatively low population density in the coastal areas. Some parts of the coast are almost uninhabited, with the few small settlements separated by long distances. The anthropogenic impact of these populations is thus considered to be low.

V. Governance

The Soviet era adopted special measures for the protection of the marine environment and the prevention of pollution in the Arctic areas adjacent to its northern coast. These provided for special navigational rules. Other issues pertain to the legal status of the Arctic areas. During the Soviet era, the East Siberian Sea was held to be internal waters. For ongoing bilateral and multilateral science projects, see International Science Initiatives in the Russian Arctic (ISIRA) under the auspices of The International Arctic Science Committee (IASC). The Arctic Research Consortium of the United States (ARCUS); the Arctic Ocean Sciences board (AOSB); Land-Ocean Interactions in the Coastal Zones (LOICZ); the Arctic Monitoring and Assessment Programme (AMAP) and Protection of the Arctic Marine Environment (PAME)--each under the aegis of the Arctic Council; The International Human Dimensions Programme on Global Environmental Change (IHDP) and the International Permafrost Association (IPA); the Canada-Russia Joint Action Plan for an Enhanced Bilateral Partnership; CNS, the Multilateral Nuclear Environmental Program in the Russian Federation and the Euro-Arctic Council are examples of international partnerships for scientific research and management in the Arctic..

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XI-33 Kara Sea LME

S. Heileman and I. Belkin

The Kara Sea LME is a high-latitude Arctic system located off northern Russia. This shallow LME has an area of 800,000 km^2, of which 2.7% is protected (Sea Around Us 2007) and is seasonally ice-covered. According to the Atlas of the Oceans (USSR Navy, 1980), the Kara Sea has an average depth of 111 m, and a water catchment area of 6,589,000 km^2. Warm ocean currents flowing into this LME from the North Atlantic Ocean result in mostly ice-free conditions from May to October. Large rivers, of which the total catchment area of 6.6 x 10^6 km^2 is equal to almost half the Russian territory, flow into this LME discharging over 1200 km^3 annually. These include (discharge in km^3/yr) the Yenisei (610), Ob' (395), Pyasina (82), Taz (45) and Taimyra (38) Rivers, of which the first two are among the largest rivers of the Arctic. Freshwater and nutrient input from these rivers, and water exchange with the Arctic Ocean, characterise this LME. Together with the Laptev Sea LME, the Kara Sea LME plays a significant role in the ice and water mass transport system of the Arctic (UNEP 2005).

I. Productivity

The Kara Sea LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}). In situ productivity data are sparse, patchy and extremely heterogeneous depending on location and season (Vetrov and Romankevich 2004). The maximum primary production (PP) of 200 mgCm^{-2}d^{-1} is observed in the Baidaratskaya Bay (west of the Yamal Peninsula). The average PP from in situ data is 43 mgCm^{-2}d^{-1} ((Vetrov and Romankevich 2004). The availability of light and nutrients has been restricted by seasonal ice cover during part of the year, limiting production to a brief period after the ice melts in the summer months. Zooplankton production is relatively low and the distribution and species composition are influenced by the proximity of the Atlantic Ocean. According to the most complete study by Lukianova (2005), benthos biomass reaches 300 g/m^{-2} in the southern Kara Sea. The sea's total biomass amounts to 41 million tons, while total annual production is between 1.4 and 2.0 million tons of carbon (Vetrov and Romankevich 2004). Generally, the coastal zone and gulfs feature high benthos biomass and highest biodiversity – nearly 400 taxa of various systematic groups. Polychaets (33%), crustaceans (30%) and molluscs (21%) dominate among all identified species (Matishov, G.G., Dzhenyuk, Sherman, K. 2006. Large Marine Ecosystems of the Shelf Seas of Russian Arctic. Paper presented at the PAME Meeting).

Numerous species of marine mammals inhabit this LME. The most abundant species are: Atlantic walrus (*Odobenus rosmarus rosmarus*), ringed seal (*Phoca hispida*), common seal (*Phoca vitulina vitulina*), Greenland seal (*Hisriophoca geonlandica oceanica*), crested seal (*Cystophora cristata*), killer whale, narwhal, and belukha whale (*Delphinapterus leucas*). Fish fauna is not well studied partly because of the lack of commercial fishery, except for the fishery for anadromous and semi-anadromous fish species in the estuaries of Siberian rivers, e.g. Yenisei, Ob', Pyasina, Taz, and Taimyra. Among 60 fish species found in the Russian Arctic Seas, a few species are considered commercial, namely Arctic cisco, European cisco, muksun (*Coregonus muksun*), Atlantic whitefish (*Coregonus huntsmani*; Russian "sig", a white fish of the salmon family), Arctic char, navaga (*Eleginus nawaga*) and sheefish (*Stenodus leucichthys*),

Oceanic fronts (after Belkin et al. (2009): The Ob' and Yenisey River discharges to the Kara Sea form a giant single freshwater plume, since both estuaries are close to each other (Figure XI-33.1). This plume spreads across the entire LME, up to Novaya Zemlya. The distribution of this plume is largely determined by the wind field that is ultimately governed by a large-scale atmospheric pressure pattern.

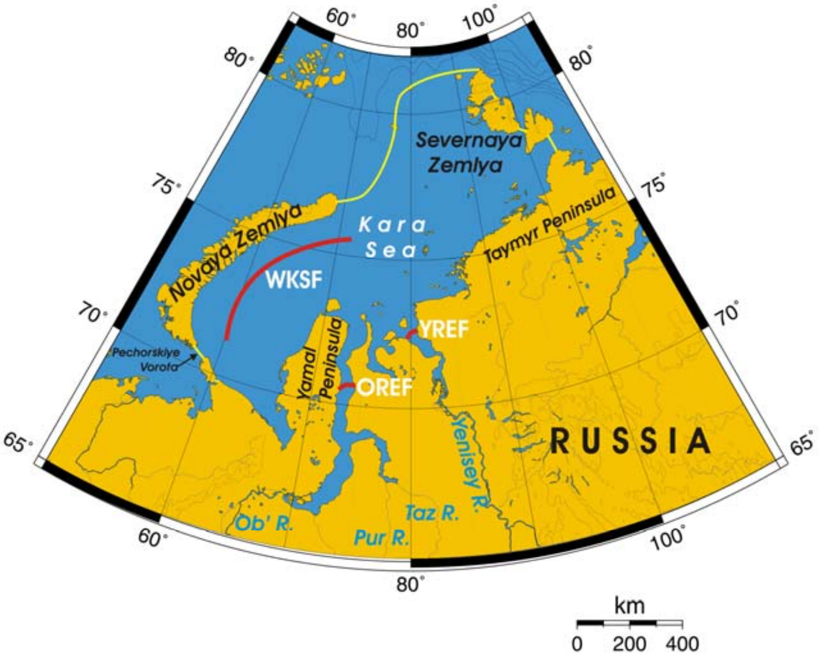

Figure XI-33.1. Fronts of the Kara Sea LME. OREF, Ob' River Estuarine Front; WKSF, West Kara Sea Front; YREF, Yenisey River Estuarine Front. Yellow line, LME boundary. After Belkin et al. (2009).

Sharp salinity and temperature fronts are observed in the outer parts of Ob' and Yenisey's estuaries called Obskaya Guba and Yeniseyskiy Zaliv, respectively, where riverine waters meet oceanic waters. In the southwestern part of the LME, a front exists between resident waters and the Atlantic inflow from the Barents Sea through Karskiye Vorota, a strait that connects the Kara Sea with the Pechora Sea, a southeastern extension of the Barents Sea.

Kara Sea LME SST (after Belkin, 2009)
Linear SST trend since 1957: 0.30°C.
Linear SST trend since 1982: 0.16°C.

The Kara Sea warming was slow, accentuated by a single event, the all-time maximum of 1995, which occurred concurrently with the Laptev Sea. Interannual variability here is moderate, with a magnitude of 0.5°C, similar to the Laptev Sea. Thermal history of the Kara Sea is negatively correlated with the Arctic Oscillation (AO) index. In this respect, the Kara Sea is similar to the Beaufort Sea LME. At the same time, the Kara Sea SST appears to be decorrelated from the adjacent Laptev Sea LME's SST since the latter is negatively correlated with the AO index (Climate Prediction Center 2007). This pattern can be explained by the lack of oceanographic connection between the Kara and Laptev seas. Indeed, the only significant connection between these seas is through the shallow Vilkitsky Strait, which is covered by sea ice year-round.

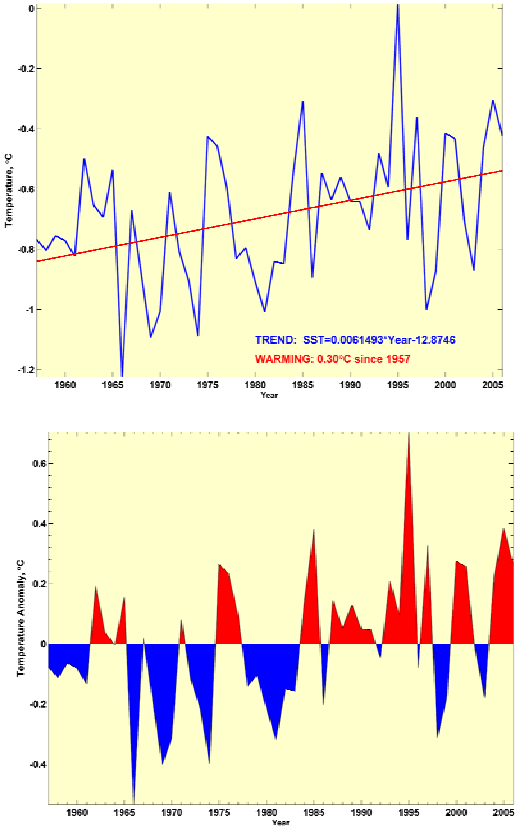

Figure XI-33.2a. Kara Sea LME annual mean SST (top) and SST anomalies (bottomt), 1957 – 2006, based on Hadley climatology. After Belkin (2009).

The standardized seasonal mean Arctic Oscillation (AO) index during cold season (**blue** line) is constructed by averaging the daily AO index for January, February and March for each year. The **black** line denotes the standardized five-year running mean of the index. Both curves are standardized using 1950-2000 base period statistics (Figure XI-33.2b. from Climate Prediction Center 2007).

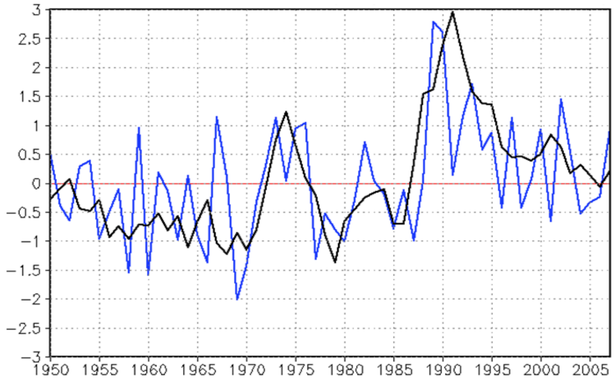

Figure XI-33.2b. Standardized Seasonal Mean (JFM) AO index (1950-2007), Climate Prediction Center 2007.

Kara Sea LME Chlorophyll and Primary Productivity: The Kara Sea LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}).

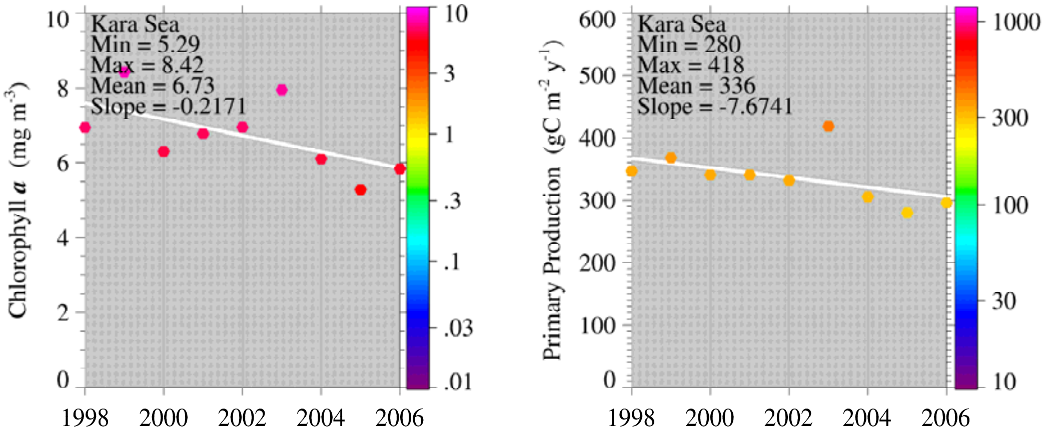

Figure XI-33.3. Kara Sea LME trends in chlorophyll *a* (left) and primary productivity (right). Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

As mentioned in the previous section, the Kara Sea benefits from the occasional intrusion of 'warm' water and its accompanying fauna, "as apparently occurred during 1919-1938, when a strong inflow of warm Atlantic water into the Kara Sea, Northern Russia, led to the eastward expansion of salmon" (Fleming and Jensen, 2002).

However, except for these occasional strays, the fish fauna of the Kara Sea is species poor (see www.fishbase.org) with the bulk of the fisheries catches contributed by the genus *Coregonus*, (Subfamiliy Coregoninae, Family Salmonidae) known as 'whitefishes' or 'sig' in Russian. Six of their species make up about 80% of the total fisheries landing in the LME (Larsen *et al.* 1996,).

Figure XI-33.4 is adapted from Pauly & Swartz (in press), who used a variety of sources, notably Larsen *et al.* (1996) to reconstruct estimated catches from the Kara Sea for 1950 to 2004. The declining catches are explained in part by extreme pollution of the estuaries and coastal areas and by overfishing (Pauly & Swartz in press). Due to the tentative nature of these catch estimates, no indicators based on these data will be presented (but see Sea Around Us 2007).

III. Pollution and Ecosystem Health

Pollution: Pollution was assessed as generally moderate in the LME (UNEP 2005), which is impacted by a variety of anthropogenic contaminant sources (Layton *et al*. 1997, Povinec *et al*. 1997). Almost 40% of the area is influenced by continental waters and substantial amounts of pollutants introduced by the Ob' and Yenisei Rivers. Obsolete technologies and the lack of facilities for processing industrial waste cause major ecological problems. In the open waters of the Arctic the concentration of pollutants are low or absent. However, localised shelf areas and most coastal zones are considerably polluted. The state of a number of bays, gulfs and estuarine areas is considered to be critical and even catastrophic, and partly explains the decline in the fisheries catch

(Figure XI-33.4). In fact, the concentrations of some chemical contaminants exceed the threshold

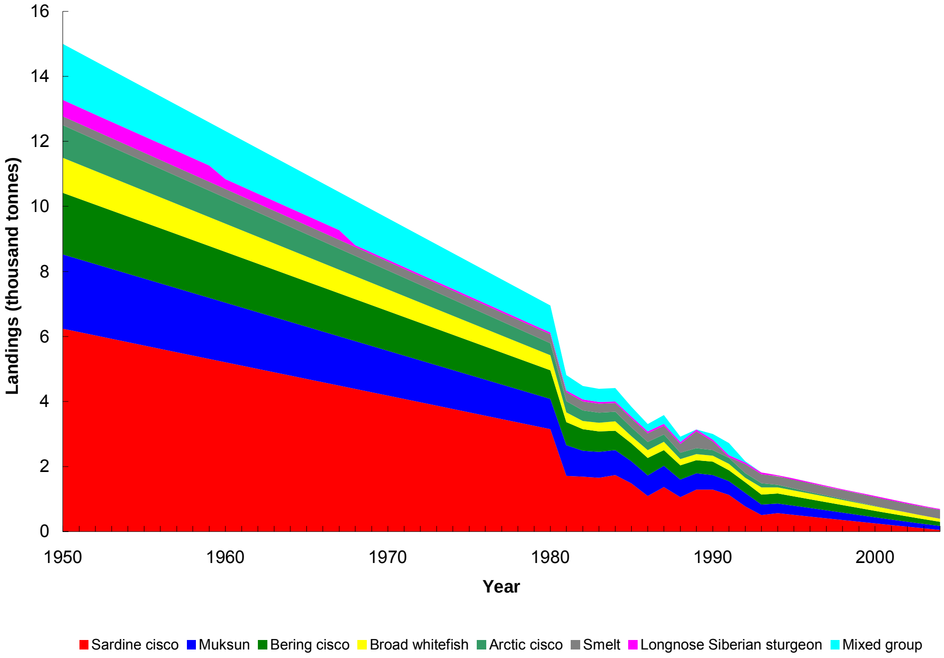

Figure XI-33.4. Total estimated catches (subsistence fisheries) in the Kara Sea LME (from Pauly & Swartz 2007).

limits defined for the country. This situation is aggravated by the accumulation of numerous contaminants in the bottom sediments. According to the chemical monitoring data of the Roshydromet network (GOIN 1996 a-d, Roshydromet 1997-2002) and the Arctic Monitoring Regional Centre, trace metals and petroleum hydrocarbons are the most widespread pollutants in the Kara Sea LME. By far the most important source of pollution is the Norilsk nickel processing plant that emits more than 1 million tons of sulfur every year (AMAP 1997).

Suspended solids in the Ob' and Yenisei River deltas carry high levels of PCBs and DDT (AMAP 1998). These toxic pollutants are found in practically all bays and estuarine zones and their chronic impacts on marine organisms cause serious concern. Long-range atmospheric transport may account for the high HCH concentrations in open areas (GOIN 1996a-d, Roshydromet 1997-2002). Although radioactive materials are dumped into the Arctic seas, there is no evidence of high concentrations of radionuclides in the LME (AMAP 1997, 2002). Pollution from solid waste is caused by domestic waste and metal barrels on the shores.

Oil and gas development, in particular oil extraction, oil spills, washing from the shore, and pipeline transportation, pose a significant environmental threat. The maximum permissible concentration of petroleum hydrocarbons has been exceeded in some areas, for example, in Cape Kharasavei and near the Arctic settlements Amderma and Dickson (GOIN 1996a). Pollution of water and bottom sediments in the hydrocarbon fields occurs from ejection of drilling slime, occasional and permanent leaks of fuel, lubricants, gas condensate and drilling and other liquids.

Habitat and community modification: Habitat and community modification was assessed as slight, with degradation of some habitats in localised areas (UNEP 2005). Modification of the highly vulnerable habitats in the Kara Sea basin has occurred as a result of rapid industrial development of the Russian Arctic region after the 1970s. The growth of oil and gas extraction is connected with the construction of ground and underwater cross-country pipelines, building of roads and sea ports, construction of artificial structures, noise and vibration that affect animals, and thermic impacts and change of habitat of migrant birds and fishes. Another threat to the habitats is posed by the mining and metallurgic industries. The immediate causes of modification of the neritic system, lagoons and estuaries are increased chemical pollution and oil spills.

The health of the LME may worsen in the future as a result of the rapid development of the oil and gas industry on the Arctic shelf, increased volume of oil and gas transport, as well as the accidental introduction of alien species with ship ballast water.

IV. Socioeconomic Conditions

Economic development associated with oil extraction, mining and fish farming will result in changes in diet and nutritional health and exposure to air-, water- and food-borne contaminants in northern peoples who rely on marine systems for food (AMAP 1998, Weller & Lange 1999, Freese 2000). Morbidity directly connected with chemical pollution is of particular concern in this LME. The biomagnification of persistent contaminants in Arctic food webs is affecting the health of Arctic inhabitants whose diet is based on species at high trophic levels in both marine and terrestrial ecosystems. Contaminant levels in some Arctic indigenous groups can be 10 to 20 times higher than in most temperate regions (AMAP 1997). Heavy metals, PAHs and other persistent toxic substances have a strong mutation effect in humans. (See Chukchi Sea LME for further information.)

V. Governance

Under the aegis of the PAME working group of the Arctic Council three LME pilot projects --West Bering Sea, Beaufort Sea (U.S. and Canada) and Barents Sea (Norway and Russia) are being undertaken. Climate change adaptability is a priority among the critical issues being addressed by the Arctic Council according to Norway's Minister of Foreign Affairs, Jonas Gahr Støre's speech to the Arctic Council Ministerial Meeting in Salekhard, Russia on 26 October 2006. The GEF CEO has endorsed two projects with the Russian Federation: Support to the National Programme of Action for the Protection of the Arctic Marine Environment, Tranche 1 (International Waters focal area project) and An Integrated Ecosystem Management Approach to Conserve Biodiversity and Minimize Habitat Fragmentation in Three Selected Model Areas in the Russian Arctic (ECORA), (a multi-focal area project).

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XI-34 Laptev Sea LME

S. Heileman and I. Belkin

The Laptev Sea LME is topographically defined by the New Siberian Islands (Novosibirskie Ostrova) in the East and the Northern Land (Severnaya Zemlya) islands in the West. The LME is a continental marginal sea, most of which is shallow with a deeper northern section and a surface area of about 500,000 km^2, of which 5.6% is protected (Sea Around Us 2007). According to the Atlas of the Oceans (USSR Navy, 1980), the Laptev Sea (defined in the north by the shelf break) has a surface area of 475,000 km^2, water volume of 57,000 km^3, and total water catchment area of 3,643,000 km^2. Severe climatic conditions with major seasonal and annual changes, perennial ice cover over extensive areas, water exchange with the deep Arctic Ocean and freshwater input from Siberian rivers. The total river runoff exceeds 700 km^3/year, including Lena (532), Khatanga (105), Olenek (38), Yana (31), Anabar, and Kotuy Rivers.

I. Productivity

The Laptev Sea LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}). The availability of light and nutrients is restricted by seasonal ice cover during part of the year, limiting production to a brief period after the ice melts in the summer months. Locally, primary production may exceed 800 mgCm^{-2}d^{-1}.in the southern part of this LME, with high values (>300 mgCm^{-2}d^{-}1) also observed in the north where the Laptev Sea waters meet the Atlantic waters (Vetrov and Romankevich 2004). The total biomass is 70 million tonnes, while the total annual production is 2.4 million tonnes of carbon (Vetrov and Romankevich 2004). Sea birds, ringed seal, beluga/belukha whale, walrus, Arctic fox and polar bear make up the top trophic level of the rich and varied fauna of this region, especially in the summer months when they can be found at the edge of the drifting ice and on the shore.

Oceanic fronts: (Belkin et al. 2009)(Figure XI-34.1): This area features a huge river runoff owing primarily to the discharge of the Lena River, as well as of the Khatanga (merger of Kheta and Kotuy), Popigay, Anabar, Olenek and Yana rivers. Estuarine offshore fronts develop as freshwater river plumes formed by Lena and Khatanga spread over the vast shallow shelf of Laptev Sea. Similar to the Mackenzie River plume, these plumes may contain multiple transient fronts that correspond to individual freshets.

The Siberian Coastal Current Front is less distinct in the Laptev Sea than in the East Siberian and Chukchi seas. This front separates low-salinity inshore waters from saltier offshore waters and acts as a conduit for the fresh waters on their route eastward. The Laptev Sea continental slope is relatively steep and the shelf break is well defined, therefore a shelf-slope front might exist along the shelf edge.

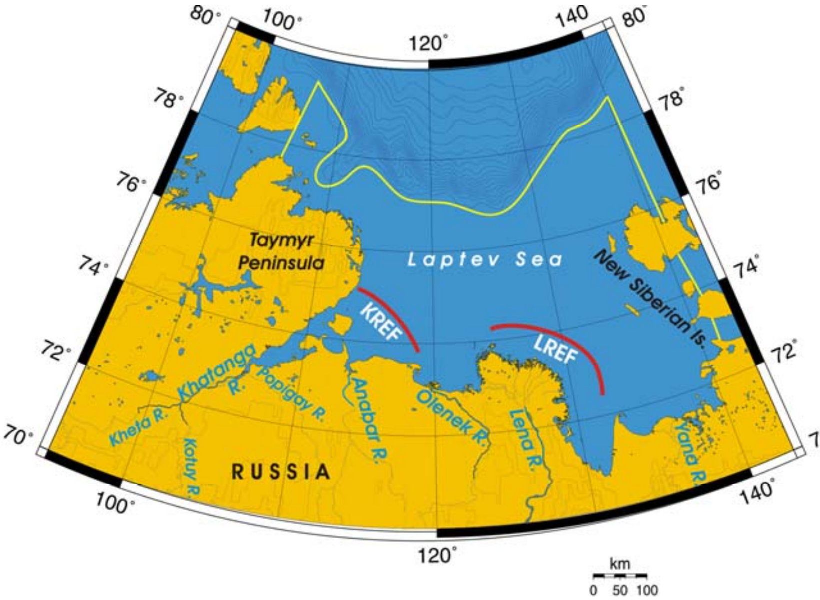

Figure XI-34.1. Fronts of the Laptev Sea LME. KREF, Khatanga River Estuarine Front; LREF, Lena River Estuarine Front. Yellow line, LME boundary. After Belkin et al. (2009).

Laptev Sea LME SST (Belkin 2009)(Figure XI-34.2)
Linear SST trend since 1957: 0.32°C.
Linear SST trend since 1982: 0.12°C.

The Laptev Sea warming was slow but steady, modulated by strong interannual variability. The largest interannual variability was observed between the all-time maximum of 0.0°C in 1995 and the all-time minimum of -1.3°C in 1996. The peak of 1995 occurred simultaneously in the adjacent Kara Sea; it was not observed elsewhere. Therefore the 1995 warm event was confined to just two contiguous LMEs, Laptev and Kara Seas. The warm episode of the late 1980s-early 1990s was positively correlated with the Arctic Oscillation index.

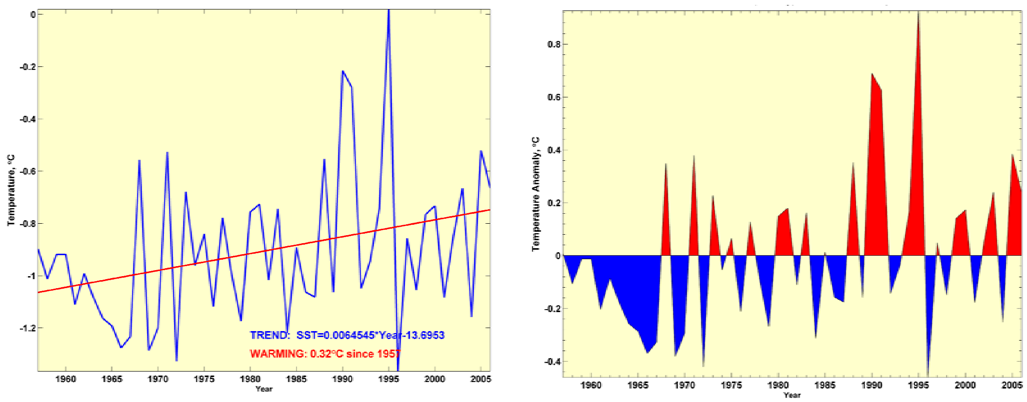

Figure XI-34.2a. Laptev Sea LME mean annual SST (left) and SST anomalies (right), based on Hadley climatology. After Belkin (2009).

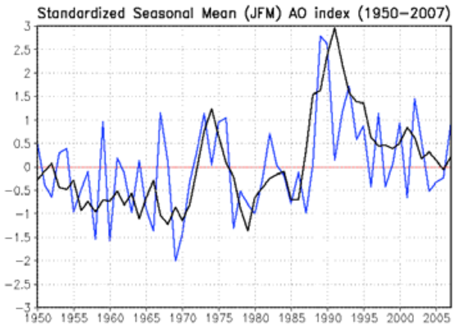

Figure XI-34.2b. The standardized seasonal mean Arctic Oscillation (AO) index during cold season (blue line) is constructed by averaging the daily AO index for January, February and March for each year. The black line denotes the standardized five-year running mean of the index. Both curves are standardized using 1950-2000 base period statistics (Climate Prediction Center, 2007).

Laptev Sea LME Chlorophyll and Primary Productivity: The Laptev Sea LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}).

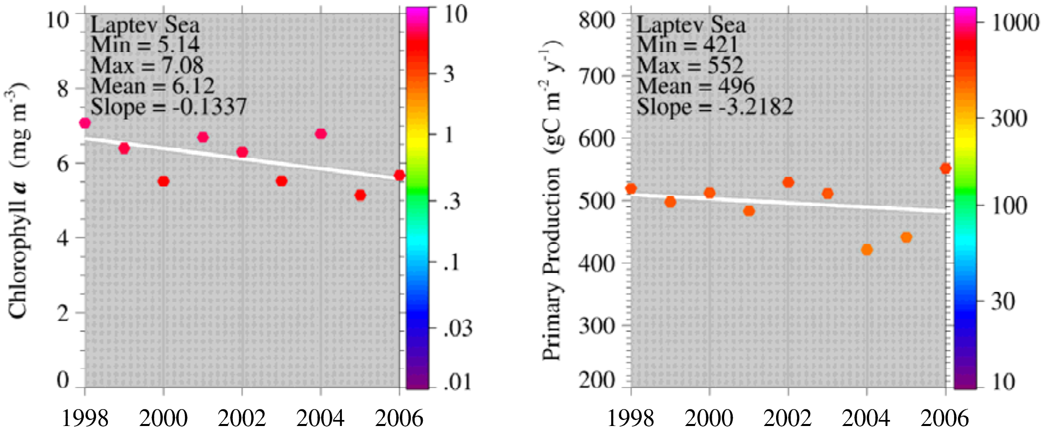

Figure XI-34.3 Laptev Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

I. Fish and Fisheries

The fish fauna of the Laptev Sea is extremely impoverished, as it is remote from both the Barents Sea to the west and Bering Sea to the east. As in the neighboring Kara and East Siberian seas, whitefish species (genus *Coregonus*), or 'sig' in Russian, form the bulk of the fisheries catch in this LME, but detailed records are available only from the lower reaches of the Lena and Yana rivers, and from Khatanga Bay for the years from 1981 to 1991 (Larsen *et al.* 1996). These data, amounting to about 3000 tonnes per year on average, do not show any consistent trend, unlike those from the Kara Sea. Pauly & Swartz (2007), in absence of other data which may support an alternative estimation procedure, extrapolated backward to 1950 the mean catch of the first three years with data (1980-1982) and extrapolated forward, for 1992 to 2004, the mean catch of the last three years with data. An additional 20% of 'other fish' was included, following Larsen *et al.* (1996). The time series of the estimated catches are presented in Figure XI-34.4.

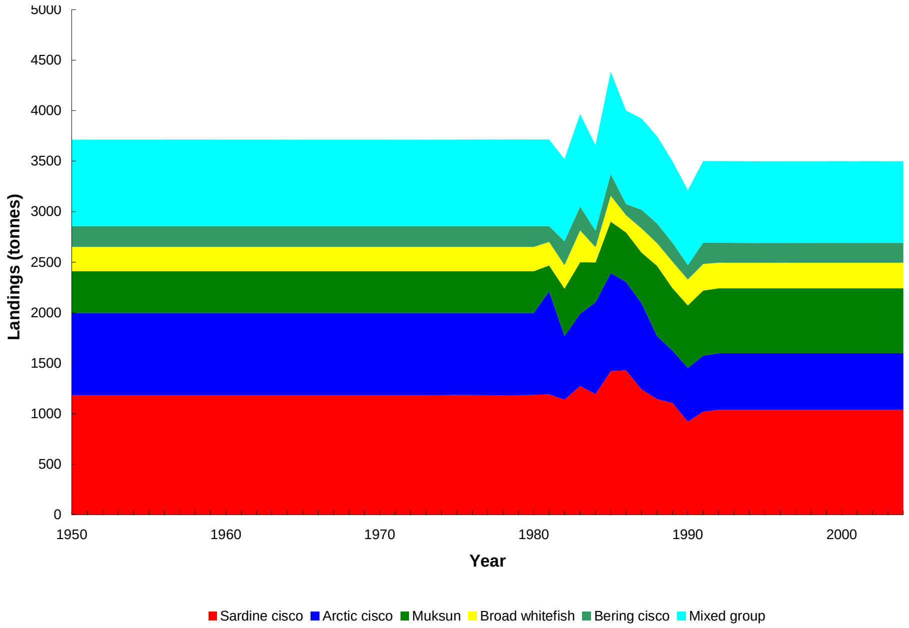

Figure XI-34.4. Total estimated catches (subsistence fisheries) in the Laptev Sea LME (see Pauly & Swartz 2007).

Due the tentative nature of these catch estimates, no indicators based on these data will be presented (but see Sea Around Us 2007).

III. Pollution and Ecosystem Health

Pollution: Overall, pollution in the Laptev Sea LME was found to be slight and attributable mainly to chemicals and spills in localised coastal areas (UNEP 2005). The highest pollution levels are found in estuarine areas, in the Zarya Strait and near the Novosibirsk Islands. River runoff and atmospheric transport play an important role in marine pollution. Major sources of pollution on the shelf are the oil and gas industry, inland water and sea transport, ore mining and processing, accidental oil spills, and towns and settlements situated on the coast and along the rivers (UNEP 2005). The air, water and soil in industrial areas are polluted with harmful substances because of obsolete technologies and the lack of facilities for processing industrial waste. Some of the rivers are reportedly polluted with PCBs, DDT, heavy metals and viral contaminants. DDT, HCH, PCBs and heavy metals have been recorded in localised areas of the Laptev Sea LME (GOIN 1996a-d, Roshydromet 1997-2002). According to the chemical monitoring data of the Roshydromet network as well as observations by the Arctic Monitoring Centre, the phenol concentrations are higher than those in other Arctic seas, with the highest phenol concentrations attributed to floating and sunken wood being found in offshore areas.

Particularly severe climatic and ice conditions increase the threat of pollution from shipping and spills. In 1991, concentrations of petroleum hydrocarbons exceeded the Maximum Permissible Concentrations (MPCs) in some localised areas such as Tiksi Bay, Bugor-Khaya Firth and Olenek Bay. In 1992, concentrations of petroleum hydrocarbons varied within narrow limits (12-39 μgl^{-1}) but in Bugor-Khaya Firth (a shipping lane route) the maximum level reached up to 200 μgl^{-1} (GOIN 1996a). In 1993 the level of petroleum hydrocarbons did not exceed the MPCs (GOIN 1996b). In more recent years, the average concentration of petroleum hydrocarbons was 17.1 µgl^{-1} in the open waters and up to 114 µgl^{-1} in Bugor-Khaya Firth (GOIN 1996c-d, Roshydromet 1997-2002).

Habitat and community modification: There are no records of serious habitat loss in the region, but there is evidence of slight degradation in some localised areas because of pollution (UNEP 2005). The ecosystem state in the open sea as a whole can be characterised as favourable. The few ecosystem health issues include endangered marine species as well as the fragile marine ecosystem, which is slow to recover from perturbations, and the thinning polar ice pack.

IV. Socioeconomic Conditions

Economic activity in the Laptev Sea LME focuses on the exploitation of oil and natural gas, although there are fewer oil and gas reserves in this LME than in the other Siberian LMEs. Vast coastal areas remain practically unaffected by human activity. There are relatively low population densities in the coastal areas and the few small settlements are separated by long distances. In the entire Far Eastern Federal District of the Russian Federation, of which the Laptev Sea coastal area is a part, the population density is approximately one person per square kilometre and is currently declining. As a result, the environmental impact of these populations is considered to be low. (See the Chukchi Sea LME for more information.)

V. Governance

Special measures for the protection of the marine environment and the prevention of pollution in the Arctic areas adjacent to Russia’s northern coast were adopted in the Soviet Era. These provided for special navigational rules on that coastline. There remain questions pertaining to the legal status of the Arctic areas. During Soviet times, the Laptev Sea was held to be internal waters. For ongoing bilateral and multilateral science projects, see International Science Initiatives in the Russian Arctic (ISIRA) under the auspices of The International Arctic Science Committee (IASC). The Arctic Research Consortium of the United States (ARCUS); the Arctic Ocean Sciences board (AOSB); Land-Ocean Interactions in the Coastal Zones (LOICZ); the Arctic Monitoring and Assessment Programme (AMAP) and Protection of the Arctic Marine Environment (PAME)--each under the aegis of the Arctic Council; The International Human Dimensions Programme on Global Environmental Change (IHDP) and the International Permafrost Association (IPA); the Canada-Russia Joint Action Plan for an Enhanced Bilateral Partnership; CNS, the Multilateral Nuclear Environmental Program in the Russian Federation and the Euro-Arctic Council are examples of international partnerships for scientific research and management in the Arctic. See the Barents Sea LME (Chapter XIII-36) for more information on governance.

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XII THE BALTIC SEA

XII-35 Baltic Sea LME

S. Heileman and J. Thulin

The Baltic Sea LME is the world's largest brackish water body, covering an area of about 390,000 km^2, of which 2.21% is protected (Sea Around Us 2007). The LME catchment area is four times larger than its surface area (Jansson 2003), comprising about 1.7 million km^2, nearly 93% of which belongs to the nine riparian countries: Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. The non-coastal countries in the catchment area include Belarus, the Czech Republic, Slovakia and Ukraine. The LME receives freshwater from a number of large and small rivers, while saltwater enters from the North Sea along the bottom of the narrow straits between Denmark and Sweden. This creates a salinity gradient from southwest to northeast and a water circulation characterised by the inflow of saline bottom water and an outflowing surface current of brackish water. It is estimated that a renewal of the total water mass of the Baltic Sea would take about 25-35 years. A permanent stratification layer exists between the upper layer of low salinity and a deeper layer of more saline water (Stigebrandt & Wulff 1987). Book chapters on this LME have been published by Kullenberg (1986), Jansson (2003) and UNEP (2005).

I. Productivity

The Baltic Sea LME is a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}). This LME is characterised by its temperate climate. Large-scale meteorological conditions cause long-term fluctuations of salinity and temperature in the deep and bottom waters. Periodic inflows of North Sea water drive changes between oxic and anoxic conditions in deeper waters (Jansson 2003). The diversity, composition and distribution of the Baltic Sea biota are influenced by its brackish-water character, the two-layered water mass and variable environmental conditions. Primary production exhibits large seasonal and interannual variability (Jansson 2003, HELCOM 2002); downward trends were found for diatoms in spring and summer, whereas dinoflagellates generally increased in the Baltic proper, but decreased in the Kattegat. The phytoplankton community is represented by only a very small fraction of the world species total and approximately 10 species of zooplankton account for most of the biomass and production.

The species composition of the zooplankton reflects the salinity, with more marine species (e.g., *Pseudocalanus* sp.) in the southern areas and brackish species (e.g., *Eurytemora affinis* and *Bosmina longispina maritima*) in the northern areas. As a result of the declining salinity, the relative abundance of small plankton species has increased in some parts of the Baltic Sea LME (Viitasalo *et al*. 1995). Since the 1980s, the abundance of *Pseudocalanus* sp. has declined in the central Baltic, whereas the abundance in spring of *Temora longicornis* and *Acartia* spp. increased (Möllmann *et al*. 2000, 2003). This change is unfavourable for cod recruitment (Hinrichsen *et al*. 2002) and herring growth (Möllmann *et al*. 2003, Rönkkonen *et al*. 2004), whereas it favours sprat, currently the dominant fish species in the Baltic Sea.

Changes have been documented in the productivity of the near coastal as well as offshore waters due to eutrophication as a consequence of increased nutrient inputs (Jansson 2003). Eutrophication is the secondary driving force of biomass change in this LME (Sherman 2003). Changes in community structure of the phytoplankton have occurred, e.g., the former dominance of diatoms, especially in the spring bloom, has switched to dinoflagellates and increased blooms of cyanobacteria (Kahru *et al*. 1994). Among the marine mammals in the LME are grey seal (*Halichoerus grypus*), ringed seal (*Phoca hispida*) and harbour seal (*P. vitulina*), and a small population of harbour porpoise (*Phocaena phocaena*).

Oceanic fronts (after Belkin et al. 2009): Several fronts (Figure XII-35.1) exist within the Baltic Sea LME (Belkin. 2004), namely the Bothnian Bay Front (BBF), Bothnian Sea Front (BSF), North Baltic Proper Front (NBPF), South Baltic Proper Front (SBPF), Gotland Front (GF), Irbe Strait Front (ISF), and Arkona Front (AF). Most fronts are topographically controlled: BBF and BSF encircle the respective depressions, while NBPF, SBPF, and GF extend along 100-m isobath that outlines the Baltic Proper basin. The ISF is situated over the outer edge of a sill that separates the Gulf of Riga from the Baltic Proper. Some fronts are distinct year-round - BSF, NBPF and SBPF- while others emerge and persist seasonally.

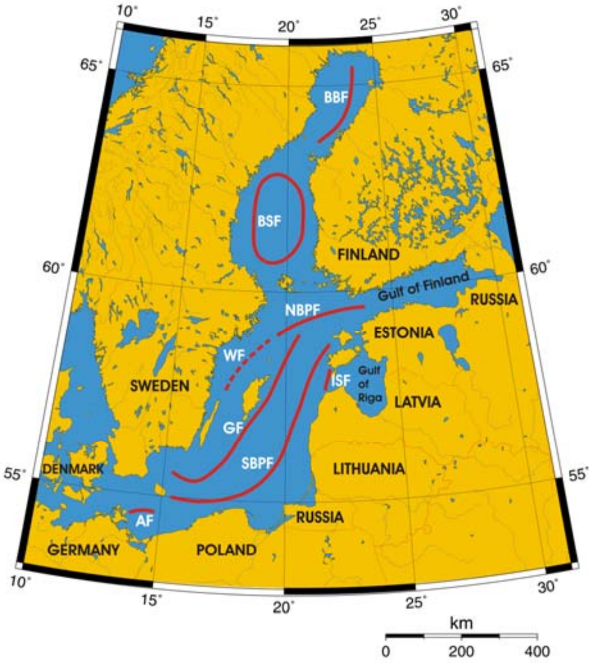

Figure XII-35.1. Fronts of the Baltic Sea LME. AF, Arkona Front; BBF, Bothnian Bay Front; BSF, Bothnian Sea Front; GF, Gotland Front; ISF, Irbe Strait Front; NBPF, North Baltic Proper Front; SBPF, South Baltic Proper Front; WF, Western Front (most probable location). After Belkin et al. 2009.

Baltic Sea LME SST (Belkin, 2009)
Linear SST trend since 1957: 0.75°C.
Linear SST trend since 1982: 1.35°C.

The long-term 50-year warming (Figure XII-35.2) was interrupted in 1976 by an abrupt cooling of nearly 2°C over just three years. After a partial rebound, SST dropped again, by >1°C in a year, and by 1987 reached the all-time minimum of 6.4°C, more than 2°C below the previous all-time maximum of 8.7°C in 1975. The exceptionally cold spell of 1985-87 was followed by a spectacular 2.3°C rebound in just two years. This is probably the most abrupt warming observed in any LME to date. The extremely rapid warming rate of 1.5°C/year in 1986-87 provided a test of the Baltic Sea LME resilience with regard to rapid climate warming. According to HELCOM (2007), from 1861–2000 the trend for the Baltic Sea basin has been 0.08°C/decade (cf. global SST trend of 0.038°C/decade between 1850-2005, according to the IPCC Fourth Assessment in 2007). Our analysis shows that the Baltic Sea warming accelerated over the last 50 years, with the average SST warming rate of 0.15°C/decade. The post-1987 warming was dramatic compared with previous years, with the average SST warming rate well over 1.0°C/decade. These results are confirmed by daily monitoring surface data (Mackenzie and Schiedek 2007): since 1985, summer SST increased three times faster than the global warming rate, and two to five times faster than other seasons' SST. "The recent warming event is exceeding the ability of local species to adapt and is consequently leading to major changes in the structure, function and services of these ecosystems" (Mackenzie and Schiedek 2007, p.1335). As the Baltic Sea becomes warmer and fresher, "marine-tolerant species will be disadvantaged and their distributions will partially contract from the Baltic Sea; habitats of freshwater species will likely expand" (Mackenzie et al. 2007, p.1348).

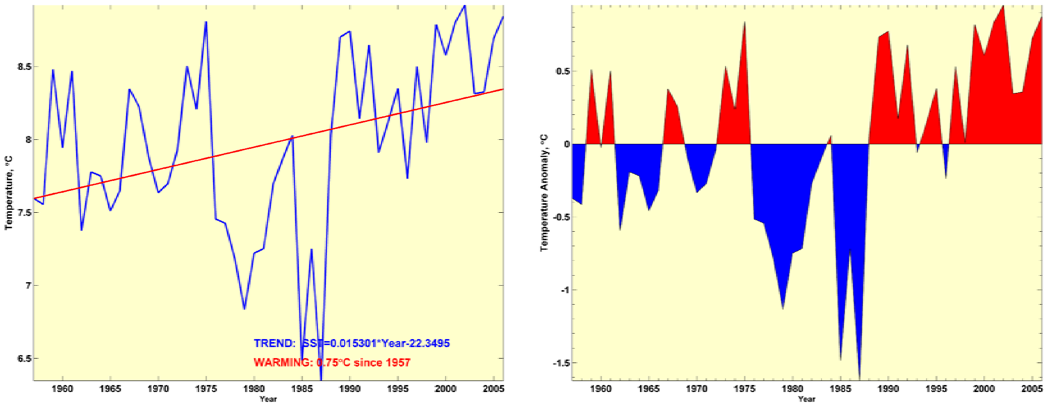

Figure XII-35.2. Baltic Sea LME annual mean SST (left) and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Baltic Sea LME Chlorophyll and Primary Productivity: The Baltic Sea LME is a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}).

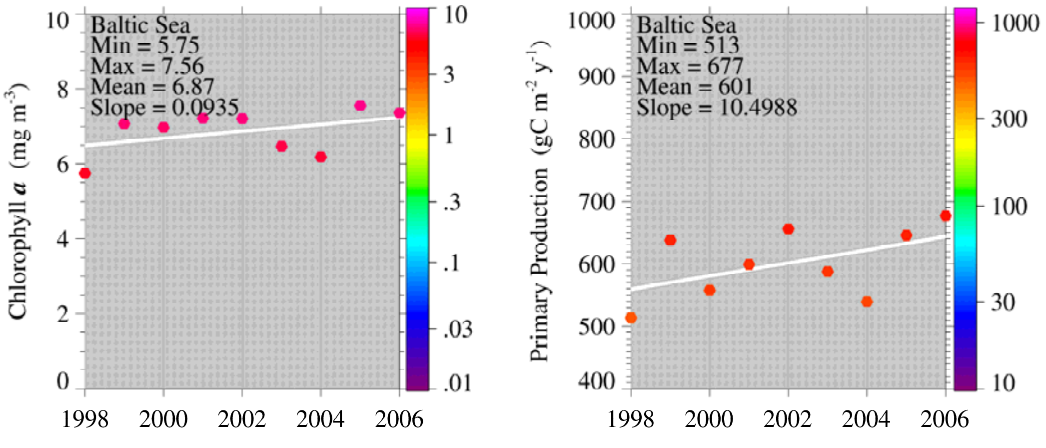

Figure XII-35.3. Baltic Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, Valuesare colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

In the Baltic Sea LME, cod (*Gadus morhua*), herring (*Clupea harengus*) and sprat (*Strattus sprattus*) dominate the fish community in terms of numbers and biomass. Commercially important marine species are sprat, herring, cod, various flatfish and salmon (*Salmo salar*). Other important target species are sea trout (*Salmo trutta*), pike-perch (*Stizostedion lucioperca*), whitefish (*Coregonus lavaretus*), eel (*Anguilla anguilla*), bream (*Abramis brama*), perch (*Perca fluviatilis*) and pike (*Esox lucius*). Total reported landings in this LME showed a steady increase from the 1950s to the 1970s and the early 1980s when the landings of over 900,000 tonnes were recorded (Figure Xii-35.4). A decline in the landings was recorded in the late 1980s, down to 560,000 tonnes in 1992 due to diminished landings of Atlantic cod. This was followed by record landings in 1997 with 975,000 tonnes, almost half of which was that of European sprat (Figure XII-35.4). The landings have since declined again, with 670,000 tonnes reported for 2004. The value of the reported landings peaked in the late 1960s and the early 1970s, estimated at US$960 million (in 2000 US dollars) in 1969 (Figure XII-35.5).

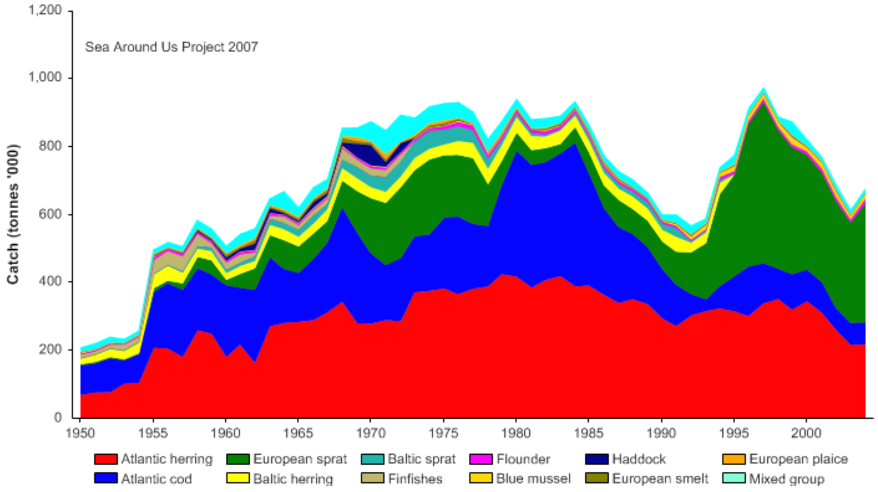

Figure XII-35.4. Total reported landings in the Baltic Sea LME by species (Sea Around Us 2007).

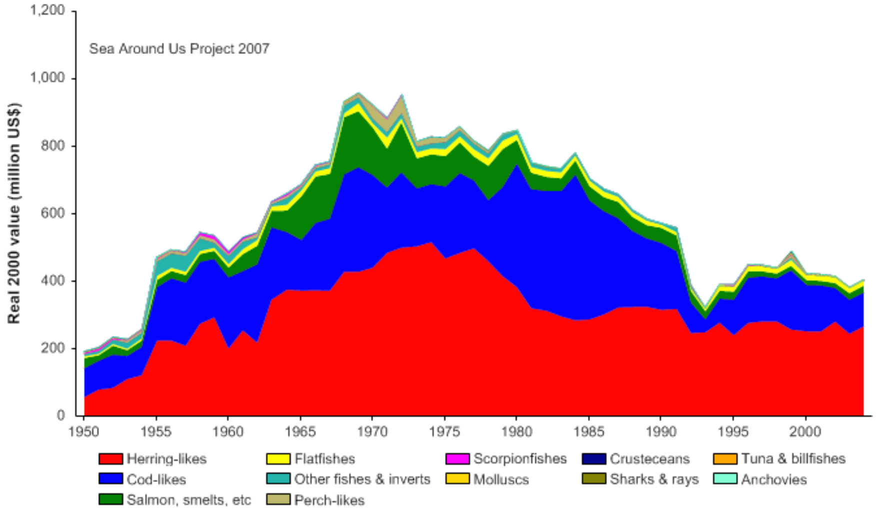

Figure XII-35.5. Value of reported landings in the Baltic Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 25% of the observed primary production in the mid-1980s, but has declined to less than 10% in recent years (Figure XII-35.6). The countries bordering the LME account for most of the ecological footprints, roughly corresponding to the extent of their coastlines.

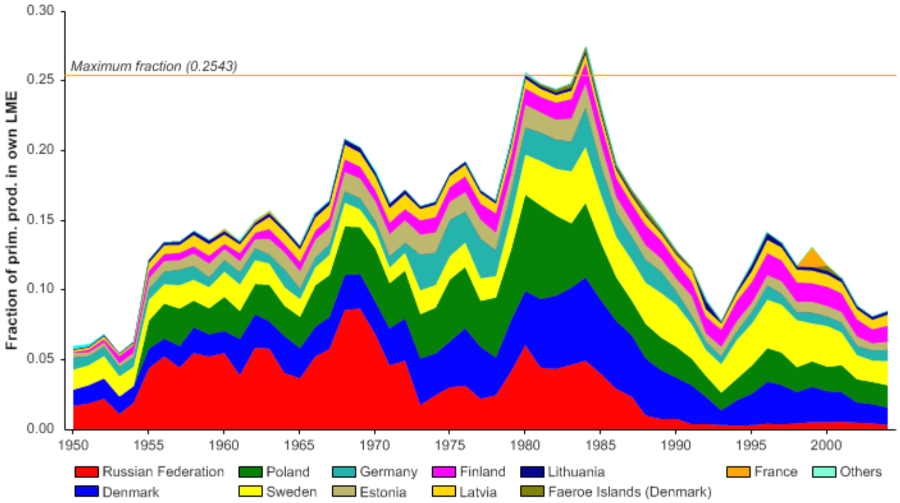

Figure XII-35.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Baltic Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) shows a significant decline from the mid 1980s to 2004 (Figure XII-35.7, top), likely due to the increased sprat landings. However, as a notable decline in Atlantic cod landings is also evident (Figure XII-35.4), and together with the decline in the mean trophic level, constitutes a case of a 'fishing down' of the local food webs (Pauly *et al.* 1998). The rapid decline in the FiB index also supports this interpretation (Figure XII-35.7, bottom).

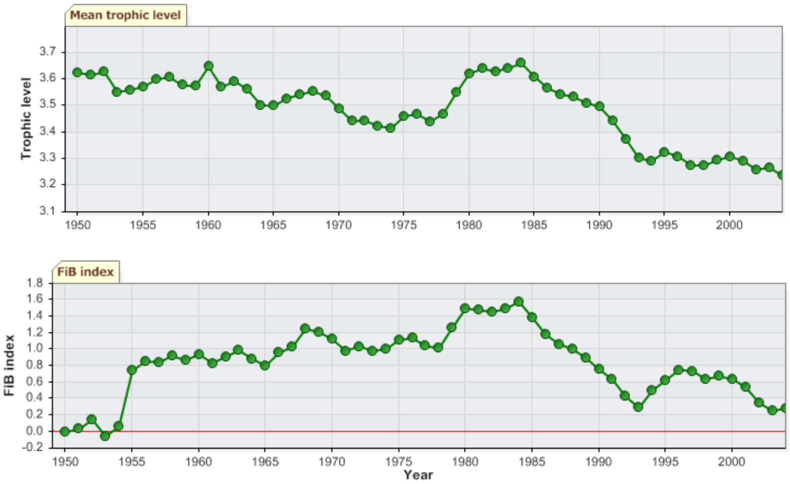

Figure XII-35.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Baltic Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that over 60% of the fished stocks in the LME have collapsed (Figure XII-35.8, top), but that the majority of the catch is supplied by fully exploited stocks (Figure XII-35.8, bottom), likely due to the large European sprat catch.

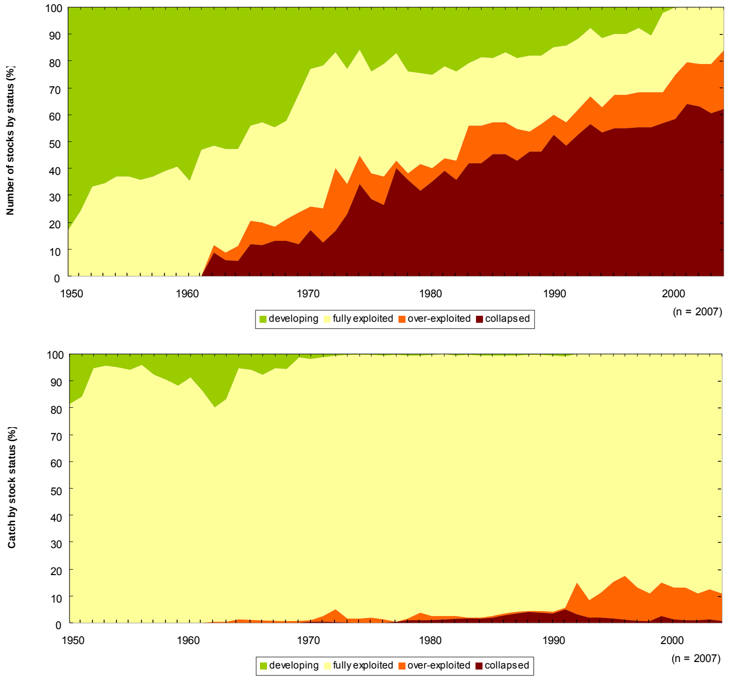

Figure XII-35.8. Stock-Catch Status Plot for the Baltic Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Overexploitation was found to be severe in the Baltic Sea LME (UNEP 2005), with intense fishing the primary driving force of biomass change (Sherman 2003). The stocks have been exploited at levels beyond those advised by ICES. Fleet capacity as well as fishing effort have not been reduced, with fishing mortality continuing to increase during stock decline (Baltic 21 1998). The fisheries for cod, herring, salmon and eel are unsustainable (Jansson 2003). High cod exploitation rates since the early 1980s resulted in a decline in its abundance (Baltic 21 1998). Cod landings were 3.5 times smaller during the 1990s (ICES 1994, 1999a, 1999b) and a number of actions to address this situation were taken by the IBSFC up to 2006. In September 2007 the EC agreed on a new management plan for cod in the Baltic Sea. Between 1984 and 1992, a decline in spawning stock size was also observed (Baltic 21 2000). During the last years ICES advice for the eastern cod stock have been a zero advice. However, the latest (May 2008) advice was placed at the level of 48,000 ton which must be considered being a trend brake. The improvement of the cod stock is mainly due to the management plans but also to the fact that the new advice is based on the ecosystem-based approach to management. A continuous decreasing trend in mean weight-at-age has been observed in most of the herring stocks since the mid-1980s. Population sizes of sea trout and eel have declined significantly, while sturgeons, once common in the Baltic Sea LME and its large rivers, are now extinct from the area. As a result of damming, pollution and fishing, wild salmon is another species of great concern to the IBSFC (Baltic 21 1998). The wild component has declined to some 10% of the total stock. A Salmon Action Plan, implemented to safeguard and increase the present wild populations, has been adopted by the IBSFC. Large-scale rearing and stocking of smolt has been undertaken to compensate for the decline of wild salmon stocks.

Excessive bycatch and discards and destructive fishing practices were considered to be slight (UNEP 2005), although their impacts are still unknown and unexplored to a large extent. The EU has supported several studies of bycatch, the results of which have been compiled by ICES (2000). These studies primarily concern the major fisheries for cod, herring, and sprat, which have low bycatches. The less important smaller fisheries can have a high proportion of bycatch (HELCOM 2002), for example, in the roe fishery (vendace, *Coregonus alba*). Bycatch of harbour porpoises has been reported in the fisheries in Danish and German waters. Seals are also taken as bycatch, but this added mortality does not seem to threaten the population since their numbers are increasing (HELCOM 2002).

A slight improvement in the fisheries of this LME is anticipated due the implementation of appropriate regulations, and the improvement of the eastern cod stock seems to be a good example of this. However, the impacts on fisheries of long-term natural environmental variability and anthropogenic pressures on the Baltic Sea ecosystem have not been fully explored, making it difficult to predict future trends in the fisheries.

III. Pollution and Ecosystem Health

Pollution: The ecosystem of the Baltic Sea LME is very sensitive to pollution, as a result of the limited water exchange and run-off from the vast catchment area (HELCOM 2003). The increasing human population after the year 1800, estimated at 85 million now living in the catchment area (HELCOM 2007) as well as intense industrialisation after the two World Wars have led to increasing emissions of contaminants into the LME (Jansson 2003). These include point sources from industries and municipalities and non-point source agricultural pollutants. Pollution is generally severe, with eutrophication being the most pressing environmental issue (UNEP 2005). The most striking changes in this LME since World War II are due to severe eutrophication from increased nutrient inputs (Jansson 2003), principally from agricultural discharges via rivers. Evidence of eutrophication includes hypoxic conditions in deep water over widespread areas, increased occurrence of HABs and significant biological changes in the littoral communities (HELCOM 2002). The occurrence of HABs increased between 1994 and 1998, with several large phytoplankton blooms in the Baltic Proper, the adjacent gulfs as well as the Kattegat and Belt Sea. About 30 phytoplankton species have been proved to be harmful. Toxic events such as outbreaks of fish kills as well as marine mammal and seabird mortalities caused by blue-green algae have been documented since the early 1960s (Baltic 21 1998). Addressing the problem of eutrophication requires an urgent, substantial reduction in nutrients from the agricultural sector (Lääne *et al*. 2002).

Microbiological pollution is often a local problem mainly related to discharges of untreated wastewater. During the last decade, the construction of biological wastewater treatment plants in the coastal and catchment areas has reduced the concentration of microbes in wastewater. Pollution from suspended solids results from the increased amounts of phytoplankton in eutrophic areas and increased coastal erosion in southern and eastern areas of the LME.

Mercury concentration in sediments was found to be highest in the Bay of Bothnia as well as the eastern Gulf of Finland, while the concentration of cadmium, zinc and copper was highest in the central basin of the Baltic Sea. Lead, however, seems to be evenly distributed (HELCOM 2002). The health of many birds of prey and mammals has improved but some species still experience reproductive problems. The concentrations of most heavy metals monitored in mussels, fish and in bird eggs have decreased or remained stable. An exception is cadmium, the concentration of which increased in fish during the 1990s. Metal concentrations at appreciable levels were found in fish in the southern part of the Gulf of Bothnia, in the eastern end of the Gulf of Finland, in the Kattegat and in the Gulf of Riga (Baltic Sea Environment 2004).

Despite the implementation of recommendations by HELCOM to reduce discharges of pollutants into the Baltic Sea LME and the steady decrease of organochlorine compounds throughout the region during the past 30 years, inputs of chlorinated compounds and other toxicants such as pesticides and polychlorinated compounds still occur. The concentration of dioxins in herring and salmon varies regionally, with the highest levels found in herring in the Bothnian Sea and salmon in the Bothnian Bay. According to HELCOM (2003), the transfer of dioxins up the marine food chain is observed in fish-eating birds and their eggs. The concentration of dioxins in guillemots' eggs decreased rapidly until the mid 1980s, but has since remained at roughly the same level. Dioxin concentrations in sediments peaked in the 1970s then began to decrease (HELCOM 2003). Evidence has been found of moderate levels of decreased viability of stocks in the Baltic Sea ecosystem caused by pollution and diseases. Examples of diseases include the mouth disease of pike, crayfish disease, salmon M-74 disease, bacterial skin ulcer in cod and diseases in eel as well as flatfish (Walday & Kroglund 2002).

Despite the designation of the Baltic Sea as a 'special area' under MARPOL 73/78, many illegal oil discharges are observed in the region. Between 1969 and 1995, about 40 major oil spills greater than 100 tonnes were registered and an average of about three accidents occur each year. However, this is not entirely surprising for an area where 7,000 voyages involving the transport of oil take place annually. The number of accidents may rise during the next decade as seaborne oil transport is expected to increase from its current level of 77 to 177 million tonnes per year (HELCOM 2002). While spills from vessels and offshore platforms contribute the most conspicuous input of oil, these account for only a small part of the total marine oil pollution in the Baltic Sea LME (Baltic Sea Environment 2004). Most of the oil input into the Baltic Sea comes from dilute but persistent land-based sources.

One major growing concern in the Baltic Sea area is the introduction of invasive/alien species, mainly by the release of ballast water from oil tankers. During the last decades over one hundred invasive species have been detected and established, and several of these have had detrimental effects on the habitat. Two of the potentially most harmful invaders are the round goby (Neogobius melanostomus), well established in the southern Baltic and the ctenophore Mnemiopsis leidyi. HELCOM and the BSRP have supported the establishment of an on-line data-base for continuous information about alien species (Baltic Sea Alien Species Database, 2007: www.corpi.ku.lt/nemo/).

Habitat and Community Modification: The coastal and marine habitats of the Baltic Sea LME are under considerable pressure mainly from human settlements, pollution and coastal construction. Habitat and community modification were found to be moderate (UNEP 2005). Approximately 90% of the marine and coastal biotopes in the LME are threatened to some degree, either by loss of area or reduction in quality (HELCOM 2001, 1998). According to HELCOM (1998), 88% of the 133 marine biotopes and 13 biotope complexes are exposed to some kind of anthropogenic threat (e.g. eutrophication, contamination, fisheries or human settlements) and are considered to be endangered or highly endangered. Out of 66 pelagic and benthic marine biotopes assessed, two were classified as heavily endangered, 58 as endangered and four as potentially endangered (HELCOM 1998).

Sandy foreshores (intertidal zone; wet-sand area) have been affected by tourism, pollution and construction. Lagoons are threatened by pollution, urbanization, industry, agriculture, and dredging, while estuaries suffer from land-based pollution and construction. Muddy and rocky foreshores in Sweden and Finland have been affected by dredging and the construction of harbours, respectively. Sea grass and *Fucus* meadows have been moderately impacted by pollution. The long-term changes in the Baltic ecosystem are described by Kullenberg (1986).

Improvements in the health of this LME are occurring as a result of several ongoing activities and the implementation of environmental protection legislation. The significant reduction in the discharge of hazardous and biogenic substances at the end of the 20th century was an important step towards reducing the pollution load of the LME. Since 1992 about 50 hot spots have been cleaned up. However, as a consequence of the slow water exchange and the accumulation of large quantities of pollutants, it may be a long time before a significant improvement in water quality is achieved (UNEP 2005). Greater public awareness of the impact of human activities on sensitive habitats is needed, although in many instances it may be too late to rehabilitate the modified ecosystems.

IV. Socioeconomic Conditions

Economically, the Baltic Sea states can be divided into two groups: old market economy countries (Denmark, Finland, Germany and Sweden), and countries in economic transition (Estonia, Latvia, Lithuania, and Poland, which acceded to the EU in 2004) and Russia. A fairly stable and largely urbanised population of nearly 85 million people of many ethnic groups lives within the catchment area, about half of them in Poland.

The fishing industry makes a significant contribution to the regional as well as local economies, with subsistence fishing critical to the social and economic welfare of the coastal communities in the eastern Baltic Sea. Fisheries traditionally play an important role in food supply, especially in Estonia, Latvia and Lithuania. The economic impact of unsustainable exploitation of fish and other living resources is moderate, although in some areas the impact is severe (UNEP 2005), for example in Poland (EU Enlargement 1998) and in Kaliningrad, Russia (Dvornyakov 2000), where fisheries are significant in the national economy. The market for fish is affected as fish landings become more variable and uncertain. Reduced landings also increase unemployment in the fisheries sector and subsequently jeopardise income growth. Worsening unemployment as well as loss of livelihood among fishermen is a growing concern especially in the recently EU-acceded countries and Russia. The unemployment level in Russian fisheries is estimated to be 1.5 to 3.5 times higher than in other sectors (Dvornyakov 2000). Declining returns from fisheries could also lead to higher demands for subsidies and other governmental fishing support. Moreover, severe protection measures to help fish stock recovery may, in the short term, further exacerbate the economic impact (Baltic 21 1998, FAO 1999).

The socioeconomic impacts of pollution include possible health risks from consuming contaminated fish (UNEP 2005). However, the potential health impacts of pollution will be reduced with the implementation of EU Directives to limit the use of fish with high dioxin levels. The recreational value of coastal areas may be affected as a consequence of pollution. Generally, the socioeconomic impacts of habitat and community modification are slight in relation to human needs for food as well as aesthetic and recreational values. Nevertheless, the loss and modification of habitats will have serious economic impacts in the future, requiring considerable investments to restore damaged habitats.

V. Governance

Water protection in the Baltic Sea region is regulated by several international conventions ratified by the Baltic Sea states. ICES is one of the main organisations coordinating and promoting marine research in the North Atlantic, including its marginal seas such as the Baltic and North Seas. The Baltic Sea Regional Seas Programme is an independent programme (not established under UNEP), but participates in the global meetings of UNEP Regional Seas and supports the developing Regional Seas Programmes.

The two most important conventions regulating the protection of the environment and living resources of the Baltic Sea LME up to 2006 were the Convention on Fishing and Conservation of the Living Resources in the Baltic Sea and the Belts, signed in Gdansk in September 1973 (Gdansk Convention)(implementing unit: IBSFC), followed by the Convention on the Protection of the Marine Environment of the Baltic Sea Area, signed in Helsinki in March 1974 (Helsinki Convention)(implementing unit: HELCOM). Each year, on the basis of recommendations from ICES, the IBSFC, and after 2006 the EU, sets total allowable catches for the four main commercial species: cod, salmon, herring and sprat. HELCOM, which is responsible for the implementation of the Convention, coordinated a joint monitoring programme of the Baltic The countries in the drainage basin initiated a Joint Comprehensive Environmental Action Programme for the Baltic Sea (JCP). This programme, was adopted in 1992 and strengthened and updated in 1998, constituted a 'Strategic Action Plan' for the Baltic Sea region. HELCOM is now finalising a new Baltic Sea Action Plan which, like the JCP, will provide an environmental management framework for the long-term restoration of the ecological balance of the Baltic Sea, recognizing the linkages between freshwater, coastal and marine resources.

Baltic 21 is a regional multi-stakeholder process for sustainable development initiated in 1996 by the Prime Ministers of the eleven member states of the Council of the Baltic Sea States. The Mission of Baltic 21 is to pursue sustainable development in the Baltic Sea Region by regional multi-stakeholder cooperation. Accordingly, Baltic 21 provides a regional network to implement the globally agreed Agenda 21 and World Summit on Sustainable Development activities, while focusing on the regional context of sustainable development (Baltic 21 2004).

The GEF supported the Baltic Sea Regional Project, the basis for which was provided by the JCP, until several of the participating countries became members of the EU. Proposals for assisting the Russian Federation with Baltic Sea LME projects are underway. A long-term objective of these projects is to introduce ecosystem-based assessments to strengthen the management of Baltic Sea coastal and marine environments through regional cooperation as well as targeted transboundary coastal, marine and watershed activities. A major objective is to develop an array of ecosystem management tools to manage the whole Baltic Sea ecosystem. Agencies collaborating in the GEF project include HELCOM, the IBSFC and ICES. Eight of the nine states surrounding the Baltic Sea are now members of the EU as of May 1, 2004. There is a need to develop the technical, scientific and local capacity of the eastern Baltic countries to enable them to fully participate with western Baltic countries in improving the long-term sustainability and socioeconomic benefits of this LME.

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XIII NORTH EAST ATLANTIC

XIII-36 Barents Sea LME
XIII-37 Celtic-Biscay Shelf LME
XIII-38 Faroe Plateau LME
XIII-39 East Greenland Shelf LME
XIII-40 Iberian Coastal LME
XIII-41 Iceland Shelf LME
XIII-42 North Sea LME
XIII-43 Norwegian Sea LME

XIII-36 Barents Sea LME

S. Heileman

The Barents Sea LME is situated within the European part of the Arctic shelf and to the north of the Polar Circle (Matishov *et al*. 2003). It is a relatively shallow sea with a surface area of about 1.7 million km^2, of which 4.32% is protected (Sea Around Us 2007), a large shelf, and an extensive polar front. Among its river systems and estuaries are the Dvinskaya Guba and Pechorskaya Guba. This LME is a transition zone where relatively warm inflowing Atlantic water is cooled and transformed into Arctic as well as Polar water (Blindheim & Skjoldal 1993). Arctic continental shelves show a complex density circulation, behaving as 'salt-wedge estuaries' in summer and, by the deep export of salt-rejection brine produced as the sea freezes, 'negative estuaries' in winter (Longhurst 1998). The surface water is more dilute and shows greater seasonal variation in salinity than the central part of the Arctic Ocean (Carmack 1990). The climate of this LME shows high spatial and temporal variability that depends mainly on the activity and temperature of the inflowing Atlantic water. A notable feature is the extreme environment with considerable annual and inter-annual variations in ice cover, which extends over one- to two-thirds of the sea with maximum extension during winter (Blindheim & Skjoldal 1993). Book chapters and reports pertaining to this LME include Blindheim & Skjoldal (1993), Dalpadado *et al*. (2002), Matishov *et al*. (2003) and UNEP (2004).

I. Productivity

The Barents Sea LME can be considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). Biological activity in the Arctic seas is determined mainly by seasonal changes in the temperature and light regimes, advection and ice cover (Matishov *et al*. 2003). Many biological processes are strongly influenced by the formation of the seasonal thermocline and convective mixing (Terziev 1990). In addition, the drifting and fixed ice masses have a significant influence on the dynamics as well as seasonality of plankton communities and consequently, the higher trophic levels (Matishov *et al*. 2003). The ice-edge zones are distinguished by increased primary production in spring and early summer in response to the melting of ice (Blindheim & Skjoldal 1993, Matishov *et al*. 2003). The total annual primary production from in situ data is estimated to be 38.4 million tonnes of carbon (Vetrov and Romankevich 2004).

More than 310 species of pelagic microalgae belonging to the Diatomea, Bacilloriophyta, Dinophyta, Chrysophyta, and Chlorophyta, among others, have been identified in the phytoplankton of the Barents Sea LME. Approximately 40% of these can be characterised as Arctic species, more than 20% as boreal species and the rest as cosmopolitan or with an undesignated geographic distribution (Biological Atlas of Arctic Seas 2000). Phytoplankton blooms in the surface water masses are dominated by *Chaetoceros* spp. and *Phaeocystis pouchetii*. Ice algae such as *Melosira arctica* and loosely attached mats of diatoms are a feature of the ice-covered portions of the Arctic seas. Algal macrophytes include *Ascophyllum nodosum*, *Fucus distichus* and blade-kelps *Laminaria saccharina* and *L. digitata* (Matishov 1998).

Boreal, arctic, and transitional species constitute the zooplankton (Biological Atlas of Arctic Seas 2000). In the Barents Sea and elsewhere in the Arctic, copepods are the dominant group of zooplankton followed by amphipods, decapods, ostracods, pteropods and chaetognaths (Melnikov 1997). The water column below the ice is inhabited by a sparse but permanent zooplankton community, its biomass dominated by calanoid copepods such as *Calanus glacialis* (*C*. *finmarchicus* in the south) and *C*. *hyperboreus* and larger numbers but smaller biomass of species such as *Pseudocalanus*, *Oithona*, and *Microcalanus* (Longhurst 1998). Dalpadado et al. 2002) have shown the richness of the zooplankton community in the northern Barents Sea.

The Arctic trophic links vary significantly according to the environmental conditions (Matishov *et al*. 2003). For example, in the Atlantic water mass, each level of the food web contains one dominant, central species or group of species on which the rest of the biota depends. These dominant groups include pelagic crustaceans (*Calanus finmarchicus* and Euphausids), herring (*Clupea harengus*), capelin (*Mallotus villosus*), polar cod (*Boreogadus saida*) (in the NE) and cod (*Gadus morhua*). Marine birds and mammals (e.g., seals, polar bears and whales) are among the top consumers in the pelagic realm. Biological activity is also closely connected with the ice cover. The Arctic sea ice biocenoses are described by Melnikov (1997). The biota within the sea ice is small (<1mm) and dominated by bacteria, unicellular plants and animals and small multi-cellular animals. Protozoans, turbellarians, nematodes, crustaceans and rotifers can be abundant in the ice year-round. Partially endemic fauna comprised mainly of gammaridean amphipods thrive on the underside of ice floes with up to several hundred individuals m^{-2}. The amphipods are a prey of cod, which in turn are preyed upon by marine mammals (e.g., seals) and birds. The polar bear (*Ursus maritimus*) and the Arctic fox (*Alopex lagopus*) are the top consumers on the drifting sea ice.

Oceanic fronts (Belkin et al. 2009): The Atlantic flow enters the Barents Sea LME along the Norwegian coast and continues along Russia's coast, carrying warm and salty waters that form distinct TS-fronts at the contact with coastal waters and resident waters of the Barents Sea proper (Belkin *et al*. 2009). North of Tromsø and Nordkapp two fronts are distinguished: a coastal front just a few miles off the coast and an offshore front farther out to sea (Figure XIII-36.1). The Polar Front (PF) south of Bear Island follows the Spitsbergen (Svalbard) continental slope, which provides bathymetric steering to the front and ensures its stability. In the absence of topographic steering elsewhere within the Barents Sea LME, the Polar Front's location is variable and depends largely on the intensity of the Atlantic inflow to the Barents Sea.

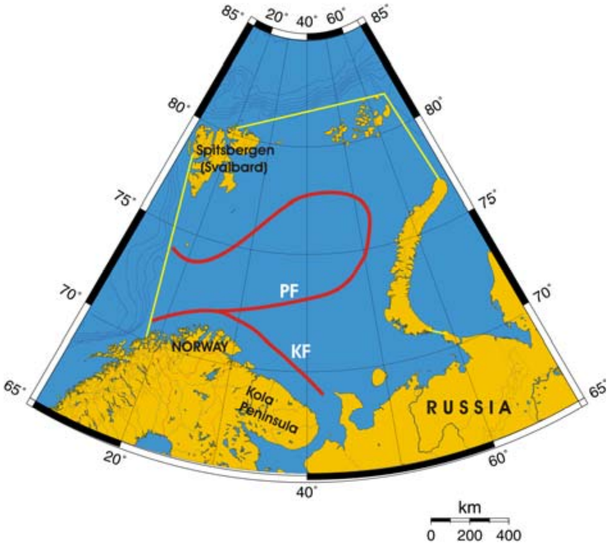

Figure XIII-36.1. Fronts of the Barents Sea LME. PF, Polar Front; KF, Kola Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

Barents Sea LME (Belkin 2009)(Figure XIII-36.2):
Linear SST trend since 1957: -0.04°C.
Linear SST trend since 1982: 0.12°C.

In the long-term, the Barents Sea LME appears relatively stable, although its interannual variability is substantial, having a magnitude of 1°C. The timing of cold events of 1978-79, 1987, and 1997-99 is consistent with passages of decadal-scale "Great Salinity Anomalies" (Dickson et al., 1988; Belkin et al., 1998; Belkin, 2004) of the 1970s, 1980s, and 1990s through the Barents Sea. The double-pronged cold event of 1966-68, which resulted in the all-time low of 2.6°C in 1966, must have had a different origin. The well-defined warming events that peaked in 1973 and 2000 also need to be explained. The last warming event, of 2000, was concurrent with a sharp maximum in the Norwegian Sea, consistent with large-scale atmospheric forcing and also with oceanic advection. The previous peak of 1974 in the Norwegian Sea may have been related to the Barents Sea maximum of 1973.

One has to be cautious while trying to determine long-term trends in the Barents Sea. Depending on choice of end points, trends could be increasing or decreasing. Most recent reports of a dramatic three-degree warming of the Barents Sea over the last 26 years are based on satellite data from 1982 on. Note that the year of 1982 was one of the coldest years on record in this area. Therefore, selection of this year as an end-point would yield a rapidly increasing SST trend.

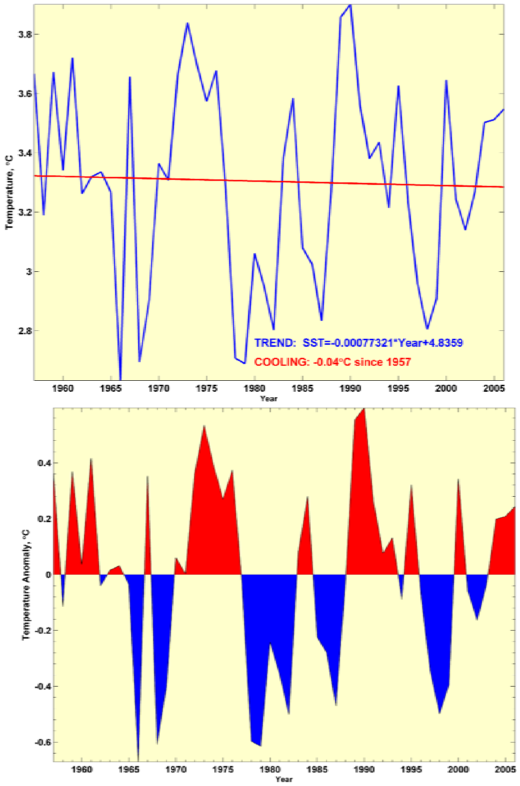

Figure XIII-36.2. Barents Sea LME annual mean SST (top) and SST anomalies (bottom), 1957-2006, based on Hadley climatology. After Belkin (2009).

Barents Sea LME Chlorophyll and Primary Productivity

The Barents Sea LME is a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1})(Figure XIII-36.3).

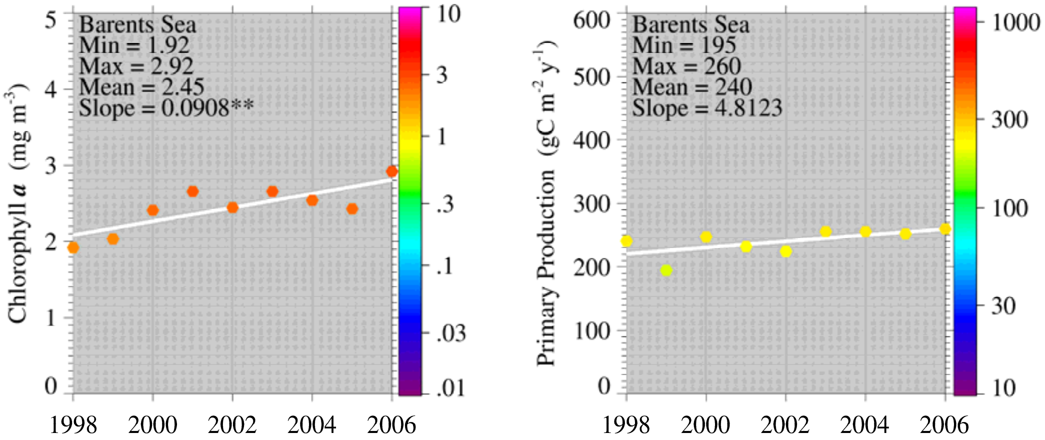

Figure XIII-36.3. Barents Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998 – 2006, from satellite ocean colour imagery; courtesy of K. Hyde.

II. Fish and Fisheries

The major species fished in the Barents Sea LME are capelin, Atlantic cod and herring, with capelin and herring being the major prey of cod (Blindheim & Skjoldal 1993). The LME is one of the world's most intensively exploited ecosystems, with severe overexploitation of the major fish stocks such as cod and haddock (UNEP 2004).Note that the Norwegian Polar Institute reports a reduction in overfishing in 2008. During the last decades, the biomass yield of the major species has fluctuated significantly because of high fishing mortality and variation in the natural environment (Skjoldal 1990, Blindheim & Skjoldal 1993, Matishov *et al*. 2003).

Total reported landings show marked fluctuations and reached a peak of 3.3 million tonnes in 1977, with capelin accounting for 70% of these landings, followed by a precipitous decline to 340,000 tonnes in 1990 (Figure XIII-36.4). Cod landings have decreased considerably from the early 1970s, possibly as a result of the temperature-salinity anomaly (indicated by cooling and reduced salinity) that occurred in the northern North Atlantic during the 1960s and the 1970s (Blindheim & Skjoldal 1993). By the beginning of 2000, the commercial cod stock was estimated at 1.5 million tonnes and its spawning stock at 300,000 tonnes, significantly lower than the average long-term values of 2.5 million and 600,000 tonnes, respectively (Borovkov *et al*. 2001). The total value of the reported landings also peaked in 1977, estimated at more than US$2.1 billion (in 2000 US dollars; Figure XIII-36.5). In her 2006 address to the North Atlantic Conference in Tromsø, Minister of Environment Helen Bjørnøy expressed strong concern for illegal, unregulated and unreported fisheries (IUU-fisheries) in the Barents Sea, stating that more than 100.000 tonnes of Arctic cod and 30–40,000 tonnes of haddock are estimated to be illegally fished there each year.

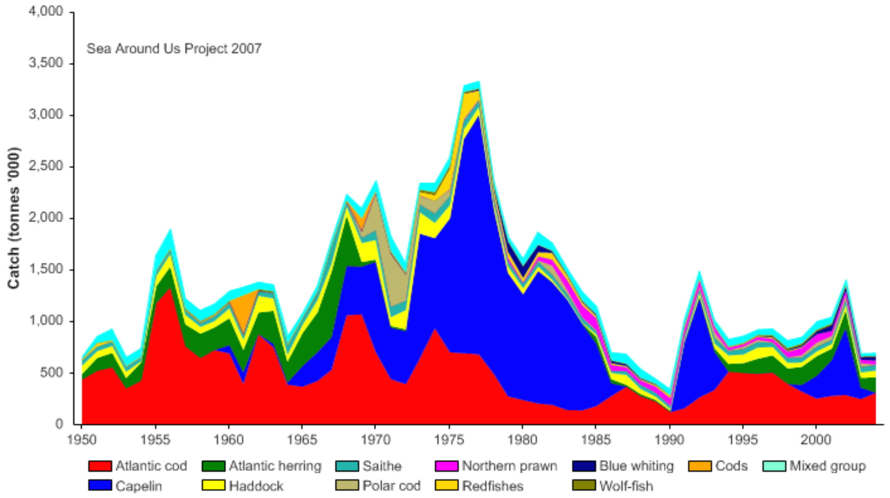

Figure XIII-36.4. Total reported landings in the Barents Sea LME by species (Sea Around Us 2007).

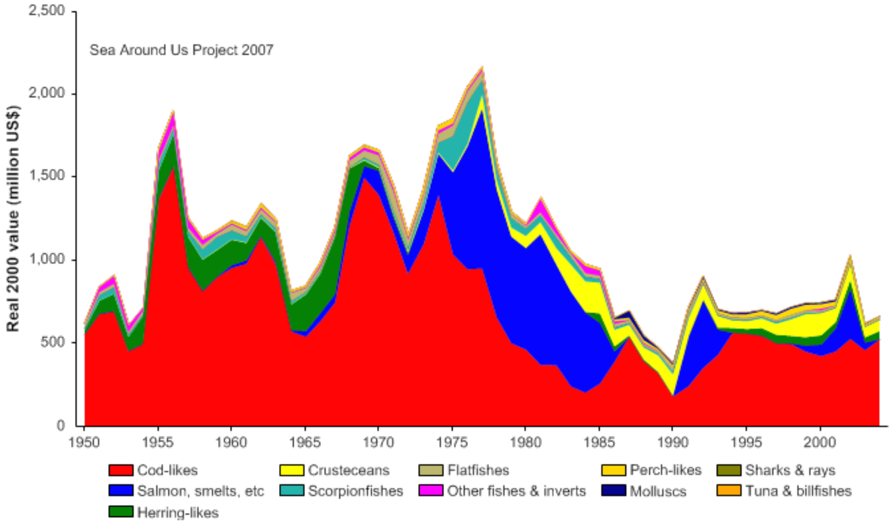

Figure XIII-36.5. Value of reported landings in the Barents Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 70% of the observed primary production in 1955 and recorded similarly high levels in mid 1970s, before declining to less than 30% in recent years (Figure XIII-36.6). The high PPR level achieved in 1955 is probably a result of the large landings of accumulated cod biomass, not of annual surplus production, whilst the levels achieved in the mid 1970s is likely due to the expansion of capelin distribution beyond the LME boundary which led to possible misreporting of capelin caught outside the LME as being caught within the LME. Russia and Norway have the largest share of the ecological footprint in this LME.

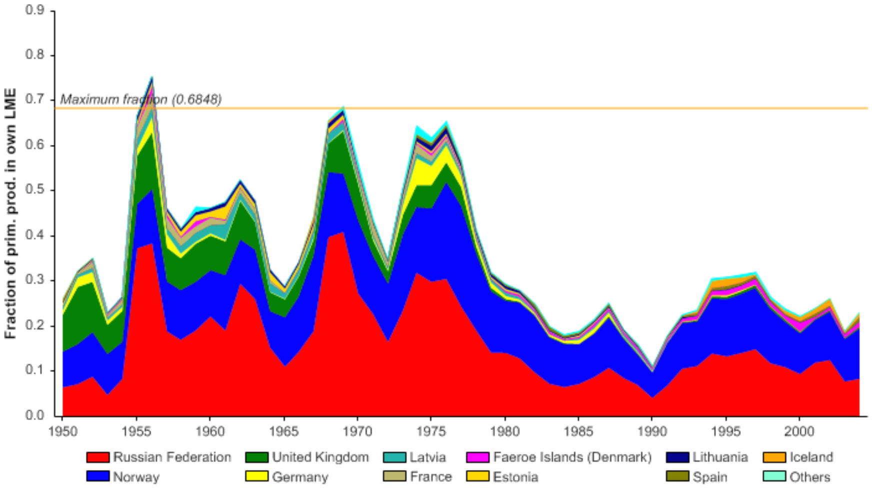

Figure XIII-36.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Barents Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the fisheries catch (i.e., the MTI; Pauly & Watson 2005) underwent a decline from 1950s to the mid-1980s, suggesting a 'fishing down' of the food web (Pauly *et al*. 1998); it then increased in a fluctuating manner (Figure XIII-36.7, top), reflecting the relative abundance of cod and capelin in the reported landings during the 1990s and the 2000s (Figure XIII-36.4). During the same period, the FiB index fluctuated without any observable trend (Figure XIII-36.7, bottom). The Nordic Council of Ministers is initiating a study on indicators for sustainable fisheries for the Barents and Norwegian Seas LMEs that is expected to shed new light on the fish abundance in these areas. Note that the Mare Cognitum Programme in the Norwegian Sea concluded that the food chains were short (phytoplankton – zooplankton – fish) with high trophic efficiency (20 % rather than 10%).

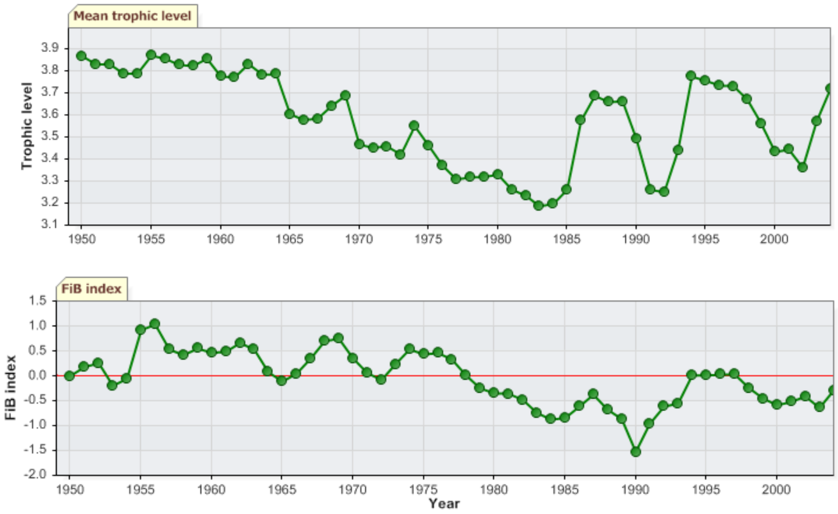

Figure XIII-36.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Barents Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that the number of collapsed stocks has been rapidly increasing, to about 80% of the commercially exploited stocks, with the remainder classed as overexploited (Figure XIII-36.8, top). The contribution to the reported landings biomass by these two stock categories is roughly equal (Figure XIII-36.8, bottom).

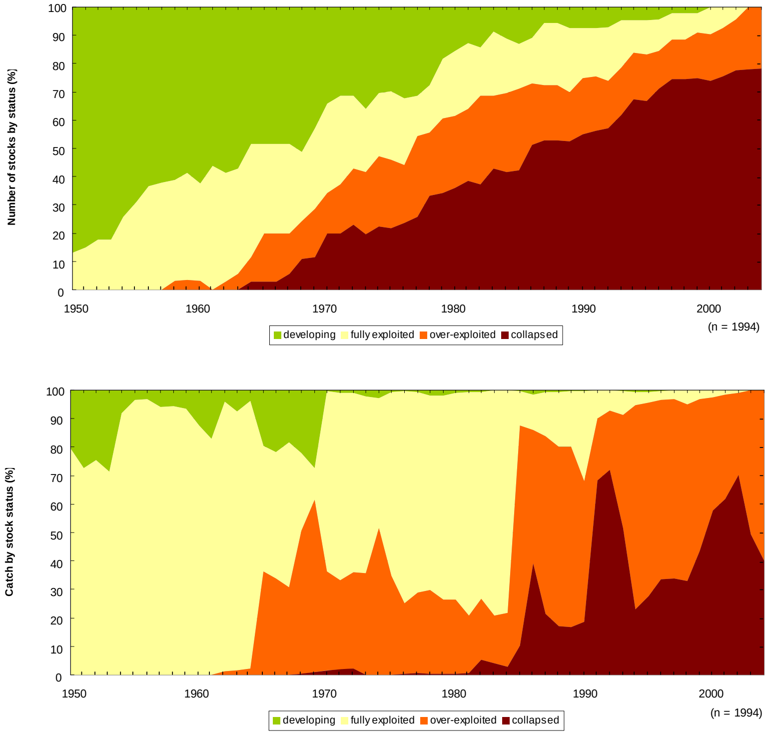

Figure XIII-36.8. Stock-Catch Status Plots for the Barents Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Over the past several decades, capelin biomass has declined significantly, falling from about 2.5 million tonnes in the late 1970s to almost zero during the late 1980s-1990s (Dalpadado *et al*. 2001, ICES 2003, Matishov *et al*. 2003). Predation on capelin larvae by young herring as well as on immature capelin by cod can have a marked impact on the capelin stock (Blindheim & Skjoldal 1993) and the formation of strong year classes of cod and herring in 1983 is thought to have contributed to the collapse of the capelin stock in 1986 (Blindheim & Skjoldal 1993). As capelin plays an important intermediate link in the food web, a decline in its biomass can have serious effects on other components of the regional ecosystem and may have led to the poor growth of local cod stocks (Monstad & Gjoesaeter 1987), high seabird mortality and massive seal invasions along the Norwegian coast (Skjoldal 1990). The capelin biomass has since increased to nearly three million tonnes in 1999-2000 (Matishov *et al*. 2003). The editors and Norwegian reviewer caution that management policies for reduction of catch for some stocks has caused an appearance of reduced amounts of fish available.

Bycatch and discards are considered to be small in the LME (UNEP 2004), but the available data are highly uncertain. These issues could, therefore, be serious (Matishov *et al*. 2003). Bycatch in the cod fishery consists mainly of under-sized cod and haddock.

According to studies by the Murmansk Marine Biological Institute and other unofficial assessments, discards of under-sized fish could be as high as 30% for several species, despite a number of regulations requiring that all bycatch must be landed. Moreover, lack of reliable data on the level of discards could be detrimental to fisheries management as it often leads to uncertainty in assessments of stock sizes (PINRO 2000). Destruction of the bottom habitat by trawling also has a negative impact on cod and bottom fish, such as catfish, perch, plaice, Greenland halibut and American plaice, which already suffer from relatively small stock sizes (UNEP 2004).

Mitigation of overfishing can be expected, as a series of management measures continue to be implemented in the LME. In fact, the total catch has shown some signs of recovery over the past decade. However, effective management and sustainable use of the LME's fisheries resources must also take into consideration the impact of environmental variability on these resources.

III. Pollution and Ecosystem Health

Pollution: The two main sources of pollution are water mass and atmospheric advection from external sources as well as industrial activities within the basin (Matishov *et al*. 2003). Water and ice exchange with adjacent areas has a significant role in the pollution of this LME, which is a sink for the Atlantic Ocean currents. However, information on the bulk of pollutants discharged into the LME is limited (Matishov *et al*. 2003). The authoritative source is the AMAP (2002) report on POPs, heavy metals, radioactivity, and other aspects affecting ecosystem health.

The overall slight level of pollution (UNEP 2004) is possibly related to the Barents Sea's high assimilating capacity and being open towards the north and the west (Matishov *et al*. 2003). Microbiological pollution, eutrophication and suspended solids are not of general concern (UNEP 2004), although elevated levels of microbiological pollution have been observed in some localised areas. Pollution by solid waste is due mainly to timber and municipal waste in localised areas.

The coastal areas are most exposed to chemical pollution. However, in these areas, the levels of chemical pollutants, such as chlorinated hydrocarbons and heavy metals and their compounds as well as organic compounds such as DDT are lower than the Maximum Allowable Concentrations, the standard set by Russian regulations and Norwegian Pollution Control Authority environmental quality assessment criteria (Molvaer *et al*. 1997). These levels are also lower than in other parts of Russia or in the European Seas (Matishov *et al*. 2003). An exception to this, however, is Kola Bay, which has high levels of contamination in the water and sediments. There are eutrophication hotspots in the estuarine zone of the Kola River (UNEP 2004). The areas adjacent to the port of Murmansk as well as the port centre of Severomorsk have extremely high levels of practically all metals. Elevated levels of POPs such as toxaphene and brominated flame retardant have been found in bottom sediments in some areas of the Kola Bay (Savinov *et al*. 2000).

Low accumulation of contaminants in the tissues and organs of the most important commercial species of fish and invertebrates has been reported (Matishov *et al*. 2003). On the other hand, elevated levels were detected in animals at higher trophic levels (seabirds, marine mammals and polar bear) due to food web bio-accumulation (Muir *et al*. 2003, Savinov *et al*. 2003).

There is concern over possible radioactive contamination. The main sources of artificial radionuclides in the marine environment include atmospheric fallout, river runoff, discharges from West-European nuclear reprocessing plants entering the region with the Gulf Stream Current, discharges of liquid radioactive wastes from sources on the Kola

Peninsula as well as a result of nuclear tests (mostly, on nearby Novaya Zemlya) and accidents such as occurred in Chernobyl (Matishov & Matishov 2001).

The oil, gas and shipping industries are potentially dangerous to the health of the LME, with the chronic pollution of the marine environment and biota from petroleum products being a serious environmental threat (UNEP 2004). The LME is covered with numerous navigation routes, including the Northern Sea Route and thousands of vessels, including oil tankers, pass through the Barents Sea year round. The presence of drifting and packed ice increases the threat of pollution because of the accumulation of concentrated oil products and other toxic substances in ice and their release into the marine environment during ice-melting in summer. Elevated hydrocarbon levels have been reported in some areas. For instance, levels of oil products higher than MAC are routinely recorded in the convergence zones and fishing grounds (Matishov *et al*. 2003). A spreading oil film covering a relatively large area has been observed in the vicinity of Kolguev Island where oil is extracted (Ivanov 2002). Pollution from petroleum products may worsen with the intensification of hydrocarbon extraction on the Arctic shelf and increased oil transport as well as shipping in the region. The Norwegian government has petitioned the UN's International Maritime Organization, IMO, to establish mandatory shipping routes, 30 nautical miles off the coast, between Vardø and Røst (Norwegian Ministry of Fisheries and Coastal Affairs 31 March 2006 press release).

Habitat and community modification: There are no records of serious habitat modification in the LME, but there is evidence of slight degradation and loss of some habitats (UNEP 2004). An important issue is the introduction of humpback salmon, snow crab (Kuzmin 2000) and red king crab into the LME (Orlov 1977). These species have caused serious changes in the faunal composition of benthic communities in localised areas. For example, sea urchin biomass in Zelenetskaya Bay decreased by a factor of five following the introduction of the red king crab (UNEP 2004). These might be natural changes in abundances, but similar changes in a number of areas may provide evidence for the impact of the crab on benthic communities. Distribution of the red king crab along the warm Atlantic water masses and its expansion into new warm water habitats has been observed (UNEP 2004). The introduction and rapid population growth of this species, which is a large mobile predator and polyphage, has limited the food resources for itself as well as for other benthic organisms including fish fry. The king crab is also an intermediate host for a cod fry parasite and an increased infection rate and potential decrease in cod abundance are expected in the coming years. The majority of the Barents Sea whales are rare or protected species and are included in the IUCN Red List.

At present the health of the Barents Sea LME is in relatively good condition. This may change, however, as a result of the rapid development of the oil and gas industry on the Arctic shelf, increased volume of oil and gas transport as well as the accidental introduction of alien species with ship ballast water. In addition, the potential threat from radionuclides may increase in the future (UNEP 2004). Therefore, regional authorities should be increasingly focused on radiological protection activities and prepared for any eventualities related to nuclear reactors, storage of radioactive waste and spent nuclear fuel.

IV. Socioeconomic Conditions

The total human population in the catchment area of the Barents Sea LME is about five million, composed partly of indigenous peoples (Nenets, Lapps, Karelians and Vepsians). About 1.5 million people live in the coastal zone (Matishov *et al*. 2003). The average population densities in the Russian and Norwegian parts of this LME are significantly below the national averages. This is a consequence of population decrease, including migration from these regions, during the last two decades (Demographic Annual

Book 2002). The countries' economies and populations are partly dependent on the Barents Sea LME and its resources, directly or indirectly through fisheries, oil and gas extraction and marine transportation. The economic development of the Russian coast of the LME is based on the exploitation of natural resources. Tourism is growing in importance in this region, with the opening of the Russian borders.

Overexploitation has had severe social and economic consequences, in terms of employment, incomes, investment activity and population growth, particularly in the coastal settlements that depend on fisheries (UNEP 2004). During the 1990s, fishing outside the LME was stopped and coastal fish processing reduced, which resulted in a significant increase in unemployment in the fisheries sector. Unemployment in Finnmark, Norway is two times higher than the Norwegian average and is principally caused by the reduction in employment in the fisheries sector. Overexploitation has also resulted in the loss of human and animal food sources, increase in poaching and conflicts over access to the resources. Fish consumption in the north of Russia declined by 50% from 1990 to 2001 (UNEP 2004).

The socioeconomic impacts of pollution can be moderate. The large metallurgy, pulp and paper, mining as well as chemical enterprises are the main source of contaminants potentially impacting human health in the neighbouring territories. The high cost of radiological protection is of particular concern.

In general, habitat and community modification have slight socioeconomic impacts, which include the cost of managing the number of intentionally introduced species, especially the red king crab, monitoring programmes, research and international agreements on management and quotas. Potentially the most damaging alien species in Norway are toxic phytoplankton, which have caused losses in the aquaculture industry of some US$5 - 8 million , and parasites and pathogens which have caused damage of at least US$630 million to farmed and wild Atlantic salmon in Norway over the last 15 years.

V. Governance

Environmental protection activities are regulated by and carried out through a number of international programmes and instruments. Among these is the Oslo Convention, adopted in 1972 to prevent the dumping of hazardous substances at sea, which was followed by the 1974 Paris Convention dealing with land-based sources of pollution. These legal instruments have now been merged into the present Convention for the Protection of the Marine Environment of the North-East Atlantic of 1992 (OSPAR Convention), which entered into force in 1998. This Convention contains a number of supporting legislative and policy instruments regarding the Northeast Atlantic. See the OSPAR website for more information on the protection and conservation of ecosystems and biological diversity, and for the optimum utilisation of the fisheries of the Northeast Atlantic (www.ospar.org/). OSPAR is a regional body for international cooperation on the prevention and elimination of pollution from land-based and off-shore sources, dumping or incineration, and assessment of the quality of the marine environment. The OSPAR Commission site has information on the 1992 Convention, ministerial declarations and statements, and the use of the ecosystem approach to the management of human activities (www.ospar.org/). Other relevant international conventions include MARPOL and the United Nations Economic Commission for Europe Protocol of the European Commission on Strategic Environmental Assessments (the UNECE SEA Protocol).

The Arctic Council is one of the main international organisations dealing with environmental issues in the Arctic and Barents Sea Region. At least three of its five programmes deal with the protection of the marine environment: Protection of the Arctic Marine Environment (PAME) addresses policy and non-emergency response measures related to protection from land and sea-based activites, the Arctic Monitoring and

Assessment Programme (AMAP) has responsibilities to monitor the levels of and assess the effects of pollutants in all components of the Arctic marine environment, as well as in humans and the Emergency Prevention, Preparedness and Response, which is responsible for emergency preparedness in the region. The countries have adopted the Rovaniemi Initiative on the Protection of the Arctic Environment, through which the Arctic Environmental Protection Strategy was launched in 1991.

The Arctic Council is an intergovernmental forum addressing many of the common concerns and challenges faced by Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the USA. Arctic Council Ministers, in a 2002 declaration, recognised that ‘existing and emerging activities in the Arctic warrant a more coordinated and strategic approach to address the challenges of the Arctic coastal and marine environment’. The Council has agreed to develop a strategic plan for protection of the Arctic marine environment under the leadership of PAME, one of the five working group of the Arctic Council. PAME is an independent partner of UNEP Regional Seas Programme. Its international secretariat has been located in Iceland since 1999. More than 20 treaties and agreements cover the Arctic area. Several countries and groups of countries, including Norway, are engaged in scientifically-driven management of marine ecosystems, with an integrated approach similar to the LME approach.

Finland, Sweden and Norway all have bilateral environmental programmes and projects under-way with Russia in the Barents Sea LME region. Norway and Russia share stocks of cod, capelin and haddock, and close cooperation is needed in the management of these transboundary resources. These two countries manage their shared fish stocks through the Joint Norwegian-Russian Fishery Commission, established in 1975. The Commission sets total allowable catches (TAC) for shared fish stocks throughout their transboundary migratory routes. Fish quotas are also allocated to third-parties with historical rights to the Barents Sea fisheries. The TAC’s are based on scientific advice from ICES and national research institutions. ICES formulates scientific advice to fisheries authorities in the North Atlantic region, and is one of the main organisations coordinating and promoting marine research in the North Atlantic, including in adjacent seas such as the Baltic and North Seas (www.ices.dk/indexnofla.asp). The Barents Euro-Arctic Council (BEAC) encourages economic intergovernmental cooperation in trade, investment, energy transport and information technology, on the environment and nuclear safety, and on human and social development. The Council has a rotating chairmanship among the 13 member countries.

Cooperation in control, enforcement and marine research is being strengthened. A GEF-supported project (Support to the National Programme of Action for the Protection of the Arctic Marine Environment) is being conducted in the region. The main objectives are: to ensure a coherent basis for the identification of priorities associated with the adverse effects of land-based activities, to meet Russia’s obligations under the GPA as well as other international agreements and to prepare the ground for environmentally sustainable development of the Arctic. Project outcomes will include an agreed SAP to address damage and threats to the Arctic environment from land-based activities in the Russian Federation, a regulatory framework complemented by adequate infrastructural and technical capacities and prepared ground for substantial investments in remediation/prevention of damage to the Arctic environment.

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XIII-37 Celtic-Biscay Shelf LME

M.C. Aquarone, S. Adams and L. Valdés

The Celtic-Biscay Shelf LME is situated in the Northeast Atlantic Ocean, and covers an area of 756,000 km^2, of which 0.98% is protected, with 0.01% of the world's sea mounts (Sea Around Us 2007). At its southern limit the shelf is steep and narrow, but it widens steadily along the west coast of France, merging with the broad continental shelf surrounding Ireland and Great Britain. Three countries, Ireland, Great Britain, and France border this LME. Spain is not part of this LME. However Spain has fishing rights in both the French Biscay and in the Celtic Shelf (e.g. the Great Sole Bank, a major fishing ground).The Celtic-Biscay Shelf is characterised by a strong interdependence of human impact and biological and climate cycles (see Koutsikopoulos & Le Cann 1996). River systems and estuaries include the Seine, Gironde (Garonne River), Bristol Channel and Firth of Clyde. Two important book chapters pertaining to this LME are Valdés & Lavin (2002) and Lavin et al. (2006), both on the Bay of Biscay. The OSPAR reports provide information on the geography, hydrography and climate of Regions 3 and 4 that together cover the Celtic-Biscay Shelf LME, (www.ospar.org). See also the ICES working group WGRED annual report at http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGRED

I. Productivity

The Celtic-Biscay Shelf LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). This LME is influenced by the North Atlantic Drift in the north, and by the Azores Current in the south. For information on circulation and currents, see Koutsikopoulos & Le Cann (1996). The region undergoes a seasonal climatic cycle that strongly affects the pelagic ecosystem through forcing factors: sunlight exposure, heat input, and mechanical forcing on the surface by wind. For more information on seasonal variability, the vertical structure of coastal and oceanic waters, river plumes, coastal runoff and tidal fronts, see Valdes & Lavin (2002) who also describe the coastal upwelling in the Bay of Biscay that affects mainly Iberian coast, being very weak and only occasional along the French coast; they also describe the warm and salty Navidad Current. Living marine resources include a wide range of organisms. The LME is a region of transition that is rich in floral and faunal species. It is difficult to determine the states of equilibrium of species and communities, since natural variability occurs on a wide range of space and time scales (seasonal, inter-annual, decadal and centennial cycles). This LME is positioned in the eastern North Atlantic, in the cyclical North Atlantic Oscillation.

Oceanic fronts (Belkin et al. 2009): The most important front within this LME is the Shelf-Slope Front (SSF) that extends along the shelf break/upper continental slope from the Bay of Biscay around the British Isles up to the Faroe-Shetland Channel where it joins the North Atlantic Current Front (Figure XIII-37.1). This front is distinct year-round but is best defined in fall when its separation from the Mid-Shelf Front (MSF) becomes evident. The SSF is associated with the Shelf Edge Current, believed to be continuous all the way up to the Faroe-Shetland Channel. The SSF, however, does not appear continuous, suggesting that the Shelf Edge Current is likely not always continuous. The areas where the SSF is broken most often are near Goban Spur and Porcupine Bank; these bathymetric features are clearly responsible for the front's instabilities in these areas. The Mid-Shelf Front (MSF) is located between the SSF and the coasts of France, United Kingdom and Ireland. Tidal mixing fronts exist off Ushant Island, south of the Irish Sea, south of Ireland, and over the Malin Shelf.

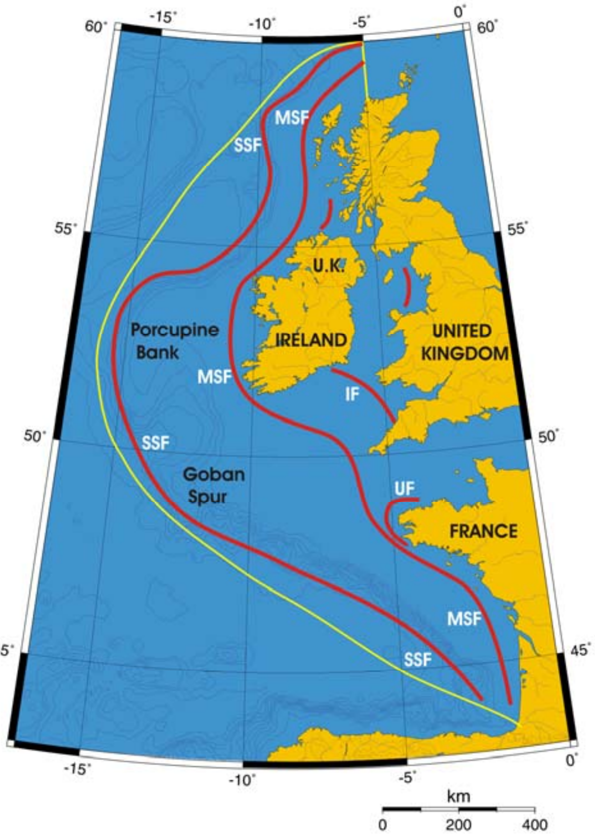


Figure XIII-37.1. Fronts of the Celtic-Biscay Shelf LME. IF, Irish Front; MSF, Mid-Shelf Front; SSF, Shelf-Slope Front; UF, Ushant Front. Yellow line, LME boundary. After Belkin et al. (2009).

Celtic-Biscay Shelf LME SST (Belkin 2009)(Figure XIII-37.2)
Linear SST trend since 1957: 0.41°C.
Linear SST trend since 1982: 0.72°C.

The thermal history of the Celtic-Biscay Shelf included (1) abrupt cooling in 1959-1963; (2) cold period until the all-time minimum in 1986; (3) very fast warming at a rate of 1.3°C over 20 years, accentuated by a major warming peaked in 1989 and interrupted by a cold spell in 1991-94.

The sequence of alternating, well-defined extremums in 1986 (cold), 1989 (warm), and 1991-94 (cold) is strongly correlated with similar events in the adjacent Iberian Coastal LME. The latter is oceanographically connected to the Celtic-Biscay Shelf by the Iberian Poleward Current and its extension off northern Spain dubbed "Navidad" (e.g. Garcia-Soto et al., 2002) flowing from the Iberian LME onto the Celtic-Biscay Shelf. Given the short distance between the two LMEs, all three events occurred nearly simultaneously in both LMEs. The same sequence of three alternating cold-warm-cold events of 1986, 1989, and 1991-94 in the Celtic-Biscay Shelf LME can be tentatively correlated with a similar cold-warm-cold event sequence of 1986, 1990, and 1995 in the Norwegian Sea LME located downstream of the Celtic-Biscay Shelf and connected to the latter by the Slope Current and North Atlantic Current. The less conspicuous minimum of 1972 on the Celtic-Biscay Shelf was likely related to the all-time minimum of 1972 in the Iberian LME. The previous minimum of 1963 was also simultaneous in both LMEs. The near-all-time maximum of 1959 on the Celtic-Biscay Shelf can be tenuously linked to the all-time maximum of 1961 in the Norwegian Sea. The above correlations suggest a dominant role of oceanic advection in transporting thermal signals across the Northeast Atlantic. The ongoing warming has already significantly affected this LME. For example, in the southern Bay of Biscay (43°–47°N), cold-water species of fish and sea birds declined; two species (puffin and killer whale) disappeared; populations of warm-water species increased; all these changes could amount to a regime shift in this LME (Hemery et al., 2007).

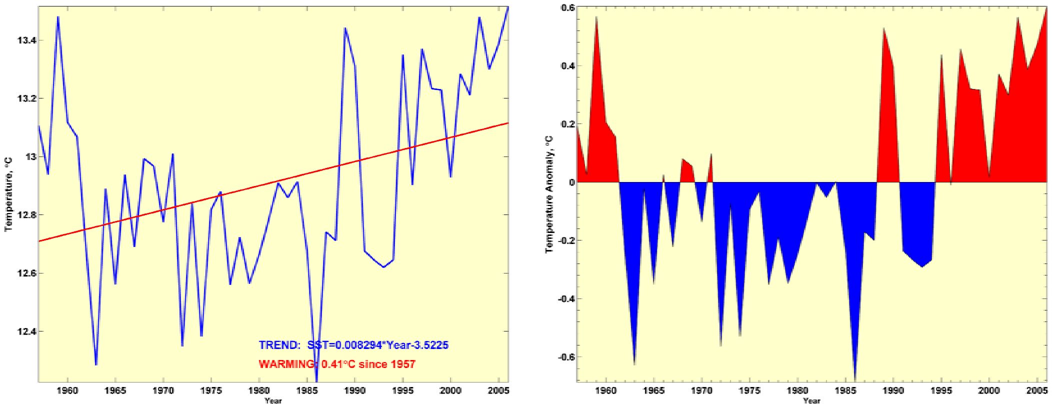


Figure XIII-37.2. Celtic-Biscay Shelf LME annual mean SST (left) and annual SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Celtic-Biscay Shelf LME Chlorophyll and Primary Productivity: This LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1})(Figure XIII-37.3).

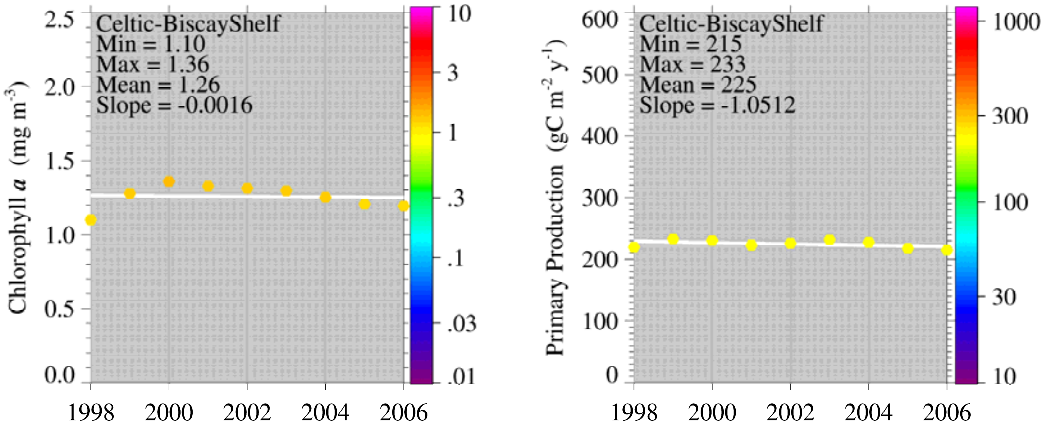


Figure XIII-37.3. Celtic-Biscay shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The natural environmental variability in this LME adds a high degree of uncertainty to the management of marine resources. Cyclical oscillations, such as the North Atlantic Oscillation, have been linked to fluctuations in the abundance of albacore and bluefin tuna (see Ortiz de Zarate *et al*. 1997 and Santiago 1997). Many stocks in the LME are intensively exploited or depleted and TAC-based regulations have been implemented for anchovy, hake and blue whiting. ICES provides general information on fisheries and other topics pertaining to the LME, while OSPAR reports on biodiversity and evolution of catches of same depleted stocks, but not with an intention of doing any management.. The main marine resources exploited in the LME include molluscs, seaweed, herring, redfish, sand eel and mackerel. The most important fish caught in its shelf waters include various pelagic fish species, as well as cod and hake. Sardine is not as important a resource in this LME as in the Iberian Coastal LME. For more on sardine recruitment, see Valdés & Lavin (2002).

Total reported landings in this LME show changes in biomass and catch composition (Figure XIII-37.4). The landings recorded a peak of 1.4 million tonnes in 1998, and declined to 1 million tonnes in 2004. The value of the reported landings reached US$1.6 billion (in 2000 US dollars) in 1976 (Figure XIII-37.5).

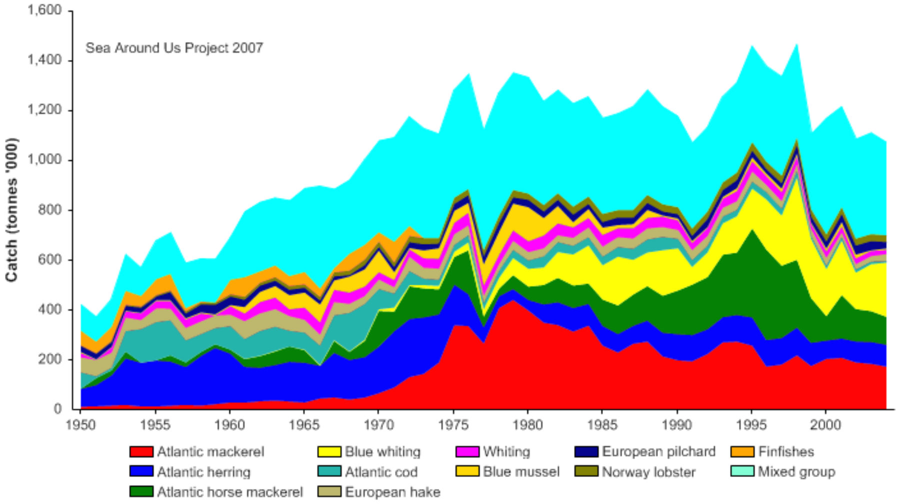


Figure XIII-37.4. Total reported landings in the Celtic-Biscay Shelf LME by species (Sea Around Us 2007).

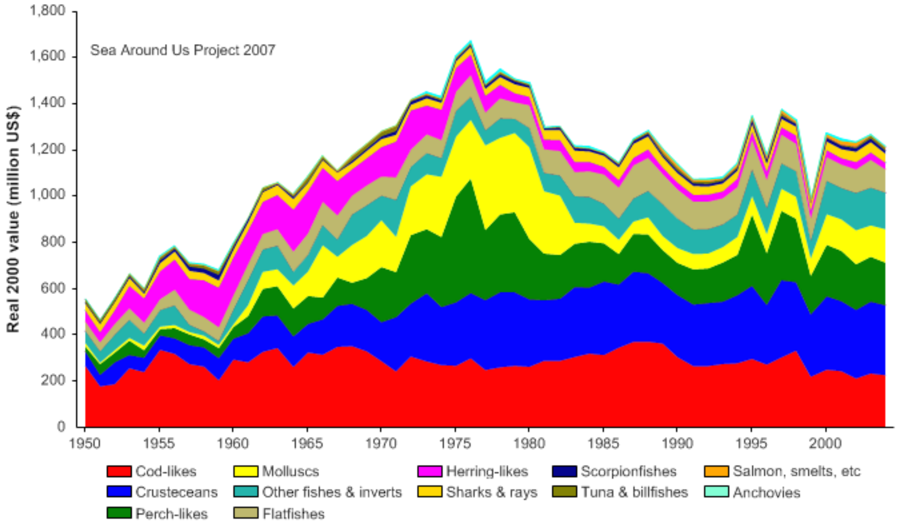
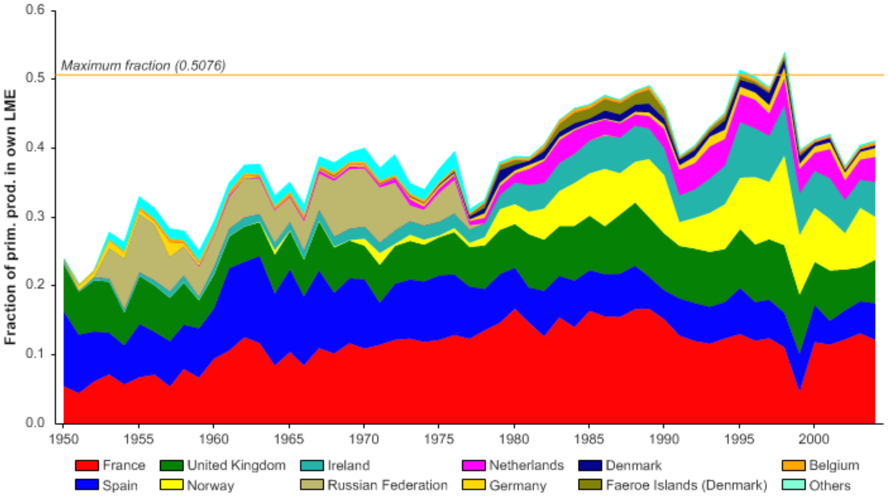


Figure XIII-37.5. Value of reported landings in the Celtic-Biscay Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 50% of the observed primary production in the mid-1990s, but has declined to 40% in recent years (Figure XIII-37.6). France and the UK account for the largest share of the ecological footprint in this LME.



FigureXIII-37.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Celtic-Biscay Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of fisheries catches (i.e., to the MTI; Pauly and Watson 2005) declined over the three decades from 1950 to 1980. In the early 1980s, however, it underwent a strong increase (Figure XIII-37.7, top) while the FiB index reached a new plateau (Figure XIII-37.7, bottom). These trends indicate that a 'fishing down' of the food web occurred from 1950 to the 1980s (Pauly *et al.* 1998), after which the effect was masked by expansion of the fisheries into new stocks (e.g., blue whiting, Figure XIII-37.4). This also confirms the results of Pinnegar *et al*. (2002), who, using fine-resolution data, concluded "there has been [in the Celtic Sea - ICES divisions VII f–j] a significant decline in the mean trophic level of survey catches from 1982 to 2000 and a decline in the trophic level of landings from 1946 to 1998."

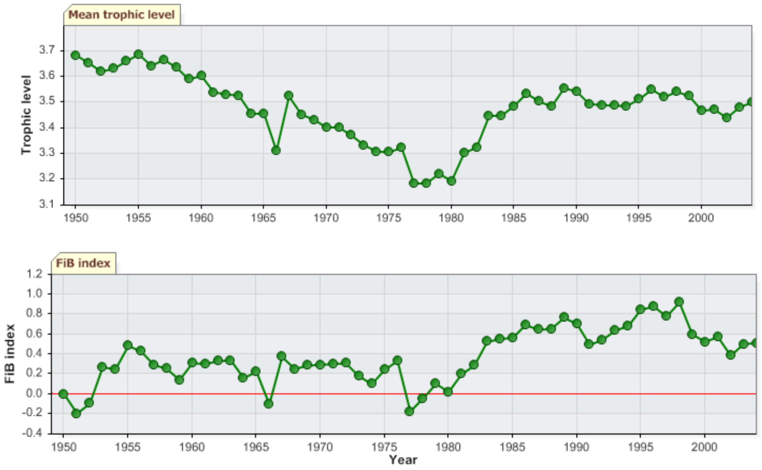


Figure XIII-37.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Celtic-Biscay Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that collapsed stocks make up half of all stocks exploited in the LME (Figure XIII-37.8, top), but that fully exploited stocks contribute almost 60% of the reported landings biomass (Figure XIII-37.8, bottom).

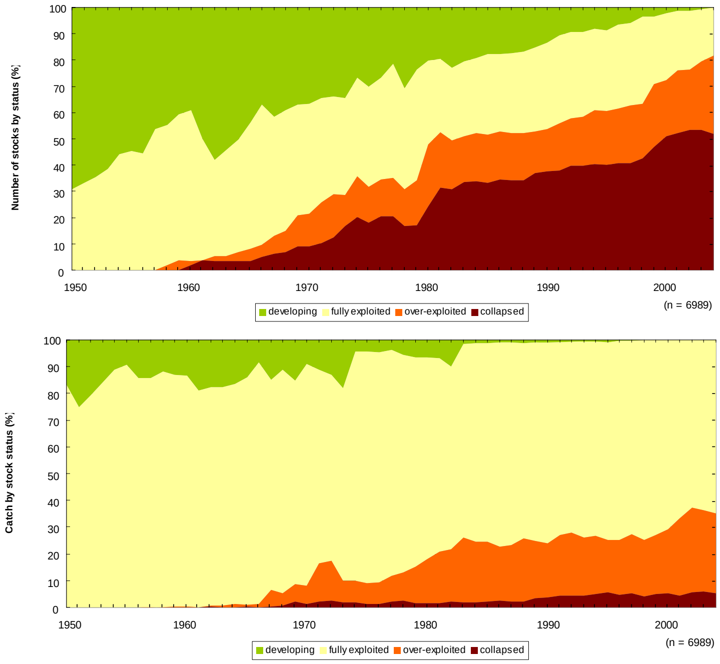


Figure XIII-37.8. Stock-Catch Status Plots for the Celtic-Biscay Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

The Celtic-Biscay Shelf LME has experienced ecological disturbances of target fish species, with alterations in the abundance, distribution and diversity of fish and marine mammals. Pollution and global change are impacting the coastal habitats (estuaries, coastal lagoons, rocky cliffs, rocky shores, sandy and muddy shores). Estuaries and coastal lagoons receive most of the impact of microbiological contamination of urban origin. Effects of ecosystem variability and human impact on species and habitats of the Bay of Biscay are described by Valdés & Lavin (2002). The ecosystem is affected by alterations to the seabed, the introduction of non-indigenous species, agriculture and sewage (Valdés & Lavin 2002). Introduced species are naturally transported by currents or are human-induced, caused by an intensification of fisheries and by transport in ballast water of commercial vessels. The use of DDT in agriculture has now been banned. There is pressure on the coastal margins from urban sources and from industrial activities, such as paper mills, petroleum refineries, iron and steel works and chemical plants.

Industrial discharges, inorganic and organic compounds, mercury (associated with paper mill industries), and PAHs (linked to human activities such as marine oil extraction, industry and oil traffic), are described by Valdés & Lavin (2002). Major oil spills have occurred in the area, listed at the EEA's website <epaedia.eea.europa.eu>, for example Torrey Canyon off Cornwall in 1967, the Ammoco Cadiz off Brittany, France in 1978, and the Sea Empress off Wales in 1992. In December 1999, the supertanker *Erika* spilled

10,000 tonnes of oil in shallow waters off the coast of France. Due to the strong wind in the area, the 'black tide' moved to the coast of the Bay of Biscay and large expanses of French beaches were contaminated by oil. The EEA reports that the remains of this ecological disaster can still be seen.

OSPAR provides information on the chemical aspects of the North-East Atlantic, the inputs of contaminants and nutrients, and their concentrations in different environments (www.ospar.org). It identifies pollution trends, the effectiveness of measures, the major causes of environmental degradation within the area and the managerial and scientific actions needed to redress this. The OSPAR Integrated Report on Eutrophication (2003) points out that in all participating countries many coastal areas, fjords and estuaries showed increased riverine N and P inputs, and some fjords and offshore sedimentation areas received increased transboundary nutrient inputs. Also reported were elevated levels of winter DIN and DIP concentrations, elevated levels in winter N/P ratios, elevated levels of chlorophyll *a* and elevated "nuisance bloom" or toxic assessment levels.

IV. Socioeconomic Conditions

Traditionally, the LME has been a region of intense fishing activity. Whale hunting began along the Spanish coast in the Middle Ages. Human activities in the coastal areas also include aquaculture and farming. Population densities at the coastal edges of the Celtic-Biscay Shelf LME are increasing. OSPAR estimates that 47.2 million people live in the catchment areas draining into the Bay of Biscay and Iberian coastal waters. In Brittany in France, more than 90% of the entire population lives on the coast, according to the EEA SOE report 2005 Part A, Ireland (together with the Mediterranean coast of Spain) has one of the two fastest growing coastal area populations in Europe, with increases of up to 50% in the past decade (http://epaedia.eea.europa.eu). Rapid population growth and socioeconomic development have resulted in environmental imbalances. EEA cites as principal threats to the Celtic Sea, Bay of Biscay and Iberian coast, eutrophication from sewage, agriculture, and fish farming; threats to fishing from overfishing, bottom trawling, discards and catch of non-targeted species; threats from industry in the form of chemicals and radionuclides; and threats from shipping accidents, pollution and oil spills. Additional pressure comes from tourism, urbanisation of coastal areas, transportation and recreational uses of beaches and shores.

V. Governance

A new Marine Strategy Framework Directive was recently enacted which promotes and integrates environmental considerations into all relevant policies areas and which forms the basis for a future Maritime Policy for the EU. The countries bordering this LME are all members of the European Union. The use of natural marine resources is governed by a number of conventions, declarations and regulations, including the European Commission directives and regulations within the Common Fisheries Policies. A large number of instruments from international bodies, such as the UN, the International Maritime Organisation and the European Union, exist to conserve natural resources, protect the environment and ensure health and safety standards. The European Community laws protect the environment in terms of air and noise, chemicals and industrial risks, nature conservation, waste and water. The EEA online summary for the Northeast Atlantic Ocean, lists the major political instruments as OSPAR, ICES, EU Birds and Habitats Directives, North Atlantic Marine Mammal Commission (NAMMCO), the Bern convention and other conventions covering part of the area including Ramsar for wetland protection, the Bonn convention for migratory species, MARPOL73/78IMO convention of marine pollution from ships in additional to national laws, and NGO organisations such as WWF are working to accelerate the establishment of no-fishing zones and offshore marine protected areas (www.eea.org).

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XIII-38 Faroe Plateau LME

M.C. Aquarone, S. Adams and E. Gaard

The Faroe Plateau LME surrounds the Faroe Islands in the northeast Atlantic Ocean. It is a high latitude environment characterised by a sub-arctic climate that affects productivity through changes in temperature, currents, tides and seasonal oscillations. The Faroe Plateau is a well-defined and geographically uniform LME, with a surface area of 150,000 km^2 (Sea Around Us 2007). The islands have a relatively broad shelf and are surrounded by a persistent tidal front that separates shelf waters from the open ocean. The circulation of water masses is anticyclonic, with a branch of the North Atlantic Drift current flowing north. Gaard *et al*. (2002) and UNEP (2004) have described this LME.

I. Productivity

For a map of the Faroe Islands and surrounding LME, with a typical position of the tidal front that separates the shelf water from the ocean water, see Gaard *et al*. (2002, p. 246). Climate (e.g., temperature) is the primary force driving the LME, with intensive fishing the secondary driving force. The dynamic system of ocean currents in the area, in particular the inflow of warm Atlantic waters to the Nordic seas, is an important feature. Currents, tides and seasonal oscillations affect productivity. The shallow parts of the shelf are well mixed by extreme tidal currents, with no stratification occurring during the summer. For a map of salinity at 50 m depth, see Gaard *et al*. (2002, p. 248).

The Faroe Plateau LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). Primary productivity and phytoplankton biomass are very low during winter, but increase during spring and summer. Neritic phytoplankton and zooplankton communities are found on the shelf, and are somewhat separated from the offshore areas while receiving variable influence from the offshore environment. The shelf production of plankton is the basis for production in the higher trophic levels. The LME also serves as an important feeding ground for pilot whales and other marine mammals. Monitoring data show simultaneous fluctuations in several trophic levels in the ecosystem. Plankton production, fish recruitment, seabird recruitment and growth, and ultimately fish landings, vary inter-annually. For more information on trophic interactions, and on the large numbers of seabirds, see Gaard *et al*. (2002).

Oceanic Fronts: The Faroe Plateau LME is surrounded by tidal mixing fronts (Belkin *et al*. 2009). These fronts (Figure XIII-38.1) define the ecosystem and its important fishery grounds, especially of herring and cod (Hamilton *et al*. 2004). Unlike their counterparts around the British Isles, the Faroese tidal mixing fronts have not been studied in detail. A large-scale water mass front between the Plateau waters and the North Atlantic waters exists at the boundary of this LME, running along the Faroe-Shetland Channel (Sherwin *et al*. 2001).

Faroe Plateau LME SST (after Belkin (2009)
Linear SST trend since 1957: -0.14°C.
Linear SST trend since 1982: 0.75°C.

Like the Iceland Sea, the Faroe Plateau experienced long-term cooling of 1.2°C from 1960 through 1993, followed by rapid warming (1.3°C in 10 years) by 2003. All major extremums – maxima of 1960 and 2003, and minimum of 1993-1995– were also observed in the Iceland Shelf LME.

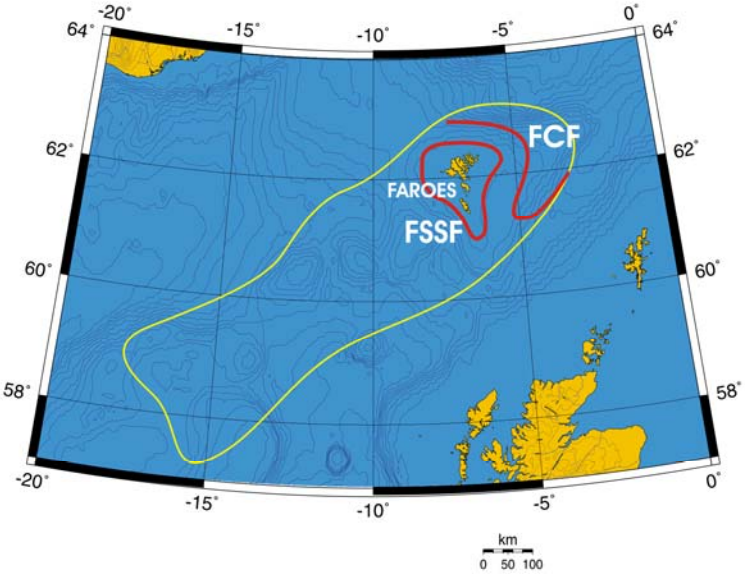

Figure XIII-38.1. Fronts of the Faroe Plateau LME. FCF, Faroe Channel Front; FSSF, Faroes Shelf-Slope Front. Yellow line, LME boundary. After Belkin et al. (2009).

The observed synchronism between Iceland Shelf and Faroe Plateau can be explained by the prevalence of northward transport, of various branches of the NAC. Therefore any SST anomaly transported by them would reach both LMEs at approximately the same time. Ocean circulation around the Faroes also effectively protects the islands from being directly affected by cold waters from the Nordic Seas. Subarctic cold waters could only reach the Faroes with easternmost branches of the North Atlantic Current, particularly the Irminger Current and Rockall Trough branch, after completing a rather circuitous journey around the Subarctic Gyre (Orvik and Niiler, 2002; Arhan, M. 1990.).

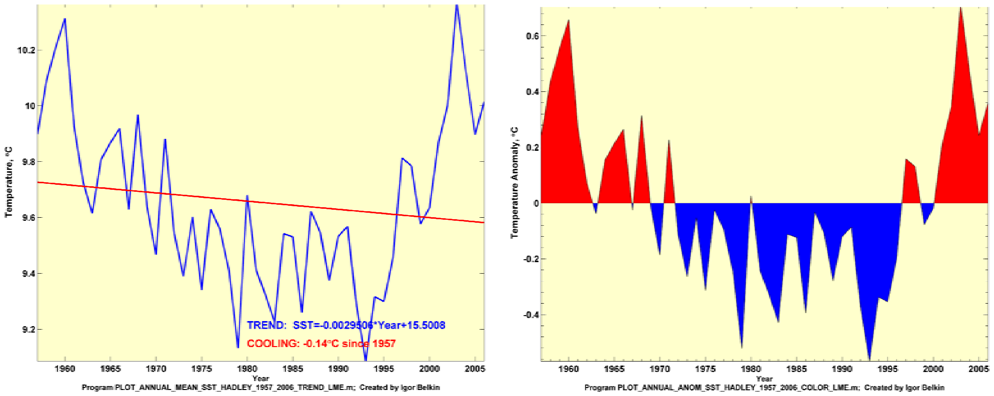

Figure XIII-38.2. Faroe Plateau LME Annual Mean SST and annual SST anomalies, 1957-2006, after Belkin (2009).

***Faroe Plateau LME Chlorophyll and Primary Productivity*:** The Faroe Plateau LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}).

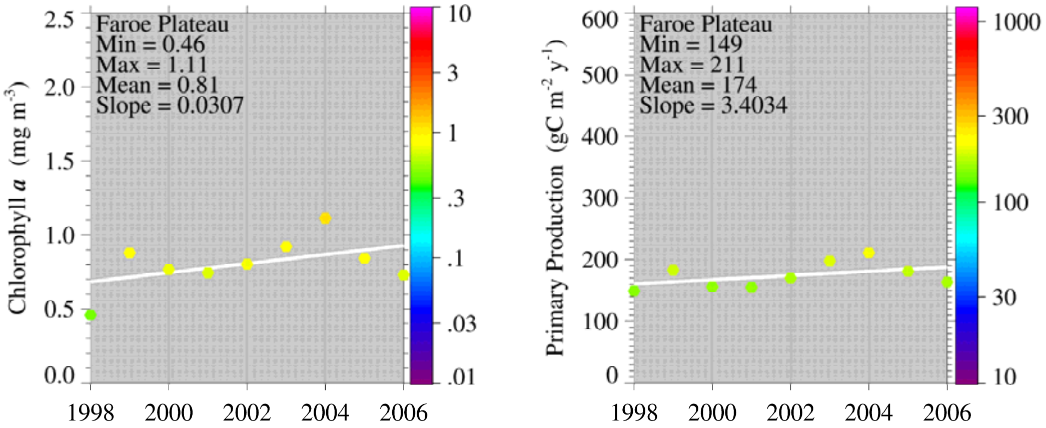

Figure XIII-38.3. Faroe Plateau LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Climatic variability has a major impact on fish landings in the LME. The most important species group is pelagic fish, representing on average 52% of the total catch, and cod, saithe and haddock, representing more than 30% of the catch. For landings of cod and haddock between 1903 and 1998, see Gaard *et al*. (2002, p. 247). The long-term average of annual landings of cod fluctuates between 20,000 and 40,000 tonnes. Landings of haddock fluctuate between 15,000 and 25,000 tonnes per year. In the early 1990s, cod and haddock annual landings reached the lowest values recorded. Cod and haddock do not always fluctuate simultaneously due to their different reproductive strategies. Other important species are saithe, halibut and the Norway pout. The latter is not caught commercially but serves as a food supply for fish (mainly cod and haddock), seabirds and grey seals. A marked increase in fishing effort has not resulted in an increase in fish landings.

Total reported landings have been on a rise, recording about 450,000 tonnes in recent years (Figure XIII-38.4). Blue whiting account for the largest share of the landings since the late 1970s, with 75% of the total landings in 2004. From 1986 to 1994, landings of Norway pout were also significant, averaging between 14,000 and 27,000 tonnes per year. The value of the reported landings recorded 355 million US$ (in 2000 real US$) in 2003 (Figure XII-38.5).

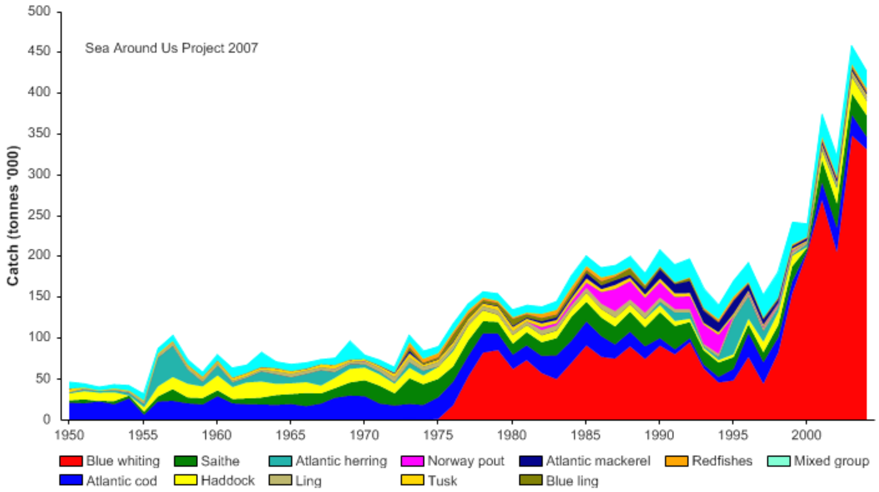

Figure XIII-38.4. Total reported landings in the Faroe Plateau LME by species (Sea Around Us 2007).

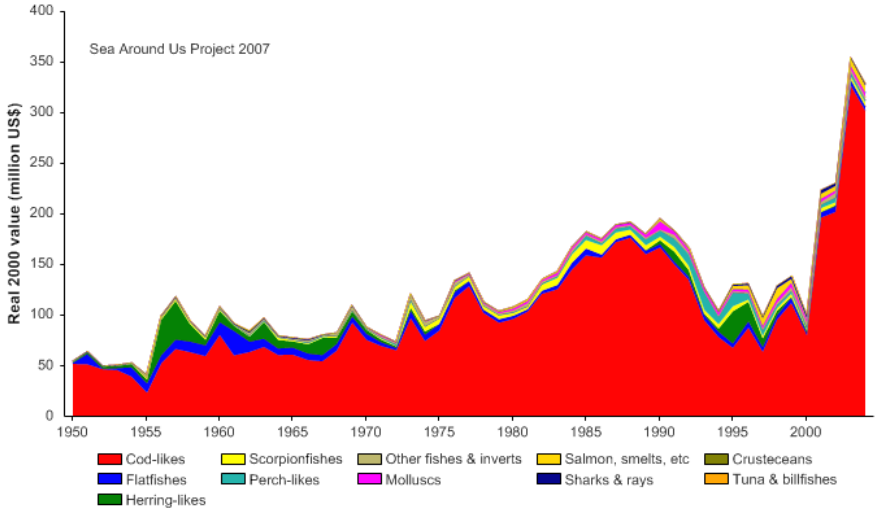

Figure XIII-38.5. Value of reported landings in the Faroe Plateau LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME has reached a level that far exceeds the observed primary production of the region (Figure XIII-38.6). While there might be other causes (e.g., problems with the landings statistics, and/or with the primary production estimate used here), it is probably due to fish being caught in the LME recruiting from and/or feeding outside the LME, which thus subsidize the productivity of the Faroe Plateau LME. Faroe Islands, Russia and Norway account for the largest share of the ecological footprint in this LME.

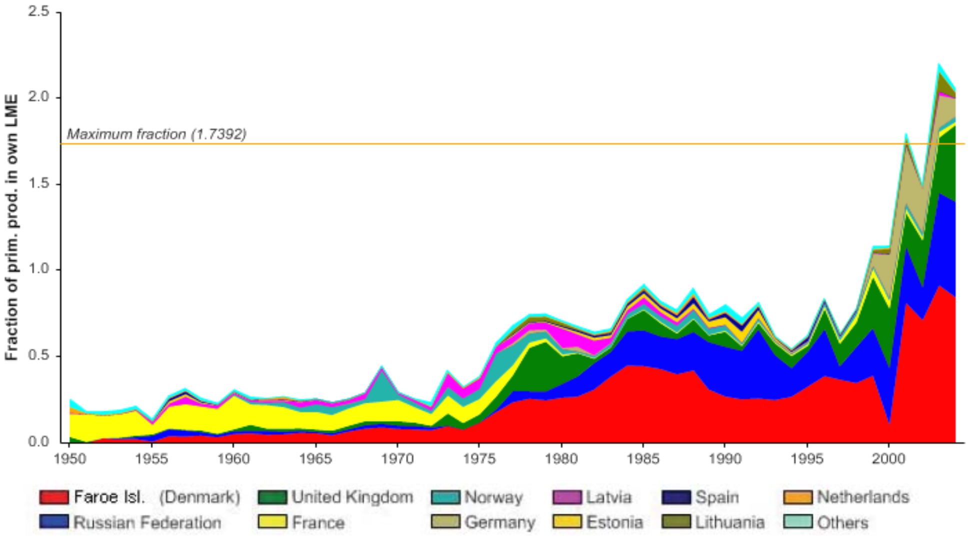

Figure XIII-38.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Faroe Plateau LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

No clear trend can be observed in the mean trophic level of fisheries landings (i.e., the MTI; Pauly & Watson 2005) until mid-1990 (Figure XIII-38.7 top). Since then, however, the level appears to increase, presumably due to the almost exclusive, and increasing landings of blue whiting (Figure XIII-38.4), which could be masking any possible 'fishing down' effect in the LME (Pauly *et al.* 1998). The expansion of the blue whiting fisheries is also evident in the FiB index (Figure XIII-38.7 bottom).

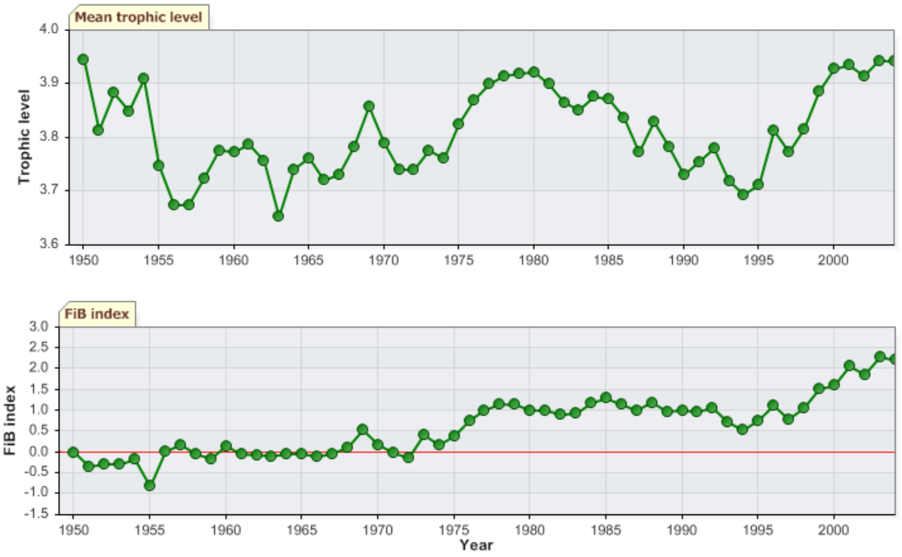

Figure XIII-38.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Faroe Plateau LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate the high proportion of stocks defined as ‘collapsed’ in the LME (Figure XIII-38.8, top). However, fully exploited stocks contribute almost 90% of the reported landings biomass (Figure XIII-38.8, bottom), a result of the increase in the blue whiting landings.

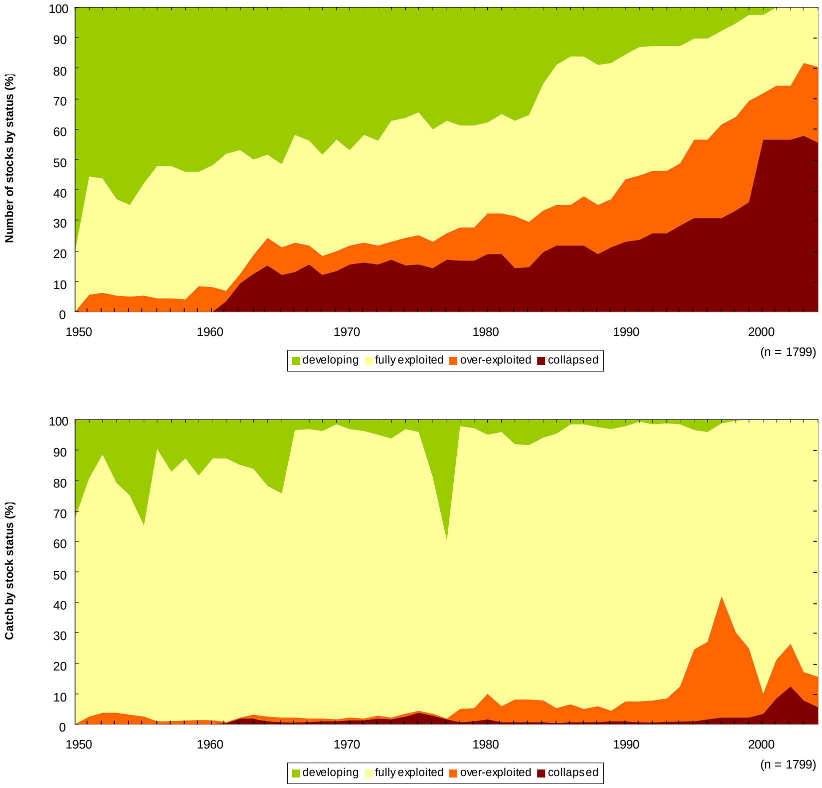

Figure XIII-38.8. Stock-Catch Status Plots for the Faroe Plateau LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The commercial fishing fleet of the Faroe Plateau is comprised mainly of coastal vessels, long-liners and ocean trawlers. The Faroese fisheries management system with restrictions on fishing-days was adopted in 1996. The fishing-day system manages fishing capacity and effort rather than allocating specific quotas for species and stocks and was put in place for the management of demersal fisheries in the 200-mile fisheries zone around the Faroe. Vessels are grouped according to size and gear type, and each group is allocated a set number of fishing days per year, which are allocated among the vessels. This scheme is combined with gear restrictions designed to protect juvenile fish, as well as closures of extensive areas to active gear such as trawls in order to protect nursery and spawning stocks (Zeller & Reinert 2004).

III. Pollution and Ecosystem Health

Fisheries are totally dependent on a sound and healthy marine ecosystem. Safeguarding the marine environment and ensuring the sustainable use of its valuable resources is a necessity, in view of the dependence of the population on these resources. Monitoring of environmental parameters of the Faroe Shelf LME was initiated in the mid 1990s. International conventions are the basis for Faroese national legislation to protect the marine environment, mainly the MARPOL convention for the Prevention of Pollution from Ships and the OSPAR Convention for the Protection of the Marine Environment in the North-East Atlantic, which, amongst others, lays down rules for the discharge from offshore installations. The 2004 GIWA assessment of the marine waters around the Faroes reports that toxic contamination of the tissue of marine mammals is causing human health problems and may also affect the economically important fisheries sector (www.giwa.net/publications/r13.phtml). The report cites long distance transport of pollutants by ocean currents and air from industrial areas in Europe, North America and Asia among the sources of the contamination. The traditional consumption of whale meat has occasioned concern that elevated levels of mercury might be found among pregnant women (Booth & Zeller 2005).

IV. Socioeconomic Conditions

In 1998, the Faroe Islands had an estimated population of 44,000 persons who are almost totally dependent on fisheries and on fish farming, which began in the 1980s. Fishery is the main industry: fishery products, including farmed salmon, represent more than 95% of total Faroese exports and nearly half of the GDP. Bioaccumulation of mercury in whales, pelagic fish, and seabirds has already warranted warnings regarding human consumption of them (online at www.giwa.net/publications/r13.phtml, causal chain analysis chapter; Booth & Zeller (2005). The phasing out of government subsidies to the fisheries sector has been a major factor in reducing over-capacity and stimulating more effective, market-driven approaches to fisheries.

The challenge for the future is to ensure that fisheries management can continue to be flexible and adaptive to changes in the resource base and the industry, in order to ensure both biological and economic sustainability. As pollution in the Faroe Islands is largely caused by long-distance transport of the pollutants by ocean and atmospheric currents from the highly industrialized countries, solutions will be international in scope. Petroleum production is being explored in areas close to the Faroe Islands, and between the Faroe and Shetland Islands.

V. Governance

The Faroe Islands are a self-governing overseas administrative division of Denmark, a major fishing nation that is attempting to integrate fisheries and environmental policies. An ecosystem approach was used officially for the first time in 1995 at the international level with the Convention on Biological Diversity. Denmark participates in ICES. The Faroe Islands participate in the NEAFC (Northeast Atlantic Fisheries Commission, see http://www.neafc.org); NAFO (North-west Atlantic Fisheries Organisation, see http://www.nafo.ca); NASCO (North Atlantic Salmon Conservation Organisation, see http://www.nasco.org.uk); and NAMMCO (the North Atlantic Marine Mammal Commission, see http://www.nammco.no). Greenland participates in the Arctic Council as part of Denmark and the Faroe Islands (see the Barents Sea LME).

The Faroese Parliament adopted UNCLOS in 2003 and the UN Agreement for the Implementation of the Provisions of the Convention relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks in 1995. Information on the Faroe Islands is available at: www.faroeislands.org.uk.

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XIII-39 East Greenland Shelf LME

M.C. Aquarone and S. Adams, D. Mikkelsen and T.J. Pedersen

The East Greenland Shelf LME extends along Greenland's east coast to the Eirik Ridge, covering an area of about 319,000 km^2, of which 13.34% is protected (Sea Around Us 2007). It is influenced by the cold East Greenland Current, which flows south along the coast from the polar area. A sub-arctic climate, seasonal ice cover and marked fluctuations in salinity, temperature and phytoplankton characterise this LME. The continental shelf varies in width, from 750 km in the north to 75 km in the south, and a large number of fiords are found. LME book chapters, articles and reports pertaining to this LME include Prescott (1989), Skjoldal *et al*. (1993) and UNEP (2004).

I. Productivity

Changes in sea and air temperature are the principal physical driving forces of this LME. Climatic variability causes large inter-annual variability in ice and hydrographic conditions. This, in turn, affects plankton production and fish recruitment, and can contribute to variations in annual catches of cod and small pelagics. Due to the cover of ice for most of the year, which inhibits the penetration of light, the East Greenland Shelf is considered a Class III, low productivity ecosystem (<150 gCm^{-2}yr^{-1}). The melting of sea ice in the summer has significant effects on ecological conditions, causing large amounts of nutrient salts to be transported into the waters around East Greenland. Owing to these climatic factors and to the high latitude of the region, the seasonal phytoplankton production is of short duration and of limited extent. Primary production is conveyed efficiently to higher trophic levels and supports large populations of fish, marine mammals and seabirds.

Oceanic fronts (Belkin *et al.* 2009): The East Greenland Polar Front (EGPF) (Figure XIII-39.1) hugs the shelf break and the Greenland continental slope, and serves as the offshore boundary of this LME. The EGPF waters originate in the Arctic Ocean, which explains their extremely low temperature and salinity. A complicated pattern is formed by the EGPF over the broad Ammassalik Shelf between 63° N and 65° N, where three separate branches of the EGPF are observed. This shelf is known as a major spawning area of cod. Therefore the multiple frontal structure discovered from satellite data is important to the local cod fishery. South of the Denmark Strait, the EGPF is joined by the Irminger Current Front that carries warm and salty waters originated in the North Atlantic Current.

East Greenland Shelf LME SST (Belkin 2009)(Figure XIII-39.2):
Linear SST trend since 1957: 0.51°C.
Linear SST trend since 1982: 0.73°C.

Like many other boreal LMEs, the East Greenland Shelf cooled down in the 1950s-1960s until it reached the all-time minimum of just 0.5°C in 1971 during the passage of the Great Salinity Anomaly (GSA) of the 1970s (Dickson et al. 1988; Belkin et al. 1998). The passage of the GSA'70s is believed to have contributed to the collapse of cod fisheries downstream, off West Greenland and Newfoundland, in the 1980s (Hamilton et al. 2003). Later on, the GSAs of the 1980s and of the 1990s were absent over the East Greenland Shelf, consistent with their local formation in the Labrador Sea (Belkin et al., 1998; Belkin, 2004).

After a quick recovery in 1972, SST rose steadily until present. The all-time maximum SST in 2003 exceeded 2.6°C. The record-breaking SST is consistent with the all-time maximum near-surface air temperature of 1.5°C recorded in Ammassalik on the east coast of Greenland in 2003. The SST maximum of 2003 correlates with the all-time SST maximum of 2004-2005 in the downstream-located West Greenland Shelf LME. In the two nearby LMEs, Iceland Shelf and Faroe Plateau, SST also reached all-time maxima in 2003. Perhaps, it is not accidental that all these anomalies peaked right after El Niño 2002-2003.

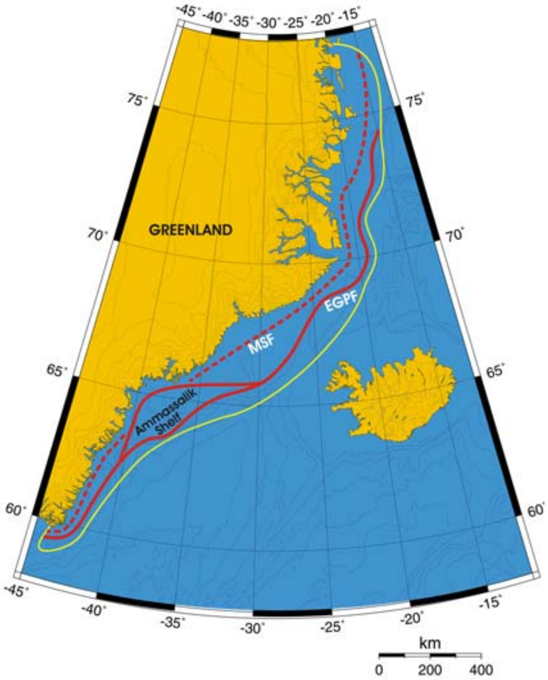

Figure XIII-39.1. Fronts of the East Greenland Shelf LME. EGPF, East Greenland Polar Front; MSF, Mid-Shelf Front (most probable location). Yellow line, LME boundary. After Belkin *et al.* (2009).

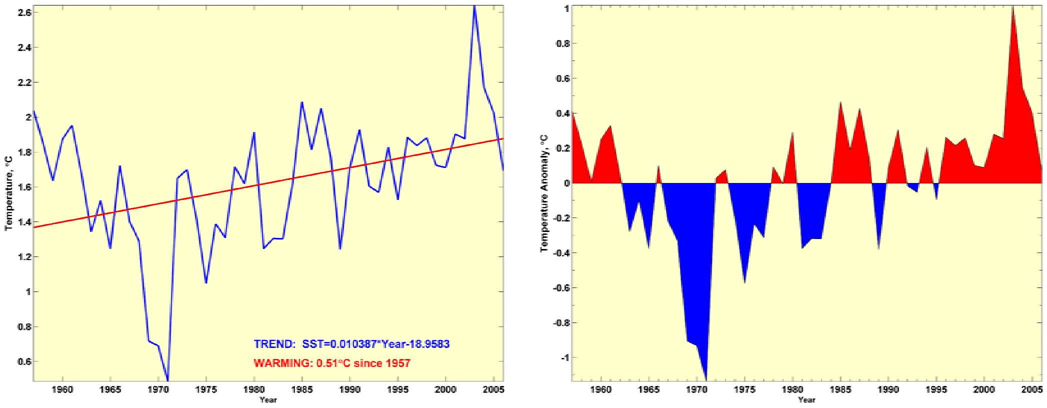

Figure XIII-39.2 East Greenland Shelf annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

East Greenland Shelf LME Chlorophyll and Primary Productivity

The East Greenland Shelf LME is considered a Class III, low productivity ecosystem (<150 $gCm^{-2}yr^{-1}$) (Figure XIII-39.3).

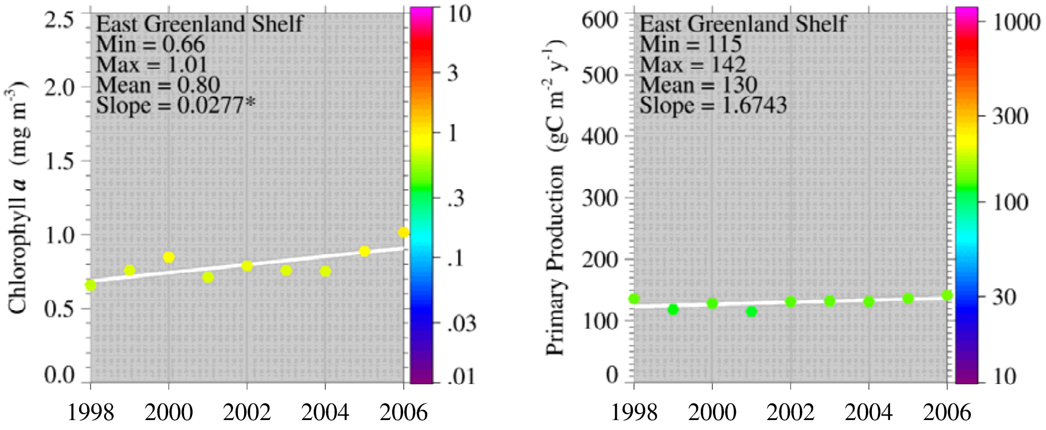

Figure XIII-39.3. East Greenland Shelf trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Total reported landings[1] from 1950 to 2003 show a series of peaks and troughs (Figure XIII-39.4). Reported landings have fluctuated from a low of 11,000 tonnes in 1983 to a high of 225,000 tonnes in 1996. While historically cod dominated reported landings, in more recent years pelagic fish, notably capelin dominate (Figure XIII-39.4)[2]

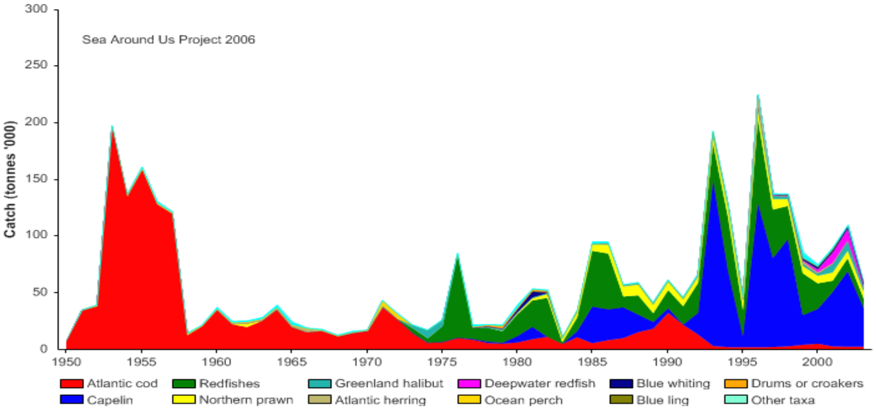

Figure XIII-39.4. Total reported landings in the East Greenland Shelf LME by species (Sea Around Us 2007).

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[1] Due to a recent adjustment to the boundaries of the East Greenland Shelf LME, the landings data presented here are based on the 1950-2003 data, computed using the boundaries defined in Figure XIII-39.1. Data for 1950-2004, based on the new LME boundaries, will be available online at www.seaaroundus.org.

[2] Information on the value of reported landings cannot be provided at this stage, due to the recent adjustments in LME boundaries (see note 1 above). Data for values using the newly adjusted boundaries will be available at www.seaaroundus.org.

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached to 35% of the observed primary production in the mid 1950s, but this relatively high value has not been achieved in recent years, and has remained mostly under 10% (Figure XIII-39.5). The countries with the largest share of the ecological footprint in this LME have changed frequently over the years, with Iceland accounting for the largest footprint in recent years.

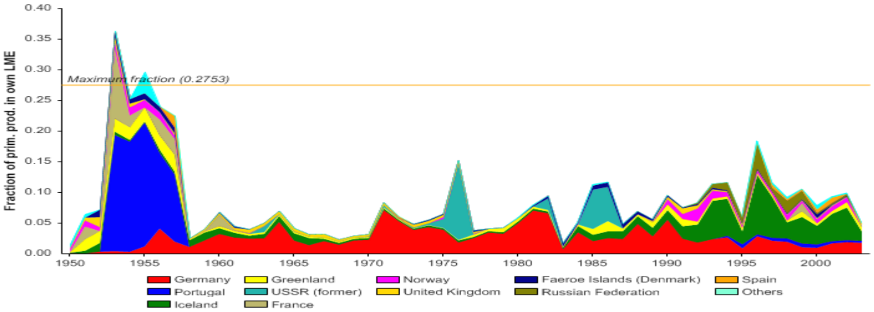

Figure XIII-39.5. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the East Greenland Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Until the early 1970s, the reported landings from this LME and the mean trophic level of the entire fisheries in the region were dominated by cod (i.e., the MTI; Pauly & Watson 2005). With new species coming under exploitation, and the gradual decline of cod landings, a classical 'fishing down' scenario ensued (Pauly *et al.* 1998), with trophic levels declining (Figure XIII-39.6, top), and some compensation through higher landings of species from lower trophic levels (e.g. capelin), the reason for the stability in the FiB index (Figure XIII-35.6, bottom).

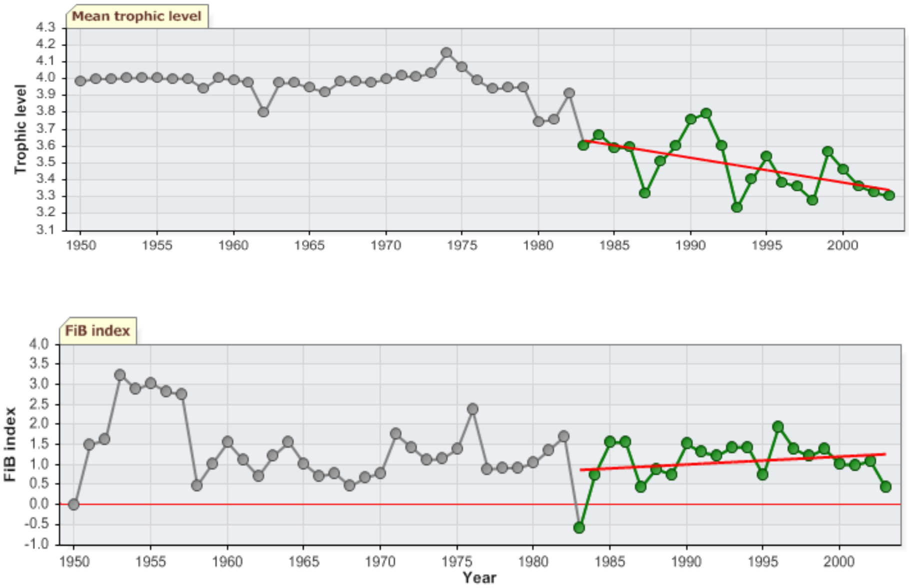

Figure XIII-39.6. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the East Greenland Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate a high proportion of collapsed stocks in this LME (Figure XIII-39.7, top), and a high contribution of these stocks to the reported landings biomass (Figure XIII-39.8, bottom). The jagged appearance of the latter plot reflects fluctuations in the reported landings (Figure XIII-39.4).

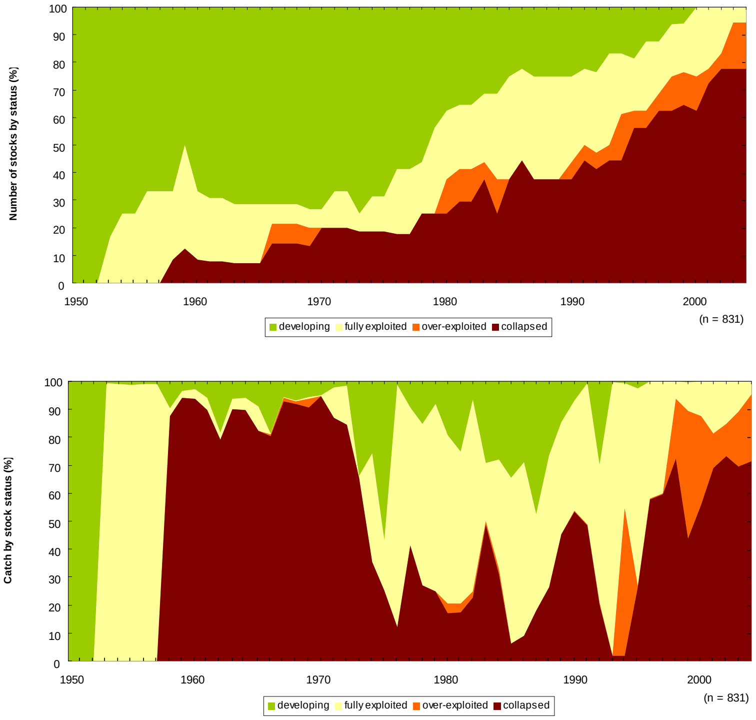

Figure XII-39.7. Stock-Catch Status Plot for the East Greenland Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

A stock of some commercial significance was cod, once central to Greenland's economy. This stock collapsed in the early 1990s, with landings falling from about 13,000 tonnes in 1992 to below 4,000 tonnes in the following years. The fluctuations of cod stocks have been linked to changes in sea temperature (see Buch *et al*.1994). Overfishing and its effects on stock size and stock interactions appear to coincide with climatically-driven variability. Atlantic herring was a major species fished in the 1950s and 1960s but it has also almost entirely disappeared in the catch statistics. Today, species landed are mostly capelin, shrimp and redfish. Shrimp (*Pandalus borealis*) is exported. Greenland halibut, Norway haddock, catfish, Atlantic halibut, salmon and char are important to the local economy. Greenland's fishing industry tries to balance the possibilities offered by modern fishing technology with the need to sustain this LME's natural resources. The near-shore quota system differs from the off-shore system for shrimp, cod and Greenland halibut. Marine mammals (five species of seal, walruses and whales) are essential for the survival of the traditional hunting communities, and the meat is traded locally. The whaling industry led to the decimation of several whale species in the region. While the recovery of the overexploited right whale has been very slow, the fin and minke whales have recovered well. Legal measures protect a number of marine species.

III. Pollution and Ecosystem Health

The International Cod and Climate Change Programme studies the response of different cod populations to climate change in various regions of the cod's North Atlantic range. A report by the OSPAR Commission describes the main human pressures in a region of the Arctic Ocean that includes the east coast of Greenland. Owing to this LME's remoteness and low population density, environmental conditions within it are generally good. However, certain activities such as fisheries give cause for concern. In terms of oil pollution, the difficulties associated with taking remedial actions in a cold environment such as this are also of concern. Levels of PCB and DDT are quite high in both biotic and abiotic media around eastern Greenland. For more information about pollutants in the Arctic region including Greenland, the AMAP website (www.amap.no) makes recent reports available. The measurement of 'new' chemicals, in particular brominated and fluorinated compounds in the Arctic environment and evidence of the biological effects of OCs (Organochlorines) in polar bears, glaucous gulls, and northern fur seals are highlights of recent research carried out on POPs in the Arctic (AMAP 2002 Report on POPs). These compounds can adversely affect immune, endocrine and reproductive systems.

The PAME Working Group is involved in assessing changing states of Arctic environments (see also the Governance module). The PAME work plan (2004-2006) will identify indicators of ecosystem health and ecosystem objectives for the Arctic LMEs. In the Arctic, the average extent of sea-ice cover in the summer has declined by 15-20% over the past 30 years. This decline is expected to accelerate, with the near total loss of sea ice in the summer projected for late this century (ACIA 2004). The OSPAR website has information on the protection and conservation of marine biodiversity and ecosystems, eutrophication, hazardous and radioactive substances (www.ospar.org).

IV. Socioeconomic Conditions

The first Europeans arrived in Ammassalik only about 100 years ago. The human population in the region is extremely small, with about 3,500 people living in the 2 towns and 9 settlements of Greenland's east coast. Many are from the traditional Inuit culture, which continues to play an important role in everyday life. The Inuit dependence on fishing and on the harvesting of wildlife formed the basis of their society, culture and economy. Today, the local population continues to be highly dependent on the fish, crustaceans and mussels obtained from the sea, and on the hunting of seals, whales, polar bears and other prey. Fishing accounts for 95% of total exports. Certain mineral deposits may be of future economic interest, including the oil fields near Jameson Island in East Greenland. Diamond, gold, niobium, tantalite, uranium and iron deposits are found on the island.

The PAME Working Group has information on the indigenous and non-indigenous communities living in the Arctic who are heavily dependent on the Arctic living marine resources. All of these groups are represented in the Arctic Council. OSPAR provides information on the offshore oil and gas industry, and the use of the ecosystem approach to the management of human activities (www.ospar.org).

V. Governance

For centuries Greenland belonged to Denmark, but since 1979 has moved towards independence. The Greenland Institute of Natural Resources is responsible for providing scientifically sound management advice to the Greenland government. Investigations on selected fish larvae and zooplankton in relation to hydrographic features is currently undertaken as part of the monitoring programme NuukBasic. The marine component of the monitoring program was initiated in 2005, and is managed by the Center of Marine

Ecology and Climate Effects at Greenland Institute of Natural Resources. Results from the monitoring programme are published in annual reports, as well as peer-reviewed scientific papers when appropriate. Issues that have been identified as important for the management of this LME include the need to improve the scientific basis for linking climatic variability and climate change to the chemical and biological processes and fishing pressure. Greenland participates in the Arctic Council and OSPAR as part of Denmark and the Faroe Islands.

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XIII-40 Iberian Coastal LME

M.C. Aquarone ,S. Adams and L. Valdés

The Iberian Coastal LME is a continental shelf region of the Eastern Atlantic Ocean lying between approximately 36° N (Gulf of Cadiz) and 44° N (Cantabrian Sea), and bordered by Spain and Portugal. A temperate climate characterises this western boundary current ecosystem. The continental shelf in this region varies from 12 to 50 km, being the narrowest in the Northeast Atlantic margin. The LME has an area of about 300,000 km^2, of which 0.45% is protected, and contains about 0.07% of the world's sea mounts (Sea Around Us 2007). One of the main geomorphological features of the Iberian Coastal LME is a series of extremely steep and deep marine canyons. The coast of Asturias has the canyons of Avilés, Lastres and Llanes; these are so abrupt that in only 7 km from the coastline the depth reaches 4500 m, making these features the steepest and deepest near-shore canyons in the world. It seems that these canyons are the refuges of giant squids (*Architeuthis dux* and *Taningia danae*) which are found here quite often (usually in October) dead on the beaches. Off Portugal there is a remarkable canyon Nazaré. Other interesting features in this LME are the seamounts or relic shelves offshore, such as the Bank of Galicia and the Bank of Le Danois (known in Spain as El Cachucho), which has been recently protected as an AMP in the Northern Spain. The Iberian seaboard has a highly convoluted coastline indented with drowned river valleys called *ria*. Book chapters and articles pertaining to this LME include Wyatt & Perez-Gandaras (1989) and Wyatt & Porteiro (2002). This LME together with the Bay of Biscay is included in OSPAR as Region 4. This is the same regionalization that the EU has done in the recently published Directive on Marine Strategy (25/06/08). ICES is supporting a Working Group named WGRED which had done quite extensive regional descriptions, including Iberian shelf. The report of last year can be found at: www.ices.dk/iceswork/wg detailacfm.asp?wg=WGRED. Additional general information on this region can be found in Valdés and Lavín (2002) and Lavín et al. (2006).

I. Productivity

Productivity and resource abundance in the Iberian Coastal LME are driven by climate and upwelling, with intensive fishing being the secondary driving force. The importance of climate is suggested by the link between sardine catches and Ekman drift, and by the link between anchovy catches in this LME and biological changes in the Western English Channel (see Wyatt & Perez-Gandaras 1989). The coastal upwelling is the most important feature in terms of natural variability in the entire LME. Upwelling takes place in late spring and summer along the coast of Portugal, Western Galicia up to the Cape Peñas in the North Spanish coast (mid-Cantabrian Sea). For more on changes in oceanographic conditions in this LME, see Wyatt & Porteiro (2002).

The Iberian Coastal LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). Margalef (1956) identified marked changes in the phytoplankton composition of Galician waters during the 1950s sardine crisis. The LME is characterised by favorable conditions for the production of clupeoids and other small pelagic fishes. For biomass changes in sardine, see Wyatt & Perez-Gandaras (1989). Changes in the upwelling regime affected the sardine stock. There were changes in the phytoplankton composition and in the patterns of water exchange between the rias and the open sea. Major changes in sardine abundance were accompanied by equally radical changes in other trophic levels. Good sardine productivity is linked with the presence of the diatom *Melosira (Paralia) sulcata*, and poor productivity with *Thalassiosira rotula* invasions. There are marked changes in the abundance of certain dinoflagellate species. See the ocean triads model for an explanation of upwelling, concentration of larval food brought about by convergences, and mesoscale circulation patterns that help to maintain larval retention (Wyatt & Porteiro 2002). Galicia is the most important region in the world in terms of production of mussels cultured in rafts (extensive culture in the rias), with annual average rates of ~250,000 tons.

Oceanic Fronts (Belkin et al. 2009): The frontal pattern off Iberia (Figure XIII-40.1) is fairly complicated and variable, especially on the seasonal and interannual scales. Most fronts are caused by coastal wind-induced upwelling, which is similar to the Northwest African coastal upwelling (Barton 1998) and also broadly similar to the California Current upwelling (Haynes *et al*. 1993). The upwelled water is entrained into large filaments that extend hundreds of kilometres offshore. SST fronts are most pronounced during the peak of the upwelling season, from July through September. The wintertime frontal pattern is quite variable from one year to another and depends, at least partially, on the poleward coastal warm current that emerges once the trade winds collapse (e.g. Garcia-Soto et al 2002); this current is, however, confined to a very narrow near-coastal band, 25-40 km wide; its thermal signature is just 1.0-1.5°C.

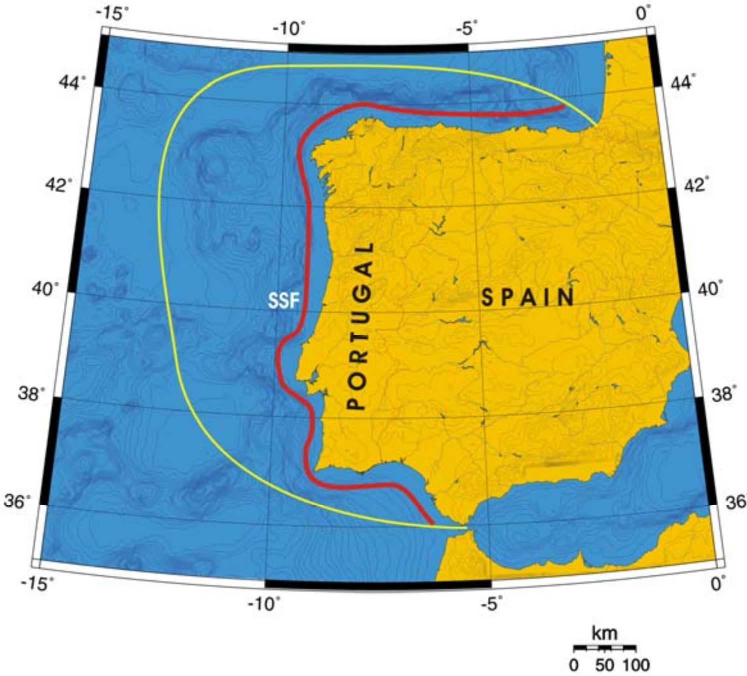

Figure XIII-40.1. Fronts of the Iberian Coastal LME. SSF, Shelf-Slope Front. Yellow line, LME boundary. After Belkin et al. (2009)..

Iberian Coastal LME SST (Belkin 2009):
Linear SST trend since 1957: 0.80°C.
Linear SST trend since 1982: 0.68°C.

Since 1957, the Iberian Coastal LME went through a cooling until the all-time minimum of 1972, followed by a rapid warming, 1.7°C over 34 years (Figure XIII-40.2). Several major events in the Iberian Coastal LME occurred practically simultaneously – within a year – with similar events in the adjacent Celtic-Biscay Shelf LME located downstream of the Iberian Coastal LME and connected to the latter by the Iberian Poleward Current and its extension off northern Spain dubbed “Navidad” (e.g. Garcia-Soto et al., 2002) flowing from the Iberian LME onto the Celtic-Biscay Shelf. These events include three minima of

1963, 1972, and 1986; a maximum of 1989; and a minimum of 1991-94. The observed synchronism between both LMEs may be more appearance than reality since annual mean data does not allow for a study of anomaly propagation over short distances where propagation time is a few months, not years. The very fast post-1972 warming by 1.7°C over 34 years has already profoundly affected this LME. Observations in the southern Gulf of Biscay in 1974-2000 revealed substantial restructuring of local ecosystems caused by the ongoing warming: cold-water fish and sea bird species dwindled, whilst two species – puffin and killer whale – disappeared completely; whereas warm-water species proliferated; taken together, these changes likely manifest a regime shift (Hemery et al., 2007).

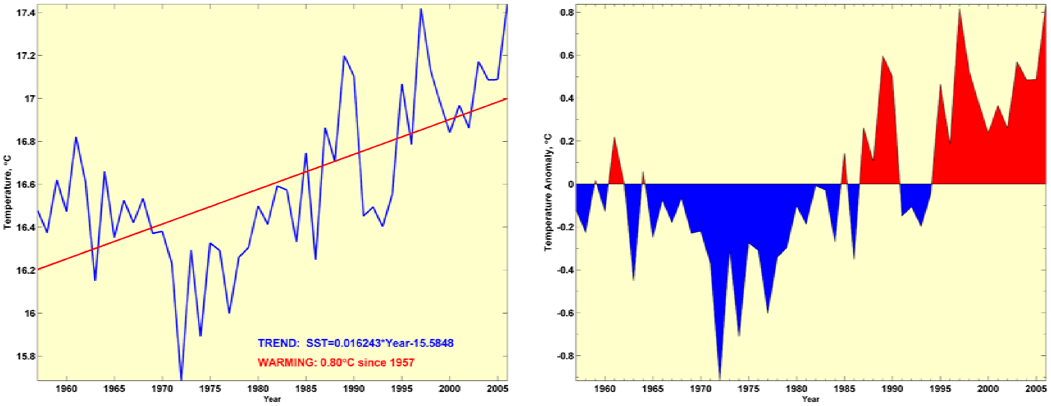

Figure XIII-40.2. Iberian Coastal LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Iberian Coastal LME Chlorophyll and Primary Productivity: This LME is considered a Class II, moderately productive ecosystem (150- 300 gCm^{-2}yr^{-1})(Figure XIII-40.3).

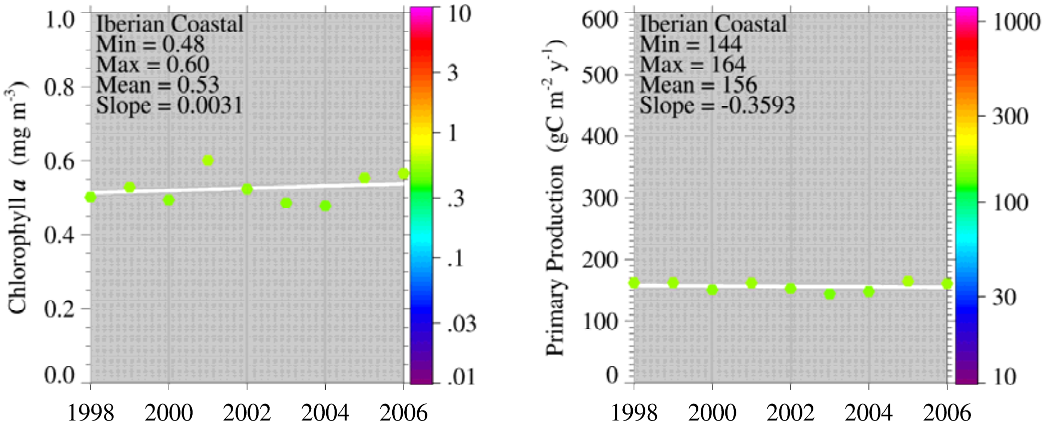

Figure XIII-40.3. Iberian Coastal LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The catch in the Iberian Coastal LME is essentially composed of three groups: herring, sardine and anchovy (42%), other pelagic fish (28%), and cod, hake and haddock. Coastal species harvested are anchovy, sardine, mackerel and horse mackerel. Hake, blue whiting, bream, bogue, pilchard, sprat and tuna are also caught. For examples of biomass changes in sardine, sprat, anchovy and other species, as well as for landings of fish in 1981, and for a description of fisheries geography and Iberian sardine fisheries in crisis in the 1940s and 1950s, see Wyatt & Porteiro (2002). Total reported landings in the LME peaked at 575,000 tonnes in 1972, but in general have fluctuated between 250,000 to 350,000 tonnes (Figure XIII-40.4). The value of the reported landings reached almost US$700 million (in 2000 real US dollars) in 1972, after which it dropped precipitously and fluctuated between US$200 million and US$500 million ever since (Figure XIII-40.5).

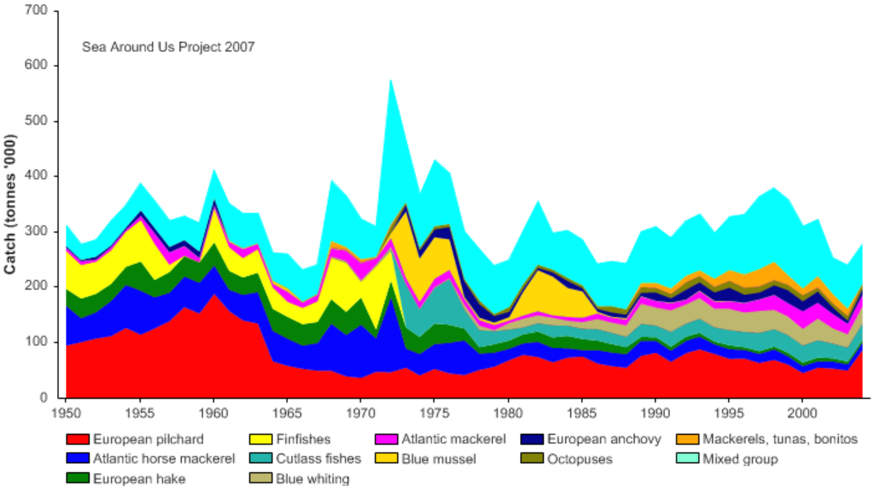

Figure XIII-40.4. Total reported landings in the Iberian Coastal LME by species (Sea Around Us 2007)

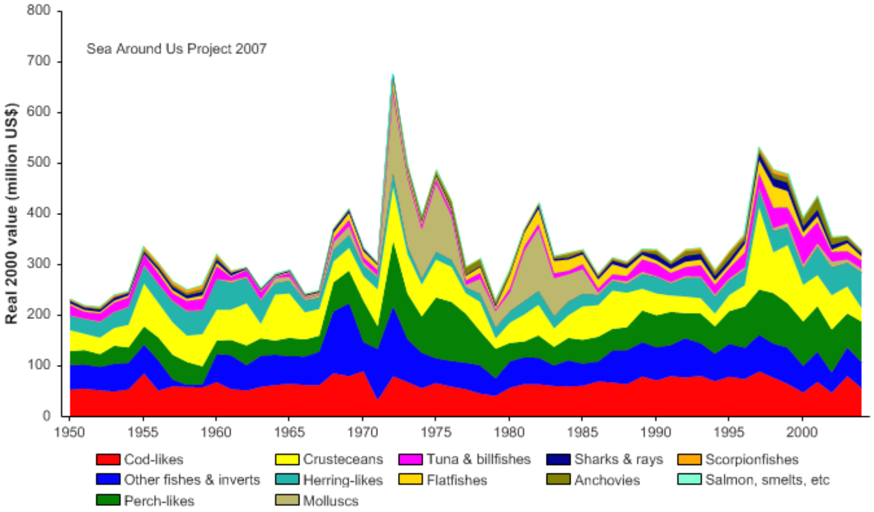

Figure XIII-40.5. Value of reported landings in the Iberian Coastal LME by commercial groups (Sea Around Us 2007)

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached extremely high level in the mid 1970s, but has declined to 30% by 2004 (Figure XIII-40.6). Spain and Portugal account for most of the ecological footprint in this LME.

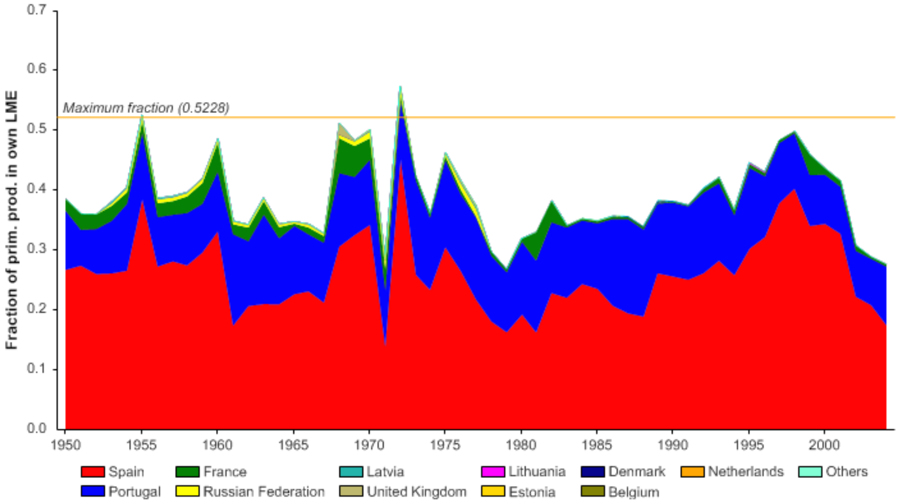

Figure XIII-40.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Iberian Coastal LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) remained more or less even, except for two 'dips' in 1973 and 1983, likely associated with the high landings of (possibly farmed) mussels (XIII-40.7, top). The FiB index is also rather uninformative, except for the very last years, which reflects the decline in the landings (XIII-40.7, bottom). The sustainable mussel farming here (established in the 1950's) stably produced ~250,000 tonnes/year since 1970's, making it one of the most important farming cultures in the world..

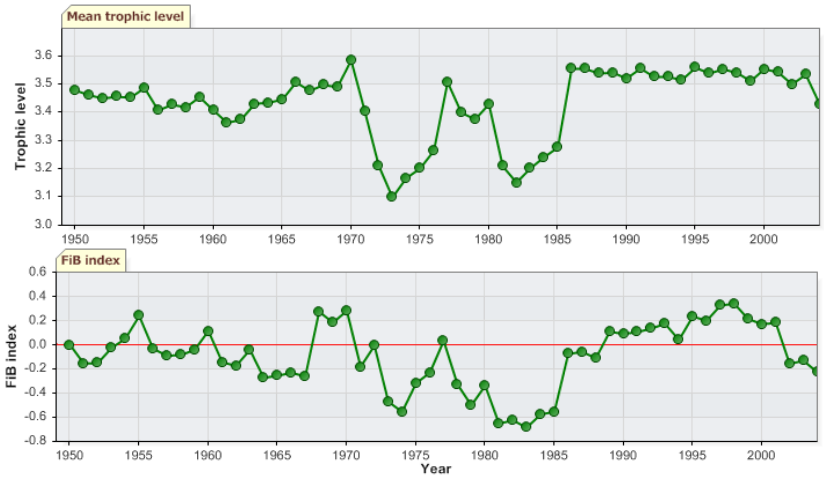

Figure XIII-40.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Iberian Coastal LME (Sea Around Us 2007)

The Stock-Catch Status Plots indicate that the number of collapsed stocks has been increasing, accounting for over 60% of the commercially exploited stocks in the LME (Figure XIII-40.8, top), while the majority of the reported landings biomass is supplied by overexploited stocks (Figure XIII-40.8, bottom).

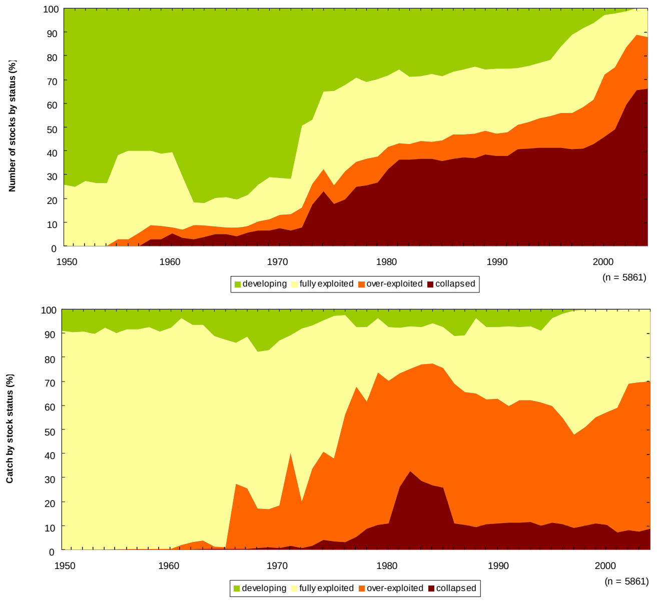

Figure XIII-40.8. Stock-Catch Status Plot for the Iberian Coast LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

Red tides were a more or less annual occurrence in the Rias Bajas from the beginning of the 20th Century until the 1950s. These were almost always due to the dinoflagellate *Gonyaulax*, and sometimes to the ciliate *Mesodinium*. Since the 1970s, *Gonyaulax* blooms have not been reported in the Rias Bajas. Instead, there have been occasional blooms of the toxic dinoflagellates *Alexandrium tamarense, A. minutum* and *Gymnodinium catenatum*. These phytoplankton changes are seen as part of a worldwide increase in the frequency and intensity of harmful algal blooms, and are attributed to various causes including eutrophication and ballast water transport. Perez *et al*. (2004) report that under strong insolation and weak synoptic forcing, typically in the summer, sea breezes and mountain-induced winds develop to create re-circulations of pollutants along the eastern Iberian coast. According to Wyatt & Porteiro (2002), on the whole, pollution is not of major importance in the Iberian LME, except in a few localised areas. OSPAR lists ballast water, mariculture itself; coastal installations intensifying stratification. Anthropogenic inputs and fluxes of nitrogen into areas susceptible to eutrophication; unbalanced nutrient ratios in N: P and N:Si for example; hydroelectric power plant exceptional discharges; and increasing inputs of humic substances from rivers are threats to mariculture (OSPAR 2000). The EEA in "Eutrophication in Europe's Coastal Waters" reports in July 2001 that the Bay of Biscay and Iberian coast eutrophication problems are restricted to estuaries and coastal lagoons, especially Ria Formosa and Huelva. The concentration in this region of ship transport towards Northern Europe requires special regulation to prevent and control pollution. The waters around

Finisterre are regulated to avoid collisions of tankers and carriers. This region has seen a high number of oil spills from wrecks such as the recent Aegean Sea (1992) and Prestige (2002). A map with the location of events can be found in Lavin et al. 2006.

IV. Socioeconomic Conditions

In its reports for 2000, OSPAR estimates population in the “Atlantic arc,” the coastal regions of France, Spain and Portugal, at 36.6 million inhabitants or 106 inhabitants per km^2. In Spain, the three northern coastal regions are densely populated: Pais Vasco (>110 inh/km^2), Cantabria (100 inh/km^2) and Asturias (104 inh/km^2). Population is concentrated in the coastal areas as are most of the economic activities and industries.

Spain and Portugal are important fishing nations in the European Union, with Spain having the largest distant water fleet of any European country. The total number of vessels in the Spanish fishing fleet decreased during the 1990s and is currently around 9000, and only part of it operates in this LME. Spanish artisanal vessels fish for hake and mackerel in the winter, anchovy in spring, and sardine and albacore in summer and autumn. Sardine is one of the most important species in both landings and price. The focus of the Spanish anchovy fishery has moved eastwards, resulting in almost the entire catch being landed in Basque ports. Technical changes in the Basque fishery accounted for part of the increase in landings after the 1960s (Igelmo *et al*. 1984). Spain is gradually being excluded from several of its traditional extraterritorial fishing grounds, and will need to focus on the management of its local resources. A blue mussel farming industry, initiated in the 1950s in the Rias Bajas, produces about 250,000 tonnes annually. In the main area of raft cultivation, the Ria de Arosa, the standing stock of mussels is near or above carrying capacity of phytoplankton production.

Coastal erosion is a major concern, with subsequent salt water intrusion into estuaries, coastal lagoons, wetlands and groundwater as sea level rises likely (OSPAR 2000). The quality of farmed shellfish, particularly near outfalls discharging domestic wastewater, is also a major concern. HABS that affect the human consumer, episodes of acute shellfish toxicity, coastal development including urban expansion, and sea invasion of important agricultural areas, present a number of environmental issues to this coastal population. Compared to its Mediterranean coast, Spain’s Atlantic coast is not a frequent destination for tourists; the total number of overnight stays in local hotels on the Atlantic coast represents 6% of overnight stays in Spain and 87% of the visitors are Spanish (OSPAR 2000) (the French Atlantic Coast represents 24%). Tourism that adds pressure to existing marine ecosystems is also a force for maintaining clean beaches, potable water and uncontaminated fish and shellfish. Currently there is no sewage sludge dumped at sea along the Atlantic coast by France, Spain or Portugal, either from land or ships.

V. Governance

Spain and Portugal are both members of the EU. Being relatively small, the LME can be surveyed with the resources already available in the two countries. Both countries collaborate effectively in various fisheries contexts. The exploitation of the natural marine resources of the Iberian Coastal LME follows a number of conventions, declarations and regulations, including the European Commission directives and regulations within the Common Fisheries Policies. All in all, a large number of instruments from international bodies, such as the UN, ICES, OSPAR, International Maritime Organisation (IMO) and the EU, exist to conserve natural resources, protect the environment and ensure health and safety standards. The European Community laws protect the environment in terms of air and noise, chemicals and industrial risks, nature conservation, waste and water. See the OSPAR website for more information (www.ospar.org).

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XIII-41 Iceland Shelf LME

M.C. Aquarone and S. Adams

The Iceland Shelf LME surrounds the island-nation of Iceland in the northeast Atlantic Ocean. It is characterised by a sub-arctic climate and environment, with seasonal ice cover and marked fluctuations in salinity and temperature off the north coast. Temperature, currents, tides and seasonal oscillations affect productivity in this LME. The area of this LME is 315,500 km^2, of which 0.06% is protected (Sea Around Us 2007). In this highly active geological region, the divergence of two tectonic plates causes the formation of oceanic crust and the crest of the Mid-Atlantic Ridge. LME book chapters and articles pertaining to this LME include Prescott (1989) and Astthorsson & Vilhjalmsson (2002).

I. Productivity

Iceland has a wide volcanic margin marked by broad valleys and a sharply defined slope. For a map of bottom topography around Iceland, see Astthorsson & Vilhjalmsson (2002, p. 220). Three ocean currents (the North Icelandic Irminger Current, the East Icelandic Current, and the Coastal Current move in a clockwise gyre around the island. For a map of ocean currents, see Astthorsson & Vilhjalmsson (2002, p. 221). A complex system of transverse ridges is oceanographically important because it separates the relatively warm and saline waters of the Atlantic from the cold, fresh Arctic waters of the Iceland Sea and Norwegian Sea to the north and northeast.

The Iceland Shelf LME is considered a Class II, moderately high productivity ecosystem (150-300 gCm^{-2}yr^{-1}). Extensive primary productivity measurements have been carried out annually in the waters around Iceland for more than four decades (see Thordardottir 1984). For a map of average primary production in Icelandic waters based on data from the period 1958-1982, see Astthorsson & Vilhjalmsson (2002). Climate is the primary force driving the LME. There are marked interannual changes in the spring development of phytoplankton (Gudmundsson, 1998). Studies on zooplankton biomass and species composition have been carried out on standard transects during late May-June in Icelandic waters. The highest biomass is found in the front area between the coastal and the Atlantic water off Iceland's south coast and in the Arctic waters of the East Icelandic Current off the northeast coast. Changes in hydrography impact the food chain through influences on primary production, zooplankton, and the capelin and cod stocks. For a conceptual model of how climatic conditions in Icelandic waters may affect production at lower trophic levels and eventually the yield from the Icelandic cod stock, see Astthorsson & Vilhjalmsson (2002, p. 240).

Oceanic fronts (Belkin et al. 2009). The Irminger Current warm and salty waters arrive on the Iceland Shelf from the south and circulate anticyclonically around Iceland. The Polar and Arctic waters, both relatively fresh and cold, arrive from the north along the North Iceland Front to meet the Irminger waters (carried by the North Icelandic Irminger Current along the Irminger Current-West Iceland Front) over the northwest, north and northeast Iceland Shelf where two major fronts form (Figure XIII-41.1). The western front is located where the Irminger waters meet the western branch of cold, fresh waters headed toward the Denmark Strait. The eastern front is located north and northeast of Iceland where the East Icelandic Current meets the North Icelandic Irminger Current. The eastern front appears to be connected to the Iceland-Faroes Front observed farther east, although this connection is rather tenuous.

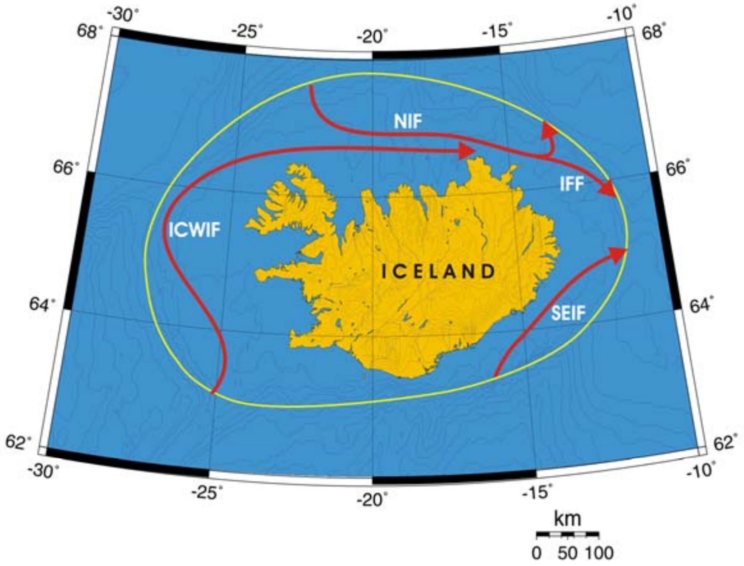

Figure XIII-41.1. Fronts of the Iceland Shelf LME. IFF, Iceland-Faroes Front (located mostly outside this LME; the link between NIF and IFF is rather tenuous); ICWIF, Irminger Current-West Iceland Front; NIF, North Iceland Front; SEIF, Southeast Iceland Front. Yellow line, LME boundary. After Belkin et al. 2009.

Iceland Shelf LME SST (Belkin, 2009)

Linear SST trend since 1957: -0.11°C.
Linear SST trend since 1982: 0.86°C.

The Iceland Shelf experienced a dramatic cooling from the all-time maximum of 7.2°C in 1960 down to the all-time minimum of 5.4°C in 1969 (Figure XIII-41.2). This event heralded the arrival of the Great Salinity Anomaly (GSA) of the 1960s-1970s (GSA'70s; Dickson et al., 1988; Belkin et al., 1998), which had a lasting effect on this ecosystem. This cold anomaly was associated with low salinities and with increased export of sea ice. Ocean currents transported the GSA'70s from the Greenland Sea southward past Iceland, then around the Subarctic Gyre, and eventually back to Iceland and past Iceland into the Norwegian Sea. A map of the circulation in the northern North Atlantic is shown at www.ospar.org.

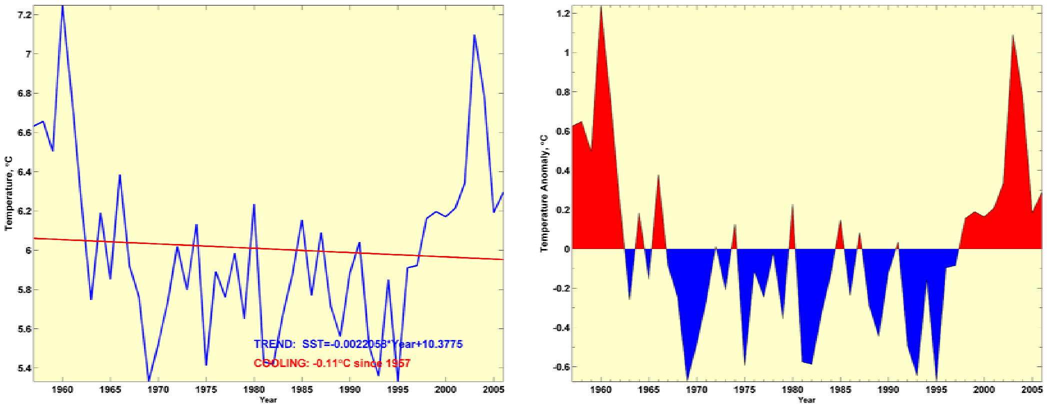

Figure XIII-41.2. Iceland Shelf LME annual mean SST (left) and SST anomaly (right), 1957-2006. After Belkin (2009).

The SST remained low through 1995, the year when SST was as cold as in 1969 (<5.4°C). Then SST abruptly rose through 2003, when it peaked at 7.1°C, a 1.7°C rise in 8 years, thereby posting an average annual warming rate of >0.2°C/year, one of the fastest warming rates observed in the world's oceans.

Iceland Shelf LME Chlorophyll and Primary Productivity: The Iceland Shelf LME is considered a Class II, moderately high productivity ecosystem (150-300 $gCm^{-2}yr^{-1}$).

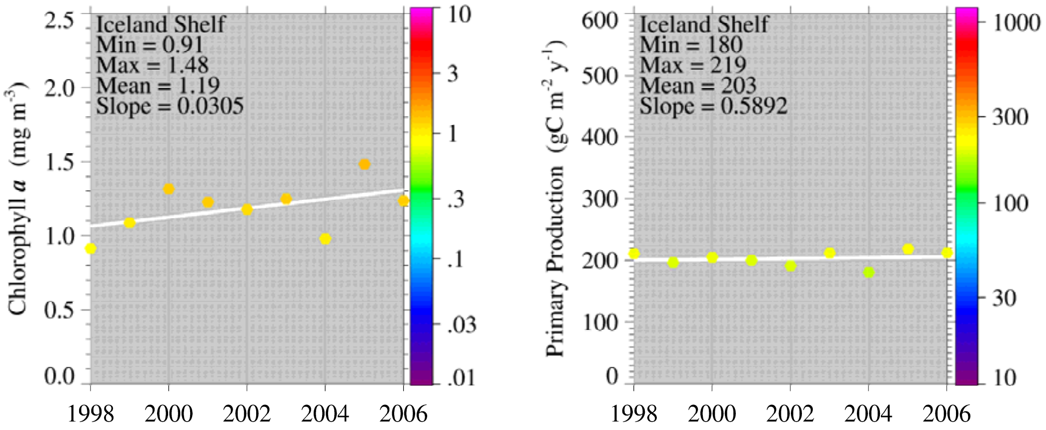

Figure XIII-41-3. Iceland Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Total reported landings[1] have increased since 1950, with occasional considerable variation mainly driven by fluctuations in capelin landings, and total reported landings peaked in 1997 at 1.6 million tonnes (Figure XIII-41.4). Landings were driven primarily by Atlantic cod before the 1970s and by herring and especially capelin afterwards (Figure XIII-41.4). Capelin, which in 1997 accounted for over 60% of the total landings, are linked to cod through a tight predator-prey relationship (Jakobsson & Stefansson, 1998). The herring catch peaked at about 615,000 tonnes in 1962, before collapsing in the late 1960s and early 1970s. An important fishery for northern shrimp developed during the 1970s to the 1990s, with landings in the mid-1990s of over 60,000 tonnes[2]. This decline has been attributed to higher predatory pressure by cod and reduced recruitment related to recent warming (Astthorsson et al., 2007)

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[1] Due to a recent adjustment to the boundaries of the Iceland Shelf LME, the landings data presented here are based on the 1950-2003 data, computed using the boundaries defined in Figure XIII-41.1. Data for 1950-2004, based on the new LME boundaries, will be available online at www.seaaroundus.org.

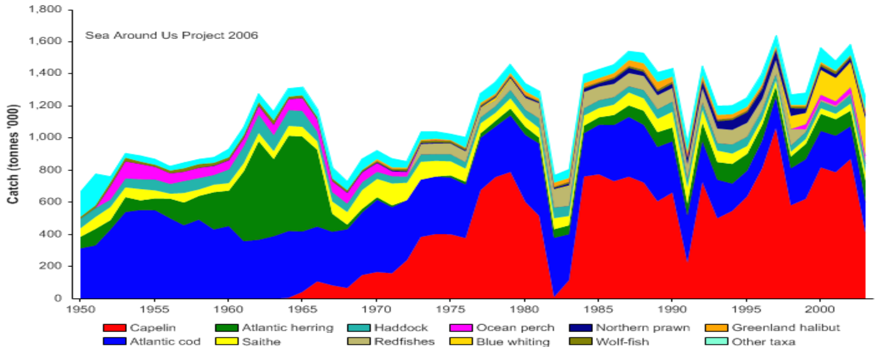

Figure XIII-41.4. Total reported landings in the Iceland Shelf LME by species (Sea Around Us 2007)

No Figure XIII-41.5. Information on the value of reported landings cannot be provided at this stage, due to the recent adjustments in LME boundaries (see note 1 above). Data for values using the newly adjusted boundaries will be available at www.seaaroundus.org..

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME exceed the observed primary production (Figure XIII-41.6). Such unrealistically high PPR likely implies that the large portion of the reported landings are supported by primary production from neighbouring marine ecosystems, i.e., large groups of exploited stocks are feeding outside of the Iceland Shelf LME and migrating in (see e.g. FAO 1981). Iceland accounts for almost the entire ecological footprint in the LME since the late 1970s, following a long, well-documented struggle against the exploitation of its shelf area by distant-water fleets (Bonfil *et al.* 1998).

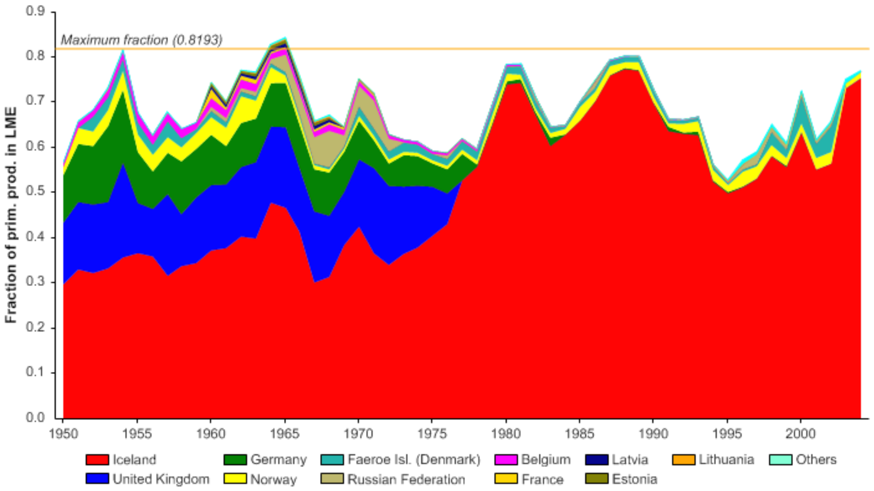

Figure XIII-41.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Iceland Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Both the mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) and the FiB index have declined over the reported period (Figure XIII-41.7). In a detailed analysis on the state of the fisheries in the Iceland Shelf LME, Valtysson & Pauly (2003) stated that the declining TL level reflected increasing interest in pelagic species and invertebrates due to new fishing technology, fish processing technology and marketing, and was also driven by restrictions in groundfish catches due to declining stocks. Note that capelin and herring were never historically harvested simultaneously until the 1980s. Furthermore, the lower trophic level blue whiting has migrated into Icelandic waters because of the warming climate in recent years. These factors help create the appearance of, but not the fact of, ‘fishing down the food web’.

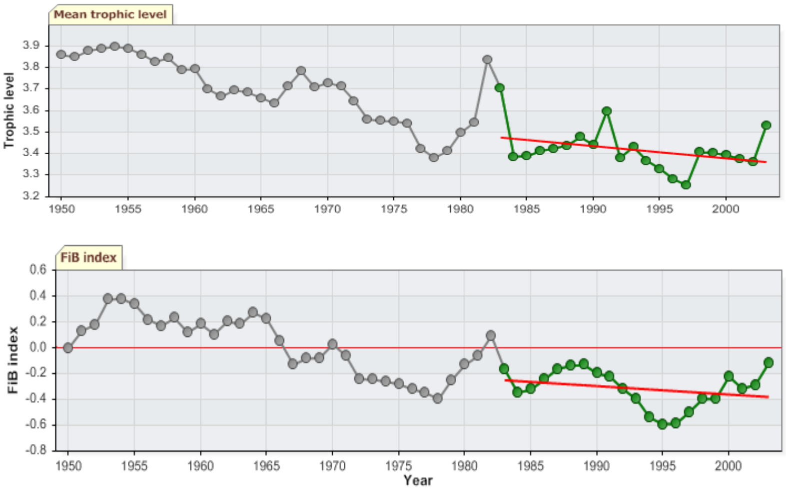

Figure XIII-41.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Iceland Shelf LME (Sea Around Us 2007)

The Stock-Catch Status Plots indicate that the number of overexploited stocks has been increasing over the years, accounting for nearly 90% of the commercially exploited stocks in the region (Figure XIII-41.8, top) with the majority of the reported landings biomass supplied by overexploited stocks (Figure XIII-41.8, bottom).

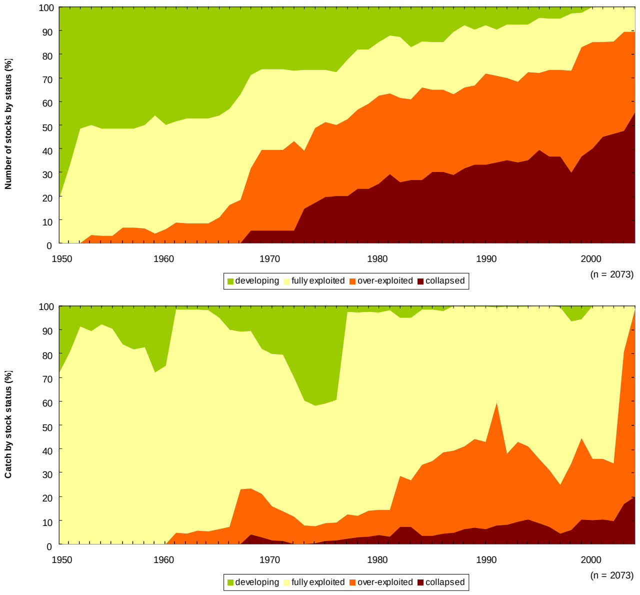

Figure XIII-41.8. The Stock-Catch Status Plots for the Iceland Shelf LME showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Fluctuations in salinity, temperature and phytoplankton contribute to variations in annual catches of cod and small pelagics. Actions are underway in Iceland to reduce overexploitation in a joint government-industry effort for achieving long term sustainability in fish stock yields. Intensive fishing is a secondary force, after climate, driving this LME. Changes in fisheries technology have also impacted the total catch from this LME. At the turn of the last century, the fishing industry gradually became more mechanised, which led to a catch increase. See Astthorsson & Vilhjalmsson (2002) for the following: information on fish yields; a graph of demersal fish catches (cod, haddock, saithe, redfish) in 1950-1998; the inshore and offshore shrimp catch in 1964-1998; a graph of the huge fluctuations of herring and capelin from 1950- 1995 (p. 232); the spawning stock biomass and total catch of the Icelandic cod stock from 1955- 1998 (p. 233); a map of feeding areas and spawning grounds of the Icelandic capelin (p. 236); and for a conceptual model of how climatic factors may affect the yield of cod through the food chain. The simplicity of the main trophic links and oscillations between warm and cold climatic regimes dramatically influence fish yield in this LME. For further information on the impact of climate on the Icelandic Shelf LME see Astthorsson *et al*., (2007) and for occurrence of new and rare species in recent years see Astthorsson & Palsson (2006). Fluctuations in temperature and salinity can be related to large-scale changes in the atmospheric circulation over the North Atlantic Ocean (Malmberg *et al*., 1999). See Dickson *et al*. (1988), Belkin et al. (1998) and Belkin (2004) for information on the ‘Great Salinity Anomalies’ in the Northern North Atlantic. Near shore, hydrographic conditions may vary considerably from year to year mainly due to timing and variations of fresh water runoff.

III. Pollution and Ecosystem Health

Marine pollution appears to be negligible in the fishing grounds of the Iceland Shelf LME. However, the Iceland’s Ministry of the Environment reports that in some seasons of the year, the quantity of persistent organic pollutants has been measured above the EU’s established critical limits in fish products such as fish oil and fish meal for animal feed. (Report on the Implementation of the GPA 2001-2006 in Iceland, p.11). Although the proportion of inhabitants with sewage treatment has risen from 40% in 1992 to almost 70% in 2005, measurements of faecal bacteria have revealed occasional contamination in the vicinity of Reykjavik. The OSPAR 2005 report reveals that in Iceland the concentration of arsenic in the vicinity of Álftafijord northwest and cadmium in the Hvalfjord southwest has increased since the last measurements and efforts are underway to determine why. Yet, heavy metal contamination in living organisms does not appear to be a problem in the sea around Iceland, largely because of the lack of heavy industry. The concentration of mercury is among the lowest measured in the Northeast Atlantic and has not increased since measurements began. The Ministry recounts that regular warnings concerning shellfish consumption had to be released in the July 2006 when in the west in Hvalfjord and Breiõafjord and in Eyjafjord in the north, the levels of Dinophysis species and the *Pseudo-nizschia pseudodelcatissima* both measured far above reference limits. Causes are being investigated. Of particular concern is the effect of the toxins on humans and on the farmed fish and cultivated shellfish. Nitrogen and phosphorous released into the ocean from Iceland’s rivers are routinely measured. Recent legislation requires ship owners to remove ships that run aground within six months following the incident. Iceland’s environment laws and their monitoring and assessments, demonstrate their intent to remain one of the cleanest places on earth.

IV. Socioeconomic Conditions

Iceland has a population of nearly 313,000 as of October 2007 according to Statistics Iceland (www.statice.is). Icelanders enjoy a per capita income among the highest in Europe and remain quite dependent on the fishing industry. Foreign fleets, specifically

British, began fishing these waters at the beginning of the 15th Century (Jonsson, 1994). Fishing by foreign fleets (particularly German and British) played an important role in the cod fisheries during the 20th Century (Schopka, 1994) but foreign investment in the fishing industry is no longer allowed. Iceland is one of the few nations in the world today that has been able to build a modern society upon the exploitation of the resources of its surrounding waters. Seafood products constitute about 60% of Iceland's exports. To address fisheries overexploitation, Iceland has successfully introduced a management system to allow stocks to recover (country profiles at <www.fco.gov.uk>). Iceland has diversified its economy away from fishing into other investments: i.e. aluminium smelting, finance and overseas investment—with some 60% of bank profits now coming from overseas operations. The country is self-sufficient in meat and dairy products. Tourism is now a major foreign exchange earner with some 400,000 visitors in 2005-2006. Whale-watching attracts some 20% of visitors to Iceland. In 2006, 70,000-80,000 visitors from Britain alone came to Iceland. Major industries today in Iceland are fish processing, aluminium smelting, ferrosilicon production, geothermal power, tourism, and pharmaceuticals (country profiles at <www.fco.gov.uk>).

V. Governance

Iceland has played a pioneering role in International Law of the Sea. The competition of foreign fishing fleets prompted Iceland to protect its fisheries by extending its territorial limits. The territorial sea was three miles in 1901, and was extended to four miles in 1952. These extensions were early and bold moves for that time. In 1958, the territorial sea was extended to 12 miles, then in 1972, to 50 miles. British protests against these extensions took the form of three 'cod wars' (in 1961, 1972 and 1975). In an arbitration opposing Iceland and Great Britain, the International Court of Justice ruled in favour of Iceland. Finally, in 1975, Iceland extended its limits to 200 miles. The Ministry of Foreign Affairs has information on Iceland's international relations (http://www.mfa.is/). Iceland has at least 8 pieces of legislation for marine conservation and is about to establish its first major marine conservation area. Iceland works closely with ICES to monitor the size of fish stocks (www.ices.dk/indexnofla.asp). There are various restrictions on fisheries. The most common methods are TAC, mesh size and gear restrictions, restrictions on season length and timing and area closures. Often all methods are used in combination but depending on species some may be more important for one species than another. The main aim is to secure sustainable fishing. The management of Icelandic capelin has been approached in a multi-species context since 1980 (Astthorsson & Vilhjalmsson 2002). The immature stock is specifically protected from fishing and the needs of cod, the main predator, are taken into account prior to the final decision on total allowable catch. Steps have been taken to obtain a better understanding of multi-species interactions in this LME (Anon. 1997). The EEA (European Economic Area) Agreement is legally binding for Iceland to harmonize their legislation and regulatory framework with EU environmental legislation. Iceland is party to UNCLOS and the OSPAR Convention. The LRTAP agreement on Long-range Transboundary Air Pollution of POPs has not been ratified by Iceland, but Iceland is party to its protocols on POPs and PAHs. Iceland is party to MARPOL for prevention of pollution from ships, the London Dumping Agreement, the Copenhagen Convention on international Nordic country cooperation on dealing with accidents caused by oils and other hazardous substances, and the Basel convention to control transboundary movement of hazardous wastes and their disposal. Iceland is working with the Arctic Council and with PAME to protect the Arctic marine environment (Iceland, Ministry for the Environment, 2006) and chaired the Arctic Council 2002-2004.

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XIII-42 North Sea LME

M.C. Aquarone and S. Adams

The North Sea LME is situated on the continental shelf of northwestern Europe. It covers an area of 694,000 km², of which 1.94% is protected (Sea Around Us 2007). Besides the North Sea with an area of 575,000 km^2 and average depth of 94 m, this LME includes a part of the deep-water basin between the Faroes and Shetland Islands. The North Sea LME includes one of the most diverse coastal regions in the world, with a great variety of habitats (fjords, estuaries, deltas, banks, beaches, sandbanks and mudflats, marshes, rocks and islands). Among its many river systems and estuaries are the Thames, Rhine, Elbe, Sheldt and Ems. A temperate climate and four seasons characterise this LME. Great Britain, Norway, Sweden, Denmark, Germany, the Netherlands, Belgium and France are the countries bordering the North Sea. LME book chapters and articles pertaining to this LME include Daan (1986, 1993) and McGlade (2002). There is a wealth of data on the North Sea. Information on climatology, and physical, chemical and biological oceanography was published by McGlade in 2002. ICES issued a report on the fisheries and fish of this region in August 2008.

I. Productivity

The North Sea LME is a Class II, moderately productive ecosystem (150-300 $gCm^{-2}yr^{-1}$). Primary production varies considerably across the LME. The highest primary productivity occurs in the coastal regions, influenced by terrestrial inputs of nutrients, and in areas such as the Dogger Bank and tidal fronts. For more information on plankton communities, benthic, fish and shellfish communities, as well as for food web dynamics and information about bird communities and marine mammals see McGlade (2002). The Sir Alister Hardy Foundation for Ocean Science has been conducting Continuous Plankton Recorder surveys, collecting data from the North Atlantic and the North Sea on biogeography and ecology of plankton since 1931. The Foundation website reports on plankton abundance in the North Sea (www.**sahfos**.ac.uk/).

Oceanic fronts (after Belkin et al. 2009): Up to ten fronts have been distinguished in the North Sea LME from satellite data (Belkin *et al*. 2009) (Figure XIII-42.1). The North Atlantic Current enters the North Sea from the north. Its branches are associated with the Fair Isle Front (FIF) and Shetland Front (ShF). The Norwegian Coastal Current Front (NCCF) extends along the Norwegian Coast and separates the low-salinity near-shore waters from Atlantic waters. Tidal mixing fronts form around Dogger Bank (DBF) and off Flamborough Head (FHF). The Atlantic waters entering the North Sea via the English Channel form two fronts, western (WECF) and eastern (EECF) fronts at their contact with resident waters; these fronts flank the Atlantic inflow. The Frisian Front (FF) origin is related to the fresh outflow from the Rhein River and Scheldt River. The Skagerrak Front (SkF) is located at the boundary with the Baltic Sea waters.

North Sea LME SST (Belkin, 2009)(Figure XIII-42.2)
Linear SST trend since 1957: 0.88°C.
Linear SST trend since 1982: 1.31°C.

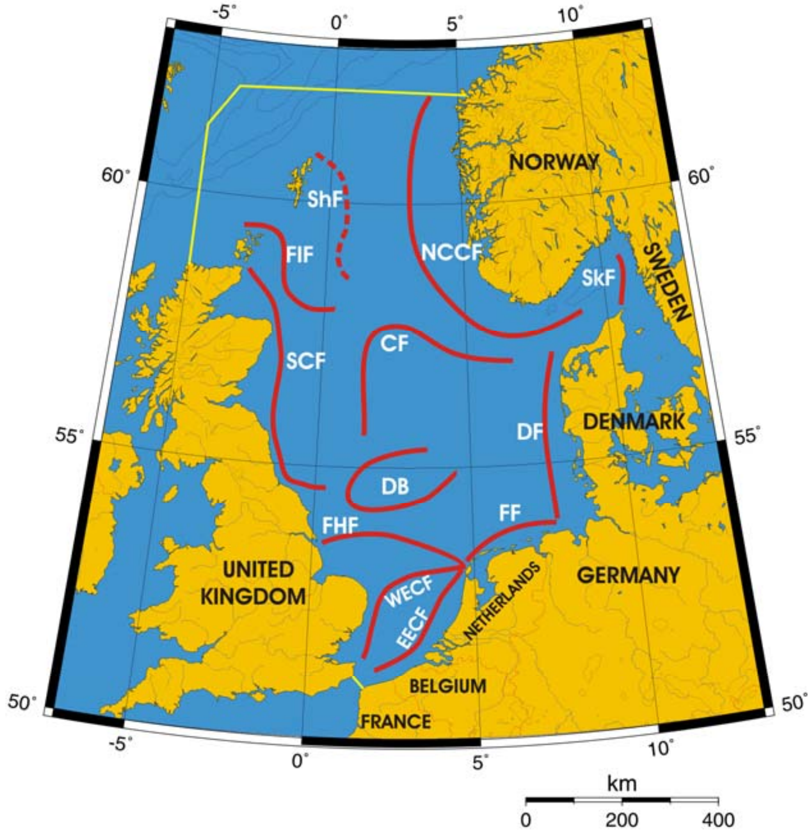

Figure XIII-42.1. Fronts of the North Sea LME. CF, Central Front; DBF, Dogger Bank Front; EECF, East English Channel Front; FF, Frisian Front; FHF, Flamborough Head Front; FIF, Fair Isle Front; NCCF, Norwegian Coastal Current Front; ShF, Shetland Front; SkF, Skagerrak Front; WECF, West English Channel Front. Yellow line, LME boundary. After Belkin et al. (2009).

The 50-year long-term warming of this LME was not uniform. In fact, the North Sea cooled in 1957-1986; this cooling culminated in two cold events of 1979 and 1986 linked to two consecutive Great Salinity Anomalies, GSAs (Dickson et al., 1988; Belkin et 1998). The cold event of 1986 was followed by a dramatic rebound by 1.3°C over the next three years. The third cold event of 1996 was linked to the GSA of the 1990s (Belkin, 2004). The above decadal-scale events were likely associated with the North Atlantic Oscillation, NAO. The cold event of 1962-63 may have been associated with a previous GSA, which is not fully documented because of scarce hydrographic data. The post-1982 warming of 1.31°C makes the North Sea the 2nd fastest warming LME of the last 25 years (after the Baltic Sea LME).

The ongoing rapid warming of the North Sea will likely have an adverse effect on recruitment and catches of boreal fish species (Stenevik and Sundby, 2007). In particular, water temperature in coastal areas of the North Sea is inversely correlated with cod recruitment and catches (Hannesson, 2007). At the same time, warm-water species are expected to become more abundant (Stenevik and Sundby, 2007).

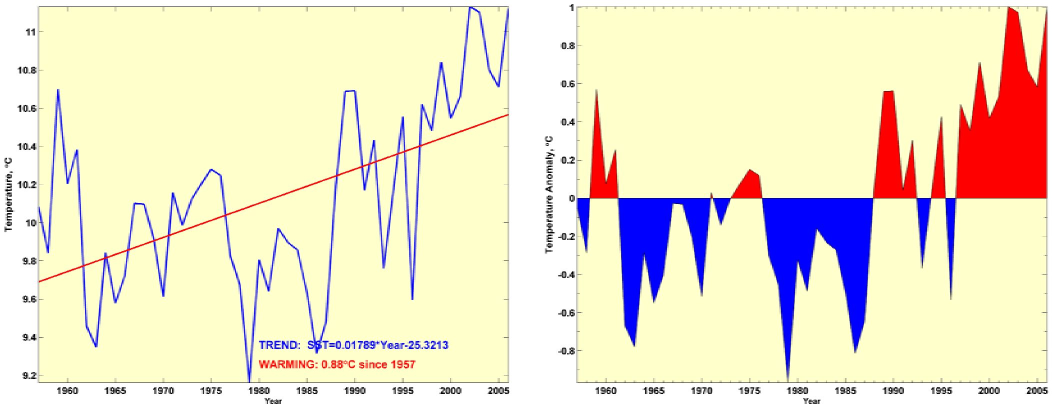

Figure XIII-42.2. North Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

North Sea LME Chlorophyll and Primary Productivity: The North Sea LME is a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}) (Figure XIII-42.3).

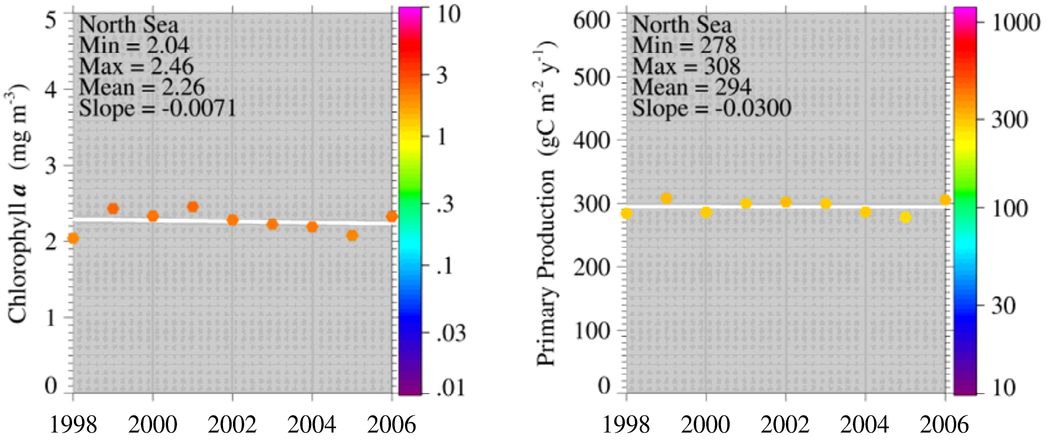

Figure XIII-42.3. North Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery; courtesy of K. Hyde.

II. Fish and Fisheries

Fishing is a long-established activity in the North Sea LME and there is a wealth of fisheries data. The most important species for human consumption represented in the catch are cod-like fishes (cod, saithe, haddock, etc.), herring, sprat and flatfishes. For more information on North Sea fishing fleets, see McGlade (2002). Landings from the industrial fishery consist mainly of sandeels, Norway pout and sprat. There are several commercially important shellfish species of molluscs and crustaceans, including shrimp, crab, lobster, oysters, mussels and scallops. The North Sea, on average, supported total reported landings of over 3 million tonnes per year from the mid 1960s to the early 1990s, with a peak landing of 4.4 million tonnes in 1968 (Figure XIII-42.4). However, reported landings have declined consistently since the early 1990s. The value of the reported landings reached US$3.5 billion (in 2000 US dollars) in 1968, following which it steadily declined (Figure XIII-42.5).

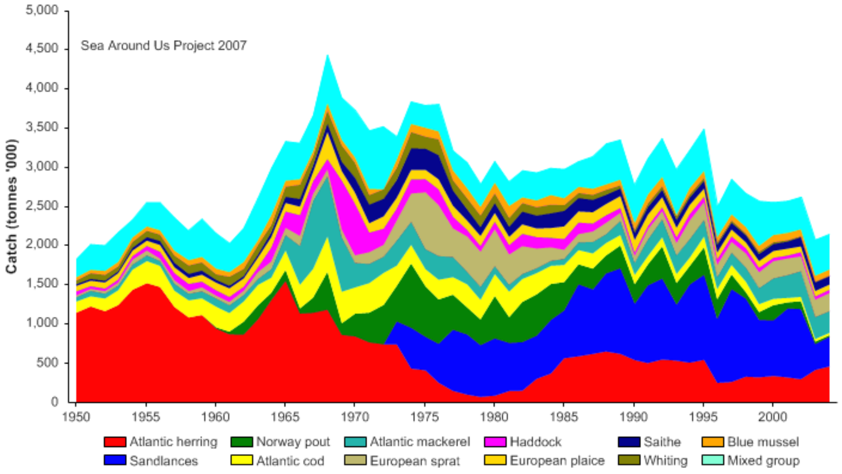

Figure XIII-42.4. Total reported landings in the North Sea LME by species (Sea Around Us 2007)

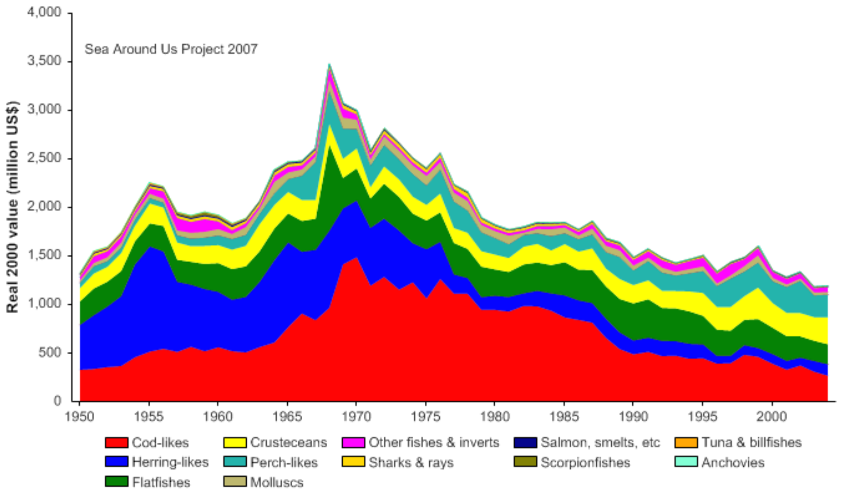

Figure XIII-42.5. Value of reported landings in the North Sea LME by commercial groups (Sea Around Us 2007)

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached an extremely high level, over 70% of the observed primary production in the late 1960s, but has declined to less than 40% in recent years (Figure XIII-42.6). Denmark, Norway and the United Kingdom account for the highest share of the ecological footprint in this LME. The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has shown a steady decline since 1970 (Figure XIII-42.7, top), an indication of a 'fishing down' of the food web in the LME (Pauly et al. 1998). The FiB index has been on a similar decline over the past three decades (Figure XIII-42.7, bottom). Both indices thus correspond with the detailed analysis by Froese & Pauly (2003), which was based on catch data starting in 1903. The Stock-Catch Status Plots, based on the first analysis of an LME using such plots (Froese and Pauly 2003), indicate that the numbers of collapsed and overexploited stocks have been increasing, accounting for close to 80% of all commercially exploited stocks in the LME (Figure XIII-42.8, top). A majority of the reported landings biomass, particularly in recent years, is supplied by overexploited stocks (Figure XIII-36.8, bottom).

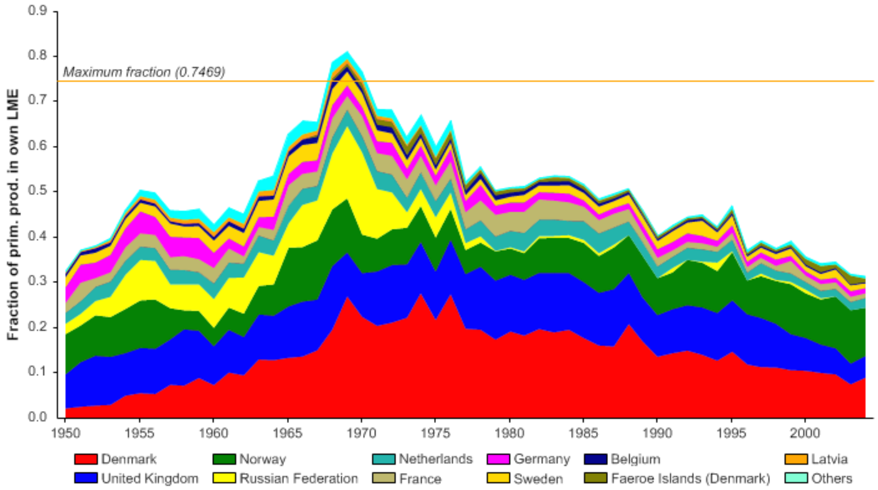

Figure XIII-42.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the North Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

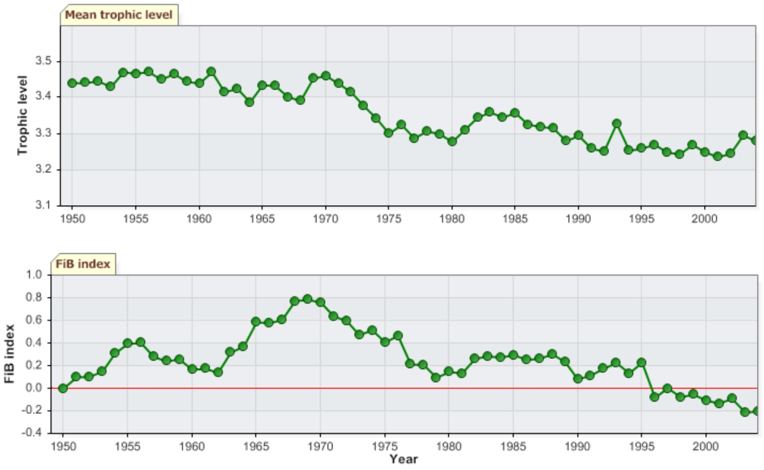

Figure XIII-42.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the North Sea LME (Sea Around Us 2007).

The LME is not stable with regard to individual fish species. Changes in the abundance of commercially important fish stocks have been monitored since the 1950s. All are heavily exploited and the majority of those exploited for human consumption are considered to be seriously depleted. In fact, intensive fishing is the primary force driving the LME. Analytical assessments of all commercially important species are carried out by ICES (www.ices.dk). Improvements in fishing equipment (more powerful engines, hydroacoustic equipment, and the purse-seine net in the mid 1960s) have changed the nature of the fisheries. Various management measures (closures, restrictions on the number of vessels, fishing gear and time) have been enacted to try to control fishing mortality, but these are not systematic throughout the LME. The inclusion in the EU of all riparian countries except Norway led to the development of the Common Fisheries Policy, the results of which are mixed.

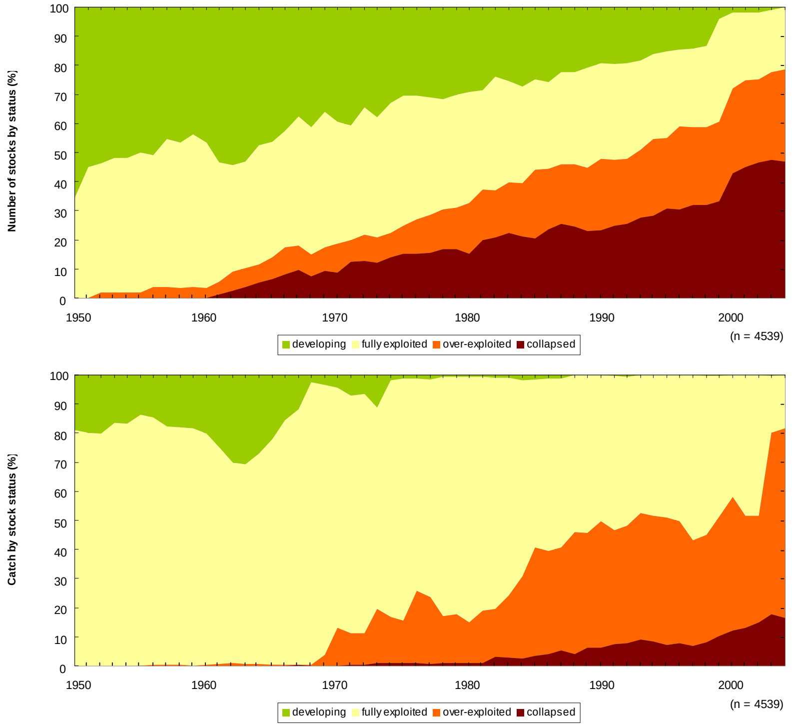

Figure XIII42.8. Stock-Catch Status Plots for the North Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

Both offshore and land-based activities have a significant effect on the North Sea LME. Eutrophication is now a major environmental issue arising from the general increase in nutrient discharges from rivers, land run-off and the atmosphere, largely resulting from sewage effluents, leaching from agricultural land, contributions from rural populations and atmospheric nitrogen deposition. Hazardous substances, oily wastes and slicks are a problem for birds and marine mammals. Alien species have been introduced into the North Sea ecosystem through ballast water and shipping. For more information on the impacts of non-indigenous species, coastal habitats, the ecological impacts of pollution and the effects of marine industries (hazardous and radioactive substances, oil and oily wastes, litter and dumping), see McGlade (2002). An assessment of the health of the North Sea LME was initiated in 1987 as part of the international ministerial activities to address concerns over the impact of human activities and climate change on the ecosystem. In 2000, ICES reviewed the effects of different types of fisheries on North Sea benthic ecosystems. Effective on 11 August 2007, the EU Directive 2005/33/EC on the North Sea SECA (Sulphur Emission Control Area) came into force to regulate sulphur emissions from all ship fuels not to exceed 1.50% m/m/ (www.imo.org and www1.veristar.com).

IV. Socioeconomic Conditions

The North Sea LME plays a key role in one of the world's major economic regions. Approximately 185 million people live in highly industrialised countries, the United Kingdom, Norway, Sweden, Denmark, Germany, the Netherlands, Belgium, France, the Czech and Slovak Republics, Switzerland, and Austria, which have part or the totality of their territory in the catchment area of the North Sea (Ducrotoy 2003). The fishing sector is important in terms of employment, with about 260,000 fishers directly involved in fishing. Currently, the European Union fishing industry comprises 97,000 vessels. The industry supports additional significant numbers of jobs in processing, packing, transportation, marketing, ship-building, fishing gear manufacture and servicing. The LME is also a source of economic resources other than fisheries. The North Sea supports highly productive extractive industries of hydrocarbons, sand and gravel. It is a transport highway as well as a sink for waste and pollution. The Straits of Dover and the North Sea itself are among the most heavily-used sea routes in the world, and are serviced by large commercial ports. Recreation and tourism are important activities in the LME. Large wind parks are in advanced planning stages.

In 2000, the EEA reported that approximately 164 million people lived in the North Sea catchment area, and use the coastline and the marine environment. Due to increased population growth and industrial activity, many of its resources are close to over-exploitation. The fisheries sector is under increasing pressure to allow fish stocks to recover. The northern seaboard will continue to supply at least 50% of the total energy requirements of the European Union, with increases in natural oil and gas production from the North Sea and off Scotland.

V. Governance

A new Marine Strategy Framework Directive was recently enacted which promotes and integrates environmental considerations into all relevant policies areas and which forms the basis for a future Maritime Policy for the EU. The exploitation of natural marine resources in the North Sea is governed by a number of conventions, declarations and regulations. These include the Geneva Convention on the Continental Shelf (1958), the joint declaration of the EU Commission on the coordinated extension of jurisdiction in the North Sea through the establishment of EEZs (1992), and European Commission directives and regulations within the Common Fisheries Policies. All in all, a large number of instruments from international bodies, such as the UN, IMO and the EU, exist to conserve natural resources, protect the environment and ensure health and safety standards. The European Community laws protect the environment in terms of air and noise, chemicals and industrial risks, nature conservation, waste and water. The European Union “North Sea Programme Progress Report” (2006) offers insight into social and environmental activities calculated to build capacity to enable sustainable management of existing resources in rural and urban areas around the North Sea. The OSPAR Commission has information on the 1992 Convention and ministerial declarations on the ecosystem approach (www.ospar.org/eng/html/ welcome.html). The Oslo and Paris Conventions (OSPARCOM) contain a number of supporting legislative and policy instruments. The Esbjerg Conference in 1995 enlarged the focus of protection to wildlife beyond territorial waters, promoted sustainable fishery management, and pushed for more research on the effects of chemicals on reproductive systems. It is expected that future conferences will be held at 5-year intervals (see Reid 1999). The principle of precautionary management has been successfully introduced in the North Sea fisheries, particularly for herring. For more information on governance of European fisheries, and on political and legal regimes, see McGlade (2002).

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XIII-43 Norwegian Sea LME

M.C. Aquarone and S. Adams

The Norwegian Sea LME is a western boundary ecosystem situated off the West Coast of Norway. It covers about 1.12 million km^2, of which 0.08% is protected, and contains about 0.13% of the world's sea mounts (Sea Around Us 2007). A sub-arctic climate characterises this LME. The Iceland-Faroe Ridge separates the relatively warm waters of the Northeast North Atlantic from the cold Arctic deep water of the Norwegian Sea. A boundary current flows along the edge of the Norwegian Shelf into the Arctic region. The cold and low salinity East Icelandic Current flows southeast towards the Norwegian Basin. LME book chapters and articles pertaining to this LME include Ellertsen *et al*. (1990), Blindheim & Skjoldal (1993) and Skjoldal *et al.* (2004).

I. Productivity

The Norwegian Sea LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). All the major marine phytoplankton groups are represented in the Norwegian Sea. Significant temporal and spatial variations in phytoplankton distribution and productivity in the open waters of the Norwegian Sea are described by F. Rey (2004). Winter is characterised by very low phytoplankton biomass, 0.05 mg m^{-3}. The end of the winter period is marked by the appearance of small diatoms (e.g. *Fragiliaropsis pseudonana* and *Thalassiosira binoculata* var. *raripora* (Dale *et al.* 1999) that become important components of the spring bloom. The dominant species during this pre-bloom period advect to the area with Atlantic water from the south, or overwinter in the water column above the permanent pycnocline (Rey 2004). The spring bloom occurs when increased light warms the upper layer, producing a deep seasonal pycnocline and an upper mixed layer. The spring bloom is dominated by early diatom production and later by small flagellates, especially *Phaeocystis pouchetii*, that can dominate the phytoplankton community after the diatom spring bloom (Rey 2004).

There is a tight coupling of primary with secondary production, especially during the spring bloom, in the Norwegian Sea. The reproductive activity of the main copepod in the Norwegian Sea, *Calanus finmarchicus*, is closely related to, and exerts grazing pressure on, the spring phytoplankton bloom (Niehoff and Hirche 2000). In the post-bloom period, coccolithophorids, dinoflagellates and other flagellates dominate the phytoplankton community while the proportion of diatoms falls. Heterotrophic flagellates such as *Leucocryptos marina* appear at this time (Rey 2004). In the autumn, one or more secondary but smaller blooms occurs, together with a reduction in zooplankton grazing pressure. Despite an increase in nutrients by October, diminished light inhibits production to less than 100 mg C m^{-2} day^{-1} in September and decreasing into winter (Rey 2004).

Oceanic fronts (Belkin *et al.* 2009)(Figure XIII-43.1): The North Atlantic Current Front (NACF) exists year-round between warm and salty Atlantic waters transported by the current into the Norwegian Sea, and resident waters of the Norwegian Sea (Belkin *et al*. 2009, Kostianoy *et al*. 2005) (Figure XIII-43.1). The Norwegian Coastal Current Front (NCCF) hugs Norway's coast. This current carries northward low-salinity waters from the North Sea with an admixture of the Baltic Sea waters. The Arctic Front (AF) follows the Mid-Atlantic Ridge meridionally up to Jan Mayen, turns NE along Mohns Ridge, then turns NNW along Knipovich Trough. The Iceland-Faroes Front (IFF) runs near the LME's southern boundary, spawning warm and cold eddies responsible for the bulk of cross-frontal exchange of heat, salt and nutrients. Decadal-scale ‘Great Salinity Anomalies’ travelled across this LME in the 1970s, 1980s and 1990s (Belkin *et al*.1998, Belkin 2004).

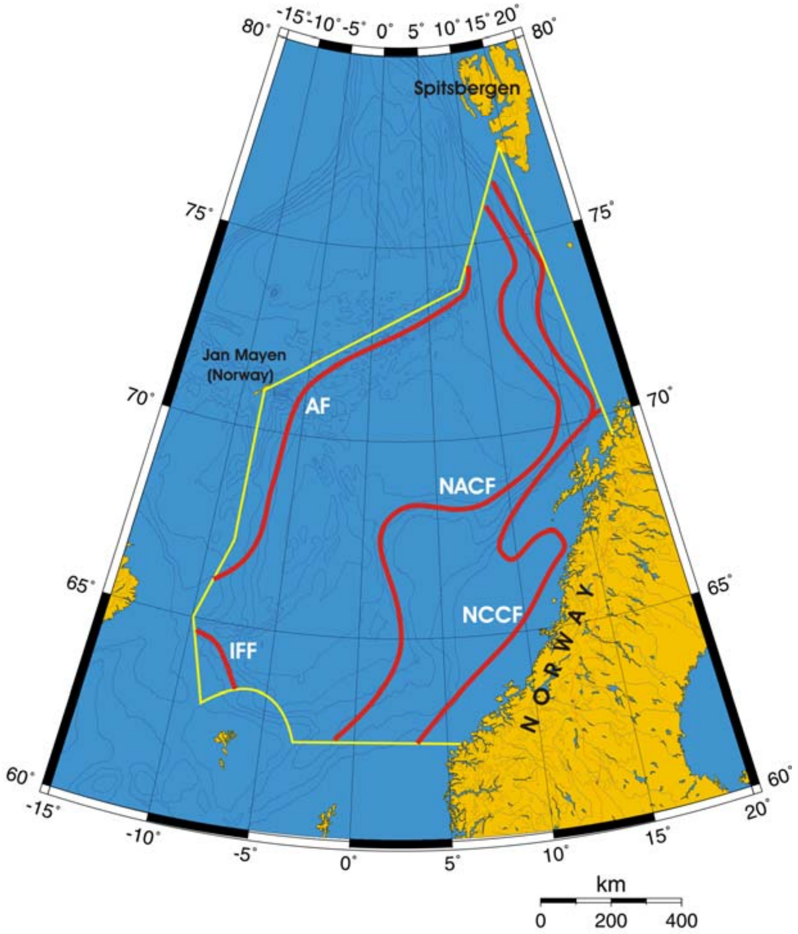

Figure XIII-43.1. Fronts of the Norwegian Sea LME. AF, Arctic Front; IFF, Iceland-Faroes Front; NACF, North Atlantic Current Front; NCCF, Norwegian Coastal Current Front. Yellow line, LME boundary (after Belkin et al. 2009).

Norwegian Sea LME SST (after Belkin 2009) (Fig. XIII-43.2)
Linear SST trend since 1957: 0.18°C.
Linear SST trend since 1982: 0.85°C.

The thermal record of the Norwegian Sea since 1957 was non-monotonous and consisted of (1) cooling until the breakpoint of the all-time minimum in 1979, followed by (2) warming until present, during which SST rose by 1.3°C over 27 years. This is a relatively fast warming rate, consistent with other fast-warming LMEs that surround Europe. The SST maxima of 1961, 1974 and 1990 seem to correspond to the SST maxima of 1961, 1973 and 1989-90 in the Barents Sea LME, which is not surprising given links between circulations in these seas. Thermal manifestations of the “Great Salinity Anomalies,” GSA (Dickson et al., 1988; Belkin et al., 1998; Belkin, 2004), are not evident here, apparently obscured by larger thermal signals, although salinity manifestations are distinct. Year-to-year variability in the Norwegian Sea is relatively small compared to sub-decadal and decadal variability, which strongly modulates long-term trends. The recent warming of the Norwegian Sea is expected to benefit cod fisheries owing to a positive correlation between temperature and cod recruitment and catches, in this area (Hannesson, 2007). Under the present warming conditions, the optimum temperature for fish is shifting north, from the northern part of West Norway towards the Helgeland coast (Stenevik and Sundby, 2007).

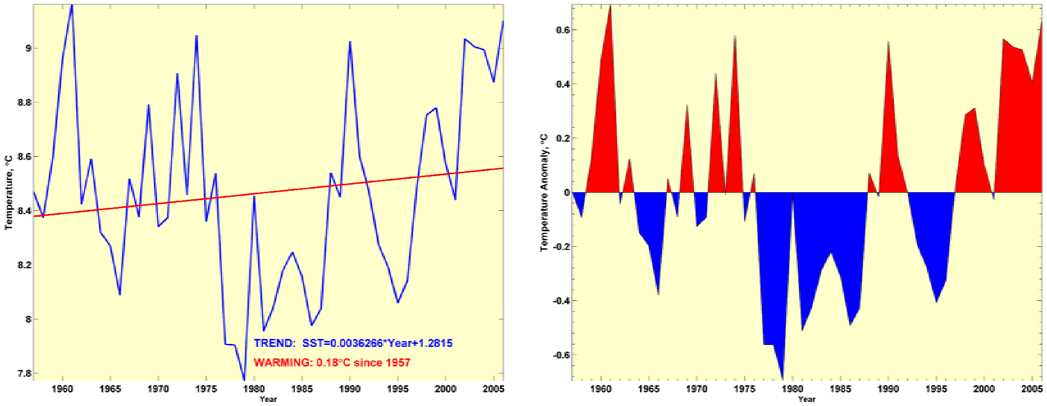

Figure XIII-43 2. Norwegian Sea LME annual mean SST (left) and annual SST anomalies (right), 1957-2006 from Hadley climatology. After Belkin (2009).

Norwegian Shelf LME Chlorophyll and Primary Productivity: The Norwegian Sea LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}).

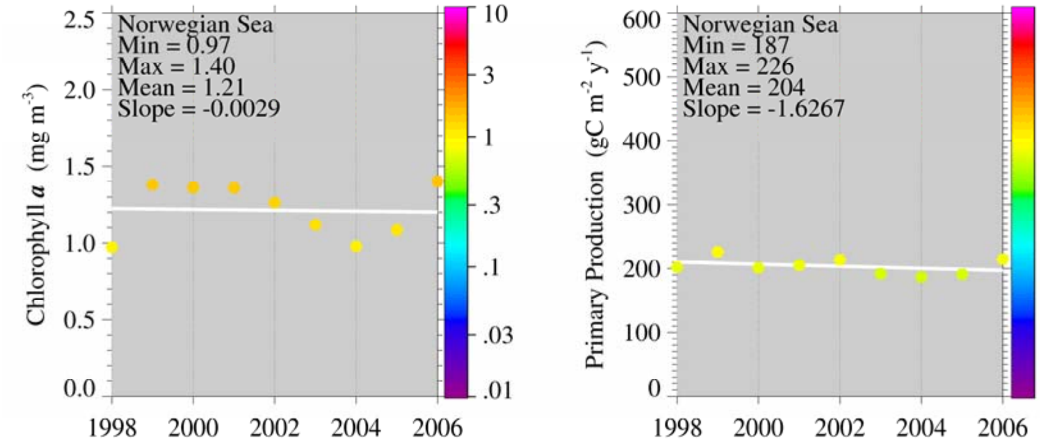

Figure XIII-43-3. Norwegian Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume..

II. Fish and Fisheries

The Norwegian Sea LME has a complex fishery history with concomitant influences of ecological anomalies, high fishing mortality and early implementation of management measures. Reported landings in the LME include Atlantic herring, capelin, Atlantic cod, saithe and blue whiting. While Capelin does not occur in the Norwegian Sea, Norway has agreed that the use of resources in Norway's neighbouring Arctic seas shall not cause species to become endangered or extinct. Populations of species that are currently believed to be endangered or adversely affected by land use, harvesting or pollution shall be conserved and if possible restored. According to the Norwegian Polar Institute brief of 30 May 2008, capelin quotas are in place in accordance with the recommendation from the International Council for the Exploration of the Sea (ICES). Reported landings show significant fluctuations in both total landed biomass and composition, particularly for herring and capelin (Figure XIII-43.4). In recent years, the total landings increased from less than half a million tonnes in 1990 to 1.5 million tonnes in 2004. The value of the reported landings peaked in 1980 at US$ 1.2 billion (in 2000 real US dollars), mainly due to the high blue whiting landings (Figure XIII-43.5).

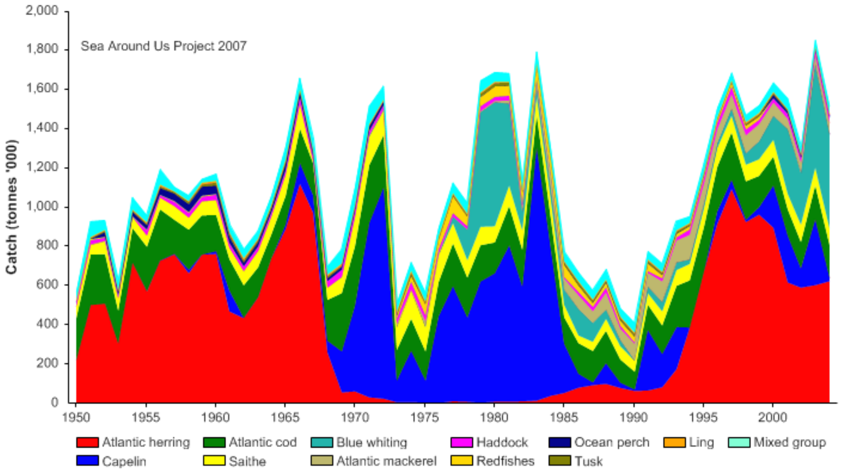

Figure XIII-43.4. Total reported landings in the Norwegian Sea LME by species (Sea Around Us 2007)

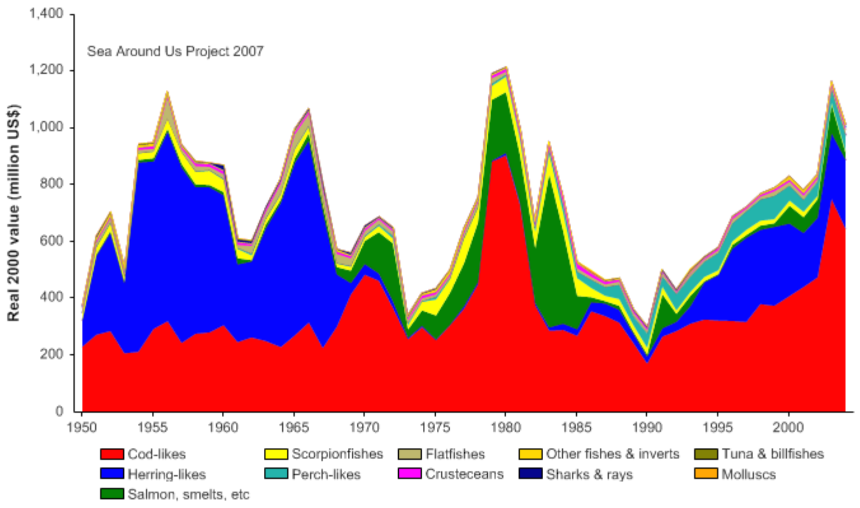

Figure XIII-43. 5. Value of reported landings in Norwegian Sea LME by commercial groups (Sea Around Us 2007)

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached above 60% of the observed primary production in the late 1970s and again in the 2000s (Figure XIII-43.6). Norway and Russia account for the largest share of the ecological footprint in this LME.

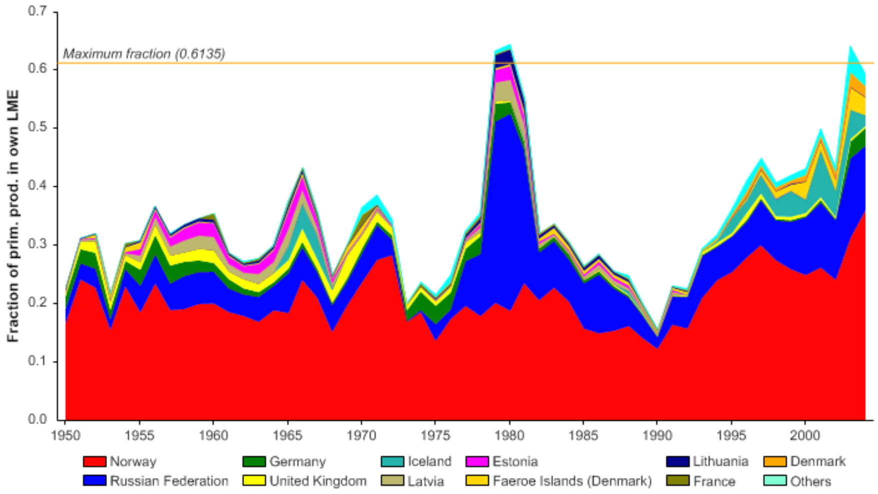

Figure XIII-43.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Norwegian Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) and the FiB index remained roughly stable (albeit with considerable year-to-year fluctuation) over the reported period (Figure XIII-43.7), which may seen as surprising, given the strong fluctuation of species composition in the landings. One possible explanation may be that the key species in the ecosystem are fluctuating in such a way that a balance is maintained in terms of feeding guilds (zooplanktivores, piscivores, etc).

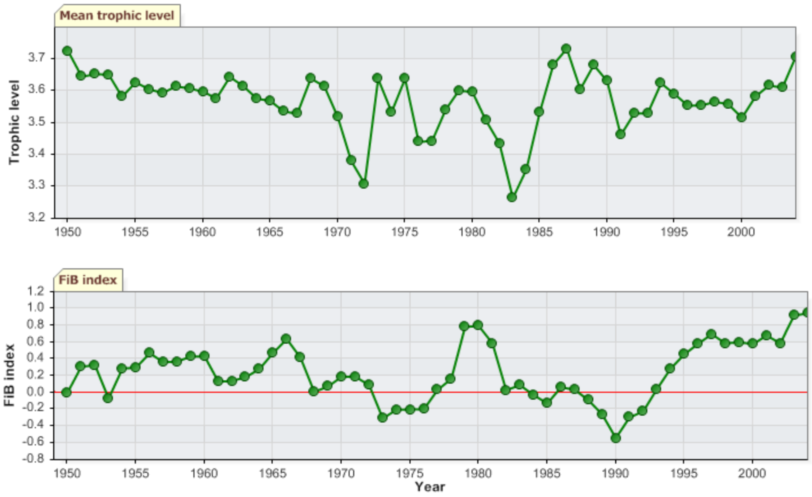

Figure XIII-43.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Norwegian Sea LME (Sea Around Us 2007).

The fluctuations in species composition of the reported landings strongly affect the Stock-Catch Status Plots, which show that the number of collapsed stocks has been consistently increasing, to about 80% of the commercially exploited stocks, in the LME (Figure XIII-43.8, top). A majority of the catch is also supplied by collapsed stocks (Figure XIII-43.8, bottom).

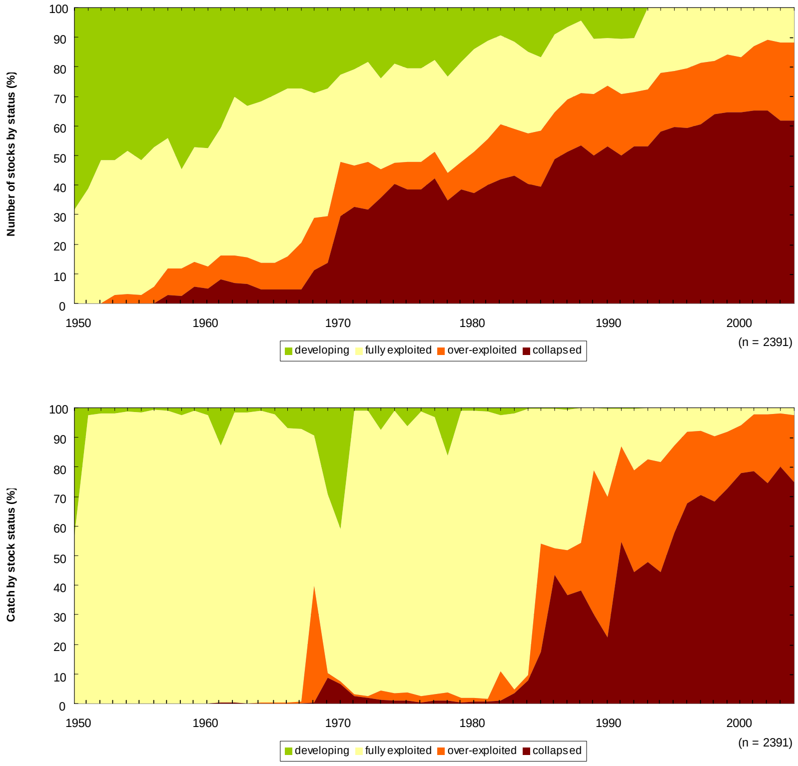

Figure XIII-43.8. Stock-Catch Status Plots for the Norwegian Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

In the 1960s and 1970s, fishing pressure increased as a result of purse seining technology. Herring was depleted, which eventually led to its collapse. After two decades of very low abundance, the herring stock has recovered to a total biomass of over 10 millions tonnes. The herring stock overwinters in the Vestfjord and feeds throughout the Norwegian Sea in summer. The main spawning grounds are off Møre, with smaller populations spawning off of Iceland and southern Norway. For a map of the distribution of the Arcto-Norwegian cod, see Ellertsen *et al*. (1990, p. 20). The spawning areas of cod are located in the Norwegian coastal current, in coastal bays and near offshore banks (see Ellertsen *et al*. 1989). Temperature is an important factor affecting cod recruitment. The data strongly suggests that a high temperature is a necessary condition for the formation of a strong year-class. Capelin migrates out of the Barents Sea into the Norwegian Sea. For more information on the influence of the marine environment on fish recruitment and biomass yields, see Ellertsen *et al*. (1990).

III. Pollution and Ecosystem Health

Some pollution issues in this LME stem from Norway's offshore oil industry, and the risk of oil spills in Norwegian waters. Poor weather and substandard ships have caused groundings and losses. In Norway, the Norwegian Pollution Control Authority is placed under the Ministry of the Environment. This agency aims to promote sustainable development. For more information about pollutants in the Arctic region including the Norwegian Sea, see AMAP (see the Barents Sea LME). The PAME Working Group of the Arctic Council is involved in assessing changing states of Arctic environments (see also Governance). The PAME work plan (2004-2006) will identify indicators of ecosystem health and ecosystem objectives for the Arctic LMEs including the Norwegian Sea. For information on the protection and conservation of marine biodiversity and ecosystems, eutrophication, hazardous and radioactive substances see the OSPAR website at www.ospar.org/.

IV. Socioeconomic Conditions

The fisheries industry is important to coastal Norway's economy. Norway exports fish and fish products to more than 150 countries world-wide. The fishing industry in Norway is divided into a marine and an aquaculture sector. The former employs some 15,000 fishermen at sea and 12,000 people in 500 fish plants along the coast. The aquaculture industry employs some 6,000 people, with fish farms all along the Norwegian north coast. PAME Working Group has information on the small indigenous and non-indigenous communities living in the Arctic that are heavily dependent on the Arctic living marine resources (see the Barents Sea LME). Lidunn Mosaker reports in Fiskeriforskning of 6-08-2007 that since 2000, almost 4,000 jobs in the fishing industry have disappeared. The OSPAR Commission has information on the offshore oil and gas industry, and the ecosystem approach to the management of human activities (www.ospar.org/). Rigzone.com, oil and gas industry news, reports on 4 December 2007 that StatoilHydro secured 6 seismic vessels for work offshore Norway. This deal valued at NOK 1.8 billion, Bjarte Ydstebø, VP for drilling and well acquisitions for StatoilHydro, says will give the company a better foundation for finding drilling targets on the NCS.

V. Governance

More than 20 treaties and agreements cover the Arctic area. Norway established an EEZ in 1977 and recently introduced protective measures for the reefs of cold water corals on the continental slope. It has negotiated a series of agreements with neighbouring countries, including Russia, to decide on management measures and allocation of quotas on shared fish stocks. Several national measures for the management of the Norwegian Sea LME have been implemented in Norway in accord with Norway's activities in the Arctic Council, ICES and OSPAR. The ICES symposium on the changing states of LMEs in the North Atlantic was held in Norway in 1999.

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XIV NORTH EAST PACIFIC

XIV-44 California Current LME
XIV-45 East Bering Sea LME
XIV-46 Gulf of Alaska LME
XIV-47 Gulf of California LME
XIV-48 Pacific Central-American
Coastal LME

XIV-44 California Current LME

M.C. Aquarone and S. Adams

The California Current LME is bordered by the USA and Mexico, between subtropical and subarctic LMEs. It has a surface area of around 2.2 million km², of which 1.31% is protected, and it contains 0.01% of the world's coral reefs and 1.04% of the world's sea mounts (Sea Around Us 2007). The LME shoreline is more than two thousand miles long. The LME features more than 400 estuaries and bays, including the Columbia River, San Francisco Bay and Puget Sound, which constitute 61% of the estuary and bay acreage. This LME is characterised by its temperate climate and strong coastal upwelling. Book chapters and articles pertaining to this LME include MacCall (1986), Mullin (1991), Bakun (1993), Bottom *et al*. (1993), McGowan *et al*. (1999), Brodeur *et al*. (1999) and Lluch-Belda *et al*. (2003). Additional information on this well-studied LME is available from the NMFS, Southwest Fisheries Science Center website, www.swfsc.noaa.gov.

I. Productivity

The effects of coastal upwelling, ENSO and the Pacific Decadal Oscillation (PDO) result in strong interannual variability in the productivity of the ecosystem and, consequently, of the catch levels of different species groups (Bakun 1993). ENSO events are characterised locally by an increase in temperature, a rise in coastal sea level, diminished upwelling and increased coastal rainfall (Bakun 1993). Miller (1996) reports a significant deepening of the thermocline off California, which he attributes to a weakening of the Aleutian Low (decadal scale), and to waves propagating through the ocean from the tropics (interannual scale). There is speculation as to what causes changes in the eastern bifurcation of the Subarctic Current into the California Current, and the possible effects of these changes on biological production in this LME.

The CCLME is one of the world's five LMEs that undergo seasonal upwellings of cold nutrient rich water that generate localised areas of high primary productivity that support fisheries for sardines, anchovy, and other pelagic fish species. (e.g. California Current, Canary Current, Guinea Current, Benguela Current, and Humboldt Current LMEs). The California Current LME can be considered a Class III, low productivity ecosystem (<150 $gCm^{-2}yr^{-1}$) (Figure XIV-44.3). The Pacific Decadal Oscillation (PDO) is a 20-30-year cooling and warming cycle between a cool and productive ocean regime and a warm and unproductive ocean regime. The latest warm regimes were in 1977-1998 and 2003-2006. Apparent biological consequences of these regime shifts are changes in primary and secondary production and changes in the abundance of eastern Pacific fish stocks. For example, there was a sharp decline in primary and secondary production following the 1977 regime shift (CalCOFI Atlas 35, 2002). The California Cooperative Oceanic Fisheries Investigations (CalCOFI) programme has sampled zooplankton biomass almost continuously from 1951 to present. Observed decline in zooplankton abundance related to water column stratification has been described by Roemmich & McGowan (1995a and 1995b), Haywood (1995), and McGowan *et al*. (1999). These biomass changes appear to be inversely related to those occurring in the Gulf of Alaska LME to the north (Brodeur & Ware 1995, Brodeur *et al*. 1999). For a study of interannual variability impacts on the LME, see Lluch-Belda *et al*. (2003), Peterson and Schwing (2003), and Hooff and Peterson (2006). There is a need to better understand the role of climate and seasonal change in the energy flow and population dynamics of species inhabiting the LME. For an analysis of chlorophyll and sea surface temperature changes during the El Niño/La Niña period of 1998/1999, see Kahru & Mitchell (2000). For an article on observing and modelling the California Current system, see Miller and Schneider (2000). Information on the U.S. GLOBEC Northeast Pacific Programme is available at: http://globec.coas.oregonstate .edu/

Oceanic fronts (Belkin et al. 2009): The California Current Front (CCF) separates relatively cold, low-salinity waters of the southward California Current from warmer and saltier waters inshore (Hickey 1998) (Figure XIV-44.1). The Subarctic Front (SAF) separates the northward Subarctic Current from inshore waters. On the inshore side of the California Current, upwelling fronts develop in summer (Belkin & Cornillon 2003, Belkin *et al*. 2003). Offshore frontal filaments, sometimes a hundred km long, carry the upwelled cold, nutrient-rich water across the entire LME (Belkin & Cornillon 2003). In winter, a second and seasonal poleward current develops over the shelf and slope, giving rise to the seasonal Davidson Current Front (DCF) between warm saline subtropical waters inshore and colder, fresher temperate waters offshore. This front can be traced from off southern California (35°N) to the northern Washington coast (48-49°N).

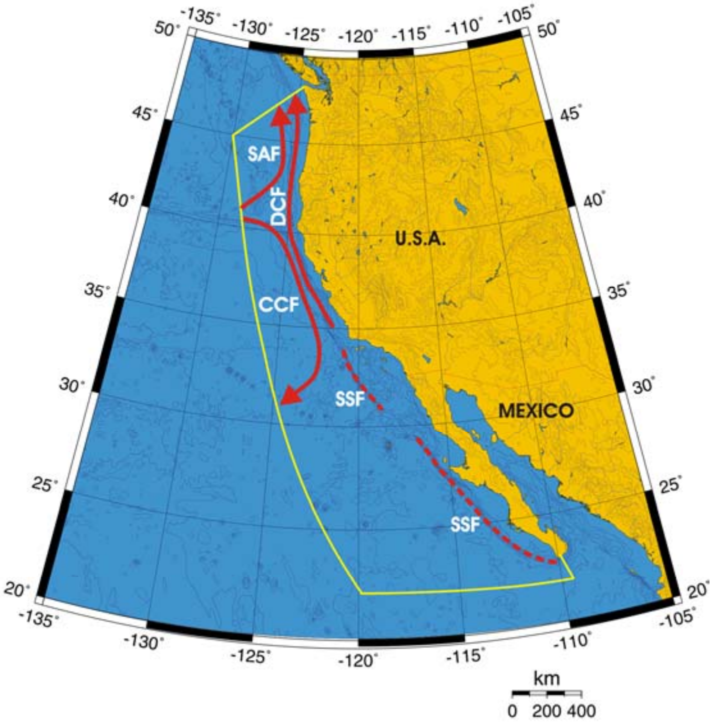

Figure XIV-44.1. Fronts of the California Current LME. CCF, California Current Front; DCF, Davidson Current Front (winter only); SAF, Subarctic Front; SSF, Shelf Slope Front; Yellow line, LME boundary. After Belkin et al. (2009).

California Current LME SST (Belkin 2009)(Figure XIV-44.2).
Linear SST trend since 1957: 0.32°C.
Linear SST trend since 1982: -0.07°C.

Like the East Bering Sea and Gulf of Alaska LMEs, the California Current cooled dramatically, by nearly 2°C, from 1958 to 1975, then warmed by 1977 as a result of the North Pacific regime shift (Mantua et al., 1997), and remained relatively warm up to 1998. Cooling was again observed from 1999-2002, then warming in 2003-2006. The absolute minimum of 1975 was synchronous with the absolute minima in two other LMEs of the East Pacific, the Gulf of California and Pacific Central American. The absolute maximum of 18.3°C in 1997 is attributable to El Niño, whereas the dramatic 1.8°C cooling in 1999 was associated with La Niña. The California Current LME and the Humboldt Current LME have experienced a slight cooling over the last 25 years. Both LMEs are situated in similar oceanographic regimes of East Pacific wind-induced coastal upwelling systems. These regimes feature strong and persistent alongshore winds directed towards the Equator, causing Ekman offshore transport of warm surface waters and upward flux of cold subsurface waters (coastal upwelling). The above-noted long-term cooling in these areas is suggestive of a long-term increase in the upwelling intensity, which in turn may have resulted from a long-term increase in the strength and/or persistence of upwelling-favorable along-coast winds. This hypothesis is supported by observed data and numerical modeling experiments (Schwing and Mendelsson, 1997; and GLOBEC at www.usglobec.org). There is no significant time lag between major thermal events in the California Current, Gulf of Alaska and East Bering Sea LMEs. The observed synchronicity among these regions suggests ocean-scale – if not global – forcing in the Northern and Northeast Pacific. The North Pacific regime shifts of 1976-1977 and 1999-2002 were broad scale events.

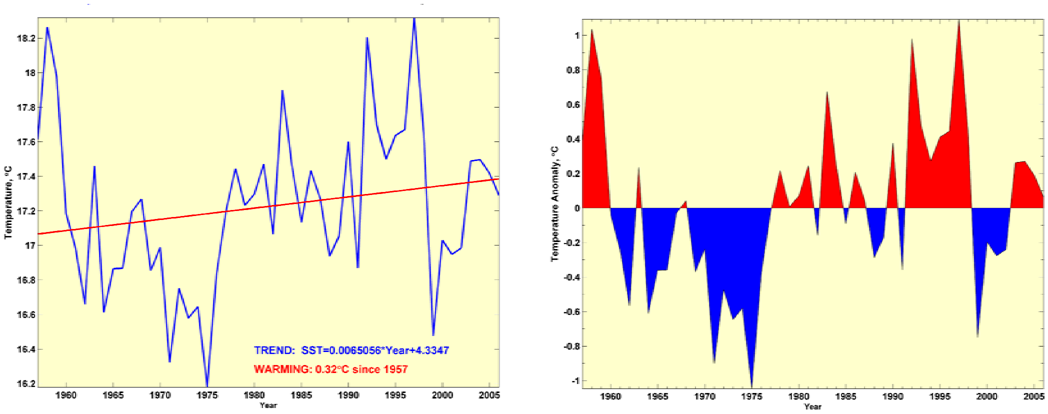

Figure XIV-44.2 California Current LME annual mean SST (left) and SST anomalies (right) based on Hadley climatology. 1957-2006. After Belkin (2009).

California Current LME Chlorophyll and Primary Productivity: The California Current LME is a Class III, low productivity ecosystem (<150 $gCm^{-2}yr^{-1}$)(Figure XIV-44.3).

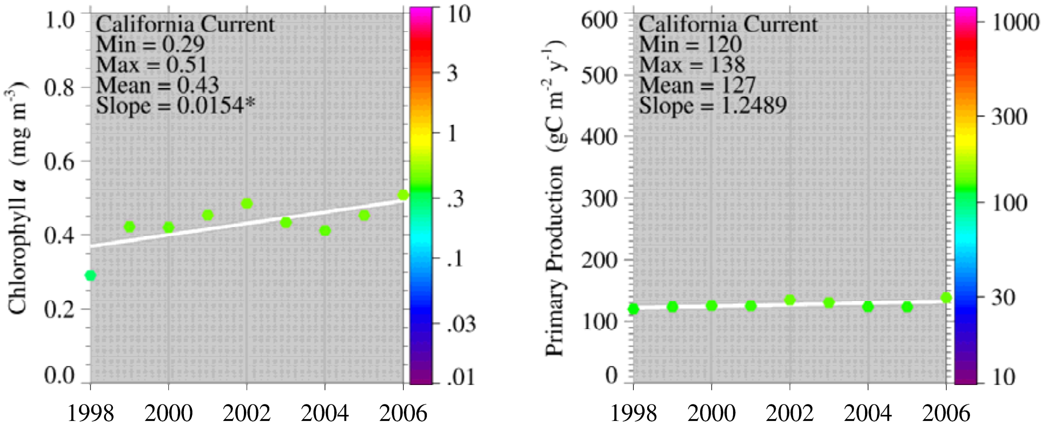

Figure XIV-44.3. California Current LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume..

II. Fish and Fisheries

Fisheries resources in the California Current LME include salmon, pelagic fisheries, groundfish, and invertebrates. Salmon fisheries harvest 5 species of salmon (Chinook, coho, sockeye, pink, and chum). The abundance of salmon stocks fluctuates considerably. Chinook and coho are harvested recreationally and commercially in Puget Sound and in freshwater rivers. Fisheries management for salmon is complex, with conflicting jurisdictions and salmon originating from several rivers. For all salmon species there is excess fishing power and overcapitalization of the fishing fleet. For coho and Chinook there is a sharp decline in abundance that has led to the closure of all salmon fisheries off the coasts of Oregon and California. Small pelagic resources in the LME are Pacific sardine, northern anchovy, jack mackerel, chub (Pacific) mackerel, and Pacific herring. Sardine, anchovy and mackerel are mostly harvested off California and Baja California. Sardine and anchovy fluctuate widely in abundance (NMFS 2009). Natural environmental change and intensive fishing are causing long-term shifts in their abundance in this LME. The CalCOFI programme was initiated to examine the reasons for the decline of the Pacific sardine and to study its physical and biotic habitat (CalCOFI 1990 results at www.calcofi.org). The collapse of the Pacific sardine has had cascading effects on other ecosystem components including marine birds. The variability in abundance levels of sardine and anchovy spawning biomass from 1930 to 1985 is analysed in MacCall (1986). Sardine catches declined after World War II, and the stock collapsed in the late 1950s. The sardine crash is one of the earliest well documented major fishery crashes (Radovich 1982) and is attributed to overfishing that accelerated a long term pattern of natural decline. Sardines today are taken for human consumption, bait, and aquaculture feed. Consumer demand for canned anchovy is low. Anchovy are harvested for reduction into fishmeal, bait, human consumption and oil. In recent years, low prices and market problems continue to prevent a significant anchovy fishery. The endangered brown pelican depends on anchovy as an important food source, and the wellbeing of the ecosystem is an important factor in resource management. Mackerel supported a major fishery in California but the stock collapsed in the 1970s. It has since reopened under a quota system. Sardine, anchovy, and mackerel are transboundary stocks exploited by both US and Mexican fleets. Squid is an important fishery in California in terms of revenue and tons landed. The vast majority is frozen for human consumption and exported to China, Japan and Europe. Landings depend on cyclical oceanographic regimes, with increases when relatively warm water events are displaced by cool water. Herring landings declined with an El Niño episode. Groundfish fisheries include sole, thornyheads, sablefish, rockfish, lingcod and cabezon, flatfish, and Pacific hake. Harvest rates have been reduced in recent years and gear designs to reduce bycatch. Nearshore fisheries are for invertebrate species including crabs, shrimps, abalones, clams, scallops and oysters (NMFS 2009). A recent compilation of species inhabiting the nearshore California Current LME can be reviewed at the California Department of Fish and Game site at: www.dfg.ca.gov/mrd/.

Total reported landings peaked at 710,000 tonnes in 1987 (Figure XIV-44.4). The value of reported landings peaked in 1970 at US$540 million (in 2000 US dollars) with a similar level recorded in 1988 (Figure XIV-44.5). The major commercial fish species are Pacific salmon, hake, albacore tuna, Pacific sardine (also known as South American pilchard), northern anchovy, jack mackerel, chub (Pacific) mackerel, Pacific herring, and Pacific halibut. Shrimp, squid, crab, clam and abalone have high commercial value.

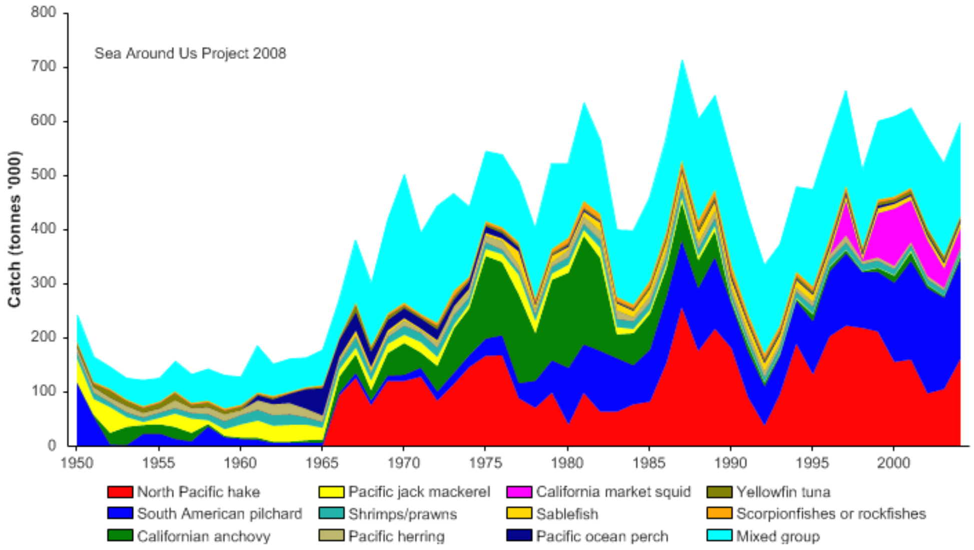

Figure XIV-44.4. Total reported landings in the California Current LME by species (Sea Around Us 2007).

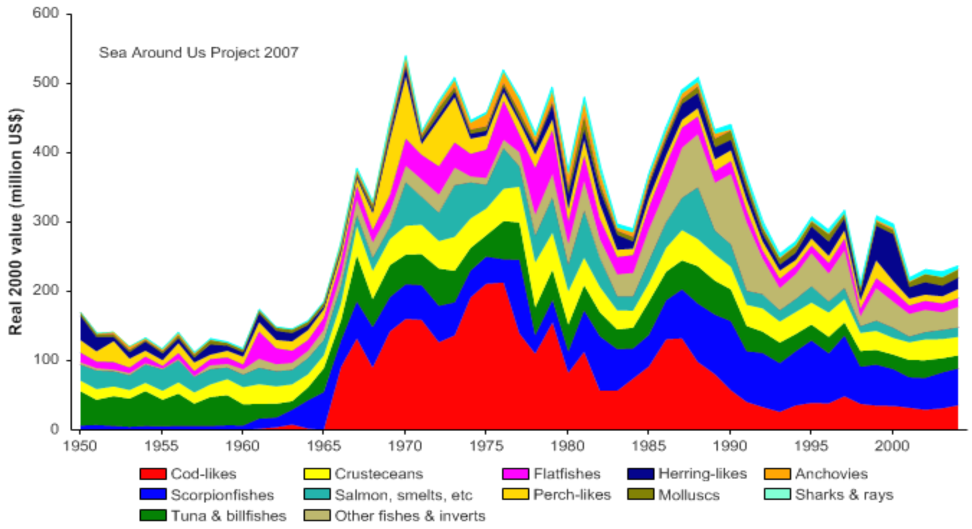

Figure XIV-44.5. Value of reported landings in the California Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR) (Pauly & Christensen 1995) to sustain reported landings in this LME reached 16% of the observed primary production in the late 1980s, and has fluctuated between 7 to 15% in recent years (Figure XIV-44-6). The USA has the largest share of the ecological footprint in the LME.

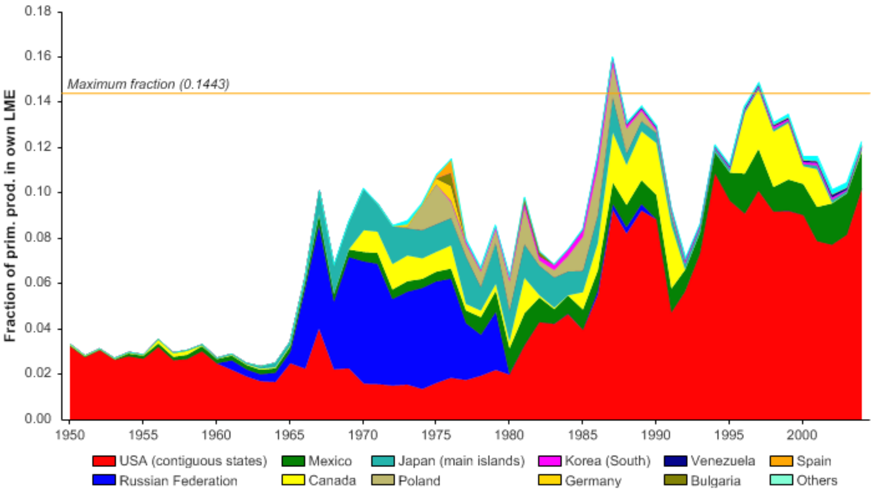

Figure XIV-44.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the California Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Both the mean trophic level of the reported landings (Pauly & Watson 2005; figure XIV-44.7, top) and the Fishing-in-Balance index (Figure XIV-44.7, bottom) show considerable fluctuation over the reported period with no clear trend, except for the initial increase in the FiB index corresponding to a growth in fisheries during the 1960s.

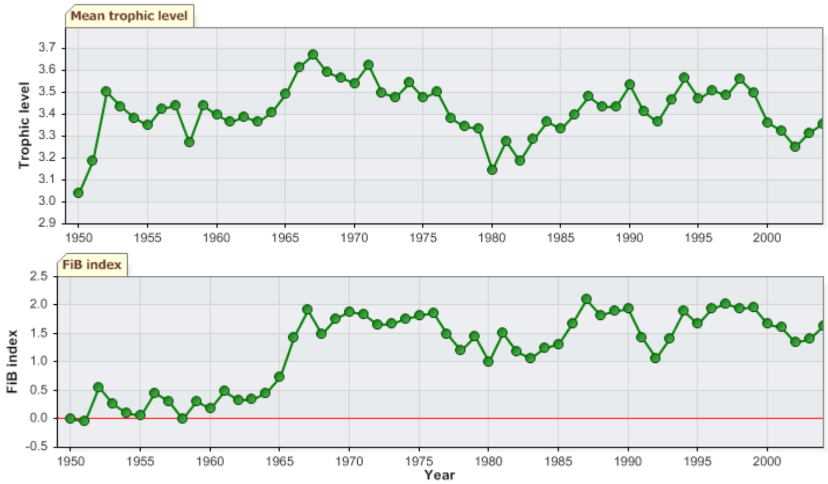

Figure XIV-44.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the California Current LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that over 80% of the stocks in the LME have collapsed or are currently over-exploited (Figure XIV- 44.8, top). Half of the reported landings biomass is still supplied by fully exploited stocks (Figure XIV-44.8, bottom). The US National Marine Fisheries Service (NMFS) includes "overfished" but not "collapsed" in its stock status categories. Currently overfished are Chinook and coho salmon, thought to be impacted by environmental conditions resulting in poor ocean survival. The other salmon species are considered fully exploited. Six other overfished species are among groundfish stocks. Hake and lingcod have been rebuilt to target levels. Jack mackerel and northern anchovy are underutilized species (NMFS 2009).

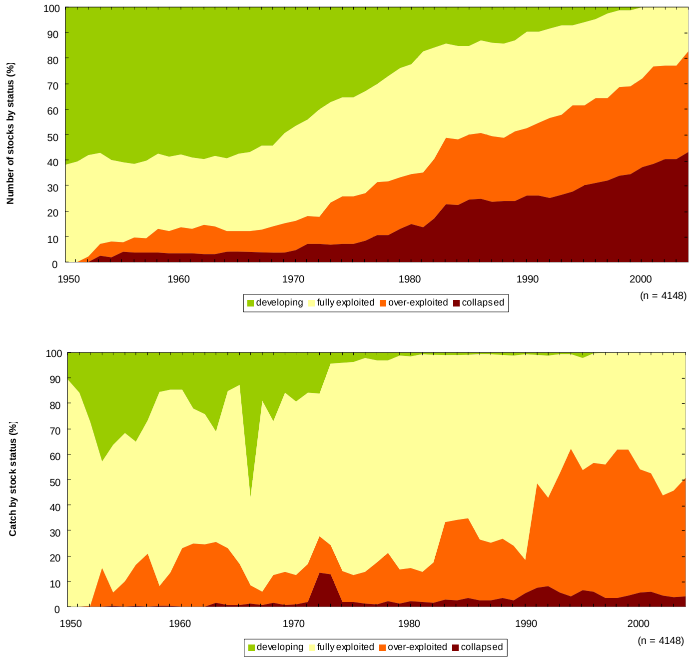

Figure IV-44.8. Stock-Catch Status Plots for the California Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only includes taxonomic entities at species, genus or family level. Higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Comprehensive plans for the management of marine resources in this LME are being developed. Efforts are underway to implement ecosystem management in this LME. There is a need to know more about competitive and predatory interactions, and about climate effects on the fish stocks.

III. Pollution and Ecosystem Health

The major stressors in this LME are the effects of shifting oceanic climate regimes, the intensive harvesting of commercial fish, releases of captive-bred salmon, and low-level, chronic pollution from multiple sources (Bottom *et al*. 1993). Population growth rates suggest that human pressures on coastal resources will increase substantially in many coastal areas (EPA 2004). Hypotheses concerned with the growing impacts of pollution, overexploitation and environmental changes on sustained biomass yields are under investigation. Pacific salmon in the California Current LME depend on freshwater habitat for spawning and rearing of juveniles. There are concerns about the interactions of hatchery and natural wild salmon regarding the genetic integrity of native stocks and productivity levels. The quality of freshwater habitat is largely a function of land management practices. Coastal habitat degradation and shoreline alteration have resulted from dam construction, logging, agriculture, increased urbanisation, grazing and atmospheric pollution. In 1990-2000, the coastal areas experienced a loss of 1720 acres, a low figure compared with other regions of the country but high in relation to existing wetlands in the California Current LME. Ecological conditions in West Coast estuaries, a valuable resource in this LME, are considered fair to poor (EPA 2004). Eighty seven percent of estuaries assessed are impaired by some form of pollution or habitat degradation. Some estuaries have extensive areas with elevated phosphorus concentrations and decreased water clarity. Considerable areas have poor light penetration. DIN concentrations in estuaries are rated good. Summer wind conditions result in an upwelling of nutrient rich deep water that enters estuaries during flood tides (EPA 2004). DIP concentrations in estuaries are rated fair. Chlorophyll a concentrations in estuaries are rated good.

The EPA rated water clarity and dissolved oxygen as good, benthos and fish tissue as fair, and coastal wetlands, eutrophic condition and sediment as poor in this LME (EPA 2001). In 2004 the EPA assessed the water quality index as fair, the sediment quality index slightly improved, and the coastal habitat index and fish tissue index as poor (EPA 2004). The primary problem in California Current estuaries continues to be degraded sediment quality, with 14% of estuaries exceeding thresholds for sediment toxicity or sediment contaminants. Seventeen different contaminants were responsible for fish advisories in this LME in 2002. Toxic sediments in Puget Sound were contaminated with DDT and metals. For a study of water quality and one on sediment contamination in Puget Sound, see EPA 2004. High concentrations of metals and PAHs were observed in the Los Angeles harbour. The potential for benthic community degradation and fish contamination is increasing. A decline in seabirds such as the sooty shearwater has been observed. The LME contains a large seabird and marine mammal population (Bakun 1993) that includes sea lions and elephant seals. Since the late 1970s, pinnipeds have been increasing and are consuming large quantities of fish (DeMaster 1983; California Department of Fish and Game 2005). For more information on marine mammals as indicators of LME health, see NOAA (1999, p. 238). Of 274 coastal beaches, 178 were closed or under an advisory for some period of time in 2002.

IV. Socioeconomic Conditions

Three major estuaries, the San Francisco Bay, the Columbia River and Puget Sound, contribute to the local economy and enhance the quality of life of the inhabitants. Human population pressures are increasing in Puget Sound, the Seattle-Tacoma region, San Francisco Bay and southern California. California's population approached 37.7 million persons on January 1, 2007 (www.dof.ca.gov), up almost 3.8 million persons from the 2000 census. The coastal population increased by 45% between 1970 and 1980 (U.S. Census Bureau 1996). Forty seven coastal and estuarine counties bordering the California Current LME increased their population by 13% between 1990 and 2000 (U.S. Census Bureau 2001). In 2008 the combined population increase of San Diego, San Bernardino, Orange and Riverside counties in California was estimated at 12 percent of the total U.S. coastal population increase (www.oceanservice.noaa.gov). These pressures require continued environmental monitoring to ensure that environmental indicators currently demonstrating fair condition do not deteriorate. The California Current LME supports important commercial and recreational fisheries. All salmon species are harvested by Native American tribes for subsistence and ceremonial purposes. The value of recreational catches is not easily measured. Recent prices for salmon have declined due to market competition from record landings of Alaskan salmon and increasing aquaculture production. Northern anchovy landings fluctuate more in response to market conditions than to stock abundance. Commercial fishing is heavily regulated in an effort to achieve sustainability. In 1998 there were 9,843 commercial fishermen licensed to fish in California waters, down from 20,363 in 1980-1981. In 2006, there were 6,354 commercial fishing licenses purchased (California Department of Fish and Game Statistics, online at <www.dfg.ca.gov/licensing/statistics>). Recreational fishing in California generates US$4.9 billion and supports 43,000 jobs paying US$1.2 million in salaries and wages (Bacher 2007). An increase in the demand for oil, gas and mineral resources (e.g., chromite-bearing black sands and titanium sands off the Oregon and Washington coasts; sand and gravel dredging) has stimulated an exploration of the non-living resources of the LME.

V. Governance

Some critical issues requiring management include wild salmon stocks and significant loss of their spawning and nursery habitats (EPA 2001, p.153). The Pacific Fishery Management Council (PFMC) is responsible for managing fisheries off the coasts of California, Oregon and Washington, with cooperation form states and tribal fishery agencies. Within Puget Sound and the Columbia River, fisheries for Chinook and coho salmon are managed by the states and tribes. The Pacific Salmon Commission, the State of Washington, and tribal fishery agencies manage fisheries for pink, chum, and sockeye salmon. All species of pink salmon have been listed as threatened or endangered under the US Endangered Species Act. There is a legally mandated tribal allocation of Coho salmon. The Pacific Salmon Treaty with Canada determines the share of Canada and the US in the transboundary stock (NMFS 2009). There are more than 80 species managed under the Pacific Coast Groundfish Fishery Management Plan (FMP) of the PFMC, no less than eight of which have been declared overfished. Many groundfish stocks have geographic ranges that extend beyond the US EEZ into Canada and Mexico. Groundfish stocks support many commercial, recreational, and Indian tribal fishing interests in state and Federal waters off the coasts of Washington, Oregon, and California. Groundfish are also caught incidentally in other fisheries, such as the trawl fisheries for pink shrimp and ridgeback prawns. Current management measures include trip limits, bag limits size limits, time/area closures, and gear restrictions. A trawl permit buy-back program was implemented in 2003 to reduce the capacity of the groundfish fishery. NOAA Fisheries Service, in cooperation with the PFMC, is assessing the impacts of groundfish fisheries on the human, biological and physical environment. A preliminary set of alternatives will be developed to take into account new stock assessments for 23 of the groundfish species managed under the FMP (NOAA Fish News 2005). For information concerning the San Francisco Bay Estuary Project, see www.abag.ca.gov/. In Northern California, commercial, recreational, and Native American fishermen have recently targeted both State and Federal water management on the Klamath River and in the California Delta charging that historic fish runs in Northern California have been destroyed by illegal pumping in the Delta area and by hydroelectric dams (Bacher, 2007).

Since the passage of the Marine Mammal Protection Act in 1972, populations of seals and sea lions have increased. Killer whales are listed as an endangered species. In the south, the Mexican portion of the LME has minimal fisheries regulation, with limited fauna and marine mammal protection. The Mexican part of this LME falls within a non-UNEP administered Regional Seas Programme, the North-East Pacific Region, which covers 8 central American countries (Colombia, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua and Panama). The Convention for Cooperation in the Protection and Sustainable Development of the Marine and Coastal Environment of the North-East Pacific (Antigua Convention) was signed in 2002. The governments also approved an Action Plan detailing how the countries concerned will improve the environment of the North-East Pacific for the benefit of people and wildlife. The Action Plan's secretariat is COCATRAM (Central America Marine Transport Commission). For information on PICES, see the East China Sea LME (Chapter X). The States of California, Oregon, and Washington are developing and implementing a network of marine protected areas.

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XIV-45 East Bering Sea LME

M.C. Aquarone and S. Adams

The East Bering Sea LME is characterised by an extremely wide, gradually sloping shelf, and by a seasonal ice cover that in March extends over most of this LME. The LME is bounded by the Bering Strait to the North, by the Alaskan Peninsula and Aleutian Island chain to the South, and by a coastline to the east that is thousands of miles in length. The surface area is about 1.4 million km², of which 0.87% is protected. It contains 0.07% of the world's sea mounts. This LME receives freshwater discharge from major rivers including the Yukon and Kuskokwim (Sea Around Us 2007). Book chapters and articles pertaining to this LME include Incze & Schumacher (1986), Carleton Ray & Hayden (1993), Livingston *et al*. (1999) and Schumacher *et al*. (2003).

I. Productivity

Temperature, currents and seasonal oscillations influence the productivity of this LME. For information on oceanographic and climate forcing in the East Bering Sea ecosystem, and the recruitment responses of many Bering Sea fish and crabs linked to decadal scale patterns of climate variability, see EPA (2004) and PICES (2005). The East Bering Sea LME is a Class II, moderately high productivity ecosystem (150-300 $gCm^{-2}yr^{-1}$). This LME is undergoing a climate driven change in species dominance and species abundance in some ecological groups (PICES 2005). On the temporal variability of the physical environment over the LME, see Stabeno et al., 2001. There is much to understand about its carrying capacity during the present period of climate change. For example, there have been nearly ice-free conditions in the mid shelf from January to May in 2000-2004. Accompanying this change are shifts in the trophic structure with walrus populations moving northward with the ice, and Alaska pollock moving east.

Oceanic fronts: Five major fronts can be found over the East Bering shelf and slope (Belkin et al., 2003; Belkin & Cornillon 2005; Belkin et al., 2009). The Coastal Front consists of three segments, the Bristol Bay Front (BBF), the Kuskokwim Bay Front (KBF), and the Shpanberg Strait Front (SSF), all extending approximately parallel to the Alaskan Coast at a depth of 10 to 20 meters (Figure XIV-45.1). Farther offshore, the Inner Shelf Front (ISF) is located at a depth of 20 to 40 meters while the Mid-Shelf Front (MSF) is found at 40 to 60 meters. These two fronts are also approximately isobathic. The most distant offshore fronts, the Outer Shelf Front (OSF; 60-100-m depth) and the Shelf-Slope Front (SSF; 100-200-m depth within this LME) are not isobathic. They extend from relatively shallow depths in the east, off Bristol Bay, to significantly greater depths in the west, where the SSF crosses the shelf break and slope to continue over the deep basin as it leaves the East Bering Sea LME and enters the West Bering Sea LME.

East Bering Sea SST (Belkin 2009)(Figure XIV-45.2)
Linear SST trend since 1957: 0.46°C.
Linear SST trend since 1982: 0.27°C.

The annual mean SST averaged over the East Bering Sea increased by 0.46°C between 1957 and 2006. The 50-year warming was not uniform: instead, the time span included two periods with opposite SST trends. In 1957 the average Bering Sea SST reached a maximum that has not been surpassed until recently (Niebauer et al., 1999). From 1957 to 1971, the SST decreased by 1.3°C. The SST drop was especially abrupt in the late 1960s-early 1970s; in 1969-71 SST decreased from 5°C to 4°C. The cold spell lasted through 1976. In the winter of 1976-77, the East Bering Sea underwent an abrupt regime shift to warm conditions, with the SST rising by 1°C in a single year and remaining relatively high through 2006. The 1°C SST jump from 4.1°C to 5.1°C between 1976-77 was a regional manifestation of a trans-North Pacific “regime shift” that occurred during the winter of 1976-77, caused by a major shift of the North Pacific atmospheric pressure pattern captured in three indexes, ENSO, PDO, and the Aleutian Low index (Mantua et al., 1997; Hare and Mantua, 2000). This has helped species such as salmon stocks rebound from previous low years of abundance. The atmosphere-ocean system shift was followed by an ecosystem shift around and across the entire North Pacific. For some species, the effects of this ecosystem shift were beneficial, for others they were detrimental. The most recent cold episode, in 1999, was short-lived. The East Bering Sea has returned to warm conditions.

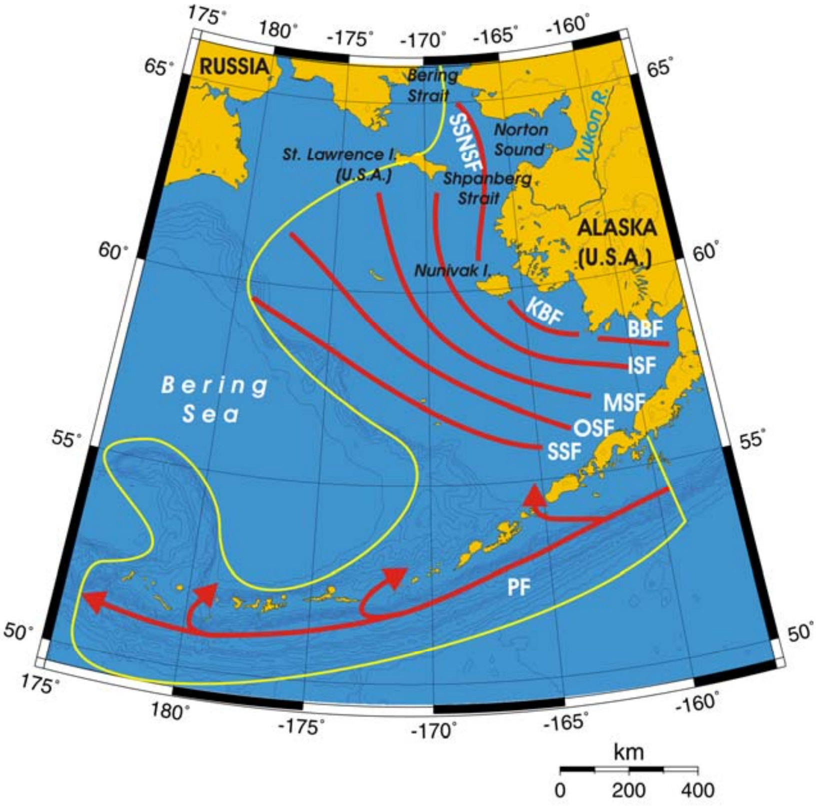

Figure XIV-45.1. Fronts of the East Bering Sea LME. BBF, Bristol Bay Front; ISF, Inner Shelf Front; KBF, Kuskokwim Bay Front; MSF, Mid-Shelf Front; OSF, Outer Shelf Front; PF, Polar Front; SSF, Shelf-Slope Front; SSNSF, Shpanberg Strait-Norton Sound Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

The bathymetry of this LME is critically important while analyzing the area-averaged SST time series. The most important feature is the presence of two different oceanographic regimes within this LME, namely an extremely wide, nearly horizontal continental shelf and a deep-sea basin. This co-existence of shallow shelf and deep sea might explain the observed discrepancy between the LME-averaged SST time series and the SST observations over the East Bering Sea Shelf alone. Indeed, the most recent observations over the southeastern Bering Sea Shelf revealed a dramatic summertime warming by 3°C in the 2000s, likely caused by a synergy of several mechanisms, including (a) persistent northward winds since 2000; (b) a later fall transition combined with an earlier spring transition that resulted in a shorter sea ice season; (c) an increased flux of warm waters from the Gulf of Alaska LME through Unimak Pass; and (d) the feedback mechanism between warm summertime oceanic temperatures and the wintertime southward advection of sea ice (Stabeno et al., 2007).

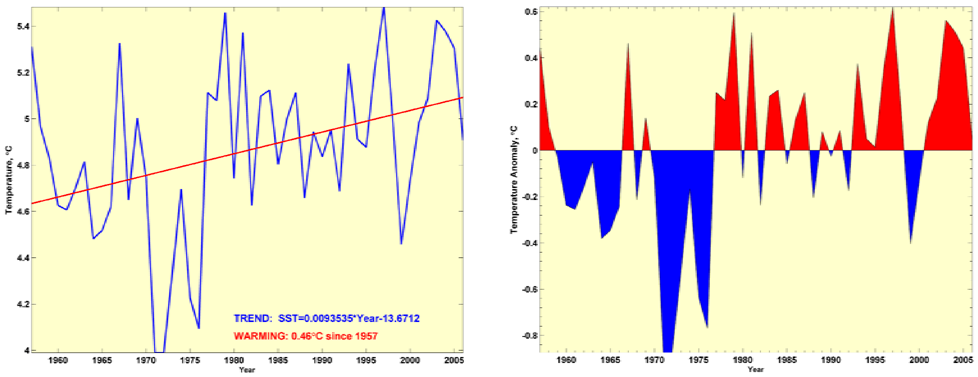

Figure XIV-45.2. East Bering Sea LME annual mean SST (left) and annual SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

East Bering Sea LME Chlorophyll and Primary Productivity: The East Bering Sea LME is a Class II, moderately high productivity ecosystem (150 – 300 gCm^{-2}yr^{-1})(Figure XIV-45.3).

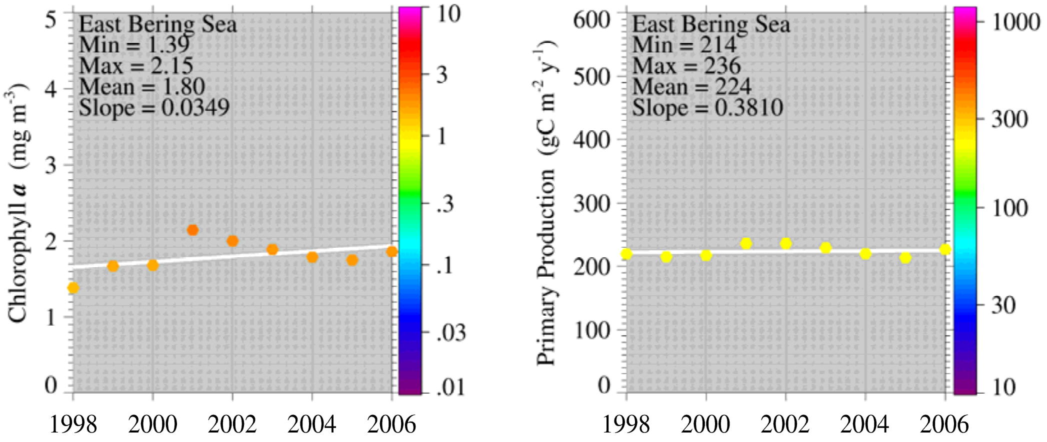

Figure XIV-45.3. East Bering Sea LME trends in chlorophyll-*a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The LME's thousands of miles of coastline support populations of five species of salmon (pink, sockeye, chum, Coho and Chinook). The high abundance of salmon is due to a number of factors including favourable ocean conditions that promote high survival rates of juveniles, hatchery production, and reduction of bycatch (EPA 2004). Sockeye salmon (in Bristol Bay, Alaska Peninsula and Aleutian Islands) is the most valuable of the salmon species but has had recent declines, along with chum salmon. In some years, significant numbers of chum salmon are caught as bycatch in fisheries that target pollock and other groundfish. Despite relatively stable Chinook stocks there is concern over abundance trends. A quota under the provisions of the Pacific Salmon Treaty regulates the Chinook salmon harvest in this LME. Coho salmon is the most popular recreational species. Salmon bycatch in US groundfish fisheries continues to be a problem in fisheries management (NMFS 2009). Groundfish (Pacific halibut, Walleye pollock, Pacific cod, flatfish, sablefish, and Atka mackerel) are the most abundant fisheries resource off the East Bering Sea LME. The dominant species harvested are pollock and cod. Catch quotas have been capped at 2 million tons for groundfish in the fishery management plan for the East Bering Sea and Aleutian Islands. Reported annual landings of Alaska pollock (*Theragra chalcogramma*), the largest catch of any species harvested in the US EEZ, now range between 1.0 and 1.5 million tonnes, a level thought to be sustainable. Pollock has fluctuated in the past decades as a result of variable year classes. Other commercially valuable species include herring, rockfish, skate, Greenland turbot, sole, plaice and crab. The centers of abundance for pelagic herring are in northern Bristol Bay and Norton Sound (EPA 2004). This fishery occurs within state waters and is managed by the Alaska Department of Fish and Game. From catch records it is clear that herring biomass fluctuates widely due to the influence of strong and weak year-classes. Species such as herring, pollock and Pacific cod show interannual variability in recruitment that might be related to climate variability (EPA 2004). Herring biomass fluctuates widely due to strong and weak year classes. Years of strong onshore transport, typical of warm years in the East Bering Sea, correspond with strong recruitment of Pollock (NMFS 2009). Annual summaries of pollock catches and other groundfish, flatfish and invertebrates in the Eastern Bering Sea from 1954 to 1998 are presented in Schumacher *et al*. (2003).

Major shellfish fisheries in the LME are king and snow crab. King and Tanner crab fisheries are managed by the state of Alaska with advice from federal fisheries. Crab resources are fully utilized. Catches are restricted by quotas, seasons, size and sex limits. Shrimp are also managed by the state of Alaska. For biomass trends of crab species from 1979 to 1993, and for finfish fishery exploitation rates compared with crab recruitment in this LME, see Livingston *et al*. (1999). Nearshore fishery resources are those coastal and estuarine species found in the 0-3 nautical mile zone of coastal state waters. Pollock is targeted in the ‘Donut Hole’ that exists in the high seas area outside of the U.S. and Russian EEZs.

Historical catches in this area were very high and unsustainable. Since 1999, however, there has been evidence of increased abundance of Alaska pollock in the Donut Hole, coincident with the reduction of annual sea-ice cover (Overland *et al*. 2005). Another species that appears to be increasing in abundance in response to warming conditions in this LME is pink salmon (Overland *et al*. 2002 and 2005, Overland & Stabeno 2004), whose catches were about 100 thousand tonnes in 2003 and 2004. Patterns of production for salmon are inversely related to those in the California Current LME.

Total reported landings experienced a historic high of over 2.5 million tonnes between 1995 and 1990 (Figure XIV-45.4), with Alaska pollock dominating. In that period, the ex-vessel value of the catches from the East Bering Sea LME was US$2.5 billion (Figure XIV-45.5). The value of the salmon catch has declined due to a number of complex worldwide factors (see IV. Socioeconomic Conditions).

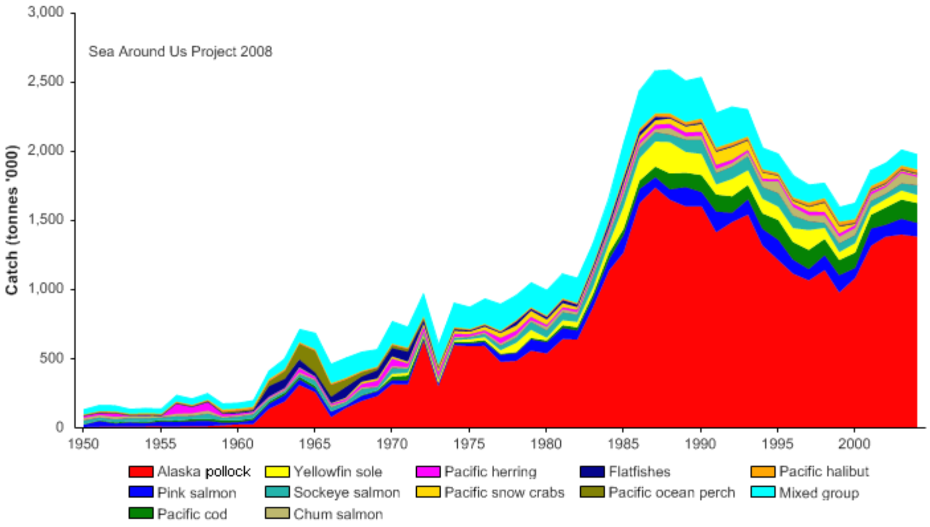

Figure XIV-45.4. Total reported landings in the East Bering Sea LME by species (Sea Around Us 2007).

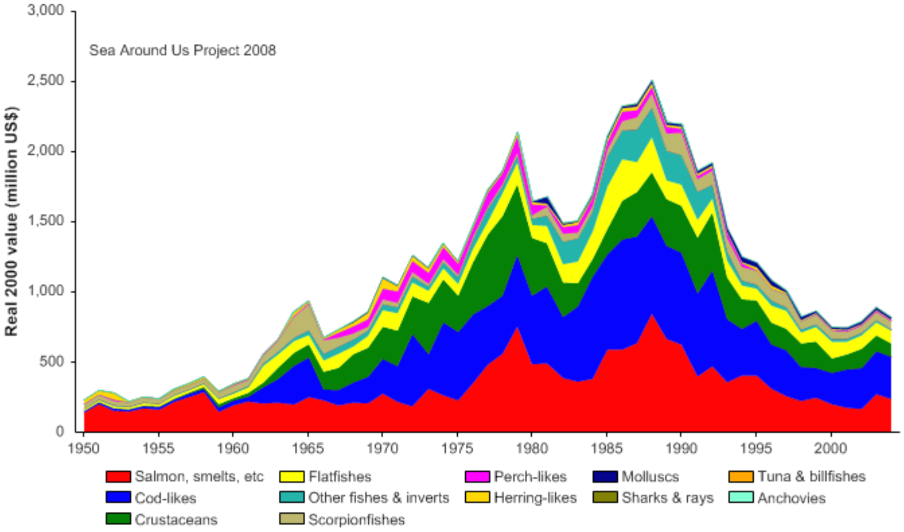

Figure XIV-45.5 Value of reported landings in the Eastern Bering Sea LME by commercial groups (Sea Around Us 2007)

The primary production required (PPR) (Pauly & Christensen 1995) to sustain the reported landings in this LME exceeded 45% of observed primary production in the late 1980s, and has remained around 40% in recent years (Figure XIV-45.6). The USA has the largest share of the ecological footprint in this LME. The mean trophic level of the reported landings (i.e., the MTI, Pauly & Watson 2005) declined from the 1950s to the early 1970s, but has since leveled off at around 3.5 due to the high catch of Alaska pollock. (Figure XIV-45.7, top). The geographic expansion which led to this dominance of Alaska pollock is represented by the increase of the FiB index from the mid 1970s to the mid-1980s (Figure XIV-45.7 bottom). The system appears sustainable according to these two indices, although it must be stressed that such an interpretation is based on the overwhelming effect of a single species.

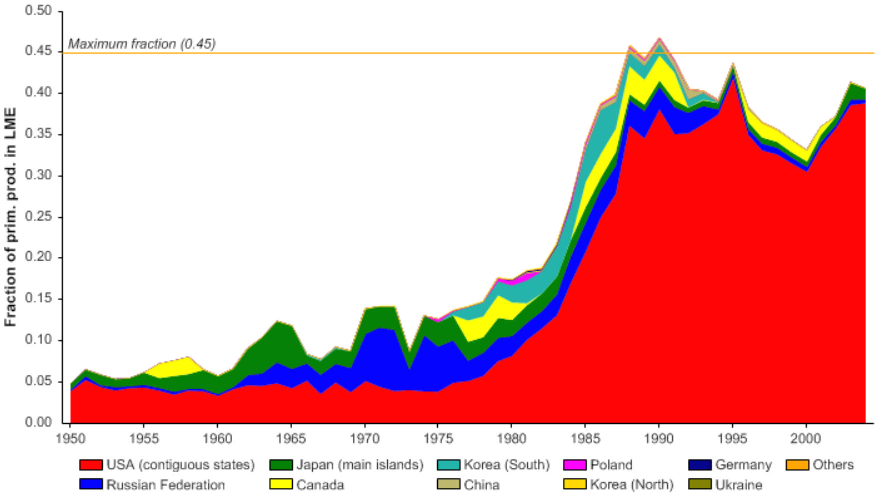

Figure XIV-45.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the East Bering LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

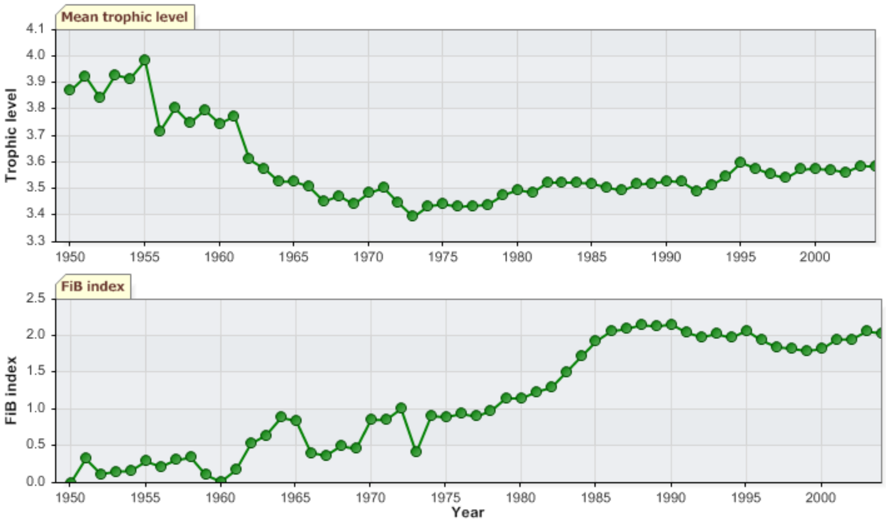

Figure XIV-45.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the East Bering Sea LME (Sea Around Us 2007)

The Stock-Catch Status Plots indicate that over 70% of the commercially exploited stocks are now generating catches of 10% less than the historic maximum, corresponding to the 'collapsed' status in Figure XIV-45.8 (top). This is in line with the findings of Armstrong *et al.* (1998), who reported, for an area immediately adjacent to the one considered here, on serial depletion of the (frequently small) stocks of commercial invertebrates. However, the overwhelming bulk of the reported landings for this LME is supplied by fully exploited stocks of Alaska pollock (Figure XIV-45.8, bottom). The US National Marine Fisheries Service (NMFS) includes "overfished" but not "collapsed" in its stock status categories. All five species of Alaska salmon are fully utilized, and stocks in the LME have rebuilt to near or beyond previous high levels. There is concern for some salmon stocks (especially Chinook and chum salmon) along the East Bering Sea LME, due to overfishing, incidental take of salmon as bycatch in other fisheries, and loss of freshwater spawning and rearing habitats. There is however growing evidence of population increases of pink salmon in Norton Sound and Kotzebue Sound, due perhaps to climatic changes. The halibut fishery is not subject to overfishing. A Pacific halibut cap constrains these fisheries. The Walleye Pollock stock in the LME is considered fully utilized and is well managed for bycatch and other issues which include minimizing impacts on Steller sea lion populations. Flatfish species are underutilized. The sablefish stock is fully utilized and is harvested under an IFQ system. Skates and squids are underutilized. Alaska crab resources are fully utilized (NMFS 2009). The difference between the two panels of Figure XIV-45.8 is the greatest of all LMEs included in this volume. It illustrates the contrast between the effect of prudent management in a few abundant stocks (bottom), combined with serial depletion of what might be seen as minor stocks (top).

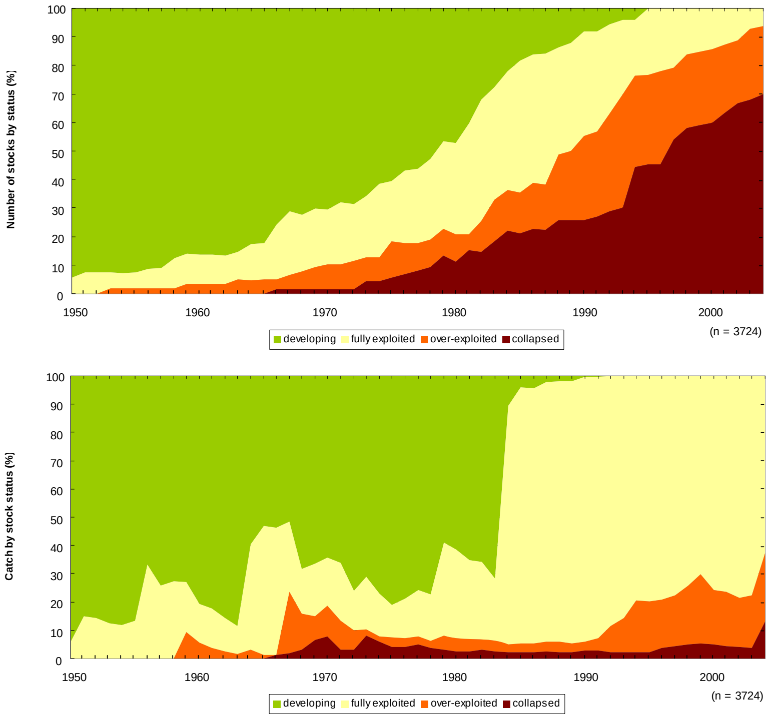

Figure XIV-45.8. Stock-Catch Status Plots for the East Bering Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The management regime annually updates fishing quotas based on biomass estimates, including those for Alaska pollock. Because of the Steller sea lion interaction with pollock, research is underway to study the dynamics and distribution of Steller sea lion prey and predators, and to evaluate the connection with commercial fishing (www.etl.noaa.gov/). An ecosystem approach is being implemented for the assessment and management of fisheries biomass yields in the East Bering Sea LME. The basic ecosystem consideration is a precautionary approach. All groundfish stocks are considered healthy, providing sustained yields of approximately 2 mmt annually. Actions are taken by the North Pacific Fisheries Management Council to annually cap a total groundfish TAC based on NOAA-Fisheries survey operations (Witherell et al. 2000).

III. Pollution and Ecosystem Health

The coastal resources in this LME are generally in pristine condition. Coastal habitats are favourable to, for instance, the high abundance of salmon and with minimal impact from extensive development. Salmon being anadromous depend on freshwater streams, rivers and lakes. Their health is directly influenced by land management practices. The conservation of the region's salmon resource requires the conservation of the thousands of miles of riparian habitat that support salmon production. Competing uses for this habitat include logging, mining, oil and gas development, and industrial and urban development. Contaminant levels are consistently below the EPA's level of concern (EPA 2001 and 2004). Hypotheses concerned with the growing impacts of pollution, overexploitation and environmental changes on sustained biomass yields are under investigation. Concerns for the health of this LME focus on petroleum hydrocarbons found in the tissue of marine mammals, and the effects of the growing industrialisation of the region. Population levels of marine mammals in the coastal areas are low compared to other shallow seas. For statistics concerning the harbour seal, Beluga whale and harbor porpoise, see NOAA (1999, p. 231). Current regulations restrict the Aleutian Islands pollock quota due to concerns over food competition with Steller sea lions in this area, which contains critical habitat for the species. Marine mammal interactions with fish and fisheries are a major concern in fishery resource management in this LME. Fisheries compete for prey items that marine mammals and seabirds depend on for food and are a major factor in the decline of sea lion populations. The Steller sea lion is listed as threatened under the Endangered Species Act.

The East Bering Sea LME has low levels of toxic contaminants, but these have been rising over the last 50 years due to increased human activities (mining, fishing and oil exploration). This increase is linked to the long-range transport of contaminants through the ocean and atmosphere from other regions. Cold region ecosystems such as the East Bering Sea LME are more sensitive to the threat of contaminants than warmer regions because the loss and breakdown of these contaminants are delayed at low temperatures. Also, animals high in the food web with relatively large amounts of fat tend to accumulate organic contaminants such as pesticides and PCBs (EEA 2004). This causes concerns for human health in the region, particularly for Alaska natives, including the Aleut community, who rely on marine mammals and seabirds as food sources. The EPA and Indian Health Service contribute $20 million annually for water and sanitation projects now underway in rural Alaska so that 85% of all Alaska households will have access to safe water and basic sanitation (www.dced.state.ak.us.AEIS).

IV. Socioeconomic Conditions

The Alaskan coast east of the LME has a low population relative to its size and is distant from major urban or industrial areas. More than 65,000 Native Americans live on the shores of the East Bering Sea LME, with a long tradition of relying on salmon and other marine resources for economic, cultural and subsistence purposes. Pacific salmon plays an important and pivotal role, along with mining, timber, and furs, keystone natural resources that led to the settling and development of the US's 49th state by non-native peoples. Many Alaskans still depend heavily on salmon for recreation, food, and industry. Recent declines in chum and sockeye salmon runs have added to the hardships experienced by fishermen in Bristol Bay. The value of the salmon catch has declined over the past decade, along with a rising trend in total worldwide salmon production with the rapid growth of farmed salmon especially in Norway, Chile and the United Kingdom. Nearshore fishery resources provide important subsistence and recreational fishing opportunities for Alaskans of the East Bering Sea LME. Subsistence fishing is distributed all along the coastline of the LME. The East Bering Sea herring fishery began in the late 1920s, with a small salt-cure plant in Dutch Harbor in the Aleutian Islands. Commercial harvesting and processing, along with rapidly growing tourism and sport fishing, provide the region with big employment opportunities (NMFS 2009). According to statistics from the State of Alaska Department of Labor and Workforce Development in 2005, nearly 80% of the private sector population was engaged in fish harvesting or seafood processing in the Aleutian Islands. In the Bristol Bay Region, 75%, of which 40% were non-residents, were employed in the regional seafood industry (harvesting or processing). In the Yukon Delta Region, about 28%.were engaged in fish harvesting or seafood processing. Recreational fishing continues to grow due to an increase in guided fishing trips for visitors and tourists.

The East Bering Sea is home to a valuable offshore fishing industry. The interests of US factory trawlers differ markedly from those of small fisheries. Much of the groundfish catches are exported, particularly to Asia. This trade is a major source of revenue for US fishermen. For an article on the political economy of the walleye pollock fishery, see Criddle & Mackinko (2000). There are increasing demands from extractive industries to log and drill for oil and gas development. Climate change is having and is expected to have a profound influence on the socioeconomics of natural resources, goods and services of the East Bering Sea LME. The U.S. National Science Foundation supports studies of the physical, chemical and biological processes and human impacts to be expected by the reduction of sea ice in the East Bering Sea (BEST 2003).

V. Governance

The East Bering Sea LME is bordered by the USA (State of Alaska). The Alaska Board of Fisheries deals with the allocation of fish resources and quotas among various fisheries. The North Pacific Fishery Management Council (NPFMC) has primary responsibility for groundfish management within the US Exclusive Economic Zone (3 to 200 nautical miles) off the coasts of the East Bering Sea and Aleutian Islands, with the goal of maintaining stable yields by regulating harvest allocations among species. It is addressing the issue of salmon bycatch through time-area closures and bycatch limits set for different gear types in groundfish fisheries. The Alaska native populations benefit from individual fishing quotas or IFQs. There are also community development quotas (CDQs). Pelagic and salmon fisheries occurring within 3 miles are managed by the Alaska Department of Fish and Game. Improved management of the salmon fishery by state and federal agencies has contributed to the high abundance of Pacific salmon. High seas drift net fisheries by foreign nations for salmon has been eliminated through UN Resolution 46/215. The management of high seas salmon is under the North Pacific Anadromous Fish Commission. Initial signatories of the Commission are Canada, Japan, Russian Federation, Korea, and the United States. The Convention for the Conservation of Anadromous Stocks in the North Pacific Ocean has eliminated a former high seas salmon fishery by Japan. An area involving salmon and negotiations with Canada concerns the stocks and fisheries of the 2,000 mile long Yukon River system. The agreement sets harvest quotas for Chinook and chum salmon stocks. The Magnuson-Stevens Fishery Conservation and Management Act extended federal fisheries management jurisdiction to 200 nautical miles and stimulated the growth of a domestic Alaskan groundfish fishery that rapidly replaced foreign fisheries. The former unregulated pollock fishery in the “Donut Hole” now comes under the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea. The Convention has been signed by the Russian Federation, Japan, Poland, China, Korea, and the United States. A moratorium on pollock fishing was voluntarily imposed in 1993 (NMFS 2009). The Bureau of Indian Affairs has responsibility to protect and improve trust assets of Alaska natives. Alaska has a Department of Environmental Conservation (ADEC) responsible for assessing and controlling potential environmental degradation.

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XIV-46 Gulf of Alaska LME

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The Gulf of Alaska LME lies off the southern coast of Alaska and the western coast of Canada. It is separated from the East Bering Sea LME by the Alaska Peninsula. The cold Subarctic Current, as it bifurcates towards the south, serves as the boundary between the Gulf of Alaska and the California Current LME. For a description of the Gulf of Alaska's major currents, see www.pmel.noaa.gov/np/. The LME has a sub-Arctic climate and is subject to interannual and interdecadal climate variations (Brodeur *et al*. 1999). The area of this LME is about 1.5 million km², of which 1.50% is protected, and includes 0.52% of the world's sea mounts (as defined in Sea Around Us 2007 and Kitchingman et al. 2007). There are 14 estuaries and river systems, including the Stikine River, Copper River, and Chatham Sound (Skeena River). A book chapter pertaining to this LME is by Brodeur *et al*. (1999).

I. Productivity

The Gulf of Alaska LME is considered a Class II, moderately productive ecosystem (150-300 $gCm^{-2}yr^{-1}$). The LME's cold, nutrient-rich waters support a biologically diverse ecosystem. Large-scale atmospheric and oceanographic conditions affect the productivity of this LME. Changes in zooplankton biomass have been observed in both the Gulf of Alaska LME and the adjacent California Current LME. These biomass changes appear to be inversely related to each other (Brodeur *et al*. 1999). A well-documented climatic regime shift occurring in the late 1970s caused the Alaska gyre to be centred more to the east (Lagerloef 1995, Anderson & Piatt 1999). Brodeur and his co-authors suggested a possibility of increases in the future production of salmon as a consequence of long-term oceanographic shifts resulting in increases in plankton biomass in the last decade. More information is available on climate variability and its effect on the abundance and production of marine organisms in this LME (Hollowed *et al*. 1998). For more information on the production dynamics of Alaska salmon in relation to oscillating periods of 'warm' and 'cool' regimes, see Francis (1993), Francis & Hare (1994), and Hare & Francis (1995).

Oceanic Fronts (Belkin et al. 2009): The Polar Front (PF) exists year-round in the western part of the Gulf (Belkin *et al*. 2002) (Figure XIV-46.1). This front is associated with the Subarctic Current that crosses the North Pacific from Hokkaido to the Gulf of Alaska where it retroflects and flows along the Aleutian Island Chain, branching first into the Eastern Bering Sea, then into the Western Bering Sea. Several fronts develop in summer over the Alaskan Shelf (Belkin & Cornillon 2003, Belkin *et al*. 2003). The conspicuous Kodiak Front (KF) is observed east and south of Kodiak Island, where its quasi-stable location is controlled by local topography. The Inner Passage Front (IPF) is located in a strait between the Queen Charlotte Islands and the British Columbia coast.

Gulf of Alaska LME SST (Belkin 2009)(Figure XIV-46.2)
Linear SST trend since 1957: 0.38°C.
Linear SST trend since 1982: 0.37°C.

Temporal SST variability in the Gulf of Alaska (GOA) LME is strong (Figure XIV-46.2). In 1957-2006, three successive regimes were: (1) rapid cooling by nearly 2°C from the sharp peak of 1958 until 1971; (2) a cold spell in 1971-1976; (3) a warm epoch, from 1977 to the present. These epochs are best defined in the central GOA and off the Queen Charlotte Islands (Mendelssohn et al., 2003, and Bograd et al., 2005). The transition from the cold spell to the present warm epoch occurred during the North Pacific regime shift of 1976-77 (see East Bering Sea LME). In general, the SST history of the GOA is very similar to the East Bering Sea (EBS). In particular, SST swings in 1996-2006 were synchronic, from the absolute maximum in 1997 to a 1.4°C drop in 1999, to a maximum in 2003-2005, followed by a drop in 2006. The observed synchronicity between the GOA and EBS is suggestive of large-scale forcing that spans the eastern North Pacific.

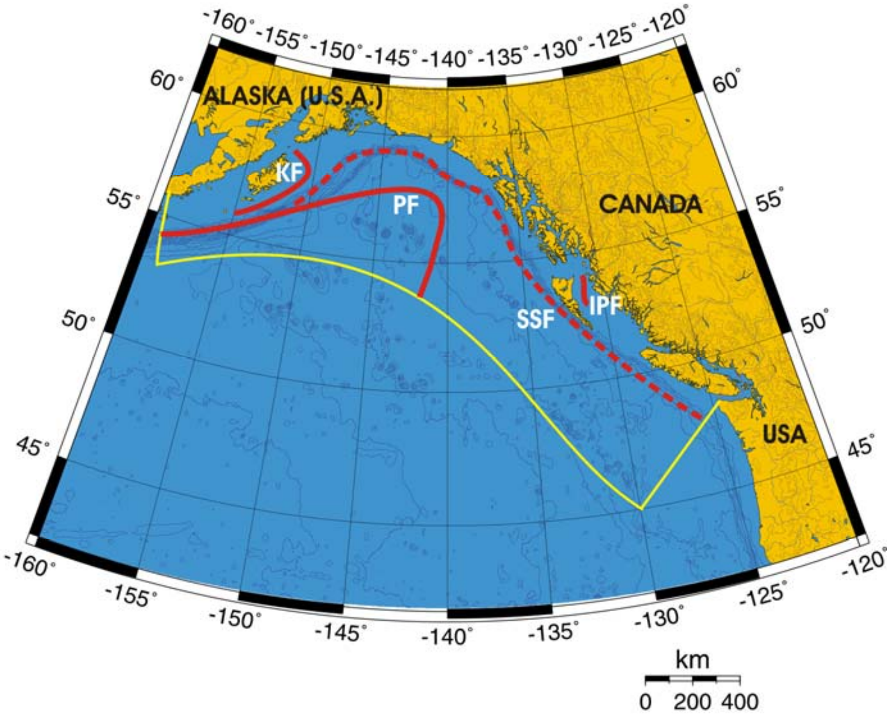

Figure XIV-46.1. Fronts of the Gulf of Alaska LME. IPF, Inner Passage Front; KF, Kodiak Front; PF, Polar Front; SSF, Shelf-Slope (most probable location). Yellow line, LME boundary. After Belkin et al. (2009).

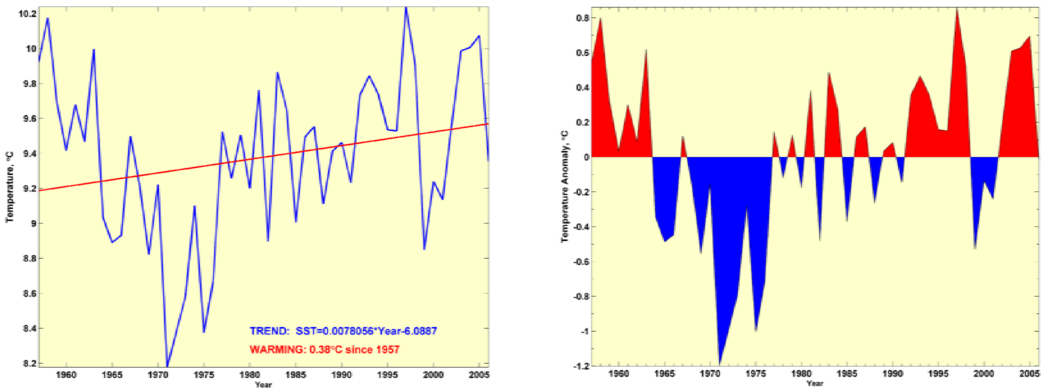

Figure XIV-46.2. Gulf of Alaska LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Gulf of Alaska LME Chlorophyll and Primary Productivity: The Gulf of Alaska LME is a Class II, moderately productive ecosystem (150-300 $gCm^{-2}yr^{-1}$)(Figure XIV-46.3).

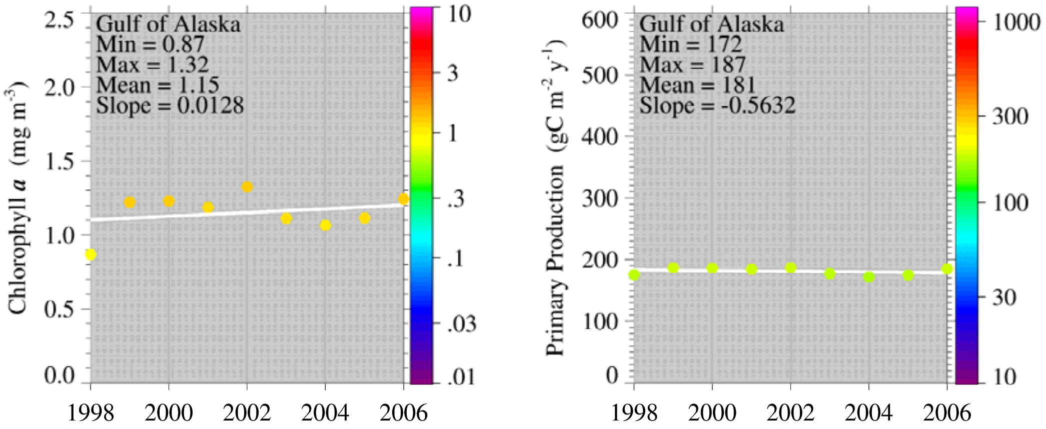

Figure XIV-46.3. Trends in Gulf of Alaska LME chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

This LME supports a number of commercially important fisheries for crab, shrimp, scallops, walleye pollock, Pacific cod, rockfishes, sockeye salmon, pink salmon and halibut. For information on salmon, pelagic, groundfish, shellfish and nearshore fisheries in Alaska, see NMFS (1999). The largest fisheries for sockeye salmon, the salmon species of highest commercial value in the US portion of the LME, occur in Cook Inlet, Kodiak Island, and Prince William Sound. Chum salmon hatcheries produce a significant portion of the catch. A quota, under the provisions of the Pacific Salmon Treaty between Canada and the US, regulates the Chinook salmon harvest in this LME. Pacific herring is the major pelagic species harvested in the LME. In Alaska, spawning fish concentrate in Prince William Sound and around the Kodiak Island-Cook Inlet area (EPA 2004). The groundfish complex (walleye pollock, Pacific cod, flatfish, sablefish, rockfish, and Atka mackerel) is an abundant fisheries resource in the Gulf of Alaska LME but less so than in the neighboring East Bering Sea LME. The extreme variation in pollock abundance is primarily the result of environmental forcing. For information on abundance of larval pollock, see Duffy-Anderson et al., 2002. Pollock are carefully managed due to concerns about the impact of fisheries on endangered Steller sea lions for which pollock is a major prey. Sea lion protection measures include closed areas and determinations of the acceptable biological catch. The western part of the Gulf (Kodiak Island and along the Alaska Peninsula) is a major area of operation for the shrimp fishery. Shrimp landings rose and are now declining. King crab catches peaked in the mid 1960s. Almost all Gulf of Alaska king crab fisheries have been closed since 1983. Dungeness crabs are harvested in the Yakutat and Kodial areas of the Gulf of Alaska. Most nearshore fisheries take place in the Gulf of Alaska LME near population centers (NMFS 2009). Current information regarding US fisheries in the GOA is available from the NMFS Alaska Region (www.fakr.noaa.gov), the Alaska Fisheries Science Center (www.afsc.noaa.gov), and the Alaska Department of Fish and Game (www.cf.adfg.state.ak.us). Current information regarding Canadian fisheries is available from Fisheries and Oceans, Canada, Pacific Region (www.pac.dfo-mpo.gc.ca).

The total of reported landings in this LME is in the order of 600 to 700 thousand tonnes, with a peak of 800 thousand tonnes in 1993 (Figure XIV-46.4). The value of the reported landings peaked in 1988 at nearly US$1.2 billion (calculated in 2000 US dollars) but has since declined to about US$500 million in 2004 (Figure XIV-46.5).

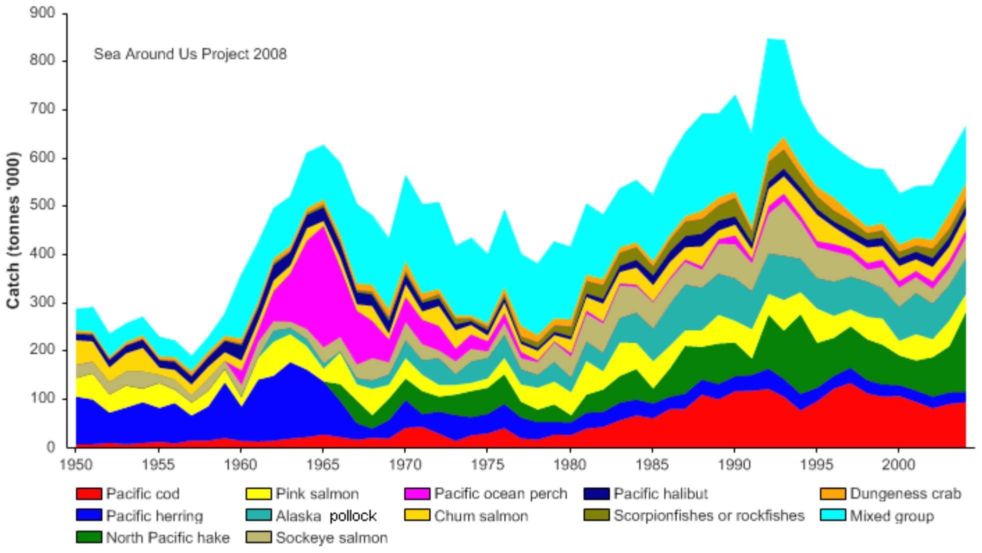

Figure XIV-46.4. Total reported landings in the Gulf of Alaska Sea LME by species (Sea Around Us 2007)

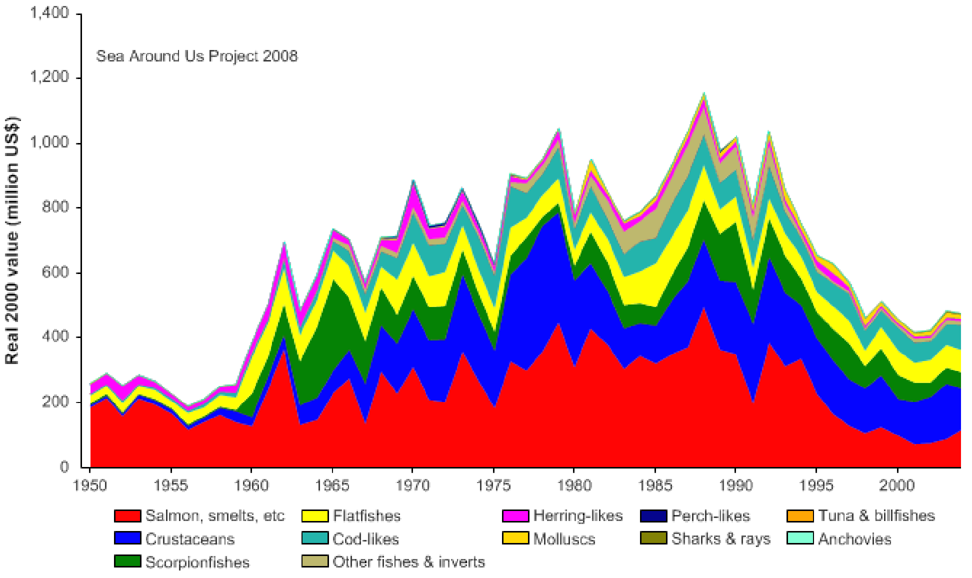

Figure XIV-46.5. Value of reported landings in the Gulf of Alaska LME by commercial groups (Sea Around Us 2007)

The primary production required (PPR) (Pauly & Christensen 1995) to sustain the reported landings in this LME reached over 25% of the observed primary production in the late 1980s, but leveled off at around 20% in recent years (Figure XIV-46.6). The USA and Canada now account for all landings (i.e. ecological footprint) in this LME.

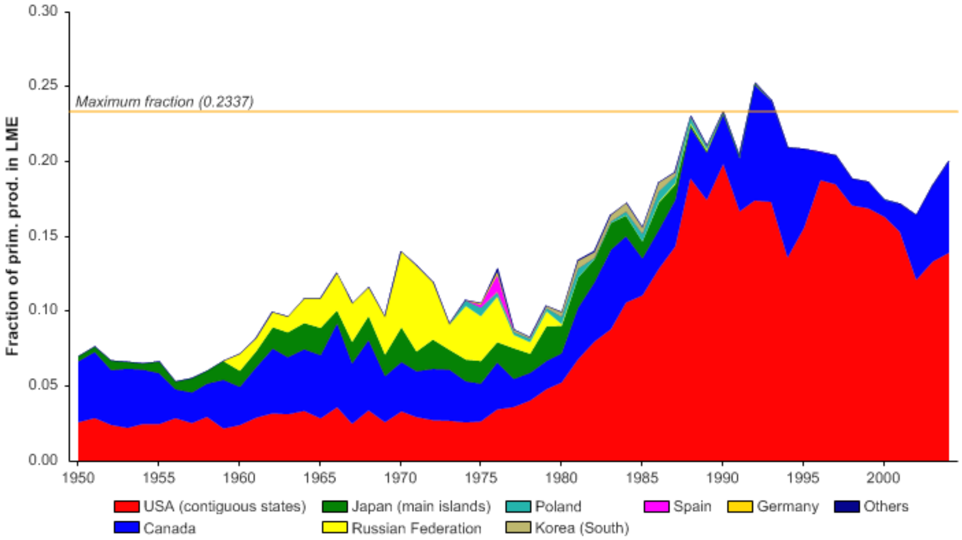

Figure XIV-46.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Gulf of Alaska LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the fisheries landings (MTI) (Pauly & Watson 2005) is rather high, especially in recent years (Figure XIV-46.7 top), while the increase in the Fishing-in-Balance index in the early 1980s reflects the increased landings reported during that period (Figure XIV-46.7 bottom).

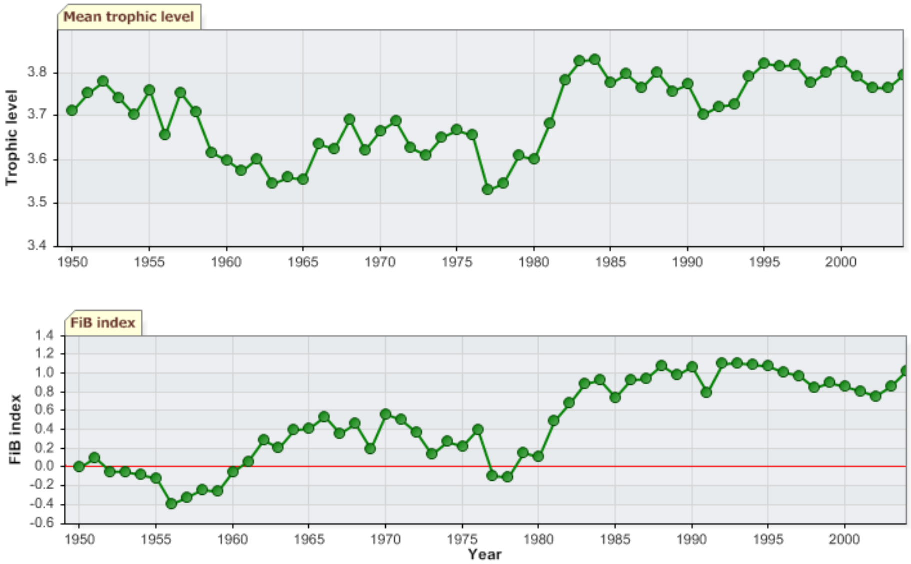

Figure XIV-46.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Gulf of Alaska LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that over 30% of the commercially exploited stocks are now generating catches of 10% or less than the historic maximum, corresponding to the ‘collapsed’ status (Figure XIV-46.8, top). Another 40% are generating catches from 50 to 10%, corresponding to the ‘overexploited ’ status (see Pauly et al. this vol.). This is explained by Armstrong *et al.* (1998), who reported on the serial depletion of (frequently small) stocks of commercial invertebrates. However, 80% (in bulk) of the reported landings in the Gulf of Alaska LME are contributed by fully exploited (i.e., not overexploited) stocks. (Figure XIV-46.8, bottom), thus confirming the positive assessment also suggested by Figure XIV-46.7. The US National Marine Fisheries service (NMFS) includes “overfished” but not “collapsed” in its stock status categories. NMFS 2009 lists no overfished species. Several groundfish are presently underutilized and cannot be fully harvested without exceeding the bycatch limits for Pacific halibut. Gulf of Alaska groundfish stocks in the US are considered to be in a healthy condition as a result of ecosystem-based management actions by the North Pacific Fishery Management Council, which include public participation, reliance on scientific assessments, conservative catch quotas built around annually determined overall fisheries biomass yield catch, and total allowable catch levels for key species with the objective of long term sustainability of fisheries stocks (Witherell et al, 2000; North Pacific Management Council, 2002).

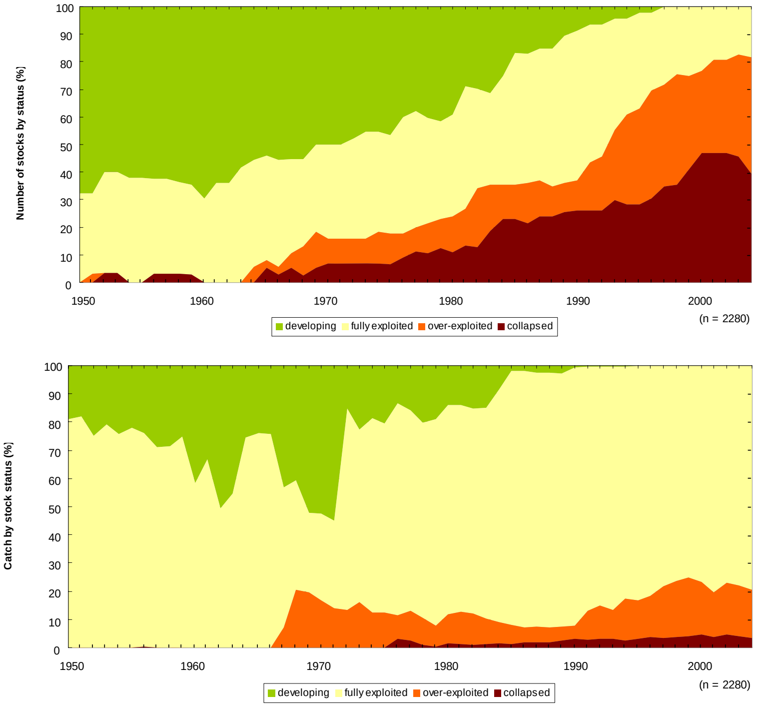

Figure XIV-46.8. Stock-Catch Status Plots for the Gulf of Alaska LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.* this vol. for definitions).

III. Pollution and Ecosystem Health

Because salmon are anadromous and spend a portion of their lives in freshwater streams, rivers, and lakes, the health of salmon populations in this LME is directly influenced by land management practices in both countries and by the loss of freshwater spawning and rearing habitats. Competing uses for the salmon habitat include logging, mining, oil and gas development, and industrial and urban development. Prince William Sound is an area of concern where large returns of hatchery pink salmon mix with lower numbers of wild fish. The Gulf of Alaska Ecosystem Monitoring and Research Program is a long-term effort to gather information about the physical and biological components of the marine ecosystem, the cooperation of agencies, public involvement and access to informative data. For pollution issues, see <www.evostc.state.ak.us/>. For information on coastal condition for all of Alaska, see EPA 2001 and 2004. A sampling survey of the ecological condition of Alaska's estuarine resources in the south-central region of the state of Alaska was completed in 2002 (EPA 2004), with data collected from 55 sites. Prince William Sound and Cook Inlet are major estuaries. The total allowable catch for pollock in the Alaska is apportioned to accommodate Steller sea lion concerns, as pollock are the major prey of Steller sea lions in the Gulf of Alaska. For information on clean water assessments in Alaska, see EPA (2004). For statistics on harbour seals and harbour porpoises in this LME, see NMFS (1999). Audubon red listed Alaskan seabirds include Steller's eider, Spectacled eider, Sooty grouse, Laysan albatross, Black-footed albatross, Short-tailed albatross, Pink-footed shearwater, Eskimo curlew, Rock sandpiper, Buff-breasted sandpiper, Ivory gull, and murrelet.

Problems affecting the LME include predation by invasive species, discharges of oil products, and industrial and agricultural contaminants that enter the LME through a variety of pathways (ocean currents, prevailing winds). Prince William Sound is routinely crossed by large oil tankers. In 1989, the *Exxon Valdez* spilled 11 million gallons of North Slope crude oil off the Port of Valdez, the terminal of the Trans-Alaskan Pipeline. This was the largest tanker oil spill in U.S. history and it contaminated over 2,000 km of the Gulf of Alaska's coastline. The livelihood of 70,000 full-time residents living in the area was directly affected by the Exxon Valdez oil spill. They had to overcome the effects of the oil-related fish mortalities. Others using the area seasonally for work or recreation were also seriously affected. There remain concerns about the lingering effects of the oil spill and the pockets of residual oil in the environment, especially in the Western portion of Prince William Sound. The effects of the oil spill interact with the effects of other kinds of changes and perturbations in the marine ecosystem. More common than spills, however, are smaller discharges of refined oil products, crude oil and hazardous substances.

IV. Socioeconomic Conditions

The LME coastal population is low relative to the length of the coastline, with the exception of the city area of Vancouver in the Canadian province of British Columbia. Native peoples have a long and rich tradition of relying on salmon for economic, cultural, and subsistence purposes. The coastal native communities rely for their subsistence largely on hunting and the harvesting of marine resources. The economy of the coastal communities is based on commercial fishing of pink and red salmon, fish processing, timber, minerals, agriculture and tourism. Pacific salmon has played a pivotal role in the history of the region. Although commercial salmon harvests are at high levels, the value of the catch has declined due to a number of world wide reasons, one of which is a rising trend in salmon farmed production in Norway, Chile, and the United Kingdom. Alaska's herring industry began in the late 19th century and expanded rapidly, with markets shifting from salt-cured herring to reduction products for fishmeal and oil (NMFS 2009). Shellfish fisheries developed in the 1960s in the Gulf of Alaska (NMFS 1999). US groundfish catches are exported to Asia and constitute a major source of revenue for US fishermen. The estuarine resources of Prince William Sound and Cook Inlet in Alaska are of major importance for the local and state economy. Conflicts have emerged between coastal and offshore interests. In addition to jobs in fishing and fish processing, people in Gulf of Alaska communities work in government, military (Kodiak U.S. Coast Guard base), logging, mining and tourism. In 1998, there was an increase of visitors to over 1 million a year in Alaska. Colt et al. (2007) estimate summer 2005 revenue from nature-based tourism activities in Chichagof Island alone at $15.5 million.

V. Governance

The Gulf of Alaska LME is bordered by the U.S. and Canada, each with separate government actions and management plans. In 2004, Amendment #66 to the Halibut and Sablefish program became a law that allowed eligible coastal communities in Alaska to purchase halibut and sablefish quota shares. The North Pacific Fishery Management Council, in conjunction with NOAA, produces a Gulf of Alaska Groundfish Fishery Management Plan for Alaska. The Gulf of Alaska Coastal Communities Coalition has identified 42 communities within Alaska eligible to participate in a program to form a CQE (Community Quota Entity), a non-profit corporation for the purchasing of quota shares (www.goac3.org). The program helps compensate for the negative impacts of Individual Fishing Quotas (IFQs) on subsistence fishers. The transboundary management of Pacific salmon (sockeye, chum, pink, chinook, coho and steelhead salmon) is conducted under the Pacific Salmon Treaty (www.oceanlaw.net), signed in 1985 by Canada and the US. The Treaty is intended to facilitate the management of these salmon stocks by preventing overfishing and providing for optimum production and equitable sharing of the salmon catch. Catch quota levels since 1999 are subject to fluctuations of salmon abundance from year to year. Major transboundary concerns between the two countries are: Chinook salmon catches in southeastern Alaska where Canadian salmon are caught along with other non-Alaska US stocks; fisheries in the Dixon Entrance where each country catches salmon originating in the other nation; transboundary river stocks associated primarily with the Taku and Stikine Rivers; Canadian fisheries off the west coast of Vancouver Island; and Strait of Juan de Fuca fisheries for salmon bound for the Fraser River in Canada (NMFS 2009). The North Pacific Anadromous Fish Commission (NPAFC) manages the salmon harvest in the high seas. Signatories are Canada, Japan, Russian Federation, United States and Korea. The Convention prohibits high seas salmon fishing and trafficking of illegally caught salmon. United Nations Resolution 46/215 bans large scale pelagic driftnet fishing in the world's oceans. The Convention for the Conservation of Anadromous Stocks in the North Pacific Ocean seeks to control the interception and incidental take of the LME's salmon resources. Pacific Halibut is also a target of transboundary management. The resource is managed by a bilateral treaty between the US and Canada, with recommendations coming from the International Pacific Halibut Commission. Both Canada and Alaska have moved to regulating halibut fisheries subareas through catch quotas, time-area restrictions, and by individual fishing quotas (IFQs). Under the IFQ system there has been a decline in the overall size of the fishing fleet.

In the aftermath of the Exxon Valdez oil spill, the US Congress crafted the Oil Pollution Act of 1990 (OPA 90). Under OPA 90, two Regional Citizen Advisory Councils were created, one for Prince William Sound, and one for Cook Inlet (EPA 2004). In the US, the Magnuson-Stevens Fishery Conservation and Management Act extended federal fisheries management jurisdiction to 200 nautical miles and stimulated the growth of a domestic Alaskan groundfish fishery that rapidly replaced the foreign fisheries. Pacific ocean perch was intensively exploited by foreign fleets in the 1960s. Inshore groundfish resources are managed by the Alaska Department of Fish and Game.

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XIV-47 Gulf of California LME

S. Heileman

The Gulf of California LME (also known as the Sea of Cortez) is a long (1,130 km) and narrow (80-290 km), semi-enclosed LME bordered by the Baja California Peninsula and mainland Mexico. It has a surface area of about 221,600 km^2, of which 3.64% is protected, and includes 0.11% and 0.06% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). The Gulf is one of the youngest ocean bodies and was formed by the separation of the North American Plate and the Pacific Plate by tectonic movement (Rusnak *et al*. 1964). Several deep basins (up to 3,600 m deep) occur in the southern part of the Gulf, including the Guaymas Basin. The northern part of the Gulf is shallower, due to the large amount of siltation produced over the years by the Colorado, the major river entering this LME. There are 898 islands of all sizes within the Gulf, included in the 'Area de Protección de Flora y Fauna Islas del Golfo de California' (Islands of the Gulf of California Flora and Fauna Protection Area) (SEMARNAP 1999). A report pertaining to this LME is UNEP (2004).

I. Productivity

Surface winds have an average direction that generally follows the axis of the Gulf (Marinone *et al*. 2004). Tropical storms and hurricanes can cause heavy rainfall and intensified water and sediment runoff. SST seasonality is very conspicuous. Highest annual SST is observed during August and September (30-31º C south of the islands). Between October and December, the SST of the northern Gulf falls by almost 20° C and of the central and southern by about 7º C. Intense tidal mixing and upwelling maintain minimum SSTs around the mid-gulf islands throughout the year (Marinone & Lavín 2003). The largest interannual variability signal in the Gulf SST is due to El Niño-La Niña. The largest SST positive anomaly in the satellite records is that of 1997-1998, 3º C over the seasonal climatology, while the largest negative anomaly is associated with the 1988-1989 La Niña (4ºC below the climatological mean). SST anomalies due to El Niño tend to be strongest in the region just south of the mid-gulf islands (Soto-Mardones *et al*. 1999, Lavín *et al*. 2003).

The Gulf has unique oceanographic characteristics because of its long axis and because the Baja California Peninsula limits moderating influences from the Pacific Ocean circulation. Water circulation varies in time from two main influences: diurnal, semidiurnal, and fortnightly tidal cycles, and annual and semiannual seasonal changes. The tides, which co-oscillate with those of the Pacific Ocean, are mixed semi-diurnal tides, with one of the greatest tidal ranges on Earth. For instance, maximum registered spring tidal range at San Felipe is 6.95 m (Gutierrez & González 1999), with even larger amplitudes at the entrance to the Colorado Delta. The best-documented features of Gulf of California circulation are large-scale seasonally reversing gyres in the northern Gulf. A cyclonic gyre lasts approximately from June to September, and an anticyclonic gyre from November to April. Estimates from ship drift and the distributions of temperature and salinity indicate surface outflow during winter and inflow during summer, with mass conservation requiring a compensating flow at depth (Lavín *et al*. 1997, Berón-Vera & Ripa 2002, Castro 2001, Palacios-Hernández *et al*. 2002, Marinone & Lavín 2003, Lluch-Cota *et al*. 2004).

The LME is a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}), and is one of the five marine ecosystems with high productivity (Enríquez-Andrade *et al*. 2005). The northern Gulf has two main natural fertilisation mechanisms: one is the year-round tidal mixing around the large islands leading to an area of strong vertical mixing and continuous flow of cool nutrient-rich water into the euphotic layer, providing a thermal refuge for temperate species during the warmer periods (Lluch-Belda *et al*. 2003); the second is wind-induced upwelling along the eastern central gulf, enriched waters from the islands and the east coast reaching the peninsular side and remaining trapped, contributing to higher primary production per unit area. Also, because this enrichment system operates only during winter, there is a strong annual gradient of pigment concentration in most of the Gulf (Lluch-Cota *et al*. 2004, 2007).

The Guaymas Trench has volcanic and hydrothermal vents, with biotic communities supported by chemosynthesis using hydrogen sulfide, rather than photosynthesis (Teske *et al*. 2002). One of the most diverse biological communities in the world is found in this LME, with 4,852 species of invertebrates, excluding copepods and ostracods, (767 endemic), 891 species of fish (88 endemic) and 222 species of non-fish vertebrates, (four endemic) (Enríquez-Andrade *et al*. 2005). An outstanding diversity of marine mammal species is also found in the LME: 36 species, including 4 pinnipeds, 31 cetaceans and one bat (Aurioles-Gamboa 1993, Brusca *et al*. 2004). This LME is also the habitat of one of the world's most endangered cetaceans, the Vaquita porpoise (*Phocoena sinus*), endemic to the upper Gulf and the world's smallest and rarest porpoise. The blue, fin and grey whales are also found in this LME. The high primary productivity supports sardine and anchovy, which are the main prey of large quantities of squid, fish, seabirds and marine mammals.

Oceanic Fronts (Belkin et al. 2009)***:*** This is one of the smallest LMEs, located between Baja California and Mexico's mainland. The temperature contrast between the northern and southern Gulf is 2ºC to 3ºC, depending on the season. This gradient is enhanced along a bathymetric step in the middle of the Gulf, where a thermal front is observed (Inner Gulf Front, IGF) (Figure XIV-47.1).

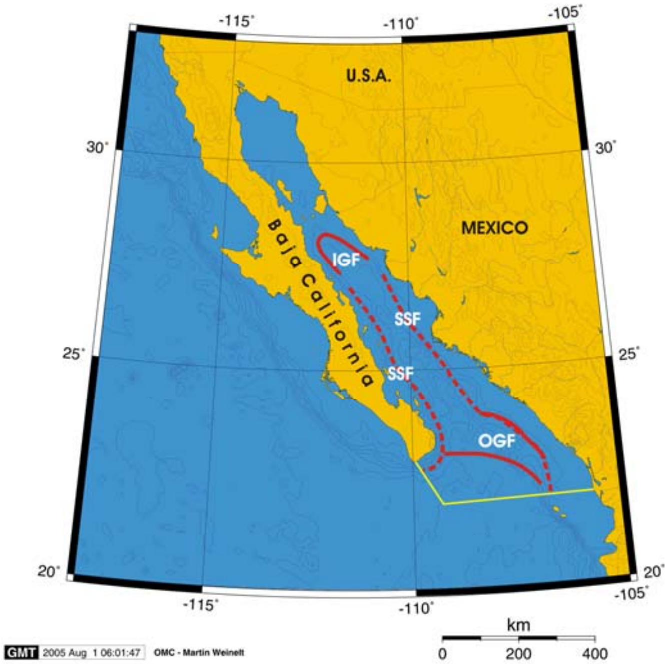

Figure XIV-47.1. Fronts of the Gulf of California LME. IGF, Inner Gulf Front; OGF, Outer Gulf fronts; SSF, Shelf-Slope Front (most probable location). Yellow line, LME boundary.(Belkin et al. 2009)

Other fronts form between Mexico's mainland and Baja California where Pacific inflow waters meet resident waters of the Gulf of California (Outer Gulf fronts (OGF) (Belkin *et al*. 2005). The Pacific and resident waters have different salinities and different temperatures; the salinity differential is the main factor responsible for the maintenance of this front.

Gulf of California SST (Belkin 2009)
Linear SST trend since 1957: 1.24°C.
Linear SST trend since 1982: 0.31°C.

The semi-landlocked Gulf of California shares some similarities with the California Current. The global cooling of the 1960s-1970s manifested here as a 2.2°C drop from 1958 to 1975. After a 2.8°C rebound in 1979-1983, the Gulf of California remained warm until the present. The sharp SST peak of 1983 attributed to a major El Niño 1982-1983 was synchronous with similar peaks in the California Current LME, the Central American Pacific LME and the Humboldt Current LME. Since 1983, the Gulf of California thermal history is strongly correlated with the California Current LME, including major events (peaks) of 1992 and 1997, associated with major El Niño events.

The relatively small warming of 0.31°C over the last 25 years is misleading since the transition from the cold epoch to the warm occurred in the late 1970s. Regardless of the exact timing of the breakpoint between the cold and warm epochs (1975 or 1979), the overall warming since then exceeded 1.5°C, which would put the Gulf of California into the league of fast-warming LMEs. The absolute minimum in 1975 was synchronous with absolute minima in both adjacent LMEs, the California Current LME and Central-American Pacific LME.

The Gulf of California is considered to be a primary source of moisture for the North American or Mexican monsoon, "the most regular and predictable weather pattern in North America" (Mitchell et al., 2002, p.2261), therefore warmer surface temperatures are expected to increase evaporation from the Gulf, which in turn would fuel stronger Mexican monsoons.

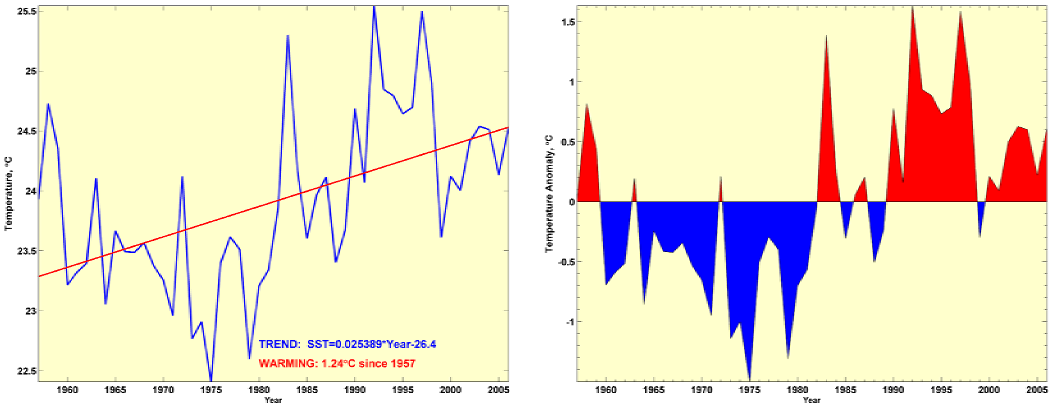

Figure XIV-47.2. Gulf of California annual mean SST and annual SST anomalies, 1957-2006. After Belkin 2009.

Gulf of California Chlorophyll and Primary Productivity: The LME is a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}),

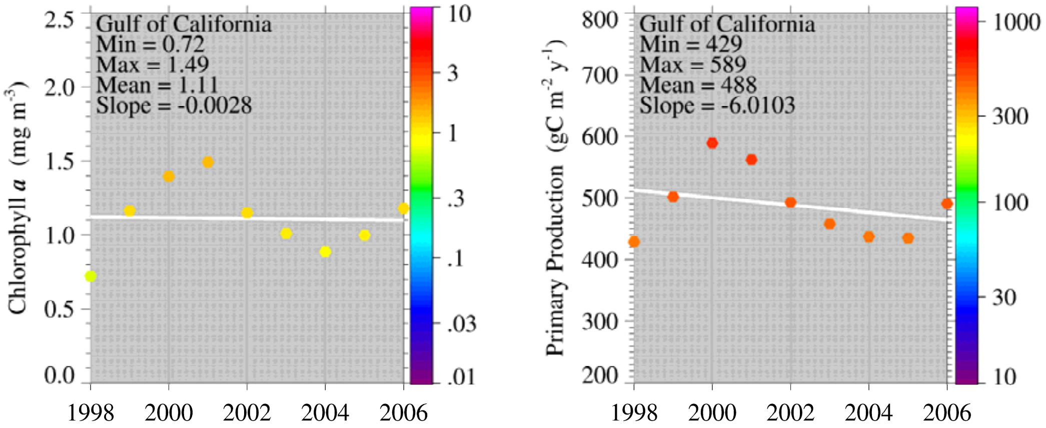

Figure XIV-47.3. Gulf of California trends in chlorophyll a and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Historically, the LME has supported numerous fisheries of commercially valuable species. Fisheries resources in the Gulf are targeted by the commercial, artisanal, and recreational fishing sectors. In terms of weight caught, the major fisheries are dominated by small pelagic fish, primarily Californian anchovy (*Engraulis* mordax) and South American pilchard (*Sardinops sagax* [formerly known as Pacific sardine, *Sardinops caeruleus*]), as well as penaeid shrimps (blue, white and brown shrimp, *Litopenaeus stylirostris*, *Litopenaeus vannamei*, *Farfantepenaeus californiensis*, respectively, together with other less important species). Californian anchovy (*Engraulis mordax*) undergoes major scale abundance fluctuations related to environmental variation (Nevárez-Martínez *et al*. 2001). Jumbo squid (*Dosidicus gigas*), also a highly variable resource, is a major constituent in recent years (Nevárez-Martínez *et al*. 2000; Lluch-Cota 2007)). At a lower level of abundance, but much more consistent, are larger pelagic tuna-like fishes (mostly yellowfin and skipjack tuna) representing important commercial fisheries. The total annual catch of tuna-like resources increased rapidly from the late 1970s to peak in the mid 1980s. This increase was followed by a general downward trend until 1995, when catches began to increase again. The trend in catch of tuna-like species is mirrored by that of small pelagic fish.

Due to difficulties in separating landing from the Mexican State of Baja California Sur into components from the Gulf of California and those from the Pacific coast (and belonging mainly to the California Current LME), the values presented in Figure XIV-47.4 are only indicative of the magnitude of the catches in this small, yet highly productive LME, In particular, they differ from catch series (1980-2002) for 'sardines', jumbo squids', and 'shrimps' (though they match for tuna) presented in the review by Lluch-Cota *et al.* (2007, Fig. 5), which was not available when Figure XIV-47.4 and derived graphs (Figures XIV-47.5-10) were obtained. However, these graphs can still be expected to give a general impression of the fisheries and their status in the Gulf of California LME. [See www.seaaroundus.org for updated version on these graphs]

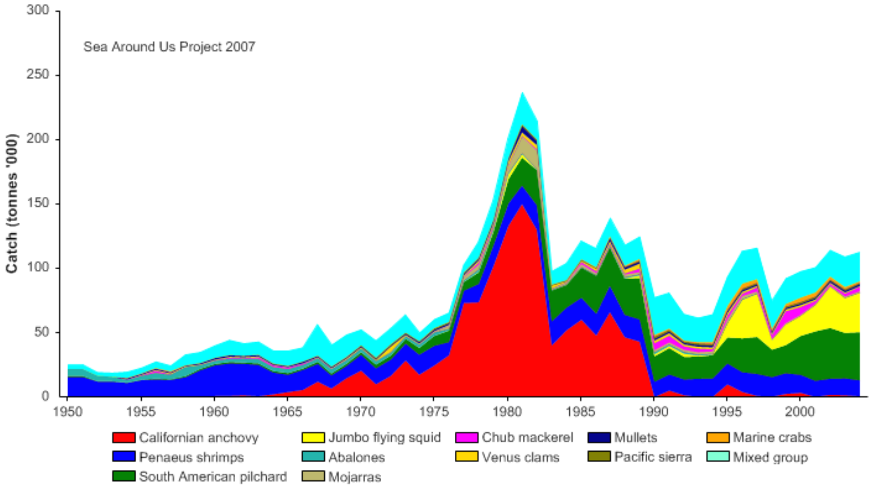

Figure XIV-47.6. Total reported landings in the Gulf of California LME by species (Sea Around Us 2007); see www.seaaroundus.org for a corrected update.

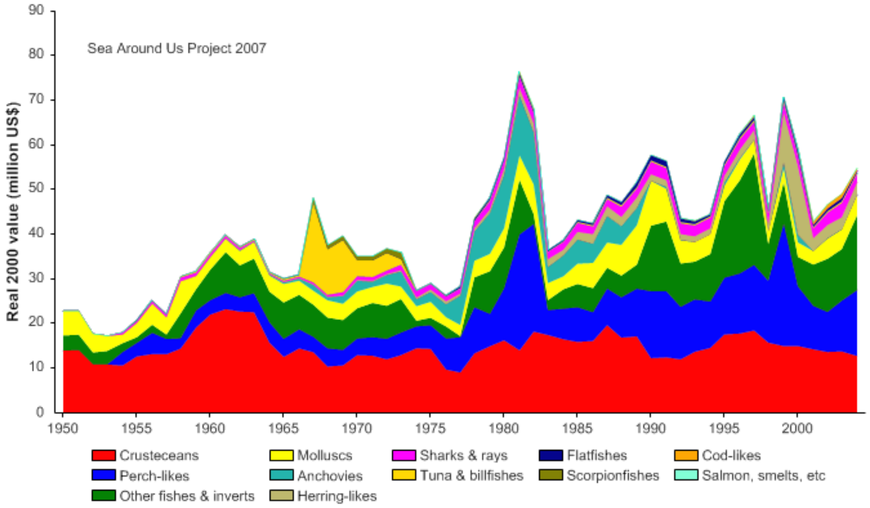

Figure XIV-47.7. Value of reported landings in the Gulf of California LME by commercial groups (Sea Around Us 2007); see www.seaaroundus.org for a corrected update.

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings reached 10% of the observed primary production in 1996 and has fluctuated between 5 to 9% in recent years (Figure XIV-47.6). Accounting for the catches in Fig. 5 of Lluch-Cota *et al.* (2007) would increase this figure to 15% at most. Since the mid 1970s, Mexico has been the only country fishing in this LME and hence accounts for all of the ecological footprint.

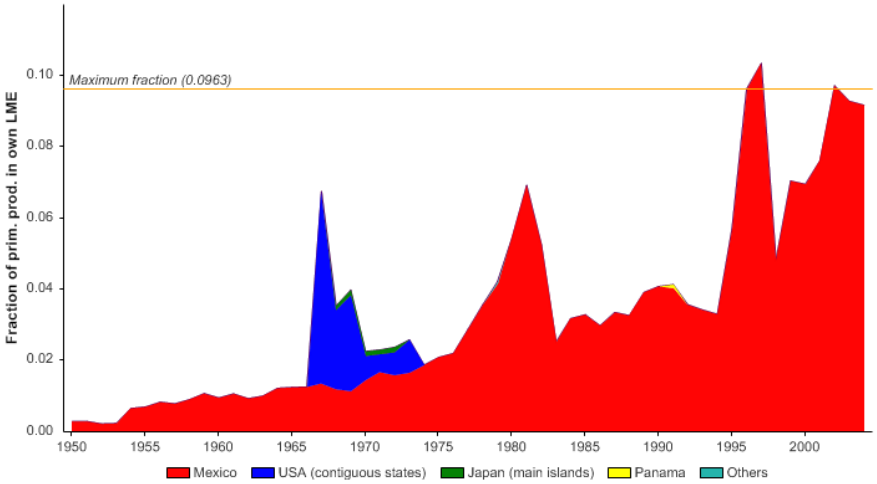

Figure XIV-47.8. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Gulf of California LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values; see www.seaaroundus.org for a corrected update.

The mean trophic level of the reported landings (MTI; Pauly & Watson 2005), has increased from 1950 to the early 1970s, and remained relatively steady thereafter, except for a more recent increase (Figure XIV-47.7 top). The FiB index suggests a spatial expansion of the fisheries until the early 1980s, and has remained relatively level since, suggesting that natural limits may have been reached (Figure XIV-47.7 bottom).

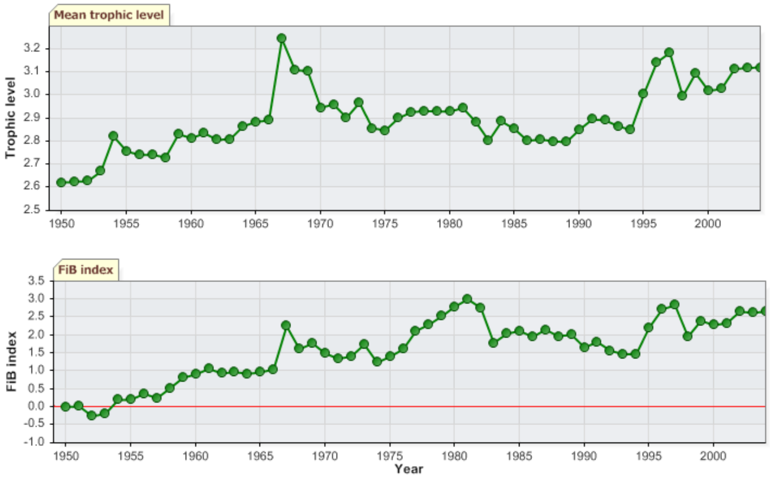

Figure XIV-47.9. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Gulf of California LME (Sea Around Us 2007); see www.seaaroundus.org for a corrected update.

A decline in trophic levels in the coastal food webs of this LME was reported by Sala *et al*. (2004), based on interviews with fishers, fisheries statistics and field surveys. According to Sala and colleagues, the decline in fish stocks has been accompanied by a marked shift in the species composition of the coastal fisheries and a decrease in the maximum individual length of fish catches by approximately 45 cm in 20 years. Large predatory fishes were among the most important catches in the 1970s, but became rare by 2000. Moreover, species that were not targeted in the 1970s have now become common in the catches. These findings contradict the conclusion of Pérez-España (2004) who, strangely, failed to find evidence of 'fishing down the food web' in this LME. The work of Saenz-Arroyo *et al.* (2005a, 2005b, 2006), and of Lozano-Montes *et al.* 2008) should, in any case, lay this controversy to rest as these authors not only demonstrated massive changes in the catch composition of the Gulf of California fisheries, but also that the bulk of these changes occurred before the period covered here, which, put them before the cognitive reach of researchers using based only on official catch statistics (Pauly 1995).

The Stock-Catch Status Plots indicate that the number of collapsed and overexploited stocks have been increasing in the LME, to about 70% of the commercially exploited stocks (Figure XIV-47.10 top). These stocks supply half of the reported landings (Figure XIV-47.10, bottom).

Several authors have suggested that the LME's fish resources are overexploited and regard the impacts of overfishing as severe, at least in the upper Gulf (Brusca *et al*. 2001). Distinct areas of concern include: impacts of fishing on shrimp populations, impacts of shrimp fishing on non-targeted populations (mostly the bycatch issue) and on the physical habitat, and catch of fish for bait and in sport fisheries.

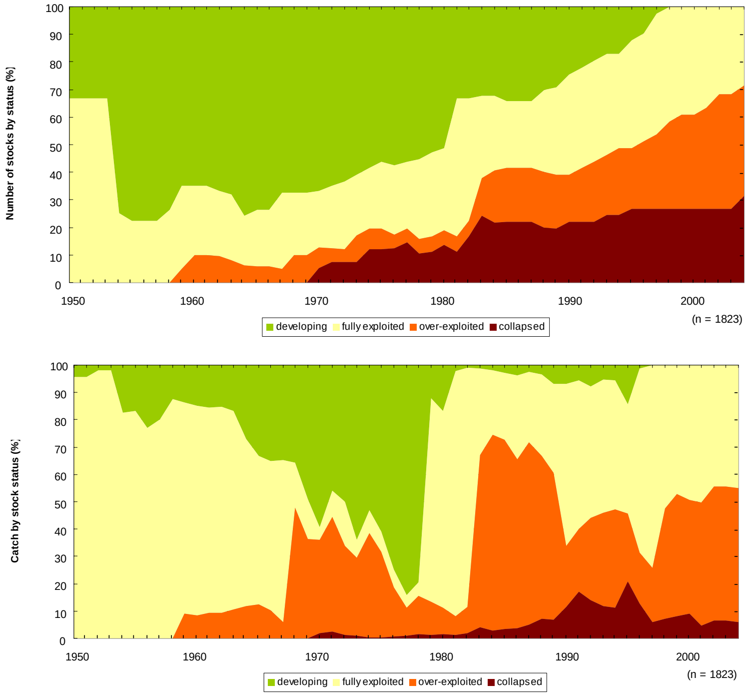

Figure XIV-47.10. Stock-Catch Status Plots for the Gulf of California LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The abundance and availability of small pelagic fish fluctuate mostly because of natural environmental variations at various interannual scales, as shown by several studies including paleosedimentary evidence for the last 250 years (Holmgren-Urba & Baumgartner 1993, Cisneros-Mata *et al*. 1995a, Lluch-Cota *et al*.1999, Nevárez *et al*. 2001). The sudden collapse of the sardine population during the 1991-1993 fishing seasons was related to overfishing and natural variation (Cisneros-Mata *et al*. 1995a, Nevárez *et al*. 1999), and resulted in the closure of more than 50% of the fish plants. However, the industry and governmental and research agencies together agreed on time and area closures, a reduction of the fishing fleet by 50% and a programme of research cruises to monitor recruitment. The fishery fully recovered after three years. No major concerns seem to be related to the fisheries for jumbo squid and tuna-like fishes.

The shrimp fishery, which has been assessed since the 1970s, was found to be overfished as a result of excessive fishing effort and small mesh size in the trawl nets. Since then, fishing effort has increased further with the increase in the number of large boats and their fishing power, but most of all, with the number of outboard powered *pangas* now fishing for offshore shrimp. According to data in Páez *et al*. (2003), total shrimp catch has been declining by an average of 600 tonnes per year in the period 1980-2001, while shrimp aquaculture has increased by 30% per year since 1990 and now exceeds the catch. Natural variation may further impact shrimp abundance, as suggested several decades ago (Castro-Aguirre 1976). Galindo-Bect *et al*. (2000) found a significant correlation between total shrimp catch in the upper Gulf and the rate of freshwater discharge by the Colorado River. Although the damming of the Colorado River may have been the principle cause of the decline in the shrimp fishery, the escalation in the number of fishing vessels and fishing gear types could have also contributed to this decline (UNEP 2004). Catches of offshore shrimp could improve substantially both in volume and individual sizes if fishing effort were to be reduced to adequate levels and mesh sizes regulated for optimum selectivity. While it would appear that the trend has been to allow more fishers to participate as a means of further distributing the benefits, it is becoming increasingly clear that such a process has involved extra financing through tax exemptions and subsidies and is no longer viable.

Conservation International Mexico (2003) has estimated that each kilogramme of shrimp caught in the commercial fishery is accompanied by at least 10 kg of bycatch. (Tis bycatch is not included in catch statistics, but should be). Estimates for the Gulf of California LME have ranged from 1:2 up to 1:10 (Rosales 1976) and larger at times. This proportion is similar to those reported for shrimp fisheries in tropical areas around the world, i.e., 1:10 (Cascorbi 2004). The magnitude of bycatch is highly variable, depending on area and season. At the beginning of the shrimp season the proportion may be lower; bycatch tends to increase towards the end of the season, when shrimps have been fished out. The National Fisheries Institute of Mexico (INP) began developing fish excluders together with Conservation International in 1992, particularly directed to the protection of totoaba *Cynoscion macdonaldi* (Balmori *et al*. 2003). Such efforts have continued with the FAO on an international project to develop suitable excluders.

Some species, such as juveniles of totoaba, a large endemic species that was heavily fished during the 1930s-1940s, and marine turtles, both vulnerable to trawl nets, are of particular concern. Cisneros-Mata *et al*. (1995b) estimated that an average of 120,300 juvenile totoaba was killed by shrimp vessels each year from 1979 to 1987. Other icon species, such as dolphins, are rarely killed by these gears. Vaquitas and sea turtles are incidentally captured in gill nets. The total estimated incidental mortality caused by the fleet of El Golfo de Santa Clara was 39 Vaquitas per year, over 17% of the most recent estimate of population size (D'Agrosa *et al*. 2000). The vaquita population is estimated to be less than 600 (Jaramillo-Legorreta *et al*. 1999). Therefore, considering normal replacement rates (maximum rate of population growth for cetaceans is of 10% per year), this incidental loss is unsustainable. Although turtle-excluder devices are mandatory for industrial fishing vessels, poaching of sea turtles is still a problem throughout western Mexico.

The impacts of the trawl fishery on the ecosystem are of major concern. Anecdotal information suggests that sweeping changes in benthic community structure have taken place over the past 30 years of these disturbances. Commercial shrimp trawling exacts a harsh toll on the Gulf's marine environment, as more than a thousand shrimp trawlers annually rake an area of sea floor equivalent to four times the total size of the Gulf. This constant bottom trawling is considered to damage fragile benthic habitats and non-commercial, small invertebrate species (Brusca *et al*. 2001). However, this area of research is in need of attention since data are not sufficient to evaluate the extent of this damage in the LME.

UNEP (2004) recalls that the American Fisheries Society's official list of marine fish at risk of extinction includes six species of large groupers and snappers, four of which are endemic to the Gulf of California and adjacent areas. Of these, two are regarded as endangered, while the remaining four are considered as vulnerable, given the fact that these species are sensitive to overfishing because of late maturity and the formation of localised spawning aggregations (Musick *et al*. 2001). The effect of fishing is particularly evident in large, slow-growing fish, and includes a decrease in abundance and in the average individual size, where both are unavoidable consequences when aiming at maximizing yield. What occurs in the Gulf of California LME is similar to what occurs in Puget Sound, Florida and the southern Gulf of Mexico, the other 'hot spots' described by Musick *et al*. (2001). Of particular concern has been the totoaba. Although overfishing has been blamed for the early decline of the fishery, the reduction in the flow of the Colorado River may have been a major cause of depletion through the alteration of the estuarine habitat of the river delta, its normal spawning and nursery area (UNEP 2004). The totoaba fishery declined since 1970 due to declining populations and to restrictions imposed (in 1975) when catch levels threatened the population. Despite closures, the totoaba gill net fishery continues on a small-scale.

The tremendous diversity and complexity of the fisheries within the Gulf of California LME and the large size of the basin make it a difficult area to manage. This is aggravated by the lack of sufficient resources for implementing and enforcing management decisions and federal laws, inadequate knowledge about the ecology of exploited species, and insufficient past efforts to actively involve fishing communities in management decision-making. However, current efforts are succeeding in conserving the natural resources upon which a large number of people depend, and an improvement in terms of overexploitation is expected in the future (UNEP 2004).

III. Pollution and Ecosystem Health

Pollution: A sizeable portion of the eastern coast of the Gulf of California LME is subject to pollution from industrial and human wastes, agricultural run-off and aquaculture residues. Other pollution threats include sedimentation from deforestation, bilge water from ships, the construction of tourist marinas in sensitive coastal areas, and the risk of oil spills from a steady traffic of oil tankers. While pollution was found to be generally slight, it is more serious in some localised coastal areas (UNEP 2004). Beman *et al*. (2005) have reported eutrophication episodes caused by agricultural irrigation in the coastal area off the Yaqui Valley. A long time series of data related to eutrophication and HABs available from Mazatlán showed an increase in the number of toxic species as well as in the length and frequency of HABs events. Mortalities of marine mammals, birds, and fish in 1995, 1997 and 1999 were related to HABs (Sierra-Beltrán *et al*. 1998, 1999). Except for La Paz Bay and Los Cabos areas, the west coast of the Gulf is nearly pristine.

In the few places where towns or villages do exist, some pollution occurs. Agricultural pesticides used in the Mexicali Valley and in Sonora and Sinaloa States have led to concerns since the early 1970s about the possibility of pesticide transport into the Upper Gulf of California. Pesticides have been found in organisms of the Mexicali Valley irrigation canals as well as the Upper Gulf of California (García-Hernández *et al*. 2001). For instance, DDE, DDT and DDD were detected in fish and invertebrate sampled from the delta wetlands even though such pesticides have been banned (Mora & Anderson 1995). Preliminary findings indicate high concentrations of zinc and lead in Navachiste Bay, Sinaloa (Orduña-Rojas *et al*. 2004).

Habitat and community modification: The delta wetlands and marine areas provide unique and valuable habitats for a large number of invertebrates, marine mammals, birds and commercial species of fish (Alvarez-Borrego 1983). These habitats are, however, being altered by various human activities, the impacts of which are magnified by the semi-enclosed nature of the Gulf. The most notable human activity to impact the upper Gulf has been the damming of the Colorado River, which has significantly modified the environment in this area. The river supplied freshwater, silt and nutrients to the delta, and helped to create a complex system of wetlands that provided feeding and nesting grounds for birds, and spawning and nursery habitat for fishes and crustaceans (Glenn *et al*. 1996). The reduced freshwater input has drastically changed what used to be an estuarine system into one of high salinity. It has also reduced the influx of nutrients to the sea and critical nursery grounds for many commercially important species such as the totoaba, Gulf curvina, and brown shrimp (Aragón-Noriega & Calderon-Aguilera 2000).

In terms of vegetation cover, the degree of mangrove deterioration in Mexico is not as evident as in other countries (Páez-Osuna *et al*. 2003). However, on a regional scale, there is evidence of mangrove destruction mainly in Sinaloa (Ceuta and Huizache-Caimanero coastal lagoons) and Nayarit (Marismas Nacionales). The drying out of lagoons in the Huizache-Caimanero system caused a 20% reduction in water surface area from 1973 to 1997 and an increase in adjacent seasonal salt pans (Ruiz-Luna & Berlanga-Robles 1999). The Huizache-Caimanero coastal lagoon supports an important shrimp fishery. Until the 1980s, this system had yields up to 1,500 tonnes (de la Lanza & García-Calderón 1991) and provided the highest yields per unit area for shrimp fisheries in coastal lagoons in Mexico. During the last decade, yields notably decreased (Zetina-Rejón *et al*. 2003). Rogerío-Poli & Calderón-Pérez (1987) considered that the changes in postlarvae density were mainly due to changes in water temperature. On the other hand, Ruiz-Luna & Berlanga-Robles (1999) suggested that the loss of freshwater, which changed the salinity in this lagoon, was a consequence of the removal of deciduous tropical forest for agricultural purposes and a 50% decrease of mangrove forests between 1973 and 1997. In addition to the elevated rate of mangrove deforestation (1.9% per year), mangrove coverage for this zone is scarce and with patchy distribution that aggravates an unstable condition (Páez-Osuna *et al*. 2003). Carrera & de la Fuente 2001 reported that in Marismas Nacionales about 1,500 hectares of wetlands have been replaced by shrimp farming. Nonetheless, DeWalt (2000) considered that shrimp aquaculture in Mexico has thus far developed largely without the major detrimental environmental effects seen in other countries and has found little evidence of mangrove destruction.

IV. Socioeconomic Conditions

The Gulf of California LME is a very economically active zone. Overall, the region accounts for approximately 10% of Mexico's GDP, with a human population of about 8.6 million. Approximately 40% of Mexico's agricultural production comes from the region, mainly from the States of Sonora, Sinaloa and Nayarit. Because of the richness of the marine basin and a very particular social-geographic situation (border with the

U.S.), key productive activities have been increasing along the littoral areas, driving an uncontrolled coastal population growth (WWF Mexico 2005). Port activities and marine traffic represent a fundamental support for agriculture, industry, mining and fishing. The region is considered a natural port for international traffic routes and tourism development. The Mexican government and the Fondo Nacional de Fomento al Turismo (FONATUR) have announced plans to proceed with a project called Escalera Nautica, or Nautical Ladder, consisting of at least 22 yachting marina resorts placed strategically along the coast. The project also contemplates new and improved highways, airports, airstrips, and the development of hotels, golf courses, etc. (Enríquez-Andrade *et al*. 2005).

An increase in the demand for oil, gas and mineral resources has stimulated the exploration of the non-living resources of the EEZ. The LME's fisheries are an important source of food and income for Mexicans (Enríquez-Andrade *et al*. 2005). Major resources are small pelagic fishes, jumbo squid, tuna-like fishes and shrimp. Shrimp production continues to be of important value, despite the decline in offshore shrimp catches in the upper Gulf in the late 1980s-early 1990s.

V. Governance

The LME is governed by Mexico. Fisheries regulations are numerous and complex, responding to the diverse array of natural resources. All fisheries resources in the country are managed by the Federal Government through the Ministry of Agriculture, Livestock, Fisheries and Food, by the National Commission of Aquaculture and Fisheries (CONAPESCA), while the environment is under the responsibility of the Ministry of Environment and Natural Resources. CONAPESCA has a technical branch, the National Fisheries Institute (INP), which conducts regular assessments and evaluations of the status of fisheries resources.

Several natural protected areas have been established in the region, including five biosphere reserves (among them the Upper Gulf of California and the Colorado River Delta, the coast of the Reserva de la Biosfera del Vizcaíno and the San Pedro Mártir Island), five marine parks (including the Bay of Loreto and Cabo Pulmo), three wildlife reserves (including Cabo San Lucas and all of the Islands of the Gulf of California) and three areas with other protection status. In addition, two new marine parks are being considered for decree (Enríquez-Andrade *et al*. 2005). There are 16 areas designated as 'priority' by the National Commission of Biodiversity. Protected areas are managed by the National Commission of Protected Areas (CONANP), reporting to Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT). After several years of relatively uncoordinated efforts by several NGOs, a Coalition for the Sustainability of the Gulf of California was created in December 1997 in an attempt to integrate available information and generate broad consensus on conservation priorities for the region (Enríquez-Andrade *et al*. 2005). At present there is an ongoing process to develop an Ecological Ordering of the Gulf of California, started June, 2004. This is a coordinated effort of the Federal Government through SEMARNAT, SAGARPA, the Ministry of Communications and Transportation (SCT), Ministry of Tourism (SECTUR), Ministry of the Interior (SEGOB) and the Ministry of the Navy (SEMAR). At the same time, SEMARNAT, Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA) and Secretaría de Turismo de México (SECTUR) signed an agreement with the governments of the states of Baja California, Baja California Sur, Sonora, Sinaloa and Nayarit to develop the ecological ordering of the terrestrial components of the coastal areas.

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XIV-48 Pacific Central-American Coastal LME

S. Heileman

The Pacific Central-American Coastal LME extends along the Pacific Coast of Central America, from 22ºN off Mexico down to 4ºS. It is shared by Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Colombia and Ecuador. The LME covers a surface area of nearly 2 million km^2, of which 1.42% is protected, and includes 0.22% of the world's coral reefs and 0.78% of the world's sea mounts (Sea Around Us 2007). Re-circulating coastal currents and milder temperatures than those of the adjacent California Current and Humboldt Current LMEs characterise this LME (Bakun *et al*. 1999). Much of the Pacific Central-American Coastal LME is influenced by the seasonal movements of the Inter-tropical Convergence Zone (Bakun *et al*. 1999). The region is vulnerable to the ENSO phenomenon, which affects productive activities, infrastructure, natural resources and the environment in general. The climate varies from tropical to temperate, with a dry period during the winter months. During the rainy season from May to September, rivers discharge significant volumes of freshwater and suspended solids into the coastal areas of this LME (Windevoxhel *et al*. 2000). Extreme ocean depths are reached very close to the coast due to a narrow and steep continental shelf. Book chapters and reports on this LME are by Bakun (1999), Bakun *et al*. (1999), Lluch-Belda (1999) and UNEP (2006).

I. Productivity

The Pacific Central-American Coastal LME could be considered a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1}). Several mechanisms, other than the classic eastern ocean upwelling produced by Ekman transport, are important sources of nutrient enrichment in this LME. The mechanisms include equatorial upwelling, open ocean upwelling driven by wind stress curl, and episodic downwind coastal upwellings forced by mountain gap winds from the Caribbean, as well as the mechanism underlying the Costa Rica Dome structure (Bakun *et al*. 1999). In addition, nutrient inputs also come from river run-off along the tropical areas of this LME (FAO 1997). Upwelling plumes extending offshore are located off the three major mountain ranges of the region (Bakun *et*. *al*. 1999). An extensive minimum oxygen layer exists off Mexico and Central America (Wyrtki 1965, Bianchi 1991), with oxygen levels low enough to have major effects on the composition and migration of the biological communities (Bakun *et al*. 1999). The large-scale monthly mean ocean temperatures remain above 26ºC throughout the year and, as a consequence, the marine fauna of this LME is tropical and distinctly different from the predominantly temperate fauna of the California and Humboldt systems (Bakun *et al*. 1999). Threatened species such as turtles and sharks are of particular concern in the region.

Oceanic Fronts (Belkin and Cornillon 2003; Belkin et al. 2009): Most fronts within this LME (Figure XIV-48.1) are generated by coastal upwelling. Some fronts off the Pacific coast of Central America originate from quasi-regular bursts of topographically generated winds blowing from the Caribbean across Central America toward the Pacific Ocean. Local orography tends to channel these winds and make their direction exceptionally stable and predictable, especially in the Gulf of Tehuantepec where these winds result in formation of upwelling zones and fronts that bound them extending far offshore (Belkin & Cornillon 2003). This is the only place in the World Ocean where such fronts are observed.

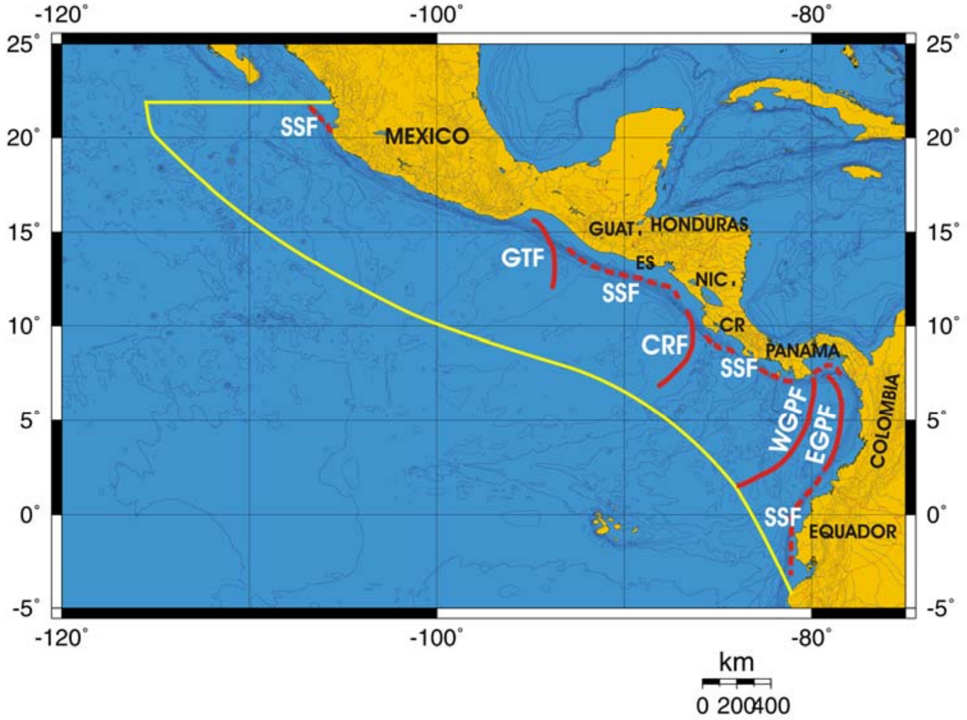

Figure XIV-48.1. Fronts of the Pacific Central-American Coastal LME. CR, Costa Rica; CRF, Costa Rica Front; EGPF, East Gulf of Panama Front; ES, El Salvador; GTF, Gulf of Tehuantepec Front; GUAT, Guatemala; NIC, Nicaragua; SSF, Shelf-Slope Front (most probable location); WGPF, West Gulf of Panama Front. Yellow line, LME boundary. After Belkin et al. (2009).

Pacific Central-American Coastal LME SST (Belkin 2009)(Figure XIV-48.2)
Linear SST trend since 1957: 0.29°C.
Linear SST trend since 1982: 0.14°C.

The Central-American Pacific LME experienced moderate warming over the last 50 years. However, the thermal history of this LME was non-monotonous. The cooling phase culminated in the two minimums, in 1971 and 1975, both associated with major La Niñas ((National Weather Service/Climate Prediction Center, 2007), after which the SST rose by approximately 1°C over the next 30 years. The absolute minimum of 1975 was synchronous with absolute minima in two other East Pacific LMEs: California Current LME and Gulf of California LME. The minimum also was roughly synchronous with the absolute minimum of 1974-1976 on the other side of the Central American Isthmus, in the Caribbean LME. The warming phase was accentuated by two sharp peaks, in 1983 and 1997, both associated with major El Niños (National Weather Service/Climate Prediction Center, 2007). Similar peaks (warm events) were also observed in other East Pacific LMEs, namely the Humboldt Current, Gulf of California, and California Current. The warm event of 1992, concurrent with a strong El Niño, was less conspicuous in this LME compared with other East Pacific LMEs. In general, all significant maxima and minima of SST observed in this LME are associated with El Niños and La Niñas respectively (National Weather Service/ Climate Prediction Center, 2007). This strong correlation is not surprising giving the location of this LME in the Eastern Tropical-Equatorial Pacific, where El Niños' and La Niñas' effects are most conspicuous.

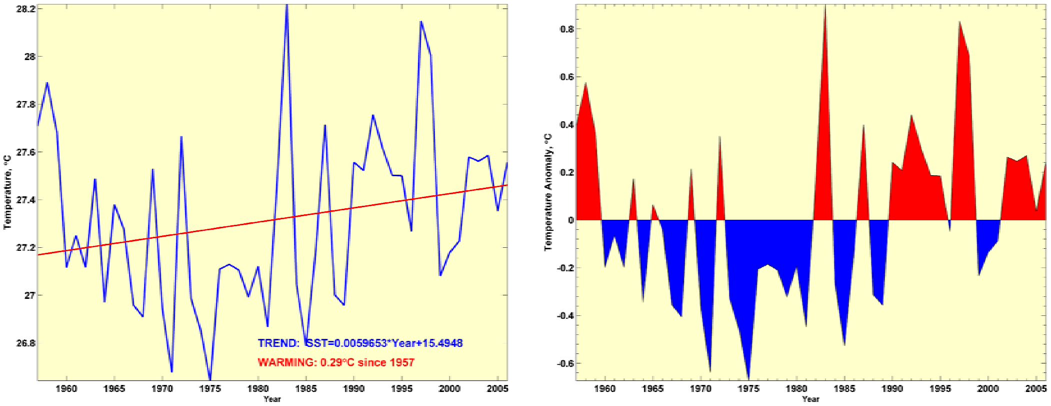

Figure XIV-48.2. Pacific Central-American Coastal LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Pacific Central-American Coastal LME Chlorophyll and Primary Productivity: The Pacific Central-American Coastal LME is a Class I, high productivity ecosystem (>300 gCm^{-2}yr^{-1})(Figure XIV-48.3).

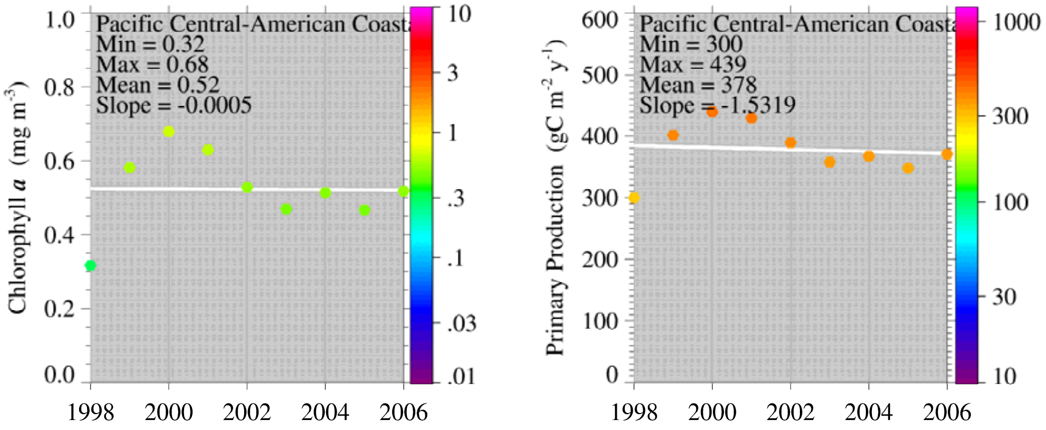

Figure XIV-48.3. Pacific Central-American Coastal LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hude. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Pacific Central-American Coastal LME is rich in both pelagic and demersal fisheries resources. The most valuable fisheries in the region are offshore tunas and coastal penaeid shrimps. More than 50% of the shelf catches consists of small coastal pelagic species such as anchoveta (*Engraulis ringens* and *Cetengraulis mysticetus*), South American pilchard (*Sardinops sagax*) and the Pacific thread herring (*Opisthonema libertate*), most of which are used for fish meal and fish oil. Artisanal shark fisheries also operate in El Salvador and Guatemala. In addition to the capture fisheries, aquaculture of penaeid shrimp is an important economic activity.

Total reported landings have risen, with some fluctuations, to peak landings of 730,000 tonnes in 1994 (Figure XIV-48.4). The species composition of the landings has also fluctuated, particularly between anchovies and South American pilchard. These fluctuations coincide with the most important El Niño events and are related to the dramatic and simultaneous inter-decadal regime shifts in marine fish populations in other Pacific LMEs associated with El Niño (Bakun 1999, Lluch-Belda 1999). Fluctuations in the value of the reported landings correspond with the landings, with a peak of US$548 million (in 2000 US dollars) recorded in 1994 (Figure XIV-48.5).

It should be cautioned, however, that the underlying landing statistics in this LME, particularly those reported by the countries south of Mexico, strongly underestimate the true catch (see, e.g., Wielgus et al. 2007 for Columbia) and represent, in several instances, a bias toward landings of exported species (e.g., lobsters, shrimps), while those sold on local markets by artisanal fishers are often ignored (see also Bakun *et al*. 1999).

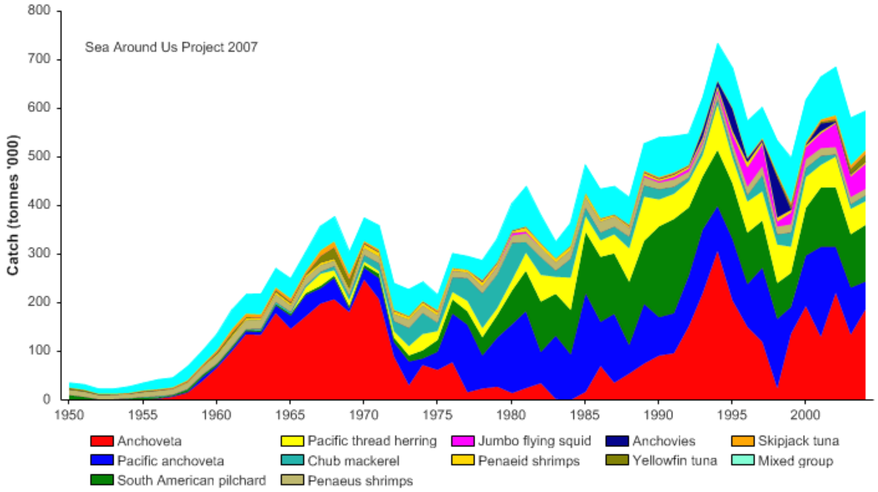

Figure XIV-48.4. Total reported landings in the Pacific Central-American Coastal LME by species (Sea Around Us 2007).

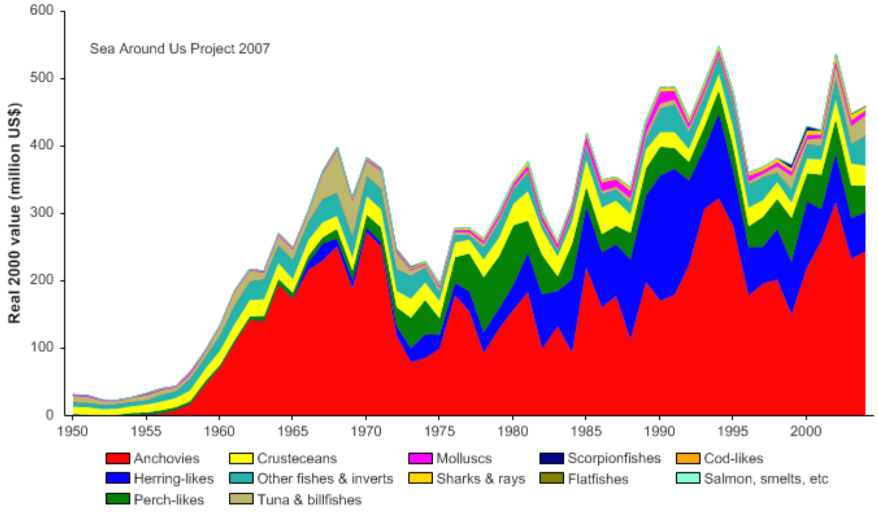

Figure XIV-48.5. Value of reported landings in the Pacific Central-American Coastal LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 5% of the observed primary production in 2002 (Figure XIV-48.6). Mexico, Ecuador, El Salvador, Peru and Panama account for most of the ecological footprint in this LME.

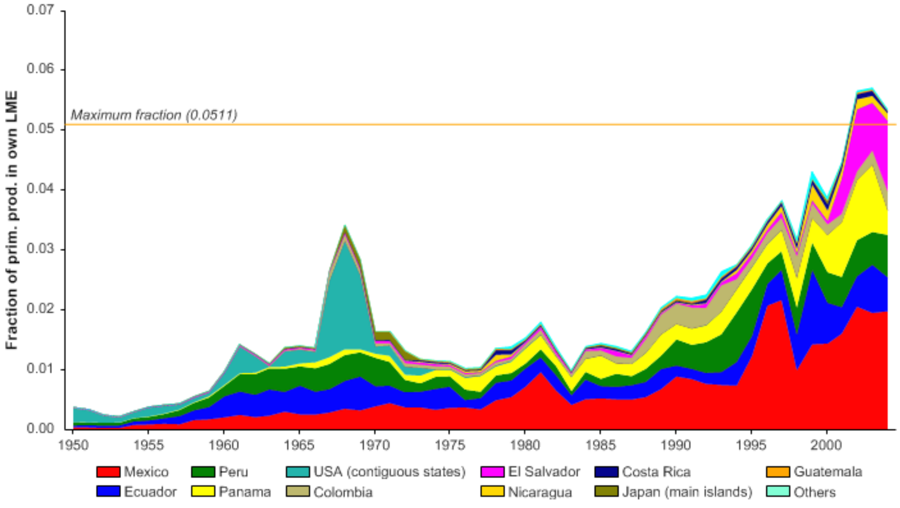

Figure XIV-48.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Pacific Central-American Coastal LME (Sea Around Us 2007). The ‘Maximum fraction’ denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) is relatively low, and shows a declining trend until the mid 1980s, after which a slight increasing trend became apparent (Figure XIV-48.7 top). The FiB index has increased, indicating that ‘fishing down’ (Pauly *et al*. 1998) occurring in the LME would be masked by either the geographic (offshore) expansion of the fisheries (Figure XIV-7.7 bottom) or the incompleteness of the underlying statistics as indicated above.

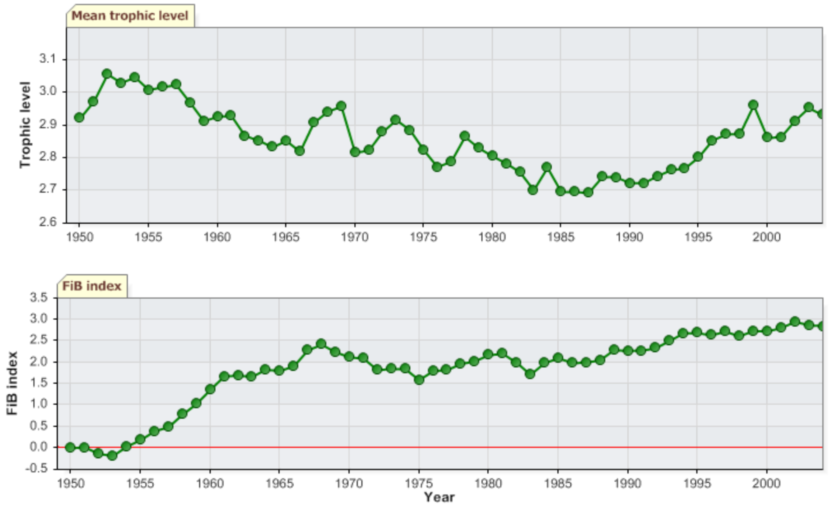

Figure XIV-48.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Pacific Central-American Coastal LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that the number of collapsed and that overexploited stocks are rapidly increasing in the LME (Figure XIV-48.8 top). Approximately 40% of the reported landings are supplied by fully exploited stocks (Figure XIV-48.8 bottom).

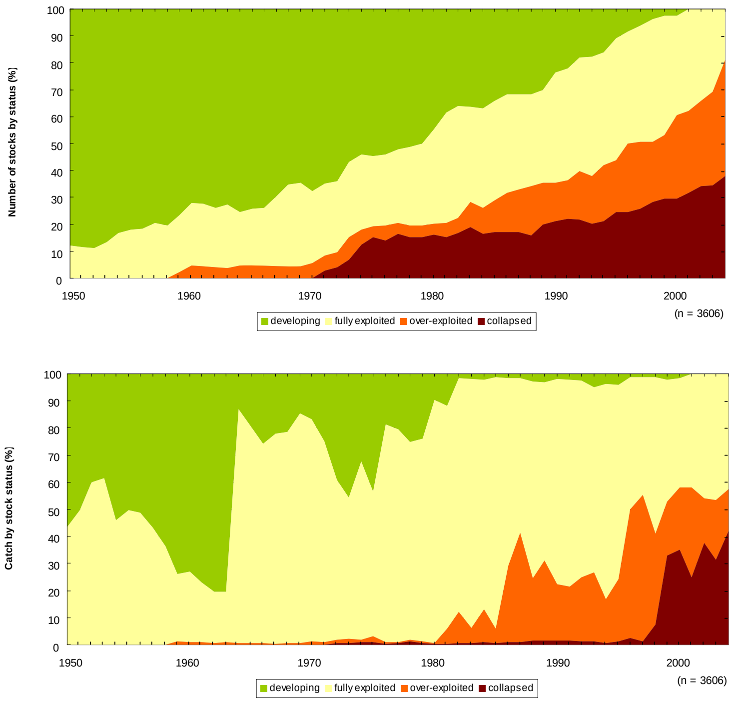

Figure XIV-48.8. Stock-Catch Status Plots for the Pacific Central-American Coastal LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

In general, overexploitation was found to be moderate in this LME, although it was severe in Colombian waters (UNEP 2006), with several traditionally fished stocks showing signs of overfishing. For example, most of the shrimp stocks are considered to be overexploited (Bakun *et al*. 1999, FAO 2005a), although the reported landings of shrimp trawlers have not substantially declined. In Costa Rica, the landings of the shrimp trawler fleet increased between 1993 and 2002. However, closer examination reveals that the increase was due to larger catches of finfish, suggesting that when the shrimp stocks were reduced, greater fishing effort was focused on high-value fish (FAO 2005a). Fishery resources in the Gulf of Nicoya have come under heavy pressure from the rapid growth of the small-scale fleet in the past 20 years. As a result, there has been a reduction in the catch per unit effort of the most valuable species and the sizes of fish and shrimp caught.

Numerous species of demersal fish are under heavy fishing pressure from the shrimp fisheries, in which they are commonly taken as bycatch (Bakun *et al*. 1999). The shark stocks in the Gulf of Fonseca are also showing signs of depletion. Other overexploited stocks include several species of Lutjanidae, Sciaenidae, Centropomidae and Serranidae (CCAD/IUCN 1999). In the Gulf of Fonseca, some molluscs and crustacean species are overexploited by the artisanal fishery and several others such as the tropical rocky oyster (*Ostrea iridescens),* green lobster (*Panulirus gracilis*) and crab (*Menipe frontalis*) are fully exploited (CCAD/IUCN 1999).

Likewise, the level of bycatch and discards and the use of destructive fishing practices were assessed as generally moderate, but severe in Colombian waters (UNEP 2006). Several hundred species of demersal fish, especially early life history stages, are taken as bycatch in the shrimp trawl fishery, which also has the highest rate of discards. Many of these bycatch species have potential economic value, but do not sustain major commercial fisheries in the region (Bakun *et al*. 1999). Nonetheless, their effective level of exploitation could be high as a result of pressure from the shrimp fishery, which probably inhibits the development of fisheries for these species (Bakun *et al*. 1999). Furthermore, the juveniles of about 30 different groups are discarded during the catching of shrimp larvae for aquaculture in the Gulf of Fonseca (CCAD/IUCN 1999). This is of particular concern since it is likely affecting the recruitment of several commercial species and threatening the long-term sustainability of both aquaculture and artisanal fisheries. No assessment of marine mammal bycatch has been conducted, although Palacios and Gerrodette (1996) suggested that the rate could be as high as that in other parts of the Pacific coast of South America.

The current level of fisheries exploitation is unsustainable, and overexploitation is expected to worsen (UNEP 2006) as a result of increasing coastal populations and further increases in fishing effort in the traditional fisheries. However, there is a potential for the development of fisheries for other species such as mid-sized pelagics and other oceanic species as well as deepwater shrimps (Bakun *et al*. 1999). Among the most pressing needs is the development of systems for improved data collection and monitoring, since the fisheries catch statistics in the bordering countries are generally poor and unreliable (Bakun *et al*. 1999). Future conditions will depend on the effective implementation of conservation and development projects directed towards the environmental sustainability of the region.

III. Pollution and Ecosystem Health

Pollution: Population growth, poorly planned urban development, tourism and industrial and agricultural activities exert significant pressures on the Pacific Central-American Coastal LME, partly as a result of the associated discharges of waste into the aquatic environment (IDEAM 2002). Although pollution was found to be generally moderate in this LME, it was assessed as severe in some localised areas, including in the transboundary Gulf of Fonseca (UNEP 2006). Land-based pollution is potentially more damaging in the coastal waters because of the numerous sheltered bays and gulfs in which pollutants are not easily dispersed. About 95% of the wastewater produced in the bordering countries is untreated and reaches the Pacific Ocean with high loads of organic matter, nutrients and other pollutants (PNUMA 2001). The limited available information indicates accumulation of pesticides, heavy metals and other pollutants in coastal areas, with unknown impacts on the marine biota. High concentrations of pathogenic micro-organisms have been recorded in some areas (CPPS 2000). For example, in Puntarenas, Costa Rica, total coliform bacteria concentrations between 16 - 20 million MPN[1]/100 ml and between 2 - 9.2 million MPN/100 ml for faecal coliforms have been reported (Wo-Ching & Cordero 2001).

Wastewater discharges and agriculture run-off are the main source of anthropogenic nutrient enrichment in the LME. Fertiliser consumption increased from 76 kg ha^{-1} in 1990 to about 131 kg ha^{-1} in 2000 in the countries in the central part of the LME. It is

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[1] MPN: Most Probable Number

estimated that the coastal waters in the region receive 120,300 tonnes nitrogen yr^{-1} and around 14,500 tonnes phosphorus yr^{-1} (PNUMA 2001). The high rate of deforestation, poor agricultural practices and associated increase in erosion and runoff also contribute to elevated nutrient levels to this LME (PNUMA 2001). As a consequence, eutrophication is evident in coastal areas of e.g. Panama (Panama Bay), Nicaragua (Corinto, El Realejo, Estero Chocolate, La Esparta, El Real), El Salvador (Jiquilisco Bay) and Costa Rica (Gulf of Nicoya) (PNUMA 2001). Harmful algal blooms (HABs) associated with eutrophication have also been observed (Rubio *et al*. 2001). These factors combined with the input of wastewater, are producing a significant amount of suspended solids and high sedimentation in some coastal areas (CCAD/IUCN 1999, Rubio *et al*. 2001, Sánchez 2001).

Chemical contamination is highly concentrated in some areas of the Pacific coast (Jameson *et al*. 2000). Heavy metals such as lead, copper and chromium have been reported in sediments and surface waters in several countries of the region, especially in Panama, Nicaragua and Costa Rica (Sánchez 2001, Wo-Ching & Cordero 2001). Discharges from agricultural areas are a major source of pollution by persistent toxic substances. The level of pesticides used in the region is one of the highest in Latin America, and their presence has been reported in discharges of several rivers (Rubio *et al*. 2001, Wo-Ching & Cordero 2001). Pesticides have been found in fish, crustacean and mollusc tissue in some areas (Rubio *et al*. 2001).

Over 15 million tonnes of solid waste are produced annually in the region, about 44% of which originates in coastal settlements (PNUMA 2001). However, the collection of solid waste is generally inadequate, or it is disposed of in inappropriate sites or discharged directly into water bodies. Litter accumulation has reduced the aesthetic value of coastal areas and presents a permanent risk for fishing and maritime traffic in the region. Most oil spills are chronic and occur in ports and storage sites. The heavy traffic on the shipping lanes to North and South America and Asia, which parallel almost the entire length of the coastline, increases the threat of oil spills in the LME. Another potential source of oil pollution is the trans-isthmus oil pipeline (PNUMA 1999). Small spills also come from the cities when oils and other hydrocarbons are eliminated through the sewerage system and finally disposed of in coastal areas.

***Habitat and community modification*:** The LME’s coast is characterised by its many peninsulas, gulfs and bays, as well as extensive intertidal areas, barriers and well developed coastal lagoons. An important geographic feature is the transboundary Gulf of Fonseca, which is shared by Nicaragua, Honduras and El Salvador. Poorly planned urbanisation and economic development along the Pacific coast is leading to the accelerated degradation and destruction of economically and ecologically important habitats. Habitat modification was found to be moderate in this LME (UNEP 2006). Even protected areas are being affected, with about 35% of protected areas showing some type of deterioration in 2001 from various causes such as sedimentation, mangrove destruction, pollution and overfishing (PNUMA 2001).

Of the coastal habitats in the LME, mangroves are the most affected by human activities and there are reports of mangrove destruction throughout the region (CCAD/IUCN 1999, Rubio *et al*. 2001, Sánchez 2001). Mangrove forests have been cleared for several purposes including aquaculture, agriculture, urban development, firewood, building material and tannin production. Conversion to aquaculture ponds is, however, a major cause of mangrove loss in the region. At least 90% of the shrimp farms have been constructed on former mangrove or salt pond areas. All mangroves in the transboundary Gulf of Fonseca have been affected (CCAD/IUCN 1999). The mangrove area in the Gulf was reduced from 1,049 km^2 in 1976 to 691 km^2 in 1997. In addition, the Gulf is also polluted by run-off from extensive banana plantations in the coastal areas. In the central parts of the LME, only a small proportion of the mangrove area is relatively stable, the remaining areas being considered vulnerable (wet Pacific coast), in danger (Gulf of Fonseca and the northern dry coast), or critical (the southern part of the dry coast) (PNUMA 2001). About 98% of the estuaries are estimated to be affected by sedimentation, wastewater and agro-industrial residuals. The effects of mangrove destruction include an increase in coastal erosion, higher penetration of the saline wedge in some estuaries, soil salinisation and decrease of biological productivity with direct effects on artisanal fisheries.

The LME's coral reefs have been affected by sedimentation, oil spills, pesticides and trawling activities (Escobar 1996, PNUMA/IUCN 1998). Also, some reefs were severely impacted by the 1982-1983 El Niño event, which caused mass coral bleaching and mortality in all areas (Spalding *et al*. 2001). In Costa Rica, recovery has generally been good and, despite repeated bleaching in 1992 and 1997-1998, coral cover remains high in most areas. In contrast, recovery on many reefs in Panama has been poor. Pollution and habitat and community modification are expected to increase in the future, if the growth of poorly planned coastal urbanisation and development continues (UNEP 2006). This could be compounded by lack of adequate sanitation service and waste treatment and disposal facilities, and requires an increase in the provision of sanitation services as well as the strengthening of measures to prevent and control pollution and habitat degradation in the region. The crucial nature of transboundary issues within this region are demonstrated by the situation in the transboundary Gulf of Fonseca (Bakun *et al*. 1999). Threats to the finely structured habitats of this LME pose important concerns for biodiversity preservation and resource sustainability.

IV. Socioeconomic conditions

In 2002, the total population of the Pacific Central-American Coastal LME region was about 180 million, 80% of which is found in Colombia and Mexico (WRI 2004). Within these countries, some of the most impoverished people have migrated to the coast where they manage to make a meagre living from subsistence fishing and farming. The main economic activities in the coastal zone are tourism, fisheries, aquaculture and agriculture, as well as shipping and industrial activities (Bakun *et al*. 1999). Fish export value is substantial for Mexico, Nicaragua, Panama and Ecuador and the export of frozen crustaceans represents a significant source of foreign exchange. In 2001, the export value of frozen crustaceans was US$281 million in Ecuador, US$450 million in Mexico, US$33 million in Nicaragua and US$80 million in Panama (FAO 2005b). This LME is located on the intercontinental maritime route with intensive commercial exchange and tourist activity through the region. The most important site of maritime traffic is the Panama Canal, with an annual average of 14,300 ships (1990-1998) and income of US$420 million (PNUMA 2001).

Overexploitation, pollution and habitat modification have moderate socioeconomic impacts in the bordering countries (UNEP 2006). Fishing is of high social and economic significance for coastal populations, being a major source of protein, employment and income. However, total catches do not satisfy the local demand because investments are directed towards international markets. This has a direct impact on coastal populations by affecting social stability and creating food insecurity. About 28% of children below five years of age have nutritional problems. A study has shown that the number of artisanal fishers has increased but fish production has decreased (CCAD/IUCN 1999). This is producing lower incomes from fishing and an increase of the population living in extreme poverty. In the Gulf of Fonseca, the increasingly restricted and scarce marine resources associated with ongoing economic activities have had negative social impacts by further marginalising traditional human users of mangroves, wetlands and marine resources (DANIDA 1997).

Pollution and eutrophication in coastal areas also threaten the food security of the coastal communities by affecting the harvesting of shellfish and other living resources. Available information indicates the accumulation of pesticides, heavy metals and other pollutants in coastal areas. Coastal water pollution also has negative impacts on commercial fisheries and tourism and endangers the health of swimmers. A growing number of environmental refugees are encroaching on sensitive areas in need of protection.

V. Governance

The Pacific Central-American LME coastline is shared by Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Colombia and Ecuador. Each of these countries has laws and institutions related to management of the marine environment and its resources at the national level. However, there is need for the strengthening of local administrations for effective monitoring and management as well as for improved data collection (Bakun *et al*. 1999). Greater awareness is also required among local people and governments of the importance of preserving ecosystem integrity, especially for key coastal habitats like mangrove swamps and coral reefs. The marine environmental initiatives in the region are partly governed by international conventions such as UNCLOS, the UN Fish Stocks Agreement and the FAO Code of Conduct for Responsible Fisheries.

Regional initiatives include the Convention for Cooperation in the Protection and Sustainable Development of the Marine and Coastal Environment of the Northeast Pacific (Antigua/Guatemala Convention), which was signed by Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama in 2002. Key parts of this convention address the high levels of sewage and other pollutants being discharged from urban areas into the Pacific Ocean. Another priority is the assessment of risks from oil pollution and a strategy to deal with such events including an evaluation of the region's access to clean-up equipment and personnel. The Northeast Pacific Regional Seas Programme includes Colombia, Costa Rica, El Salvador, Guatemala, Honduras and Panama and is based on the Antigua/Guatemala Convention. The Central American Commission for Maritime Transportation acts as secretariat for the Northeast Pacific Regional Seas Programme. El Salvador, Honduras, Nicaragua are preparing the project ‘Integrated Ecosystem Management of the Gulf of Fonseca’ for GEF support. The development objective of the proposed project is to prevent the degradation and maintain the ecosystem integrity of the Gulf of Fonseca through an integrated approach to managing its land and water resources and promoting their sustainable use. The project’s global objective is to implement a regional cooperative framework for the management of the Gulf that will result in enhanced environmental protection of international waters and strengthen the conservation of globally significant coastal and marine habitats.

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XV WIDER CARIBBEAN

XV-49 Caribbean Sea LME
XV-50 Gulf of Mexico LME
XV-51 Southeast U.S. Continental Shelf LME

XV-49 Caribbean Sea LME

S. Heileman and R. Mahon

The Caribbean Sea LME is a tropical sea bounded by North America (South Florida), Central and South America and the Antilles chain of islands. The LME has a surface area of about 3.3 million km^2, of which 3.89% is protected, and contains 7.09% and 1.35% of the world's coral reefs and sea mounts, respectively (Sea Around Us 2007). The average depth is 2,200 m, with the deepest part, the Cayman Trench, at 7,100 m. Most of the Caribbean islands are influenced by the nutrient-poor North Equatorial Current that enters the Caribbean Sea through the passages between the Lesser Antilles. A significant amount of water is transported northwestward by the Caribbean Current through the Caribbean Sea and into the Gulf of Mexico, via the Yucatan Current. Run-off from two of the largest river systems in the world, the Amazon and the Orinoco, as well as numerous other large rivers dominates the north coast of South America (Müller-Karger 1993). A book chapter and reports pertaining to this LME have been published by Richards & Bohnsack (1990) and UNEP (2004a, 2004b, 2006).

I. Productivity

The Caribbean Sea LME can be considered a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1}). There is considerable spatial and seasonal heterogeneity in productivity throughout the region. Areas of high productivity include the plumes of continental rivers, localised upwelling areas and nearshore habitats such as coral reefs, mangroves and seagrass beds. Relatively high productivity occurs off the northern coast of South America where nutrient input from rivers, estuaries and wind-induced upwelling is greatest (Richards & Bohnsack 1990). The remaining area of the LME is mostly comprised of clear, nutrient-poor waters.

The Wider Caribbean Region is a biogeographically distinct area of coral reef development within which the majority of corals and coral reef-associated species are endemic (Spalding *et al*. 2001, Wilkinson 2002), making the entire region particularly important in terms of global biodiversity. Among the LME's coral reefs is the Meso-American Barrier Reef, the second largest barrier coral reef in the world. There have been yearly migrations of marine mammals such as the humpback, sperm and killer whales. Manatees are not as common as they once were along many of the river mouths. Sea turtles, such as hawksbill, green and leatherback nest on beaches within this LME.

Oceanic Fronts (Belkin *et al.* 2009)(Figure XV-49.1): In the southern Caribbean Sea, fronts are generated by coastal wind-induced upwelling off Venezuela and Colombia at 75°-78°W, 70°-75°W, and 62°-66°W. A 100-km-long front dissects the Gulf of Venezuela along 70°40'W, likely caused by the brackish outflow from Lake Maracaibo combined with coastal upwelling. Two shelf-break fronts off Cuba encompass two relatively wide shelf areas off the southern Cuban coast, east of Isla de la Juventad (83°W) and along the Jardines de la Reina island chain (79°-80°W), both best developed in winter. The Windward Passage Front between Cuba and Hispaniola (73°W) separates the westward Atlantic inflow waters moving into the Caribbean in the western part of the passage from the Caribbean outflow waters heading eastward in the eastern part of the passage. A 200-km-long front in the Gulf of Honduras peaks in winter, likely related to a salinity differential between the Gulf's apex and offshore waters caused by high precipitation in southern Belize (Heyman & Kjerfve 1999).

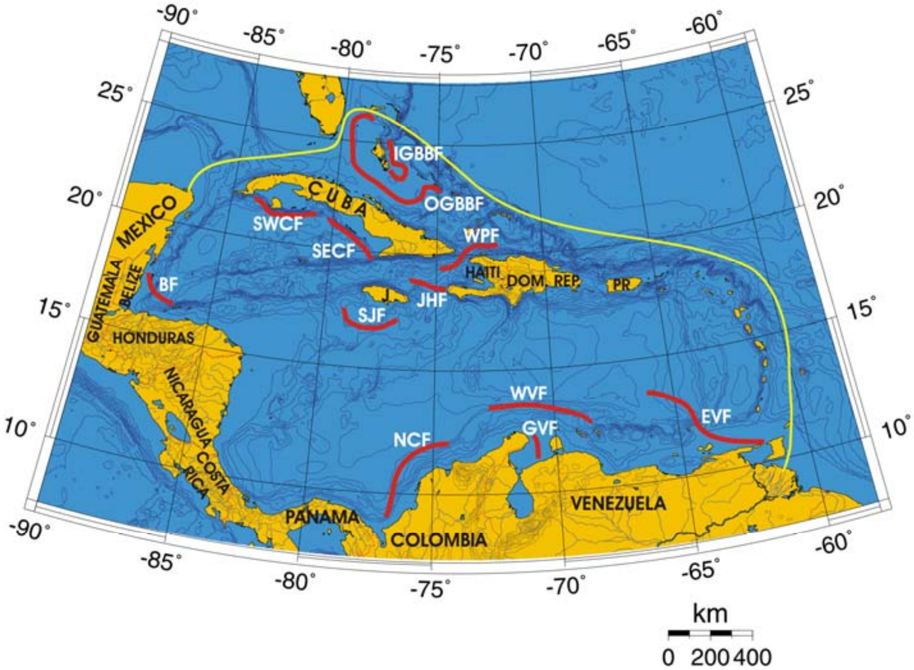

Figure XV-49.1. Fronts of the Caribbean Sea LME. Acronyms: BF, Belize Front; DOM.REP., Dominican Republic; EVF, East Venezuela Front; GVF, Gulf of Venezuela Front; IGBBF, Inner Great Bahama Bank Front; JHF, Jamaica-Haiti Front; NCF, North Colombia Front; OGBBF, Outer Great Bahama Bank Front; PR, Puerto Rico (U.S.); SECF, Southeast Cuba Front; SJF, South Jamaica Front; SWCF, Southwest Cuba Front; WPF, Windward Passage Front; WVF, West Venezuela Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

Caribbean Sea LME SST (Belkin 2009)(Figure XV-49.2):
Linear SST trend since 1957: 0.03°C.
Linear SST trend since 1982: 0.50°C.

The Caribbean Sea went through three phases over the last 50 years: (1) cooling until 1974; (2) cold phase with two cold spells of 1974-1976 and 1984-1986; (3) warming since 1986. Using the year of 1985 as a true breakpoint, the post-1985 warming amounted to >0.6°C over the last 20 years. Both cold spells were synchronous with cold events across the Central American Isthmus, in the Central American Pacific LME. The first cooling period was interrupted by a major warm event (peak) of 1968-1970, when SST reached its all-time maximum of 28.2°C in 1969. This event was confined to the Caribbean Sea. None of the adjacent LMEs experienced a pronounced warming in 1968-1970. If the warm event of 1968-1970 cannot be explained by anomalous atmospheric conditions, the reason should be in the open ocean east of the Caribbean Sea, in the trade winds zone, where the Canary Current LME experienced a warm event that peaked in 1969.

Virtually all significant maxima and minima of SST in the Caribbean Sea correlate strongly with El Niños and La Niñas respectively (National Weather Service/Climate Prediction Center 2007). This strong correlation is a good example of atmospheric teleconnections across the Central American Isthmus. This link is so strong that El Niños' and La Niñas' effects in the Caribbean Sea have comparable magnitudes with their counterparts in the Pacific Central-American Coastal LME on the other side of the Isthmus.

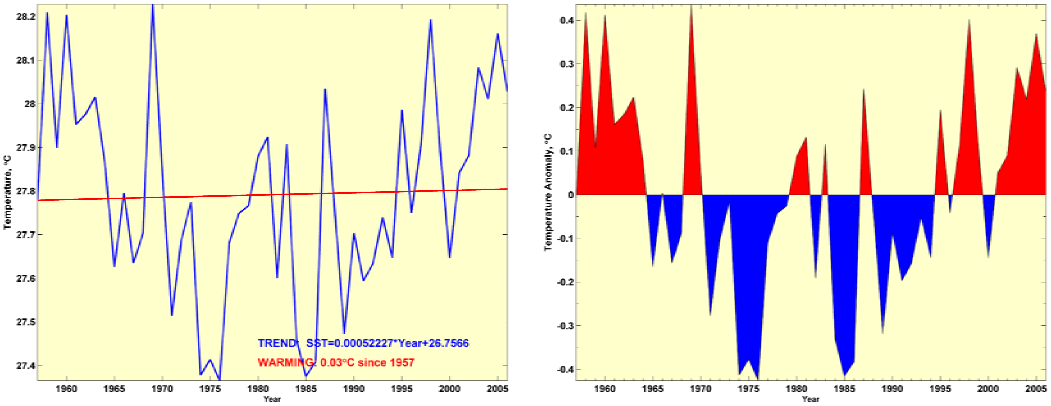

Figure XV-49.2. Caribbean Sea LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Caribbean Sea LME Chlorophyll and Primary Productivity

The Caribbean Sea LME is considered a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1})(Figure XV-49.3).

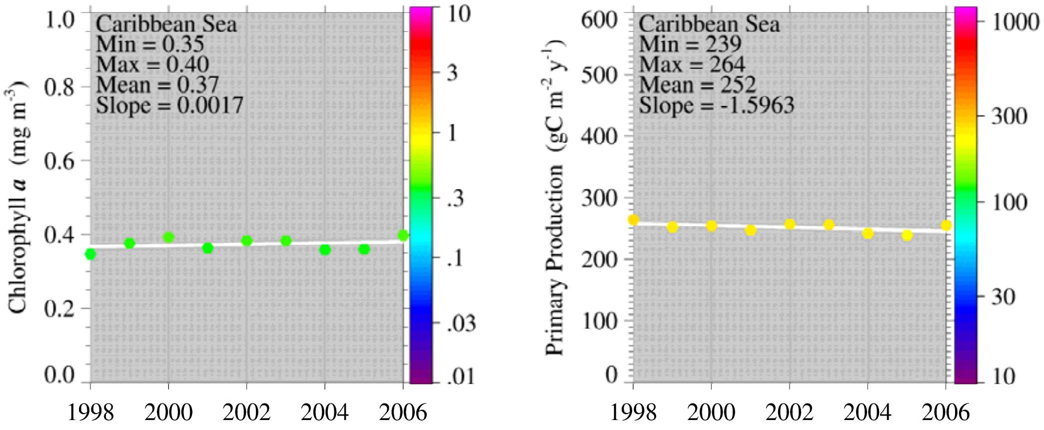

Figure XV-49.3. Caribbean Sea LME trends in chlorophyll *a* (left) and primary productivity (right), 1998 – 2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The fisheries of the Caribbean Sea LME are based on a diverse array of resources (Mahon 2002). Those of greatest importance are spiny lobster (*Panulirus argus*), queen conch (*Strombus gigas*), penaeid shrimps, reef fish, continental shelf demersal fish, deep slope and bank fish and large coastal pelagics such as king mackerel (*Scomberomorus cavalla*), Spanish mackerel (*S. maculatus*), dolphinfish (*Coryphaena hippurus*) and amberjack (*Seriola* spp.). In addition, fisheries based on stocks of large oceanic fish such as yellowfin tuna, skipjack tuna, Atlantic blue marlin and swordfish, several of which have been considered underexploited, have expanded considerably in recent years (Chakalall & Cochrane 2004). All of the large pelagic stocks are transboundary or Highly Migratory Species (HMS) and Straddling Stocks (SS), moving in and out of all or most of the EEZs and extending into the High Seas (Mahon 2003, Die 2004). The distribution of the large coastal pelagics, which occur largely within the EEZs of Caribbean countries, also extends into the High Seas (Mahon 2003). The fishery resources are mostly coastal and intensively exploited by large numbers of small-scale fishers using a variety of gears, while foreign fleets from distant water fishing nations are known to exploit the region's High Seas fisheries (Singh-Renton & Mahon 1996). Caribbean countries are often perceived to be fishing for HMS & SS on the High Seas when they flag foreign vessels on their open registries (Mahon 2003). This has resulted in problems for several countries of the Caribbean Community (CARICOM) and there are attempts to eliminate this practice (FAO 2002). Recreational fishing is an important activity in some of the countries, particularly for large pelagic fishes (Mahon 2004). Developments in fishing technology, as well as growing demands for fish have resulted in increasing pressure on the LME's fish stocks. Additionally, government initiatives have led to substantial increases in fishing effort, despite the inadequate institutional capacity to manage and monitor the fishing industry. Total reported landings in this LME, which are probably underestimated (see e.g., contributions in Zeller *et al.* 2003) showed a general increase to about 430,000 tonnes in the mid-1990s, followed by a slight decline (Figure XV-49.4). In the mid 1990s, the reported landings were valued at over US$360,000 (in 2000 US dollars; Figure XV-49.5).

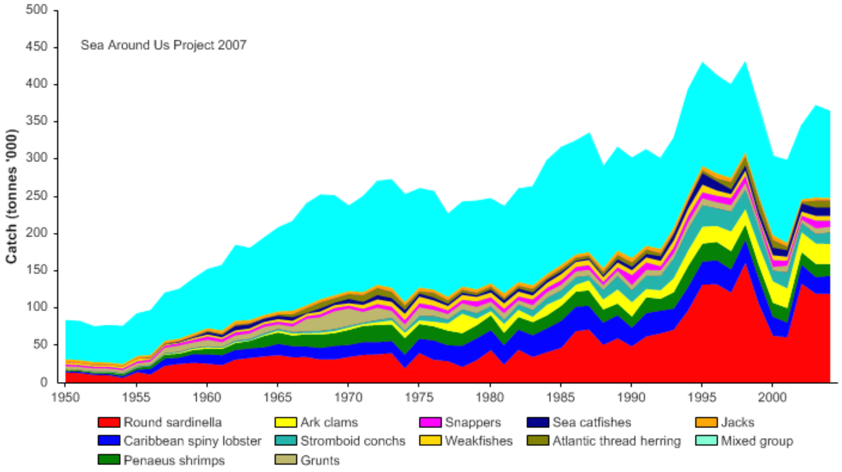

Figure XV-49.4. Total reported landings in the Caribbean Sea LME by species (Sea Around Us 2007).

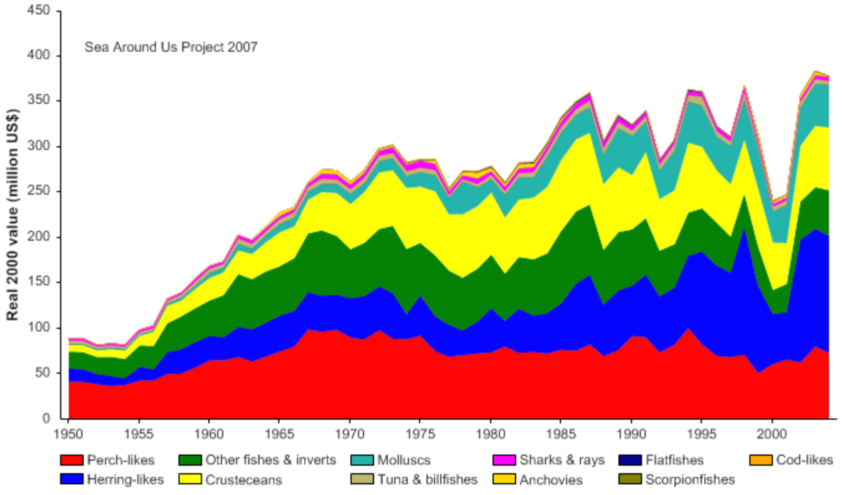

Figure XV-49.5. Value of reported landings in the Caribbean Sea LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached 3% of the observed primary production in 1994 and have fluctuated between 2.5 to 3% in recent years (Figure XV-49.6). Venezuela accounts for the largest share of the ecological footprint in this LME.

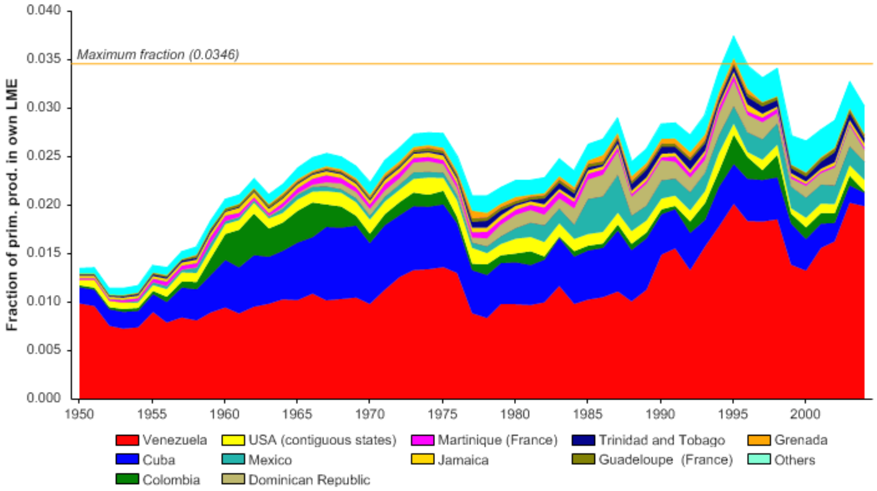

Figure XV-49.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Caribbean Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The decline of the mean trophic level of the reported landings (i.e., the MTI, Pauly & Watson 2005) is almost linear over the reported period (Figure XV-49.7, top), representing a classic case of a 'fishing down' of the food web in the LME (Pauly *et al*. 1998). This confirms Pauly & Palomares (2005), who performed a preliminary analysis of MTI in this region. Indeed, the decline in the mean trophic level would have been greater were it not for the expansion of the fisheries from the mid 1950 to the mid 1980s as implied by the increasing FiB index (Figure XV-49.7, bottom).

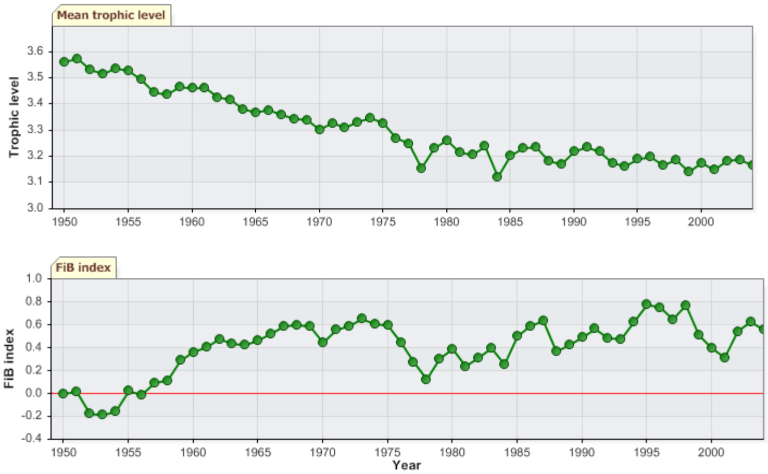

Figure XV-49.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Caribbean Sea LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that nearly 80% of the commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XV-49.8, top) and these stocks now contribute 60% of the reported landings (Figure XV-49.8, bottom).

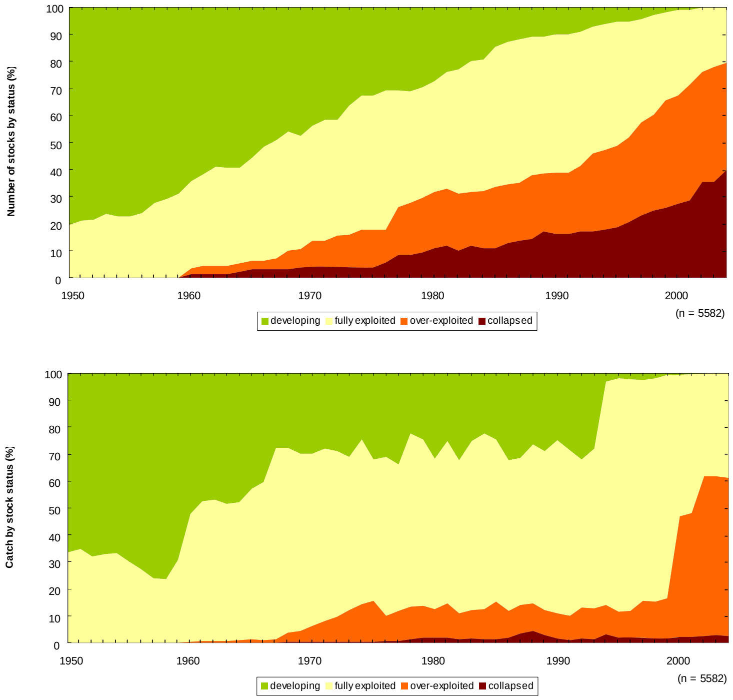

Figure XV-49.8. Stock-Catch Status Plots for the Caribbean Sea LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al,*, this volume, for definitions).

Overexploitation was found to be severe throughout the Caribbean Sea LME (UNEP 2004a, 2004b, 2006). Most coastal resources are considered to be fully or overexploited and there is increasing evidence that pelagic predator biomass has been depleted (Mahon 2002, Myers & Worm 2003). Many local fisheries had collapsed by the mid-1980s following the depletion of lobster, conch and finfish stocks (UNEP 2000). Overfishing, particularly of herbivorous species, has been identified as a key-controlling agent on Caribbean reefs leading to shifts in species dominance (Aronson & Precht 2000, Eakin *et al*. 1997; Hughes, T.P. 1994).

There is concern over the long-term sustainability of spiny lobster stocks due to an increase in fishing effort for this species. Furthermore, the minimum legal size of lobsters is well below the size of reproductive maturity in some areas (Richards & Bohnsack 1990). The conch fishery has collapsed in many areas and it is unlikely that conch catches can be sustained (Richards & Bohnsack 1990, Smith *et al*. 2000). Several species of sea turtles are threatened or endangered in many areas as a result of overexploitation (FAO 1997). Overfishing and reduced abundance of large-sized carnivorous reef fish such as snappers (*Lutjanus spp*.) and groupers (*Epinephelus spp*.) have been observed in several locations throughout the LME (e.g., Manickchand-Heileman and Phillip 1999, Charuau *et al*. 2001, Kramer 2003). Regardless of location, legal designation or local fishing regulations, these species have been overexploited in the entire Western Atlantic region (Ginsberg & Lang 2003). The sustainability of the groundfish fisheries in the southern Caribbean is also of concern in countries such as Venezuela and Trinidad and Tobago (Booth *et al*. 2001). These stocks have experienced high fishing pressure, particularly from trawlers. In the Gulf of Paria (between Trinidad and Venezuela), intense pressure from bottom trawling is thought to have contributed to a reduction in the abundance of species at higher trophic levels and the predominance of low trophic-level species (Manickchand-Heileman *et al*. 2004).

There is a clear trend of increasing landings of large pelagic fishes, both coastal and HMS and SS, by Caribbean countries. This indicates that these fisheries are expanding steadily, despite the absence of any indication of the levels that may be sustainable (Mahon 2003). In fact, some of these HMS and SS are already considered to be overfished, based on assessments carried out by the International Commission for the Conservation of Atlantic Tunas (ICCAT) (Die 2004). These include the Atlantic swordfish (ICCAT 2001a) and Atlantic blue marlin and white marlin (ICCAT 2001b). As a result of both management interventions and high recruitment levels in recent years, the swordfish stock has been slowly recovering (ICCAT 1999). The Atlantic yellowfin tuna stock is considered to be fully fished (ICCAT 2001a) but there is concern that the tendency for fishing effort to increase will ultimately result in overfishing of this species (ICCAT 2001a). The abundance of Western Atlantic sailfish fell dramatically in the 1960s and has not increased much since. Current catches seem sustainable, but it is not known how far the current levels are from maximum sustainable yield (ICCAT 2001b).

The quantity of bycatch and discards in the Caribbean Sea LME is significant, with bottom trawling for shrimp producing the greatest quantity of bycatch (UNEP/CEP 1996). Immature individuals of commercially important species generally dominate the shrimp bycatch. Moreover, the bycatch species composition has changed over the years and several species have practically disappeared, indicating a dramatic shrinking of their populations, notably in the case of sharks (Charlier 2001). Considerable quantities of bycatch, which includes sharks and large coastal pelagics, are also taken in the longline and other High Seas fisheries (Mahon 2003).

Destructive fishing practices such as dynamite and poison fishing are also contributing to the decline of some fish species throughout the region (Garzón-Ferreira *et al*. 2000). There is a lack of monitoring and enforcement to prevent these illegal practices, except for coast-watching by communities and coast guards.

Overfishing could have significant transboundary implications in the Caribbean Sea LME. In addition to the large migratory pelagic fishes, reef organisms, lobster, conch and small coastal pelagics are also likely to be shared resources by virtue of planktonic larval dispersal. In many species, larval dispersal lasts for many weeks or months, resulting in transport across EEZ boundaries (Richards & Bohnsack 1990). Therefore, even these coastal resources have an important transboundary component to their management. Therefore, fisheries management should be based on the status of the stock evaluated at the scale of the entire stock (Die 2004).

III. Pollution and Ecosystem Health

Pollution: Pollution of marine and coastal areas of the Caribbean Sea LME is a major and recurrent transboundary environmental issue in the region. Land-based pollution and physical alteration and destruction of habitats are among the major threats to the coastal and marine environments of the Caribbean Small Island Developing States (SIDS) (Heileman & Corbin 2006). In addition to land-based sources of pollution, the discharge of solid waste, wastewater and bilge water from both commercial and cruise ships as well as other offshore sources are of increasing concern (CAR/RCU 2000, GEF/CEHI/CARICOM/UNEP 2001). Pollution is moderate in general and severe in some coastal hotspots particularly around the large cities, especially in the Central America/Mexico sub-region (UNEP 2004a, 2004b, 2006). The entire Caribbean Sea may be considered a hotspot in terms of risks from shipping and threats to coral reefs (Heileman & Corbin 2006).

Sewage is one of the most significant pollutants affecting the coastal environments of the Wider Caribbean Region (CAR/RCU 2000). Rapid population growth, urbanisation and the increasing number of ships and recreational vessels have resulted in the discharge of increasing amounts of poorly treated or untreated sewage into the coastal waters (CAR/RCU 2000). Of even greater concern are the high bacterial counts that have been detected in some areas, including in bays where there is a large concentration of boats and berthing facilities. In addition to microbiological contamination, the input of sewage contributes high levels of nutrients to coastal areas. This, as well as inputs of fertilisers from agricultural run-off, have promoted hotspots of eutrophication as well as harmful algal blooms in some localised areas throughout the region (UNEP 2004a, 2004b). The estimated nutrient load from land-based sources is 130,000 tonnes nitrogen yr^{-1} and 58,000 tonnes phosphorus yr^{-1} (UNEP 2000). Discharges of suspended and dissolved solids have intensified through human activities, such as deforestation, urbanisation and agriculture. The region's rivers supply about 300 million tonnes suspended solids per year to the Greater Caribbean Region (PNUMA 1999). High turbidity and sedimentation have reduced biodiversity in shallow coastal waters throughout the region (UNEP 2000).

Of growing concern is the increasing amount of solid waste generated within the Caribbean countries. Because of inadequate collection and disposal facilities, much of this material eventually ends up on beaches and other coastal areas. About 70-80% of marine debris originates from the intense shipping traffic, especially cruise ships and oil tankers that cause an important transboundary movement of marine debris and tar balls (UNEP 2004a, 2004b). In addition to reducing the aesthetic value of the coastal areas, solid waste such as plastics are of considerable threat to marine fauna such as turtles, marine mammals and sea birds.

Chemical contamination from industrial and agricultural activities is severe in some localised areas (UNEP 2004a, 2004b). For example, pollution by copper, lead and zinc was found in water and sediments in Cuba, the Dominican Republic and Jamaica (GEF/UNDP/UNEP 1998). Coastal areas near to oil installations show significant heavy metal concentrations in sediments, for example, the Santo Domingo coastal zone and Havana Bay (GEF/UNDP/UNEP 1998, Beltrán *et al*. 2001). Chemical pollution is severe in some coastal areas of Central America, which has the highest use of pesticides per capita and which is expected to increase in the future.

One of the biggest potential threats to the Caribbean Sea LME is that of oil spills. Because of their petroleum-based industry, countries such as Trinidad, Tobago and Venezuela continue to have a higher risk of oil spills within their marine environments. Large volumes of hydrocarbons are discharged from tankers and private vessels in the region. More than one third of oil spilled at sea between 1983 and 1999 was caused by accidents at ports and oil installations located in the coastal zone (UNEP 2000). Thousands of large vessels, including those passing through the Panama Canal, transport nuclear and other hazardous materials through the Caribbean Sea annually, which increases the threat of spills of these materials.

Habitat and community modification: The coastal areas of the Caribbean Sea LME are comprised of habitats such as mangrove wetlands, seagrass beds and coral reefs, which dominate the land-sea margin and harbour high biological diversity. These habitats, however, are being impacted by a range of anthropogenic activities that have resulted in severe habitat and community modification, particularly around the smaller islands and along the mainland coast (UNEP 2004a, 2004b, 2006).

Signs of stress are particularly evident in the shallow-water coral reef habitats (Richards & Bohnsack 1990). Major threats to coral reefs are linked to overexploitation of reef fish communities, sewage, industrial and agricultural pollution, as well as tourism and sedimentation (Bryant *et al*. 1998, Garzón-Ferreira *et al*. 2000) and global warming. Recent studies have revealed a trend of serious and continuing long-term decline in the health of Caribbean coral reefs (Wilkinson 2002, Gardner *et al*. 2003, Lang 2003, Wilkinson and Souter 2005). About 30% of Caribbean reefs are now considered to be either destroyed or at extreme risk from anthropogenic threats (Wilkinson 2000). More was lost in the 2005 bleaching event (Wilkinson and Souter 2008). Another 20% or more are expected to be lost over the next 10-30 years if significant action is not taken to manage and protect them over and beyond existing activities. Dramatic changes in the community structure of coral reefs have taken place over the past two decades. Prior to the 1980s, scleractinian (stony) corals dominated Caribbean coral reefs and the abundance of macroalgae was low. Over the past two decades a combination of anthropogenic and natural stressors has caused a reduction in the abundance of hard corals and an increase in macroalgae cover (Richards & Bohnsack 1990, Kramer 2003). This has been exacerbated by the mass mortality of an important algal grazer, the sea urchin *Diadema* sp., in 1983 (Lessios *et al*. 2001). The worldwide mass coral bleaching events of 1997-1998 resulting from elevated sea surface temperatures affected coral reefs in almost the entire Wider Caribbean region (Hoegh-Guldberg 1999), where bleaching continued until the severe event of 2005. The impact of the bleaching events varied across the Wider Caribbean, with the Meso-American Barrier Reef sustaining severe damage.

Hurricanes have also impacted coral reefs in localised areas, for example, in Mexico and Belize, with varying degree of recovery (Gardner et al. 2005). A range of diseases has also affected Caribbean coral reefs, starting with black band disease in the early 1970s followed by white band disease in the late 1970s. Diseases of stony corals and gorgonians have been reported with increasing frequency (Woodley *et al*. 2000).

The major threats to the region's mangroves include coastal development and charcoal production. Many islands have reported deforestation of mangroves for fuel wood, often by squatters (GEF/CEHI/CARICOM/UNEP 2001). Between 1990 and 2000, 21 out of 26 countries showed decreasing mangrove cover, with annual rates of decline ranging from 0.3% in the Bahamas to 3.8% in Barbados (FAO 2003). Clearing of mangrove forests has made the coast more vulnerable to erosion and destroyed the habitat of many species (UNEP/CEP 1996). Sandy foreshores have also been severely destroyed and modified due to sand mining and poorly-devised shoreline protection structures (BEST 2002). Seagrass beds in some areas are affected by chronic sedimentation. Habitat destruction and alteration is significantly impacting the LME's biodiversity. For example, the population of the West Indian manatee has dramatically declined because of degradation of essential habitats and because they have been hunted (UNEP/CEP 1995).

Recognising the importance of the Caribbean Sea LME and its resources to economic development and human well-being, the countries are embarking on numerous programmes and activities to address the degradation of the marine environment. As a result, some improvements in the health of this LME are expected in the coming decades (UNEP 2004a, 2004b).

IV. Socioeconomic Conditions

The Caribbean Sea LME is bordered by 38 countries and dependent territories of the U.S., France, U.K. and the Netherlands. Sixteen of the independent states and the 14 dependent territories are Small Island Developing States (SIDS). The population of the Caribbean Sea region is approximately 107 million, with the majority inhabiting the coastal zones. In addition, each year the population increases considerably due to the influx of large numbers of tourists during the tourist season. The Caribbean countries, especially the SIDS, are highly dependent on the marine environment for their economic, nutritional and cultural well-being. There is a high dependence of the economies of the islands on tourism, with revenues from tourism ranging between 15 to 99% of total exports in 90% of the islands (CIA 2005). Marine fisheries also play an important social and economic role, and are an important source of protein, employment and foreign exchange earnings in many of the countries.

The socioeconomic impacts of overexploitation vary among the countries, but are generally slight to moderate (UNEP 2004a, 2004b). The Lesser Antilles Islands suffer the greatest socioeconomic impacts of overexploitation. Decreasing inshore resources, increasing harvesting expenses and increasing demand have led to an increase in the market prices of fish as well as conflicts between traditional and recreational fishers. Reduced employment opportunities in the fisheries sector have forced fishers to seek other sources of income. Declining fisheries resources also threaten the food security of fishers and others who are dependent on fisheries resources.

The socioeconomic impacts of pollution are moderate to severe, particularly in the Lesser Antilles and the Central American countries (UNEP 2004a, 2004b). Human health is threatened and the propagation of disease vectors promoted by the discharge of non-treated sewage and other contaminants (UNEP 2000). Where algal biomasses are significantly elevated due to eutrophication, such as in nutrient/sewage-enriched areas, the risk of disease and ciguatera poisoning is high (PNUMA 1999). Pollution has also diminished the aesthetic value of some parts of the region resulting in a loss of revenue from tourism (UNEP/CEP 1997).

The socioeconomic impacts of habitat modification range from slight to severe (UNEP 2004a, 2004b). The Caribbean islands are particularly affected by habitat degradation, as are the Central American countries. The impacts include medium to long-term loss of employment and income opportunities in the tourism sector, loss of recreational, cultural, educational, scientific values as well as costs of restoration of modified ecosystems (UNEP 2004a, 2004b). Habitats, such as mangroves and coral reefs, perform an important role in coastal protection and stabilisation. Therefore, the destruction of these coastal habitats has serious implications for the Caribbean Sea countries, particularly the SIDS, in view of rising sea levels and an increase in the frequency and intensity of storms and hurricanes (UNEP 2005).

V. Governance

With 38 countries and dependencies in the LME, the EEZs form a complete mosaic, resulting in many transboundary resource management issues, even at relatively small spatial scales. The need for countries of the Wider Caribbean to pay attention to the management of transboundary marine resources is well documented (Mahon 1987, FAO 1997). The fisheries initiatives in the region are partly governed by international frameworks such as UNCLOS, the UN Fish Stocks Agreement and the FAO Code of Conduct for Responsible Fisheries. At the regional level, there are several initiatives for the coordination of fisheries management (Mahon 2003). These are broad in scope, covering resources that range in distribution from coastal/national to HMS & SS. Among them are the FAO Western Central Atlantic Fisheries Commission, the Latin American Organisation for Fishery Development, CARICOM Regional Fisheries Mechanism, the Caribbean Fisheries Management Council and the Intergovernmental Oceanic Commission Sub-commission for the Caribbean (IOCARIBE). Operating at the international level are ICCAT and the International Whaling Commission. In 2001, the UN Fish Stocks Agreement that seeks to implement the provisions of UNCLOS related to conservation and management of HMS & SS came into force.

Despite a recognised need, there is no Regional Fisheries Management Organisation for the Wider Caribbean, including the Caribbean Sea LME, with a mandate to manage the fisheries resources. The most established and operational fisheries management organisation with relevance to the Caribbean Sea LME is ICCAT, which has the mandate to manage all tuna and tuna-like species in the Atlantic. The coastal species are perceived as being western Atlantic stocks that could be managed by the countries of the Wider Caribbean, whereas the oceanic stocks require a level of collaboration that would be best facilitated by an organisation such as ICCAT (Mahon 2003).

Regional programmes related to the marine environment include the UNEP's Regional Seas Programme, the Caribbean Coastal Marine Productivity Programme and the Caribbean Environment Programme (CEP), a sub-programme of UNEP's Regional Seas Programme. The aim of CEP is to p*romote regional cooperation for the protection and development of the marine environment of the Wider Caribbean Region. C*EP, which is facilitated by the Caribbean Regional Coordinating Unit located in Jamaica, is involved in several regional projects and initiatives including the International Coral Reef Initiative and its Action Network.

A number of marine environmental policy frameworks have been developed in the Caribbean. These include the 1981 CEP Caribbean Action Plan and the Convention for the Protection and Development of the Marine Environment in the Wider Caribbean Region (the Cartagena Convention) and its three protocols (Protocol Concerning Cooperation in Combating Oil Spills in the Wider Caribbean Region, Protocol Concerning Specially Protected Areas and Wildlife in the Wider Caribbean Region, and Protocol Concerning Marine Pollution from Land-Based Sources and Activities). In 1991, the Marine Environment Protection Committee of the International Maritime Organisation designated the Gulf of Mexico and the Wider Caribbean Region as a Special Area under Annex V of the MARPOL Convention. An ongoing initiative to have the Caribbean Sea internationally recognised as a special area in the context of sustainable development led to the adoption in 2003 by the UN General Assembly of the resolution ‘Promoting an integrated management approach to the Caribbean Sea area in the context of sustainable development’.

GEF is supporting the project ‘Integrating Watershed and Coastal Area Management in Small Island Developing States of the Caribbean’. The overall objective of this project is to assist participating countries in improving their watershed and coastal zone management practices. The project ‘Sustainable Management of the Shared Living Marine Resources of the Caribbean Large Marine Ecosystem and Adjacent Regions’ has been developed by IOCARIBE and is being implemented. The goal of this project is the sustainable management of the shared living marine resources of the LME and adjacent areas through an integrated management approach. The project is focused on aligning institutions on the national and regional scales to sustainably manage near shore and deep-water fisheries and related habitats of the LME, including the development and use of a knowledge base to support institutional decision-making. One of the objectives of this project is the preparation of a Transboundary Diagnostic analysis (TDA) and Strategic Action Plan (SAP) for the Caribbean Sea LME and Adjacent Regions.

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XV-50 Gulf of Mexico LME

S. Heileman and N. Rabalais

The Gulf of Mexico LME is a deep marginal sea bordered by Cuba, Mexico and the U.S. It is the largest semi-enclosed coastal sea of the western Atlantic, encompassing more than 1.5 million km^2, of which 1.57% is protected, as well as 0.49% of the world's coral reefs and 0.02% of the world's sea mounts (Sea Around Us 2007). The continental shelf is very extensive, comprising about 30% of the total area and is topographically very diverse. Oceanic water enters this LME from the Yucatan channel and exits through the Straits of Florida creating the Loop Current, a major oceanographic feature and part of the Gulf Stream System (Lohrenz *et al*. 1999). The LME is strongly influenced by freshwater input from rivers, particularly the Mississippi-Atchafalaya, which accounts for about two-thirds of the flows into the Gulf (Richards & McGowan 1989). Forty-seven major estuaries are found in this LME (Sea Around Us 2007). Important hydrocarbon seeps exist in the southernmost and northern parts of the LME (Richards & McGowan 1989). A major climatological feature is tropical storm activity, including hurricanes. Book chapters pertaining to this LME are by Richards & McGowan (1989), Brown *et al*. (1991). A volume on this LME is edited by Kumpf *et al*. (1999).

I. Productivity

The Gulf of Mexico LME is a moderately high productivity ecosystem (<300 gCm^{-2}/yr^{-1}). Conditions range from eutrophic in the coastal waters to oligotrophic in the deeper ocean. Lohrenz *et al*. (1999) distinguished among local scale, mesoscale and synoptic scale processes that influence primary productivity in the LME. Upwelling along the edge of the Loop Current as well as its associated rings and eddies are major sources of nutrients to the euphotic zone. It has been suggested that this upwelling causes a 2- to 3-fold increase in the annual rate of primary production in the Gulf (Wiseman & Sturges 1999). The region of the Mississippi River outflow has the highest measured rates of primary production (Lohrenz *et al*. 1990). The Gulf's primary productivity supports an important global reservoir of biodiversity and biomass of fish, sea birds and marine mammals. Each summer, widespread areas on the northern continental shelf are affected by severe and persistent hypoxia (Rabalais *et al.* 1999a).

Oceanic Fronts (Belkin *et al.* 2009)(Figure XV-50.1): From December through March, two major fronts emerge over two shelf areas, the West Florida Shelf (WFS) and Louisiana-Texas Shelf (LTS). The WFS Front (WFSF) extends over the mid-shelf, whereas the LTS Front (LTSF) is located closer to the shelf break. Both fronts form owing to cold air outbreaks (e.g., Huh *et al*. 1978). Huge freshwater discharge from the Mississippi River Estuary (MRE) and rivers of the Florida Panhandle contributes to the fronts' development and maintenance. Compared to these northern fronts, the Campeche Bank Shelf-Slope Front (CBSSF) and Campeche Bank Coastal Front (CBCF) in the south are weak and unstable. The Loop Current Front (LCF) is always present at the inshore boundary of the namesake front, best defined in winter.

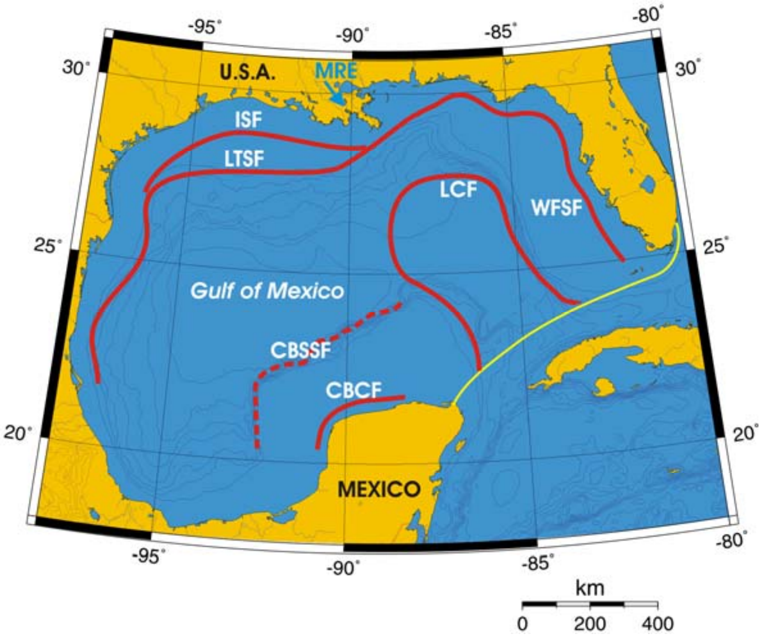

Figure XV-50.1. Fronts of the Gulf of Mexico. Acronyms: CBCF, Campeche Bank Coastal Front; CBSSF, Campeche Bank Shelf-Slope Front (most probable location); ISF, Inner Shelf Front; LCF, Loop Current Front; LTSF, Louisiana-Texas Shelf Front; MRE, Mississippi River Estuary; WFSF, West Florida Shelf Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

Gulf of Mexico LME SST (Belkin 2009)(Figure XV-50.2):
Linear SST trend since 1957: 0.19°C.
Linear SST trend since 1982: 0.31°C.

The Gulf of Mexico thermal history is quite peculiar. The global cooling of the 1960s transpired here as an SST drop of <1°C, followed by a slow warming until present. The relatively slow warming of the last 50 years was modulated by strong interannual variability with a typical magnitude of 0.5°C. The all-time record high of 26.4°C in 1972 was a major event since SST increased by nearly 0.8°C in just two years. This event was probably localized with the Gulf of Mexico. An alternative explanation involves a gradual drift of a record-strong positive SST anomaly of 1969 from the Caribbean Sea LME. The time lag of three years between the Caribbean Sea SST maximum and the Gulf of Mexico SST maximum makes this correlation tenuous.

The relatively slow warming, if any, of the Gulf of Mexico is also evident from satellite SST data from 1984-2006 assembled and processed at NOAA/AOML (Figure XV-50.2a). Even though the annual mean SST change little since 1957, summer SST in the Atlantic tropical areas rose substantially since the 1980s, which is thought to have resulted in a recent increase of destructiveness of tropical cyclones, including those that hit the Gulf of Mexico (Emanuel 2005).

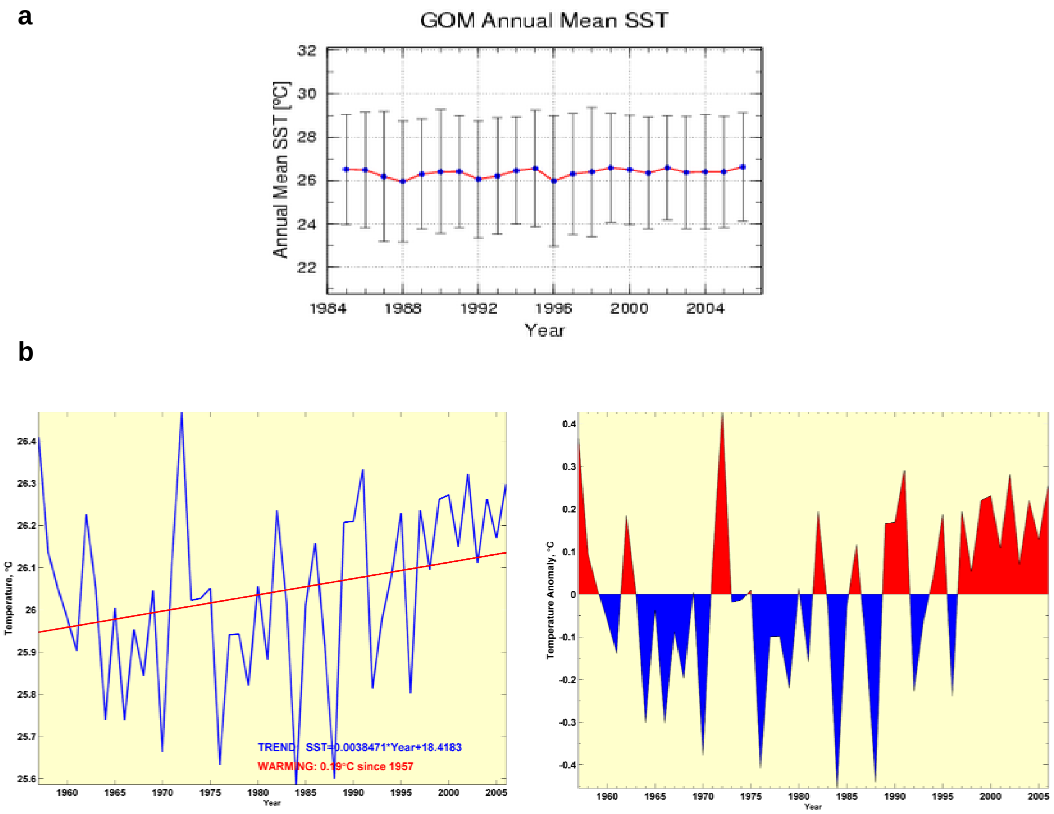

Figure XV-50.2a. Time series of annual mean SST in the Gulf of Mexico derived from satellite data, 1984-2006, processed at NOAA's Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida. Source: www.aoml.noaa.gov/phod/regsatprod/gom/sst_anm.php. Figure XV-50.2b. Gulf of Mexico LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Gulf of Mexico LME Chlorophyll and Primary Productivity: The Gulf of Mexico LME is a Class II, moderately-high productivity ecosystem (150-300 gCm^{-2}/yr^{-1})(Figure XV-50.3).

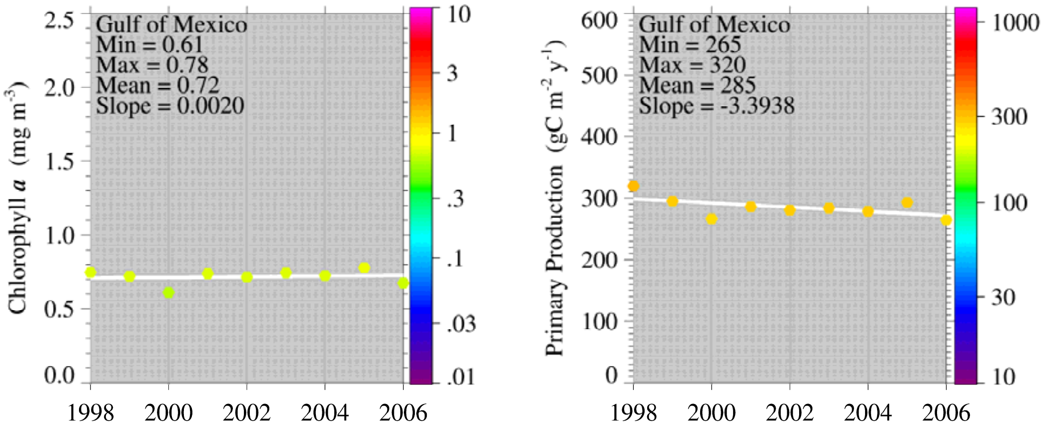

Figure XV-50.3. Gulf of Mexico LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Gulf of Mexico LME fisheries are multispecies, multigear and multifleet in character and include artisanal, commercial and recreational fishing. Species of economic importance include brown shrimp (*Farfantepenaeus aztecus),* white shrimp (*Litopenaeus setiferus*), pink shrimp (*Farfantepenaeus duorarum*), Gulf menhaden (*Brevoortia patronus*), king mackerel (*Scomberomorus cavalla*), Spanish mackerel (*S. maculatus*), red grouper (*Epinephelus morio*), red snapper (*Lutjanus campechanus*), seatrout, tuna and billfish (NOAA/NMFS 1999). Reported landings from this LME are dominated by herrings, sardines and anchovies (FAO 2003), but they underestimate total catches, due to non-inclusion of much of the discarded fish bycatch of shrimp trawlers (see e.g. contributions in Yañez-Arancibia, 1985). Total reported landings increased to over 1.5 million tonnes in 1984, and then declined to 780,000 tonnes in 2004 (Figure XV-50.4). Between 1969 and 1999, the annual value of the reported landings has been over US$1 billion (in 2000 US dollars) and reached US$2 billion in 1979 (Figure XV-50.5).

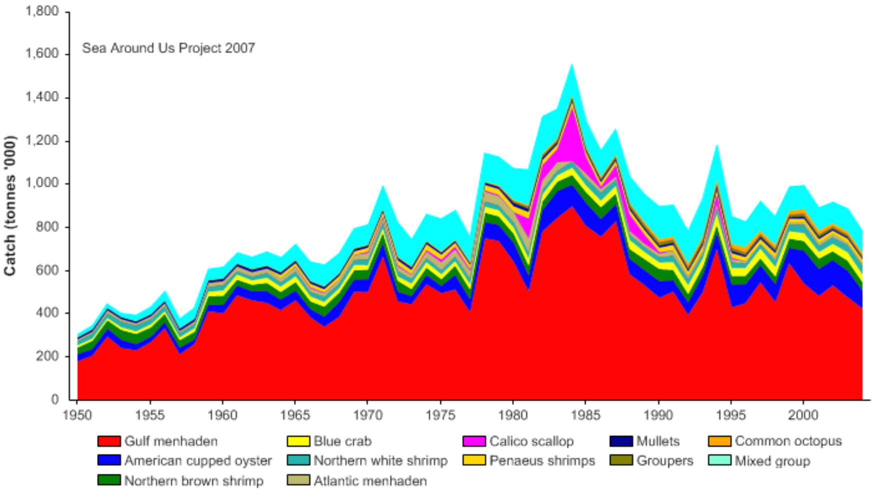

Figure XV-50.4. Total reported landings in the Gulf of Mexico LME by species (Sea Around Us 2007).

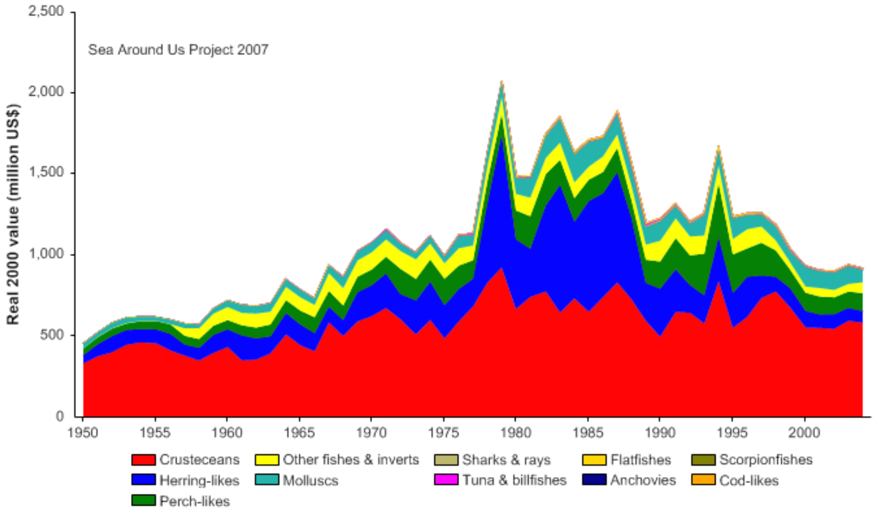

Figure XV-50.5. Value of reported landings in the Gulf of Mexico LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached 8% of the observed primary production in 1994 (Figure XV-50.6), but this PPR underestimate due to the high level of shrimp bycatch not included in the underlying statistics. Mexico and the USA account for the majority of the ecological footprints in this LME.

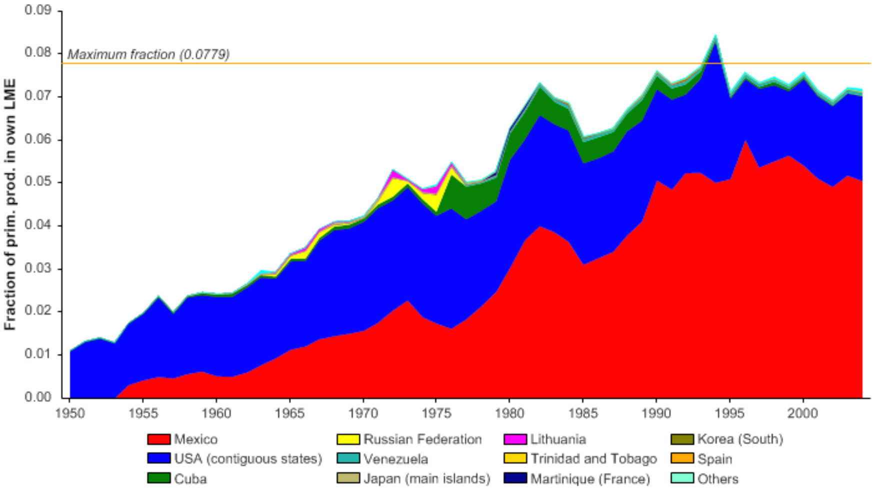

Figure XV-50.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Gulf of Mexico LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has increased slightly from the early 1950s to 2004 (Figure XV-50.7, top). The very low value of MTI (2.3-2.5) is due to the high proportion of small low trophic pelagic fishes, especially Gulf menhaden and shrimps in the landings, and the exclusion of the shrimp trawler bycatches in valuation of the mean trophic level.

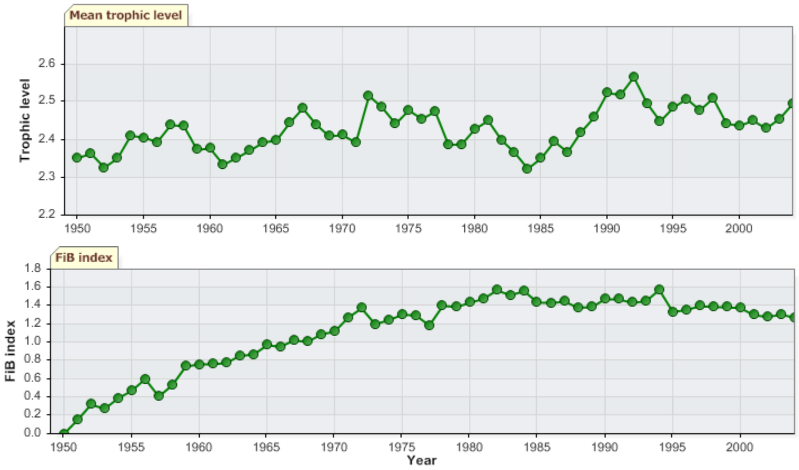

Figure XV-50.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Gulf of Mexico LME (Sea Around Us 2007).

As for the observed increase in MTI, this may also be an artefact, as can be inferred from the work of Baisre (2000). He found, based, on detailed catch data from Cuba that included bycatch and covered an extended period (1935-1995), that a 'fishing down' of food webs (Pauly *et al*. 1998) is occurring in the region. The decline of the FiB index from the mid 1980s (Figure XV-50.7, bottom) is likely a result of the diminished reported landings.

The Stock-Catch Status Plots indicate that collapsed and overexploited stocks now account for over 70% of all commercially exploited stocks in the LME (Figure XV-50.8, top), with overexploited stocks contributing 60% of the reported landings (Figure XV-50.8, bottom).

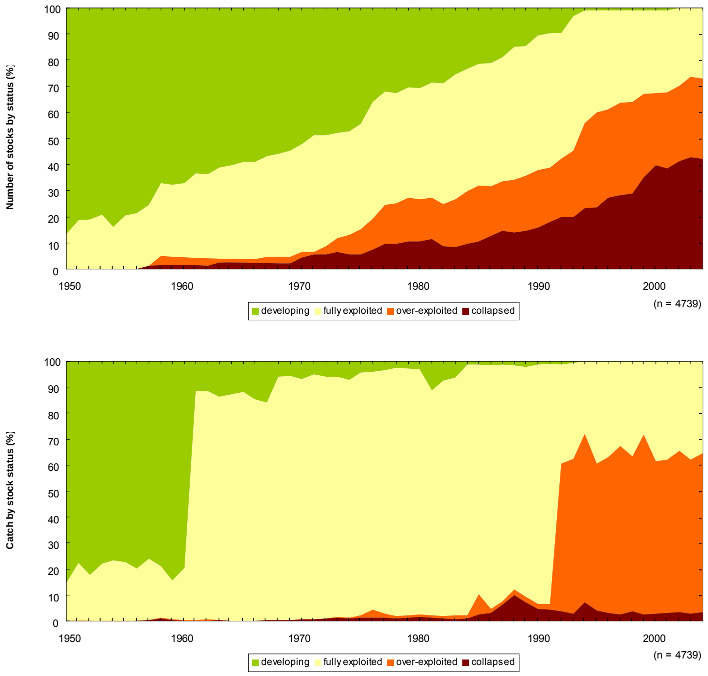

Figure XV-50.8. Stock-Catch Status Plots in the Gulf of Mexico LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this volume for definitions).

Overexploitation was found to be moderate as a whole, but severe on the Campeche Bank in the southwestern Gulf. Intensive fishing is the primary force driving biomass changes in the LME, with climatic variability the secondary driving force (Sherman 2003). In general, the fish stocks of this LME are impacted by excessive recreational and commercial fishing pressure (Birkett & Rapport 1999). Both the traditional and the more recent fisheries have reached their harvesting limits and several species are overexploited (Arreguín-Sánchez *et al*. 1999, Brown *et al*. 1991, NOAA/NMFS 1999, Shipp 1999). Spanish mackerel, shark and coastal pelagics showed severe declines under intense fishing pressure during the late 1980s (Shipp 1999). Other commercially important species that have been overexploited are the red drum and spotted seatrout, and there has been concern over the sustainability of the fishery for amberjack and gag grouper (Shipp 1999). The Gulf menhaden stocks fluctuated and then declined under heavy fishing pressure and other stresses (Birkett & Rapport 1999). Several stocks of reef fish, including red, Nassau and goliath groupers, are also overexploited (NOAA/NMFS 1999). The red snapper is considered the most severely overexploited species in the Gulf, and its recovery is deterred by the high mortality of its juveniles in shrimp trawl bycatch. Stocks of large migratory pelagic fish are also under threat from overfishing. Landings of bluefin tuna dropped precipitously in the late 1970s and the stocks are also considered to be severely overexploited. Likewise, other large pelagics such as swordfish and blue and white marlin are also thought to be overexploited.

In the early 1980s, the shrimp fishery on the continental shelf off Campeche in the southwestern Gulf of Mexico LME formed the base of the economy in this area (Arreguín-Sánchez *et al*. 2004). This fishery, particularly for the pink shrimp has collapsed, with annual harvests falling from 27,000 tonnes in the early 1970s to 3,000 tonnes or less (Arreguín-Sánchez *et al*. 1997). There has been evidence of marked declines in the abundance of pink and white shrimps in this area as a result of heavy fishing on juveniles inshore as well as on spawners in offshore areas (Gracia & Vasquez-Bader 1999). Also in this area, the red grouper and the brackish water clam fisheries collapsed in the late 1980s (Arreguín-Sánchez *et al*. 1999). As a result of these declines, the fisheries in the Campeche area focus on other, less valuable species, such as finfish and octopus (Arreguín-Sánchez *et al*. 2004).

Many of these fisheries are now under management (e.g., seasonal closures, size limits, quotas) and some have started to show recovery (Arreguín-Sánchez *et al*. 1999, Brown *et al*. 1991, NOAA/NMFS 1999, Shipp 1999). For example, Spanish mackerel, Gulf menhaden as well as white, pink and brown shrimps are now considered to be either in a state of recovery or at least are no longer overexploited. However, concern still exists over continued overcapitalisation and the shift of fishing to lower tropic levels and smaller sizes of fish, which are the prey of species supporting valuable, fully developed fisheries (Brown *et al*. 1991, UNDP/GEF 2004). Harvest of prey species may therefore have long-term negative impacts on the production of currently harvested species in the Gulf and should be accompanied by research into important ecological relationships and multispecies effects (Brown *et al*. 1991, Pauly *et al*. 1999). Several studies along these lines have already been undertaken (e.g., Browder 1993, Manickchand-Heileman *et al*. 1998, Arreguín-Sánchez *et al*. 2004, Vidal-Hernandez & Pauly 2004).

Excessive bycatch and discards are associated with the shrimp trawl fishery, in which small mesh nets are used. The 10:1 ratio of bycatch to shrimp implies that vast quantities of non-target species are caught in shrimp trawls. Juveniles of sciaenids (e.g., croaker, seatrout, spot) constitute the bulk of the finfish bycatch, with many billion individuals discarded every year (NOAA/NMFS 1999). The populations of species that are heavily fished as bycatch in the shrimp fishery have declined significantly, in parallel with the increase in shrimping effort (Brown *et al*. 1991). This loss through bycatch may slow the recovery of overfished stocks (NOAA/NMFS 1999). Results from mass-balance, trophic models suggest the ecosystem is rather robust as a whole, although continued increases in fishing effort, especially by bottom (shrimp) trawlers, will have serious impacts, reverberating through the entire shelf subsystem (Vidal-Hernandez & Pauly 2004).

III. Pollution and Ecosystem Health

Pollution: Shoreline development, the oil and gas industry, pollutant discharges and nutrient loading are among the principal sources of stress on the Gulf of Mexico LME (Birkett & Rapport 1999). In general, pollution was found to be slight to severe in this LME. Most notable is the high input of nutrients and associated eutrophication and hypoxia in the northern areas of the Gulf. Agricultural activities, artificial drainage and other changes to the hydrology of the U.S. Midwest, atmospheric deposition, non-point sources and point discharges, particularly from domestic wastewater treatment systems, industrial discharges and feedlots all contribute to the nutrient load that reaches the Gulf (Goolsby *et al*. 1999). The outflows of the Mississippi and Atchafalaya Rivers, however, dominate the nutrient loads to the continental shelf (Rabalais *et al*. 1999a, 2002b). The input of nutrients in the Mississippi River has increased dramatically in the last century and has accelerated since 1950, coinciding with increasing fertiliser use in the Mississippi Basin (Turner & Rabalais 1991). The high input and regeneration of nutrients result in high biological productivity in the immediate and extended plume of the Mississippi River (Lohrenz *et al*. 1990).

Most of the primary production fluxes to the bottom waters and the seabed, fuelling hypoxia in the bottom waters. The areal extent of the hypoxic or ‘dead’ zone during the mid-summer of 1993-1995 ranged from about 16,600 to 18,200 km^2 (Rabalais *et al*. 1999a, 1999b). The EPA predicted size of the dead zone by the end of summer 2007 was 22,127 km^2 or more than 8,500 mi^2. This is the largest zone of anthropogenic coastal hypoxia in the western hemisphere. Evidence from chemical and biological indicators in sediment cores shows the worsening hypoxic conditions in this LME (Rabalais *et al*. 1996, 2002a). The U.S. EPA has classified the estuaries in the northern Gulf as poor in terms of eutrophication (EPA 2001). In addition, HABs are of concern in this LME. They debilitate fisheries for shellfish and affect tourism in Florida and Texas (Anderson *et al*. 2000).

Inadequate management of sewage in the region has led to sewage contamination of bays, lagoons and wetlands (Wong Chang & Barrera Escorcia 1996, Birkett & Rapport 1999). In some areas, microbiological pollution levels exceed permissible limits (Wong Chang & Barrera Escorcia 1996). For example, high coliform levels (up to 300 faecal coliforms MPN[1]/100 ml), greatly exceeding the sanitary regulation of 14 faecal coliforms MPN/100 ml, have been detected in waters of Mecoacán, Tabasco and Terminos Lagoons. In Galveston Bay, Texas, oysters have been severely affected by pollution, and many public reefs have had to be closed due to organic pollution from municipal sewage (Birkett & Rapport 1999).

Direct discharges and non-point sources of chemical pollutants are a major environmental threat in the Gulf of Mexico LME (Birkett & Rapport 1999). The high use of pesticides in agricultural areas has contributed to considerable levels of these substances in the Mississippi and other rivers. These contaminants ultimately reach the coastal waters. Heavy metals are released into the LME from numerous sources such as municipal wastewater-treatment plants, manufacturing industries, mining and rural agricultural areas. Elevated levels of heavy metals and pesticides have been detected in water and sediments, in some cases exceeding permissible limits (Villaneuva Fragoso & Paez-Osuna 1996, EPA 2001). The oil and gas industry has also had a significant environmental and ecological impact on the LME (Botello *et al*. 1996, Birkett & Rapport 1999). Furthermore, the Gulf is a major thoroughfare for shipping, and accidental oil discharges from tankers and oil installations are a constant threat. The Mississippi River also delivers hydrocarbons to the Gulf, primarily from non-point source runoff. The chronic exposure to oil residues from marine oil production is a significant source of stress on the coastal habitats.

There is evidence of bioaccumulation of heavy metals, petroleum residues and PCBs in the tissue of some finfish and invertebrate species (e.g., Botello *et al*. 1996, Villaneuva Fragoso & Paez-Osuna 1996, Birkett & Rapport 1999, EPA 2001). In 2000, 10 out of

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[1] Most Probable Number

14 fish consumption advisories for the coastal and marine waters of the northern Gulf coast were issued for mercury, with each of the five US Gulf states having one state-wide coastal advisory for mercury in king mackerel (EPA 2001). The widespread incidence of fish diseases (e.g., lymphocytosis, ulcers, fin erosion, shell disease) thought to be related to pollution has been reported in marine and estuarine species in the northern Gulf (Birkett and Rapport 1999). The overall coastal condition for the U.S. part of this LME, according to the EPA's primary indicators is: fair water quality, poor eutrophic condition, poor condition of sediment and fish tissue (in terms of contaminants) and poor condition of benthos (EPA 2001). In addition to the fish consumption advisories, the poor coastal condition has also led to many beach closures throughout the northern Gulf coast, which also has the lowest percentage of approved shellfish growing waters in the U.S. (EPA 2001).

Habitat and community modification: The LME's coastal and marine habitats are threatened by both natural processes and anthropogenic factors and their modification is severe throughout the LME (UNEP, unpublished). Hypoxia in the northern Gulf has reduced the suitable habitat for living organisms and modified the benthic communities in the affected area (Rabalais & Turner 2001). The more stressed community is characterised by limited taxa, characteristic resistant fauna and severely reduced species richness, abundances and biomass. The effects of hypoxia on fisheries resources include direct mortality, altered migration, changes in food resources and disruption of life cycles. Anectodal information from the 1950s to 1960s shows low or no catches by shrimp trawlers from 'dead' waters in this zone (Rabalais *et al*. 1999b).

Wetlands in particular have experienced severe loss and degradation due to coastal development, interference with normal erosional/depositional processes, sea level rise and coastal subsidence (EPA 2001). The EPA coastal wetlands indicator for the northern Gulf of Mexico shows these wetlands to be in poor condition (EPA 2001). The periodic sediment input to the Mississippi deltaic plain has been reduced by the construction of flood control levees and dams upstream, the changing agricultural and urban water-use practices and increasing alteration of the river system for navigation. The suspended sediment load of the lower Mississippi decreased by about 50% during the period 1963-1982 in response to dams built on the Arkansas and Missouri rivers (Meade 1995). Wetlands are being converted to open water at an alarming rate because wetland accretion is insufficient to compensate for the natural process of subsidence. In addition, large areas of wetland have been drained for industrial, urban and agricultural development. Wetland habitats are also being altered by increased salinities due to saltwater intrusion, which is destroying coastal flora. This loss of wetlands also increases erosion by waves and tidal currents and is exacerbated by sea level rise.

The effects of natural processes combined with human actions at large and small scales have produced a system on the verge of collapse. Wetland losses in the U.S. Gulf of Mexico from 1780s to 1980s are among the highest in the nation, with 50% having been lost in this time period (EPA 2001). The rate of coastal land loss in Louisiana, which contains the largest coastal wetland complex in the U.S., has reached catastrophic proportions. Within the last 50 years, land loss rates have exceeded 104 km^2yr^{-1}, representing 80% of the coastal wetland loss in the entire continental U.S. (Day *et al*. 2000).

In the coastal waters of the State of Campeche in Mexico, unregulated fishing, the use of destructive fishing methods, as well as cutting of mangrove for aquaculture and other purposes have destroyed fish habitats and reduced shrimp and other shellfish stocks (Yañez Arancibia *et al*. 1999). The Usumacinta/Grijalva deltaic system is also being modified because of changes in land use and the growing human population in this area.

As a consequence, coastal habitats and communities are being degraded and lost. For example, the populations of some species such as the horseshoe crab (*Limulus polyphemus*) and West Indian manatee (*Trichechus manatus*) have diminished as a result of habitat and community modification in this system. Activities related to the oil industry are also thought to have affected the distribution and abundance of commercially important fisheries resources such as shrimp on the continental shelf and coastal lagoons, particularly in the south of Tabasco and Campeche (Arreguín-Sánchez *et al*. 2004).

The LME's coral reefs are also threatened by natural and anthropogenic pressures. Almost all the reefs of the Florida Keys are under moderate threat, largely from coastal development, inappropriate agricultural practices, overfishing of target species such as conch and lobster as well as pollution associated with development and farming (Bryant *et al*. 1998). Other major threats in the last 20 years have arisen from direct human impacts such as grounding of boats in coral, anchor damage and destructive fishing (Causey *et al*. 2002). Reduced freshwater flow has resulted in increase of plankton bloom, sponge and seagrass die-offs as well as the loss of critical nursery and juvenile habitat for reef species, which affects populations on the offshore coral reefs. Serial overfishing has dramatically altered fish and other animal populations. Alien species introduced on the reefs in the last decade through ship hull fouling or ballast water dumping have placed additional stress on the reefs (Causey *et al*. 2002).

Stresses from distant sources are also involved in the degradation of the region's reefs. Waters from the Mississippi River periodically reach the Florida Keys while Saharan dust has been implicated in the origin of nutrients and possibly disease spores, particularly during El Niño years (Bryant *et al*. 1998). Florida reefs have been repeatedly stressed in the past 25 years by coral bleaching, which has contributed to the dramatic declines in coral cover in the Florida Keys National Marine Sanctuary since 1997 (Causey *et al*. 2002). Disease is also a serious problem. Two of the most important reef-building species (*Acropora palmata* and *A*. *cervicornis*) are now relatively uncommon due to white-band disease, while others have proved particularly susceptible to black-band disease (Bryant *et al*. 1998). Algae continue to dominate all sites, with average cover generally above 75% in the Keys and above 50% in the Dry Tortugas (Causey *et al*. 2002). The Flower Garden Banks off Texas, however, remain amongst the least disturbed coral reefs in the region and can be considered nearly pristine. Nevertheless, these reefs are threatened by atmospheric pollution and effluent discharges from nearby oil and gas development and marine transportation. The reefs off Veracruz in the southwestern gulf are influenced by high turbidity water from the coast and sewage and other effluents from the port and city of Veracruz, resulting in low coral diversity. The reefs on the Campeche Bank suffer from overfishing and the impacts of oil exploration (Almada-Villela *et al*. 2002).

Seagrass habitats have declined dramatically during the past 50 years, mostly because of coastal population growth and accompanying municipal, industrial and agricultural development. In addition, boat propellers have permanently damaged over 120 km^2 of seagrass in the Florida Bay (Causey *et al*. 2002). Loss of seagrasses in the northern Gulf of Mexico over the last five decades has been extensive and ranges from 20% to 100% for most estuaries, with only a few areas experiencing increases in seagrass.

Some experts believe that habitat loss is the greatest threat to the Gulf's biodiversity. Unsustainable resource use is also contributing to species loss in this LME. In 2000, the American Fisheries Society officially identified 11 of the Gulf's 15 managed grouper species as 'vulnerable to risk of extinction'. The only known nesting beach in the world of the Kemp's ridley, the world's most endangered sea turtle, is along the Gulf of Mexico coast. There has been considerable success, however, with the Ridley Head Start

Program and establishment of nests along Padre Island in addition to Rancho Neuvo, Tamaulipas, Mexico. Invasive species are also a major threat to biodiversity. Ballast water discharges from transoceanic vessels are now known to be the single largest source of introduction of aquatic non-indigenous species invasions worldwide and this threat is particularly serious in the Gulf of Mexico LME, since the region contains some of the world's largest ports (Nipper *et al*. 2005).

IV. Socioeconomic Conditions

The coastal areas of the LME are densely populated with about 55 million inhabitants. This population is projected to increase by 144% between 1960 and 2010 (Cato & Adams 1999). The LME is a major economic asset to the three bordering countries, with the value associated with various economic activities adding up to several billions of dollars (Cato & Adams 1999, Adams *et al*. 2004). Commercial and recreational fisheries, tourism and petroleum production are among the major economic activities. The Gulf is also a major source of employment. For example, coastal employment in the five U.S. Gulf states was more than 4 million in 1993 (Cato & Adams 1999).

In 2003, the U.S. domestic commercial landings from the Gulf amounted to about 800,000 tonnes valued at over US$680 million (NOAA/NMFS 2004). Nearly 3.3 million instate marine recreational fishers made about 23 million trips and caught over 160 million fish (excluding Texas) in 2003 (Gulf of Mexico Program 2002). The Gulf accounts for 30% of the U.S. offshore oil production and about 23% of its gas production. More than 80% of the economic activities of each of the six Mexican Gulf states are located in or associated with the coastal zone. These states contribute 12.9% of the total national gross internal product (Sánchez-Gil *et al*. 2004). The tourist industry encompasses thousands of businesses and tens of thousands of jobs worth well over 20 billion US$ annually (Gulf of Mexico Program 2002). Major port facilities and shipping lanes exist in the LME.

Many important ecosystem services derived from the LME are threatened or have already been lost (Birkett & Rapport 1999), with severe socioeconomic consequences. Overexploitation of fisheries has resulted in deteriorating quantity and quality of the catches and the imposition of restrictions and quotas (Birkett & Rapport 1999). Overfishing has also led to reduced revenue from fisheries, user conflicts and loss of employment in the affected states. The socioeconomic impacts of pollution as well as habitat modification and loss are also severe. Analyses of the distribution of shrimp catch on the shelf in relation to hypoxia suggest that the catch of shrimp was consistently low where hypoxia was extensive (Zimmerman & Nance 2001). On the other hand, to date, there are no clear indications of hypoxic effects in fisheries or fish populations in the published literature or data evaluated by Diaz & Solow (1999). Nevertheless, the lack of obvious detrimental economic effects does not preclude the possibility of future ecological and economic disaster, as seen in other water bodies (e.g., the Black Sea) affected by hypoxia (Diaz & Solow 1999).

Of particular concern are the potential health risks posed by marine biotoxins and HABs, fish and shellfish poisoning and pollution. The contamination of seafood by pesticides and heavy metals has led to loss in revenue from the closure of harvesting areas, consumption advisories and risk to human health. This has been accompanied by an increase in the costs of monitoring programmes and ecosystem protection and recovery. Human society and its infrastructure in the coastal zone of the Gulf have already been affected by wetland loss and will face considerably more threats as additional wetlands are lost. Increased vulnerability to storm surge, coastal flooding and shoreline erosion will result in damage to homes and loss of transportation and industrial infrastructure as well as long-term degradation of critical resources such as domestic and industrial water supplies. Coastal wetland deterioration will be devastating to culturally based subsistence users as well as the recreational and tourist economies based on these resources. If the recent loss of wetlands continues, it is estimated that Louisiana will lose about 2,500 km^2 more of coastal marshes, swamps and islands by 2050. The public use value of this loss is estimated to be in excess of US$37 billion by year 2050; the losses associated with cultures and heritage is immeasurable (Louisiana Coastal Wetlands Conservation 1998). Major efforts at addressing the degradation of the Gulf of Mexico LME (see Governance) are expected to reduce or reverse the current trends.

V. Governance

There is a multitude of programmes and policies to protect, restore and enhance the coastal and marine waters and habitats of the Gulf of Mexico LME. For example, the EPA's Gulf of Mexico Program, established in 1988, is conducting research, monitoring, restoration and management projects in selected sites through its National Estuary Program's Habitat Restoration Program and Gulf Ecological Management Sites Program. In 2001, the EPA sent to Congress the final 'Action Plan for Reducing, Mitigating and Controlling Hypoxia in the Northern Gulf of Mexico'. This Action Plan was the culmination of work undertaken by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force and establishes the blueprint for addressing the hypoxia problem. The U.S. Gulf Restoration Network and the Gulf of Mexico Foundation are engaged in various programmes and projects aimed at protecting and restoring the Gulf's valuable resources (e.g., CWPPRA, CIAP. The National Marine Fisheries Service (NMFS) Southeast Regional Office is responsible for sustainable fisheries management, habitat conservation and protected resources management (Kemmerer *et al*. 1999). This office provides technical and administrative support to the Gulf of Mexico Fisheries Management Council.

In Mexico, the Programme of Ecology, Fisheries and Oceanography of the Gulf of Mexico (EPOMEX) was created in 1990 by the Autonomous University of Campeche. The main focus of this programme is to generate and integrate information for the proposal of management measures, development plans, ecological protection ranking, conservation and sustainable use of coastal marine ecosystems and their natural resources in the gulf. GEF is supporting the project 'A Transboundary Diagnostic Analysis (TDA) and Strategic Action (SAP) Programme for the Gulf of Mexico Large Marine Ecosystem' involving Cuba, Mexico and the U.S. The main objective of this project is to address critical threats to the coastal as well as marine environment and to promote ecosystem-based management of coastal and marine resources in the Gulf of Mexico LME. The expected outputs of this project will be a TDA and the development of a regional SAP for the LME. The full GEF intervention will address the priority transboundary and biodiversity concerns of the Gulf of Mexico LME in the context of fluctuating climate conditions.

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XV-51 Southeast U.S. Continental Shelf LME

M.C. Aquarone

The Southeast U.S. Continental Shelf LME extends from the Straits of Florida to Cape Hatteras, North Carolina in the Atlantic Ocean. It is characterised by its temperate climate. The LME has a surface area of about 300,000 km², of which 2.44% is protected, and contains 0.27% of the world's coral reefs and 18 estuaries and river systems (Sea Around Us 2007). It also contains many bays including the Albemarle-Pamlico Sound, the second largest estuary in the nation, nearshore and barrier islands, freshwater and estuarine habitats and extensive coastal marshes that provide unique habitats for living marine resources. A book chapter pertaining explicitly to this LME is by Yoder (1991).

I. Productivity

The Southeast U.S. Continental Shelf LME is considered a Class II, moderately productive ecosystem (150-300 $gCm^{-2}yr^{-1}$). Additional information is provided by NOAA statistics in Our Living Oceans (NOAA 1999). A chapter on marine resources for the southeast region (with the Gulf of Mexico LME and Caribbean islands), including information on status and trends of the nation's biological resources, primary and secondary productivity, benthic resources, fisheries resources, marine birds and marine mammals can be found at the USGS biology website. The North Carolina Albemarle-Pamlico Sound is one of the largest and most productive aquatic systems in North America. Upwelling along the Gulf Stream front and intrusions from the Gulf Stream cause short-lived plankton blooms. The offshore upwelling regime is not as intense as in the higher latitude regions (see Yoder 1991).

Oceanic Fronts (after Belkin et al. 2009)*:* Adjacent to this LME, the warm, saline, northward flowing Gulf Stream is bounded by two fronts (Figure XV-51.1). The inshore Gulf Stream Front (IGSF) extends over the upper continental slope and shelf break, approximately aligned with the 50-m isobath (Atkinson & Menzel 1985), while the offshore Gulf Stream Front (OGSF) runs parallel to the IGSF, approximately 100 km offshore of the latter.

This LME is radically different from the Northeast U.S. Continental Shelf LME, where the Shelf-Slope/Shelf Break Front is associated with a cold, fresh southward Slope Current. The Gulf Stream forms a semi-permanent offshore deflection near a deepwater bank SE of Charleston, NC, called the 'Charleston Bump' (CB), at 31.5°N in the Southeast Shelf LME. The Mid-Shelf Front (MSF) is aligned approximately with the 35-to-40 meter isobaths. Other shelf fronts separate a mixture of water masses formed by wintertime cold air outbreaks, river discharge, tidal mixing and wind-induced coastal upwelling (Pietrafesa *et al*. 1985, Belkin *et al*. 2009).

U.S. Southeast Shelf LME SST (after Belkin 2009)
Linear SST trend since 1957: -0.15°C.
Linear SST trend since 1982: 0.16°C.
The Southeast US Continental Shelf is one of a few LMEs that experienced long-term cooling since 1957. Like most LMEs, the Southeast US Continental Shelf first went through a cooling phase before switching to a warming phase in 1976. Warming over the last 25 years was small, just 0.16°C. Given 1976 as a well-defined break point, this warming would amount to 0.5°C. The 1976 breakpoint could be tentatively associated with a similar break point in 1976 in the Gulf of Mexico LME, however the latter breaking

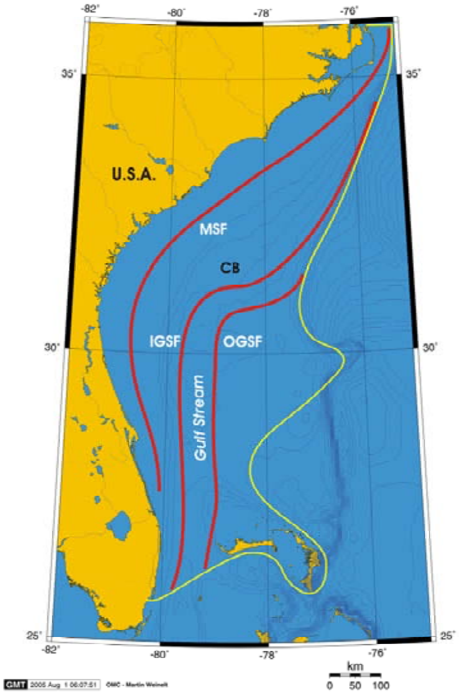

Figure XV-51.1. Fronts of the Southeast U.S. Continental Shelf LME. CB, Charleston Bump; IGSF, Inshore Gulf Stream Front; MSF, Mid-Shelf Front; OGSF, Offshore Gulf Stream Front. Yellow line, LME boundary. After Belkin et al. 2009.

point is not well defined. Nonetheless, the possible link between these LMEs cannot be dismissed since they are connected by the Gulf Stream flowing from the Gulf of Mexico past the Southeast US Shelf. Therefore, advection of SST anomalies from the Gulf of Mexico to the Southeast US Shelf is expected to play a key role in the thermal regime of the Southeast US Shelf. The two major SST peaks of 1961 and 1975 did not have immediate upstream precursors in the Gulf of Mexico. The 3-year time lag between the Gulf of Mexico SST peak of 1972 and the Southeast US Shelf SST peak of 1975 makes this connection tenuous. On the other hand, the 3-year time lag between the Gulf of Mexico and the Southeast US Shelf is consistent with the 3-year time lag between the Caribbean LME and the Gulf of Mexico.

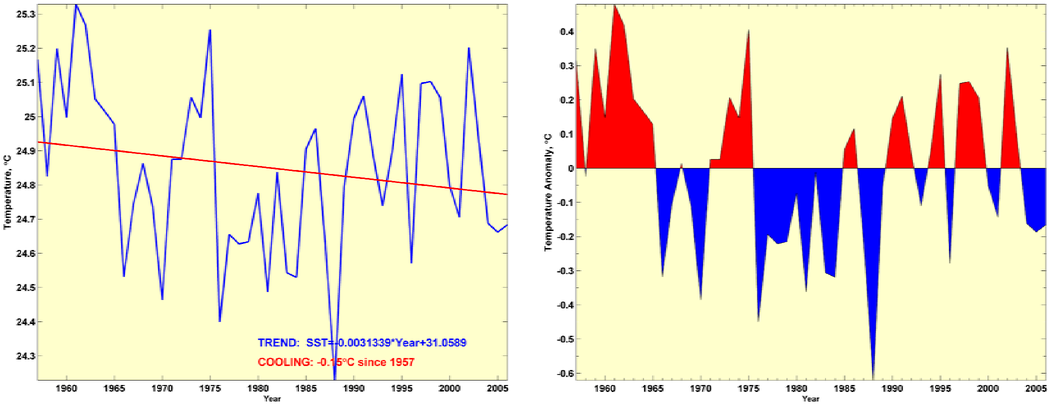

Figure XV-51.2. Southeast US Shelf LME annual mean SST and annual SST anomalies, 1957-2006, based on Hadley climatology. After Belkin 2009.

U.S. Southeast Shelf LME Chlorophyll and Primary Productivity: The Southeast U.S. Continental Shelf LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}).

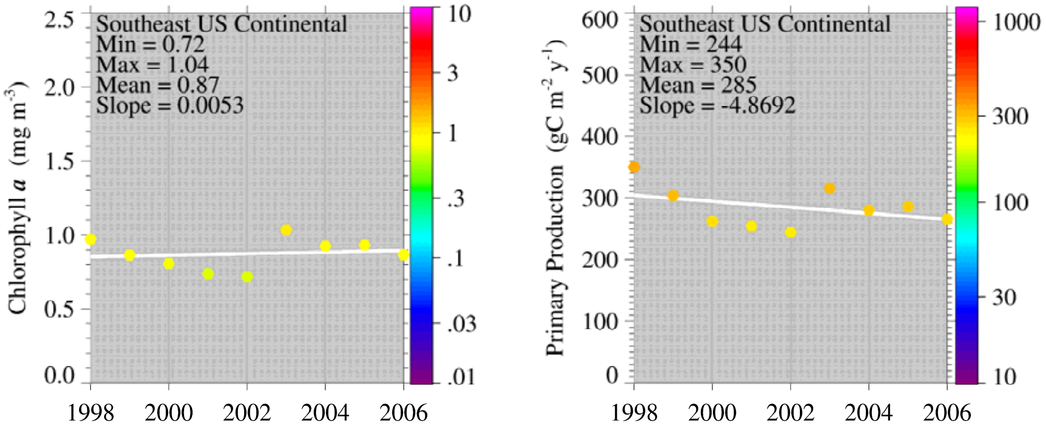

Figure XV-51.3. U.S. Southeast shelf LME trends in chlorophyll *a* and primary productivity, 1998-2006. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The estuaries support diverse aquatic organisms and complex food webs in a nursery system that promotes the recruitment and development of juvenile fish and invertebrate species important to recreational, commercial, and ecological interests (EPA 2004). The major species are coastal pelagics (mackerel, dolphinfish, and cobia), highly migratory pelagics (swordfish, tuna, albacore, marlin, sailfish, spearfish and sharks), Atlantic menhaden, invertebrates (shrimp, lobster, crab and conch), reef fish, drum and croaker, and Atlantic sharks. Major species landed include the coastal pelagic species, highly valued and sought after as game fish, the Atlantic highly migratory pelagic fish (especially yellowfin tuna), menhaden, and white and northern brown shrimps, centered off Georgia and the Carolinas. Shrimp stocks are affected by environmental conditions and by increased fishing pressure (NMFS 2009). Total reported landings increased from 1950, recording over 150,000 tonnes in 1981 and 1984, but have since declined to 62,000 tonnes in 2004 (Figure XV-51.4). There are major fluctuations in the landings of Atlantic menhaden, with peaks in the 1950s, drops in the late 1960s, another peak in 1983, followed by less than 2,000 tonnes landed in 1984 and 1997. Combined commercial and recreational landings of reef fishes have fluctuated since the 1970s, showing a slightly decreasing trend over time (EPA 2004). The value of the reported landings for the Southeast US Continental Shelf LME reached almost 400 million US$ (measured in year 2000 US$) in 1979, two-thirds of which was from the landings of crustaceans (Figure XV-51.5).

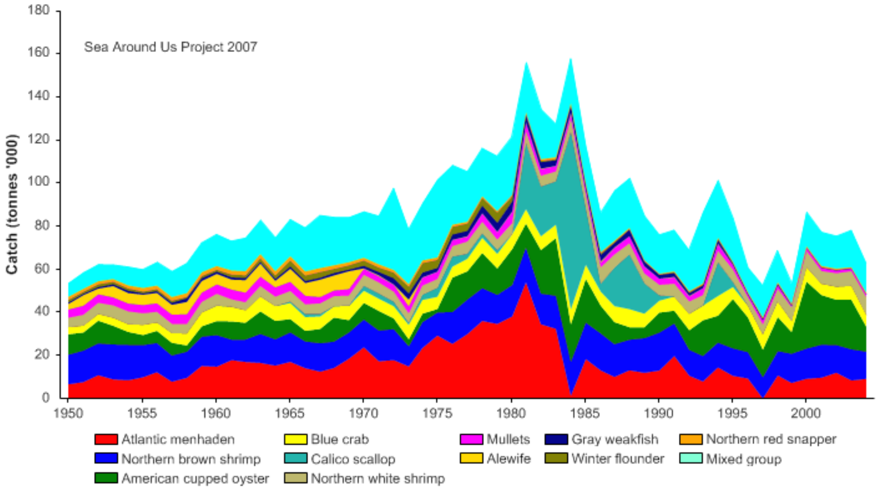

Figure XV-51.4. Total reported landings in the Southeast U.S. Continental Shelf LME by species (Sea Around Us 2007).

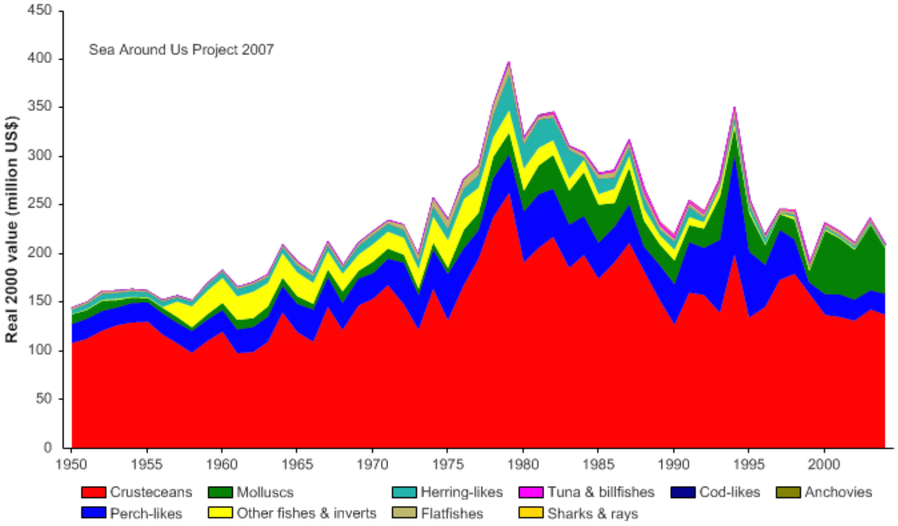

Figure XV-51.5. Value of reported landings in the Southeast U.S. Continental Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR) (Pauly & Christensen 1995) to sustain the reported landings in the LME reached 6.5% of the observed primary production in 1980 but has not reached this level since (Figure XV-51.6. The US accounts for the largest share in this LME of the ecological footprint measured as the primary production required to support reported landings by countries.

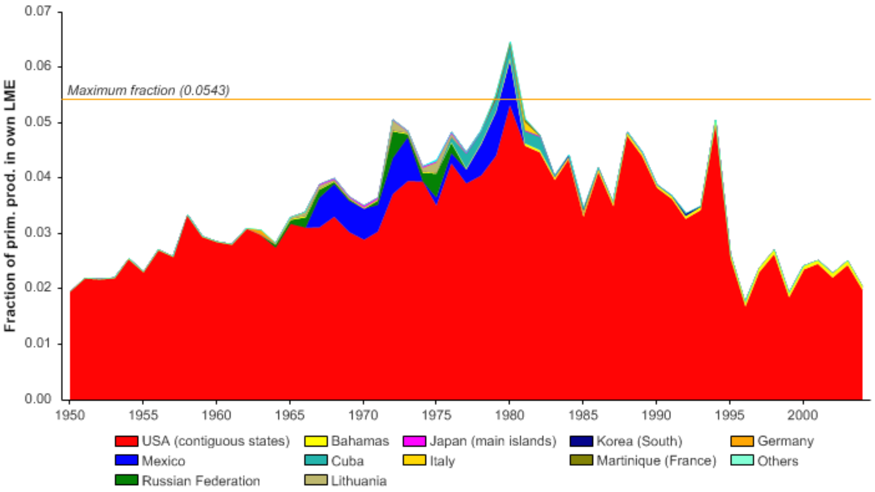

Figure XV-51.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Southeast U.S. Continental Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic index (MTI) of the reported landings (Pauly & Watson 2005) shows a decreasing mean trophic level, though with some fluctuations (Figure XV-51.7 top). The trend becomes more pronounced when tuna landings are excluded and examined at a local level (see Figure 4 in Chuenpagdee *et al.* 2006). With the FiB index also declining sharply since the mid 1970s (Figure XV-51.7 bottom), the state of the LME can be diagnosed as undergoing a 'fishing down' of the food web (Pauly *et al.* 1998) with no increase in the landings to compensate for the decline in the mean trophic level of the catch.

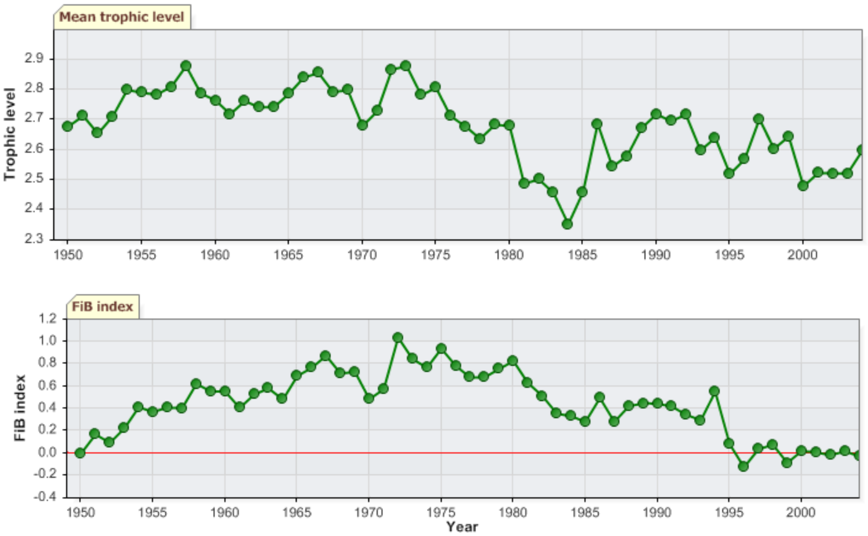

Figure XV-51.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Southeast U.S. Continental Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that collapsed and overexploited stocks now account for over 80% of all commercially exploited stocks in the LME (Figure XV-51.8, top), with fully exploited stocks contributing more than half of the catch (Figure XV-51.8, bottom). The US National Marine Fisheries Service (NMFS) includes “overfished” but not “collapsed” in its stock status categories. Currently overfished are reef fishes (grouper, black sea bass, red porgy), highly migratory pelagic fisheries (albacore, blue marlin, bluefin tuna, yellowfin tuna, and sailfish,) and sciaenids such as red drum in some states. Bigeye tuna and swordfish are rebuilding (NMFS 2009). The populations of several species of sciaenids, most notably Atlantic croaker, appear to be closely linked to environmental conditions resulting in large annual fluctuations in population levels (EPA 2004). Removals of apex predators from the reef complex may result in shifts of species composition (i.e. trophic and ecological cascades) and increased variability in population dynamics of targeted species. Stock rebuilding plans are in effect for all reef fish species classified as overfished. The latest NMFS catch statistics indicate that commercial shrimp species are being harvested at maximum levels. Atlantic Spanish mackerel are considered to be at or near their full maximum fishery potential. Following declines in the abundance of large coastal sharks, new management measures to control catch levels were introduced in 1997.

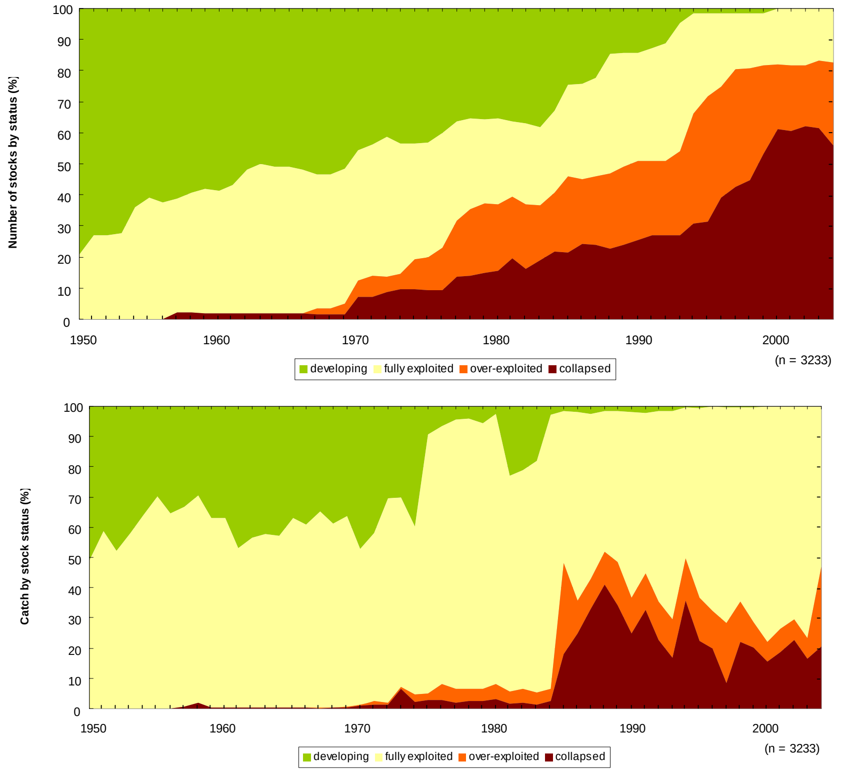

Figure XV-51.8. Stock-Catch Status Plots for the Southeast U.S. Continental Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level. Higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Our Living Oceans (NOAA 1999) has statistics on landings of blue crab, sea urchin and oyster from the Atlantic coast, and landings and spawning biomass for menhaden from 1950 to 1997 (NOAA 1999, p. 141). The 2008 (quarterly) NOAA Status of U.S. Fisheries

Report to Congress (www.noaa.gov) contains the status (fished or overfished) of selected species. The annual report on fishery landings in the US provided by the NOAA-Fisheries Office of Science and Technology can be found at www.st.nmfs.noaa.gov. Information on large marine ecosystem fisheries is available in EPA 2004. This includes reef fish resources (see graph of coast reef fish landings, 1978-2000) as well as sciaenid, menhaden, mackerel and shrimp fisheries. The Georgia Department of Natural Resources Red Drum Project highlights the importance of habitat for all life stages of red drum (EPA 2004), an important fishery resource along the Atlantic coast since the late 1800s. Currently, these fish species support substantial harvests for both commercial and recreational fisheries and are captured in almost every type of gear used to fish the coastal waters of this LME.

III. Pollution and Ecosystem Health

The dynamic fringe of estuaries varies constantly with tidal fluctuations and levels of runoff, and it serves as an important habitat for waterfowl, reptiles, mammals, fish and invertebrates, as well as a diversity of plants. It also serves as a natural filter to remove pollutants and sediments from upland regions (EPA 2004). Species such as shrimps, crabs and menhaden, which account for much of the catch in this LME, are estuarine-dependant. There are habitat concerns impacting many of the Southeast invertebrate fishery resources. Additional studies are needed to further assess the impacts of human-induced changes in habitat availability, environmental conditions, predator abundance, and pollution in nursery areas. Florida spiny lobsters depend on reef habitat and shallow water algal flats for feeding and reproduction, but these habitat requirements can conflict with expanding coastal development in the region. The small mesh used in shrimp trawls can catch non-target species such as sea turtles, red snappers, croakers, seatrouts, and other species (NMFS 2009). All sea turtle species are listed as endangered or threatened under the Endangered Species Act. Shrimp vessels are required to use turtle excluder devices in their nets since 1988.

Of the regularly monitored U.S. Continental Shelf LMEs, the Southeast U.S. Continental Shelf LME has the best ecological condition. The U.S. EPA provides data on environmental stressors (water quality, sediment quality and tissue bioaccumulation) throughout the U.S. See EPA (2001, 2004) for the coastal condition of the Southeast region, which includes this LME. In 2001, the index for dissolved oxygen and fish tissue condition was good. Water clarity, coastal wetlands, eutrophic condition, sediment and benthos were fair (see EPA's 7 primary indicators in EPA 2001). The condition of the southeastern estuaries was fair. Approximately 54% of estuarine areas are in good ecological condition (EPA 2001, EPA 2004), based on five primary indicators: water quality (rated fair to good); sediment quality (rated fair to good); benthic index (fair); coastal habitat index (fair); and fish tissue index (good). The Albemarle-Pamlico Estuarine System's resources are threatened by increased pollution from urban and agricultural development in its watersheds (EPA 2004). For estimates of coastal wetland habitat loss from 1780 to 1980, see EPA (2001). By 1980, 40% of all wetlands existing in 1780 had disappeared.

The increasing population growth could contribute to increased water quality degradation in this region. A primary problem is sediment contamination by pesticides and metals. Municipal wastewater treatment plants and pesticides applied to agricultural lands are sources of coastal pollution. NOAA's National Status and Trends program provides data on toxic contaminants and their ecological effects. See EPA 2004 (www.epa.gov/) for information on South Carolina's Estuarine and Coastal Assessment Program which monitors the biological condition of 60 sites throughout the state's coastal zone (p.119), comparing and predicting PAH concentrations in urban and non-urban settings in South Carolina (p. 120), Clean Water Act assessments, and fish consumption and beach advisories. In 2002, 15% of beached were affected by advisories or closures. The reasons were pre-emptive closure because of rainfall (24%), or elevated bacteria levels (75%).

IV. Socioeconomic Conditions

The Southeast U.S. Continental Shelf LME contains a wealth of resources including both commercial and recreational fisheries. Bycatch of Atlantic highly migratory species, and increasing numbers of recreational spiny lobster participants, cause conflicts between commercial and recreational fisheries and reduce the impact of conservation efforts. Other resources and economic activities in the LME include barrier islands such as North Carolina's outer banks, and busy shipping ports in Miami and Jacksonville, Florida, Savanna, Georgia, and Charleston, South Carolina. Non-consumptive uses of reef resources (e.g. ecotourism, sport diving, education, and scientific research) are economically important and may conflict with traditional commercial and recreational fisheries. Balancing the competing interests of these user groups is an important management issue.The Albemarle-Pamlico Sound is North Carolina's key resource base for commercial and recreational fishing and tourism. This resource and other coastal resources of the Southeast Coast states generate vast amounts of sales tax income for those states (EPA 2004).

Fishing pressure has increased over time in correlation with growing human populations, greater demands for sea food, and technological improvements in gear, electronic fish finders, and navigational aids. The coastal population has shown a growth rate of almost 2% per year (EPA 2004). The population increase amounted to 64% between 1970 and 1990 (U.S. Census Bureau 1996). In 1999, the southern region of the U.S. was the most populous area of the nation, accounting for 96 million residents. Florida was among the five most populous states in 1999 (U.S. Census Bureau 2001). The influx of people and businesses to this region, and added pressure on the coastal zone, will require additional programs and more environmental awareness in order to correct existing problems of ecosystem health.

V. Governance

The South Atlantic Fisheries Management Council (SAFMC) manages this LME's fish stocks in collaboration with the NMFS Southeast Fisheries Centre within the US Exclusive Economic Zone (EEZ), seaward of territorial waters out to 200 miles from the shore. Coastal pelagic fishes are jointly managed under the Coastal Migratory Pelagic Resources Fishery Management Plan and the regulations adopted by the SAFMC. Management regulations have included total allowable catches (TACs) and minimum size restrictions. Effective management of migratory coastal pelagic species will continue to require the coordination of Federal and state regulatory agencies in North Carolina, South Carolina, Georgia and Florida. US fleets for highly migratory pelagic fisheries operating in this LME are regulated under the Magnuson-Stevens Fishery Conservation and Management Act and the Atlantic Tunas Convention Act (ATCA). Management of Atlantic tunas and swordfish in US waters are based largely on recommendations by the International Commission for the Conservation of Atlantic Tunas (ICCAT). Some shark species are included in the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species as vulnerable. Because Atlantic menhaden migrates long distances, interstate coordination of fishery management is required (NMFS 2009). Specific fishery management plans, including for the shrimp fishery, are available in Our Living Oceans (NOAA 1999). MPAs are used as management tools for deepwater species of reef fish. There is an increasing need for effective management of these resources given the predicted influx of people to the LME boundary coastal states (EPA 2001).

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XVI SOUTH WEST ATLANTIC

XVI 52 North Brazil Shelf LME
XVI 53 East Brazil Shelf LME
XVI 54 South Brazil Shelf LME
XVI 55 Patagonian Shelf LME

XVI-52 North Brazil Shelf LME

S. Heileman

The North Brazil Shelf LME extends along northeastern South America from the boundary with the Caribbean Sea to the Parnaíba River estuary in Brazil (Ekau & Knoppers 2003). It has a surface area of about 1.1 million km^2, of which 1.69% is protected, and contains 0.01% of the world's coral reefs and 0.06% of the world's sea mounts (Sea Around Us 2007). The hydrodynamics of this region is dominated by the North Brazilian Current, which is an extension of the South Equatorial Current and its prolongation, the Guyana Current. Shelf topography and external sources of material, particularly the Amazon River with its average discharge of 180,000 m^{3}s^{-1} (Nittrouer & DeMaster 1987), exert a significant influence on the LME. This is complemented by discharge from other rivers such as Tocantins, Maroni, Corantyne, and Essequibo. A wide continental shelf, macrotides and upwellings along the shelf edge are some other features of this LME. Book chapters and reports pertaining to the LME include Bakun (1993), Ekau & Knoppers (2003), UNEP (2004a, 2004b).

I. Productivity

The North Brazil Shelf LME is considered a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}), with the Amazon River and its extensive plume being the main source of nutrients. Primary production is limited by low light penetration in turbid waters influenced by the Amazon, while it is nutrient-limited in the clearer offshore waters (Smith & DeMaster 1996). Primary productivity on the continental shelf has been found to be greatest in the transition zone between these two types of waters, occasionally exceeding 8 gCm^{-2}day^{-1} (Smith & DeMaster 1996). In addition to high production, the food webs in this LME are moderately diverse. Brazil's coral fauna is notable for having low species diversity, yet a high degree of endemism.

Oceanic Fronts (Belkin *et al.* 2009) (Figure XVI-52.1): Major fronts within this LME are associated with outflow from the Amazon River and, to a lesser extent, that of the Orinoco River. The Amazon plume initially turns northwestward and flows along the Brazil coast as the North Brazil Current. Off the Guyana coast, between 5°N and 7°N, the North Brazil Current retroflects and flows eastward. This retroflection develops seasonally and produces anticyclonic rings of warm, low-salinity water that propagate northwestward toward Barbados, the Lesser Antilles Islands and eventually the Caribbean Sea. The second major source of fresh water is the Orinoco River plume. Most thermal fronts are associated with salinity fronts related to freshwater lenses and plumes originated at the Amazon and Orinoco estuaries. Such fronts are relatively shallow, sometimes just a few meters deep. Nonetheless, these fronts are important to many species whose ecology is related to the upper mixed layer. Fresh lenses generated by the Amazon and Orinoco outflows persist for months, largely owing to the sharp density contrasts across TS-fronts that form their boundaries (in case of fresh, warm tropical lenses, the temperature and salinity contributions to the density differential reinforce each other).

North Brazil Shelf LME SST (Belkin 2009)(Figure XVI-52.2):
Linear SST trend since 1957: 0.22°C.
Linear SST trend since 1982: 0.60°C.

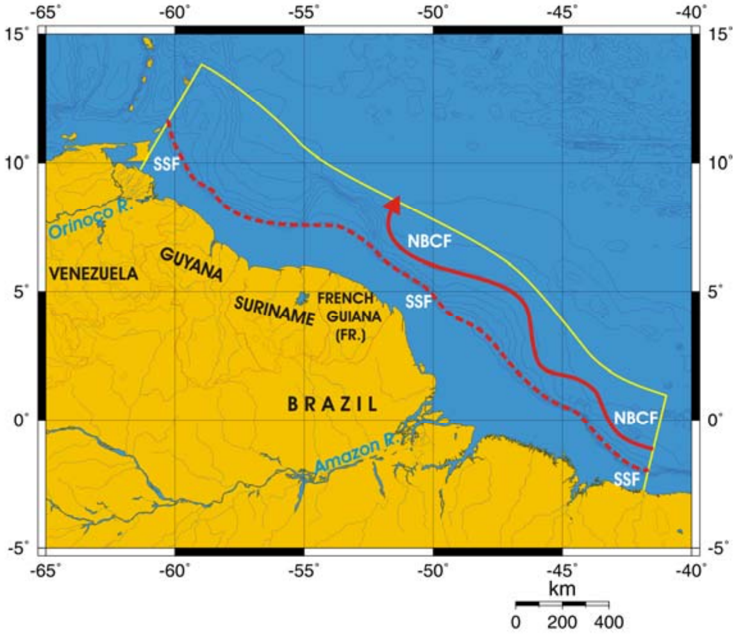

Figure XVI-52.1. Fronts of the North Brazil Shelf LME. Acronyms: NBCF, North Brazil Current Front. SSF, Shelf Slope Front (most probable location. Yellow line, LME boundary. After Belkin *et al.* (2009).

The North Brazil Shelf's thermal history over the last 50 years started with a long-term cooling that culminated in the all-time minimum of 27.3°C in 1976, followed by warming until present. Using the year of 1976 as a true breakpoint, a linear trend would yield a 0.9°C increase over 30 years, which would place the North Brazil Shelf among moderate-to-fast warming LMEs. The North Brazil Shelf thermal history differs from the adjacent South Brazil Shelf. This can be explained by the decoupling of their oceanic circulation. Indeed, the North Brazil Shelf is strongly affected by the North Equatorial Current and Amazon Outflow, whereas the South Brazil Shelf is principally affected by sporadic inflows of Subantarctic waters from the south and also by offshore oceanic inflows from the east.

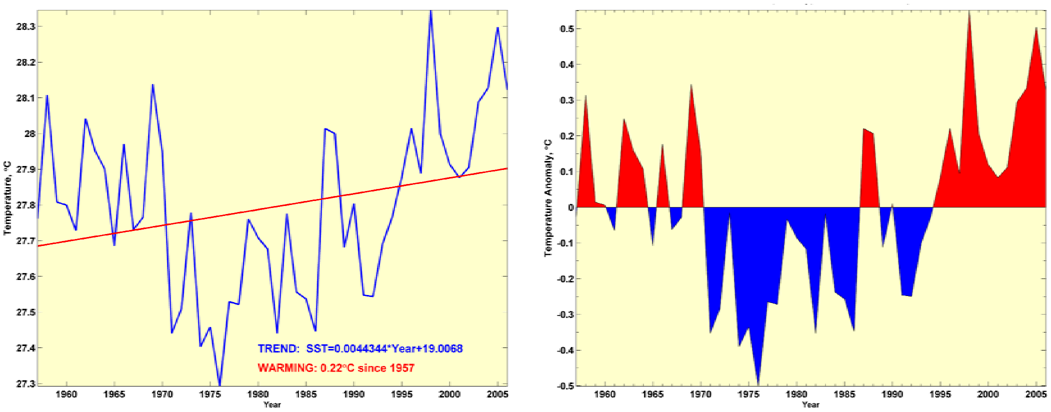

Figure XVI-51.2. North Brazil Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

North Brazil Shelf LME Chlorophyll and Primary Productivity: The North Brazil Shelf LME is a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1})(Figure XVI-51.3).

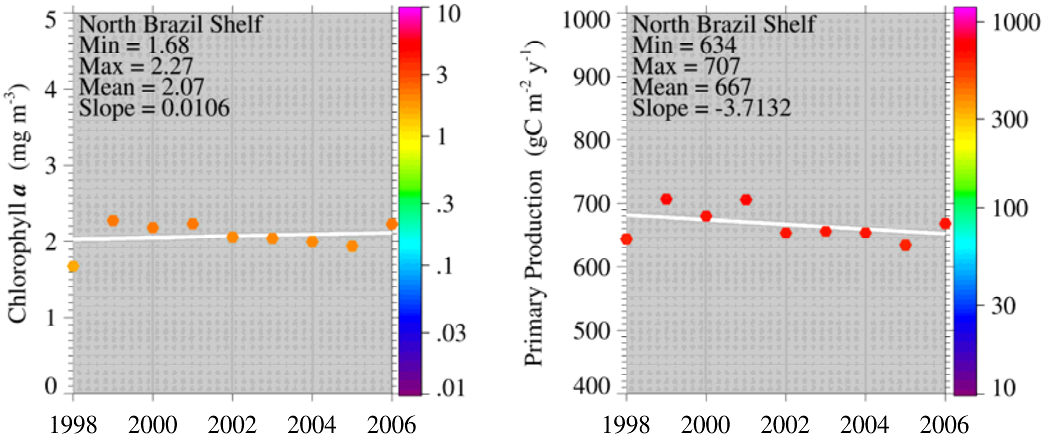

Figure XVI-51.3. North Brazil Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The multispecies and multigear fisheries of the North Brazil Shelf LME are targeted by both national and foreign fleets (FAO 2005 and see below). Major exploited groups include a variety of groundfish such as weakfish (*Cynoscion* sp.*)*, whitemouth croaker or corvina (*Micropogonias furnieri*) and sea catfish (*Arius* sp.). The shrimp resources, such as southern brown shrimp (*Penaeus subtilis*)*,* pink spotted shrimp (*P. brasiliensis*), southern pink shrimp (*P. notialis)*, southern white shrimp (*P. schmitti*) as well as the smaller seabob (*Xiphopenaeus kroyeri*) support one of the most important shrimp fisheries in the world. Tuna is also exploited, and although its catch weight is relatively small, its value is significant. Total reported landings in this LME underwent a steady increase from 1950 to just over 290,000 tonnes in 2004 (Figure XVI-52.4) and the value of the reported landings reached US$532 million (in 2000 US dollars) in 2004 (Figure XVI-52.5).

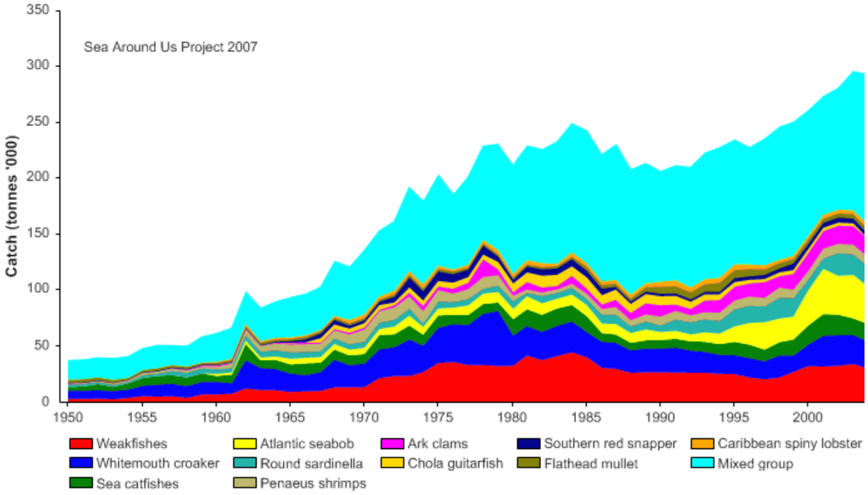

Figure XVI-52.4. Total reported landings in the North Brazil Shelf LME by species (Sea Around Us 2007).

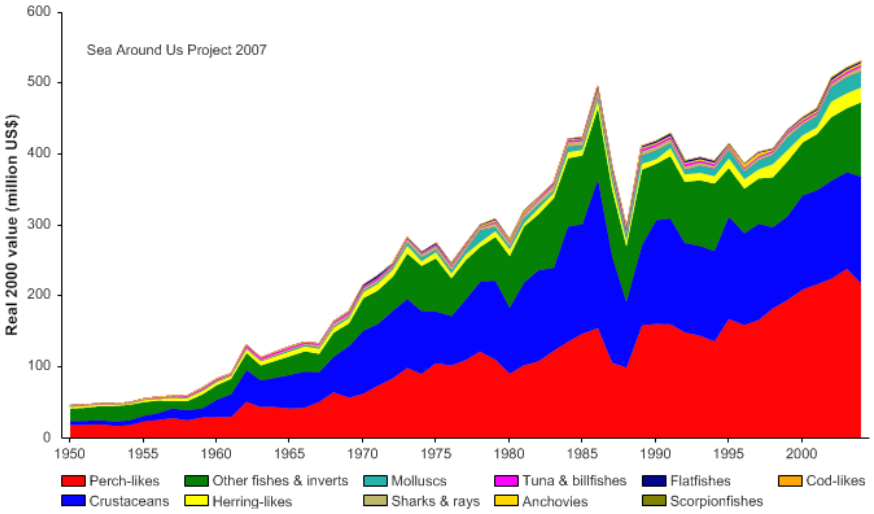

Figure XVI-52.5. Value of reported landings in the North Brazil Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME is low, currently at 3% of the observed primary production (Figure XVI-52.6). Brazil has the largest share of the ecological footprint in this LME, followed by Venezuela and Guyana.

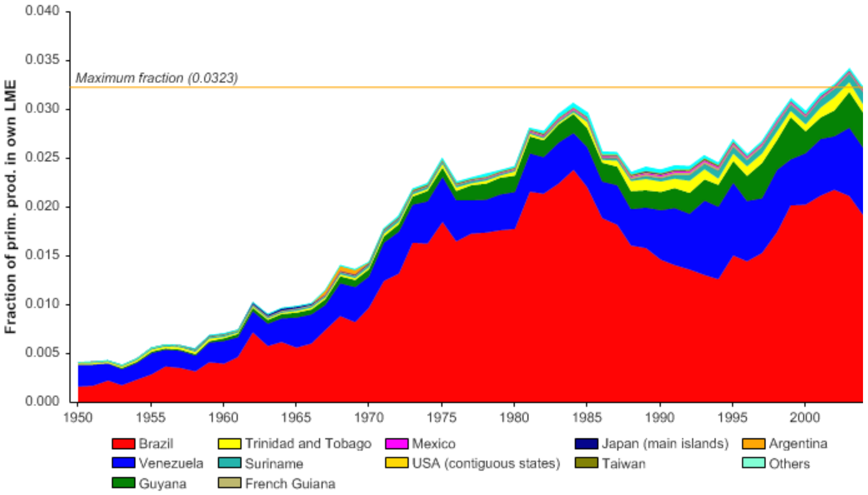

Figure XVI-52.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the North Brazil shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

From the mid 1980s, the mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) has undergone a steady decline (Figure XVI-52.7, top), a trend indicative of a 'fishing down' of the food webs (Pauly *et al.* 1998) in the LME, while the flatness of the FiB over the same period (Figure XVI-52.7, bottom) implies that the increase in the reported landings has not compensated for the decline in the mean trophic level. A detailed study of ecosystems in the region by Freire (2005) has found similar trends using local catch data.

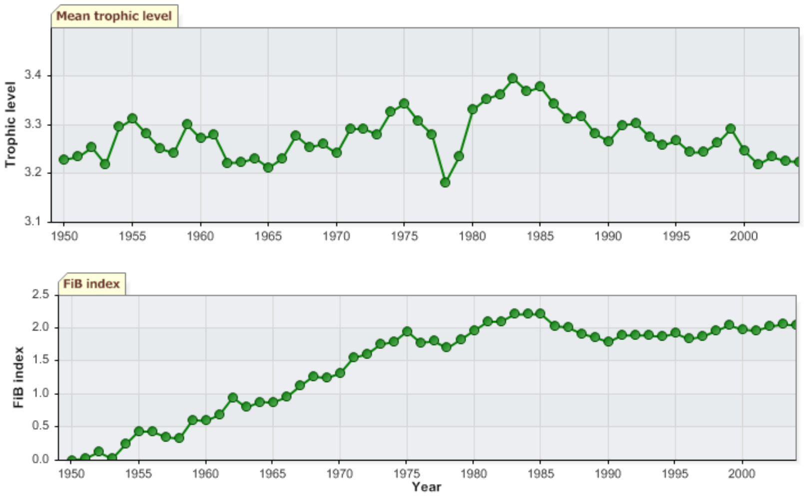

Figure XVI-52.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the North Brazil Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that over 60% of commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XVI-52.8, top). However, 70% of the reported landings come from fully exploited stocks (Figure XVI-52.8, bottom).

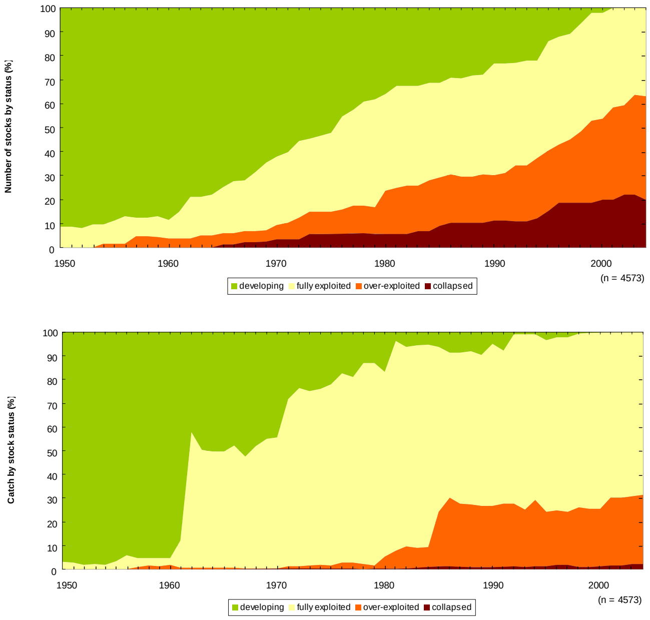

Figure XVI-52.8. Stock-Catch Status Plots for the North Brazil Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Detailed analysis of the fisheries in this LME confirms this diagnosis of severe overexploitation. There is evidence that some of the fisheries may be fully exploited or overexploited in relation to MSY, particularly some of the groundfish stocks. Where assessments have been undertaken, there are clear signs of overexploitation of the southern red snapper (*Lutjanus purpureus*) resource (UNEP unpubl), with declining catch rates and a decrease in the size of this species (Charuau *et al*. 2001, Charuau & Medley 2001). Recent trends in catch per unit effort and other analyses indicate that the corvina is now overexploited in some areas, with the low stock levels of this species being commensurate with exploitation levels beyond the MSY level (Alió *et al*. 2000, Alió 2001). Similarly, lane snappers (*L. synagris*), bangamary (*Macrodon ancylodon*) and sharks are also showing signs of overexploitation (Alio 2001, Ehrhardt & Shepard 2001a). Moreover, a decrease in the average size of some groundfish species has raised sustainability issues (Booth *et al*. 2001, Chin-A-Lin & IJspol 2001). The increasing capture of small individuals is potentially compromising recruitment to the spawning stock (Souza 2001). For instance, in Brazil, immature southern red snappers comprise over 60% of the catch of this species (Charuau *et al*. 2001). Trawl and Chinese seines harvest bangamary at ages far below the age at maturity (Ehrhardt & Shepherd 2001a).

In general, all the shrimp species in the region are subjected to increasing trends in fishing mortality (Ehrhardt 2001) and the fishery is generally overcapitalised (Chin-A-Lin & M. IJspol 2001). Stocks of brown and pink spotted shrimp may be close to being fully exploited (Charuau & Medley 2001, Ehrhardt 2001, Ehrhardt & Shepherd 2001b, Negreiros Aragão *et al*. 2001), with the latter being overexploited in some areas (Ehrhardt & Shepherd 2001b). There has been a general downward trend in the abundance of brown and pink shrimps, particularly during the late 1980s and throughout the 1990s. The trends in fishing mortality were not high enough to have created the very conspicuous decline in abundance, which implies that environmental factors (seasonal river run-off and rainfall) may be more significant than fishing in determining recruitment in these species.

Excessive bycatch and discards and destructive fishing practices are severe, and are of concern throughout the LME. The shrimp bycatch issue is well known in the region, where the bycatch/shrimp ratios are typically between 5 and 15:1 (Villegas & Dragovich 1984, Marcano *et al*. 1995). Many commercial species, predominantly young individuals, comprise the bycatch, most of which is discarded dead at sea. Several species have practically disappeared from the bycatch, indicating a dramatic shrinking of their populations, notably in the case of sharks (Charlier 2001). The operation of trawlers in shallow areas also causes extensive physical damage to benthic habitats and their communities (Charlier 2001). The use of explosives and poisons on the reefs (bleach for capturing octopus) and mangroves (toxic chemicals to capture crabs), capture of immature individuals through diving as well as the use of nets to catch lobsters, which drag sediments, animals and calcareous algae from the sea floor, have also been reported in this region (UNEP 2004a).

III. Pollution and Ecosystem Health

Pollution: Overall, pollution was found to be moderate, but severe in localised hotspots near urban areas. Most of the pollution is concentrated in densely populated and industrialised coastal basins, and not widespread across the region. Water quality in the coastal areas is threatened by human activities that give rise to contamination from sewage and other organic material, agrochemicals, industrial effluents, solid wastes and suspended solids (EPA/GEF/UNDP 1999).

Effluents from industries are released, sometimes untreated, into the water bodies. Contamination by mercury as well as by chemical agricultural wastes is the main source of chemical pollution in the Amazon Basin (UNEP 2004b). Gold is exploited in all the countries of the region and mercury from gold mining operations is dispersed into the air. It is assumed that the largest part ends up in rivers, transforms into methyl-mercury and other chemical compounds and concentrates along the food chain. Mercury contamination could, on the longer-term, become a hazard for the coastal marine ecosystem and for human health, if suitable measures to limit its use are not implemented. There is also the potential risk of pollution from oil extraction, both in the coastal plain and the sea.

Agricultural development is concentrated along the coast and includes intensive cultivation of sugarcane, bananas and other crops. This involves the application of large quantities of fertilisers and pesticides, which eventually end up in the coastal environment. Sugarcane plantations along the coast are also suspected to contribute persistent organic contaminants, which are widely used in pest control, to the coastal habitats (UNEP 2004b).

As a result of the coastal hydrodynamics in this LME, the potential for transboundary pollution impacts is significant. River outflow is deflected towards the northwest and influences the coastal environment in an area situated west of each estuary. It has been estimated that 40-50% of the annual Amazon run-off transits along the Guyana coast (Nittrouer & DeMaster 1987). In fact, Amazon waters can be detected as far away as the island of Barbados (Borstad 1982). As a result, most of the coastal area of the Brazil-Guianas region has been described as an ‘attenuated delta of the Amazon’ (Rine & Ginsburg 1985). This implies that contaminants in river effluents, particularly those of the Amazon, could be transported across national boundaries and EEZs.

Habitat and community modification: Human activities have led to severe habitat modification in this LME. Mangroves, which dominate a major part of the shoreline, have been seriously depleted in some areas, for example, in Guyana, where mangrove swamps have been drained and replaced by a complex coastal protection system (EPA 2005. Likewise, on the Brazilian coast, the original mangrove area has been significantly reduced by cutting for charcoal production and timber, evaporation ponds for salt and drained and filled for agricultural, industrial or residential uses and development of tourist facilities (Marques *et al*. 2004). In Brazil, erosion also threatens coastal habitats and some coastal lagoons have been cut off from the sea.

In the past, the coral reefs were mined for construction material. Currently, they are exposed to increased sedimentation due to poor land use practices and coastal erosion, chemical pollution from domestic sewage and agricultural pesticides, overfishing, tourism and development of oil and gas terminals (Maida & Ferreira 1997). Additionally, there has been some coral bleaching associated with climate variation (Charlier 2001).

Trawlers often operate without restriction in the shallower areas of the shelf, over ecologically sensitive areas inhabited by early life stages of shrimp. The environmental impact of such activities is likely to be high, considering the intensity of shrimp trawling operations in these areas (Ehrhardt & Shepherd 2001b). Evidence from other regions suggests that precautionary measures should be undertaken in environmentally sensitive areas of the continental shelf (Ehrhardt & Shepherd 2001b). Trawlers also catch significant quantities of finfish as bycatch, of which dumping at sea is still a widespread practice in the region (FAO 2005). This is especially damaging to the stocks when the bycatch includes a significant portion of juvenile fish. In Suriname, small-scale fishers have reported the incidence of ‘dead waters’, in shallow areas, following fishing activity by trawlers (Charlier 2001). These dead waters were scattered with dead fish in larger amounts than could have been discarded by the trawlers. Vast areas were devoid of live fish, as they had apparently died or moved out of the area. Such mortality could be the result of local oxygen depletion, caused by the re-suspension of anoxic sediment combined with the presence of organic matter dumped from the vessels.

Growth of the local human population and pressures associated with urban and industrial development will continue to threaten the health of the LME. The problems are, however, potentially reversible, considering that there is a greater public and governmental awareness about environmental issues and several measures at national and regional levels are being taken to address some of these problem.

IV. Socioeconomic Conditions

Brazil (states of Amapá, Pará, Maranhão), French Guiana, Guyana, Suriname and the southeastern part of Venezuela border this LME. A high percentage of the total population consists of indigenous communities. Human uses of the coastal zone include subsistence agriculture, fisheries, exploitation of clay and sand and limited ecotourism. Marine fisheries constitute an important economic sector in the region, providing foreign exchange earnings, employment and animal protein. A significant portion of the region's population depends upon fishing for its survival and is unable to substitute other sources of animal protein for fish protein (UNEP 2004b). In Guyana, the fishery sector is of critical importance to the economy and to social well-being. The economic contribution of Guyana's fisheries has grown dramatically in recent years, contributing about 6% to GDP and employing about 10,000 persons (FAO 2005). Furthermore, fish protein is the major source of animal protein in Guyana, with per capita consumption of about 60 kg in 1996, more than four times the world average (FAO 2005). In general, unsustainable overexploitation of living resources as well as environmental degradation may result in threats to the food security of fishers and loss of employment, as well as loss of foreign exchange to the countries of this LME. Because of shrinking resources and degradation of habitats, a number of development projects have been implemented to support local communities.

V. Governance

Fisheries management issues in the countries bordering the North Brazil Shelf LME are complicated because of the variety of gears used, and the multi-species and multinational nature of the groundfish fisheries. This situation is further complicated by the paucity of data pertaining to the biology and productivity of the region's fish stocks and catch and fishing effort. As a consequence, confidence in stocks assessments is low (Booth *et al*. 2001). The countries have ongoing programmes for environmental and natural resource management and coastal zone management and most have established several national marine parks and protected areas.

The countries are parties to several international environmental agreements, for example CBD, UNFCCC, UNCLOS, MARPOL and Ramsar Convention on Wetlands. Brazil, Guyana, Peru, Suriname and Venezuela, along with Bolivia, Colombia, Ecuador and Peru have developed a project for support by GEF: 'Integrated Management of Aquatic Resources in the Amazon' For the Brazilian Amazon River Basin. The project, approved for Work Program Entry in June 2005, recognises the close linkages between integrated water resource management and the protection of marine habitats. The general objective of this project is to strengthen the institutional framework for planning and executing, in a coordinated and coherent manner, activities for the protection and sustainable management of the land and water resources of the Amazon River Basin, based upon the protection and integrated management of transboundary water resources and adaptation to climatic change.

The first phase of the project will involve strategic planning and institutional strengthening, including the development of a TDA of the Basin and preparation of a Framework SAP. Brazil has applied for the GEF biodiversity project 'Strengthening the Effective Conservation and Sustainable use of Mangrove Ecosystems in Brazil through its National System of Conservation Units'. The aim of the project is to develop conservation and sustainable management of mangrove ecosystems in Brazil to conserve globally significant biodiversity and key environmental services and functions important for national development and the well-being of traditional and marginalised coastal communities.

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XVI-53 East Brazil Shelf LME

S. Heileman

The East Brazil Shelf LME encompasses that part of the Brazilian coast from the Parnaíba Estuary in the North to Cape São Tomé in the South (Ekau & Knoppers 2003). It covers a surface area of about 1.1 million km^2, of which 0.86% is protected, and contains 0.33% of the world's coral reefs and 0.58% of the world's sea mounts (Sea Around Us 2007). The South Equatorial Current, which splits into the North Brazil Current and the southward-flowing Brazil Current, dominates the LME. Coastal upwelling of nutrient-rich South Atlantic Central Waters characterises the area south of Abrolhos Bank in spring and summer (Summerhayes *et al*. 1976). About 35 rivers, the largest of which are the Jequitinhonha, Mucuri, Doce and Paraíba do Sul rivers, drain into the coastal areas. Estuaries include São Francisco and Paraíba. Apart from the Abrolhos Bank, this LME has a narrow continental shelf. A tropical climate characterises this LME. LME book chapters and articles pertaining to the South Brazil Shelf LME include Bakun (1993), Ekau & Knoppers (2003), UNEP (2004).

I. Productivity

The East Brazil Shelf LME is a typical oligotrophic system, poor in nutrients and phytoplankton biomass, except in areas of upwelling where primary production is enhanced (Gaeta *et al*. 1999). The oligotrophic character of the eastern shelf system and its diverse food web structure is in clear contrast to the Southeast-South shelf system (Ekau & Knoppers 1999). The LME can be considered a Class II, moderate productivity ecosystem (150-300 $gCm^{-2}yr^{-1}$). Highest biomass and densities of pico-, nano-, micro- and macro-plankton typify the southern coast and the Abrolhos Bank (Susini-Ribeiro 1999). The macro-zooplankton is dominated by calanoid and cyclopoid copepods. Mesopelagic species dominate the ichthyofauna community in waters more than 200 m deep. On the Abrolhos Bank, demersal ichtyoplankton species, largely herbivorous fish, dominate the system possibly relying on the primary production of benthic algae. The Abrolhos Bank and the Vitória-Trindade Ridge form a topographical barrier to the Brazil Current, inducing fundamental changes and spatial variability in physical, chemical and biological features over the shelf and along the shelf edge (Castro & Miranda 1998, Ekau & Knoppers 1999).

Oceanic Fronts (Belkin *et al.* 2009)(Figure XVI-53.1): This LME includes the bifurcation of the westward South Equatorial Current near Cabo de São Roque (5.5°S; Belkin *et al*. 2008) that gives rise to two currents and associated fronts: the northward North Brazil Current Front (NBCF) and the southward South Brazil Current Front (SBCF). Within this LME the SBCF is most noticeable in salinity; it becomes distinct as a temperature front from the South Brazil Bight southward (see South Brazil Shelf LME). The NBCF is year-round, best defined in austral winter; it extends along the coast into the North Brazil Shelf LME. The Southern Bahia Front (15°S-19°S) and the Cabo Frio Front (20°S-24°S) are caused by wind-induced upwelling and are best developed during austral summer and fall, from January through June.

East Brazil Shelf LME SST (Belkin 2009)(Figure XVI-53.2):

Linear SST trend since 1957: 0.57°C.
Linear SST trend since 1982: 0.30°C.

Figure XVI-53.1. Fronts of the East Brazil Shelf LME. Acronyms: NBCF, North Brazil Current Front; SBCF, south Brazil current Front; SSF, Shelf Slope Front (most probable location). Yellow line, LME boundary. After Belkin *et al.* (2009).

Like the adjacent South Brazil Shelf, the East Brazil Shelf experienced a long-term warming at a slow-to-moderate rate. The most significant event since 1957 was a 1°C warming in 1981-84, similar to and concurrent with the South Brazil Shelf warming. Both LMEs are linked by shelf-slope along-frontal currents that transport SST anomalies from one LME to another; therefore the observed synchronism can be explained by advection, although large-scale atmospheric forcing spanning both LMEs also could have played a role.

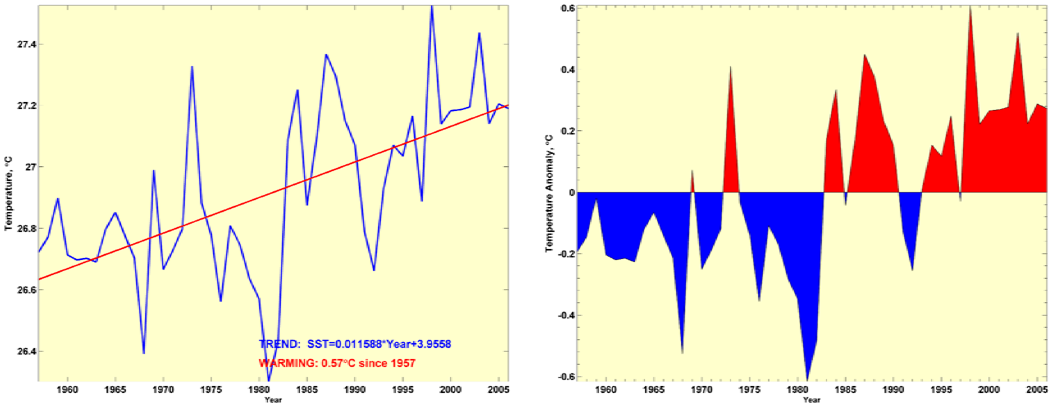

Figure XVI-53.2. East Brazil Shelf LME annual mean SST (left) and SST anomalies (right) , 1957-2006, based on Hadley climatology. After Belkin (2009).

East Brazil Shelf Chlorophyll and Primary Productivity: This LME is a Class II, moderate productivity ecosystem (150-300 gCm^{-2}yr^{-1})(Figure XVI-53.3).

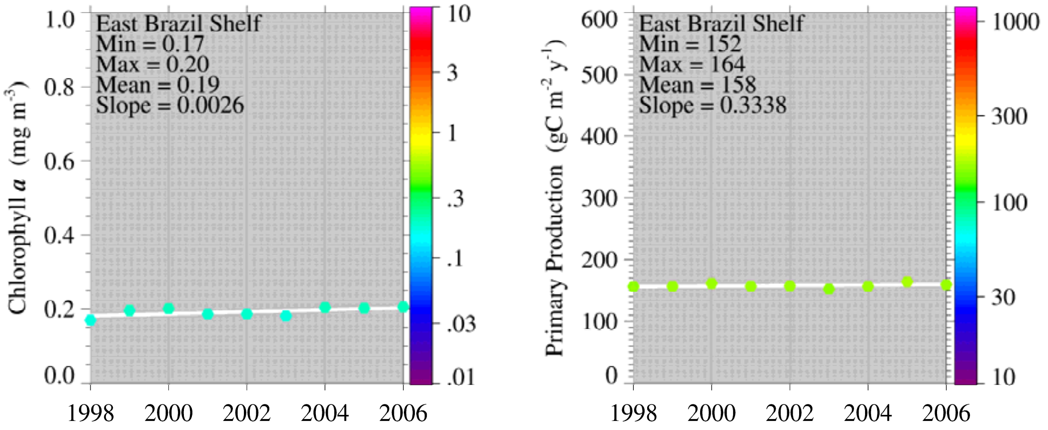

Figure XVI-53.3. East Brazil Shelf trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The fisheries are mainly artisanal although commercial fisheries for lobster, shrimp and southern red snapper are significant in the states of Ceará, Rio Grande do Norte and Espírito Santo (Ekau & Knoppers 1999). Tuna (mainly bigeye) are fished in offshore areas and landed mainly in Rio Grande do Norte and Paraíba. Total reported landings in the LME increased to 300,000 tonnes in 1973 with Brazilian sardinella (*Sardinella brasiliensis*) accounting for two-third of the landings, but have declined over the past three decades, recording 130,000 tonnes in 2004 (Figure XVI-53.4). However, a large quantity of fish bycatch from shrimp trawlers is not included in the underlying statistics and, there are reasons to believe that a substantial fraction of the landings from small artisanal fisheries (predominantly fishes) may not be included in the statistics as well (Freire 2003). The high likelihood of misreporting in the underlying statistics makes 'ecosystemic' diagnosis of catch trends difficult if not impossible (see below).

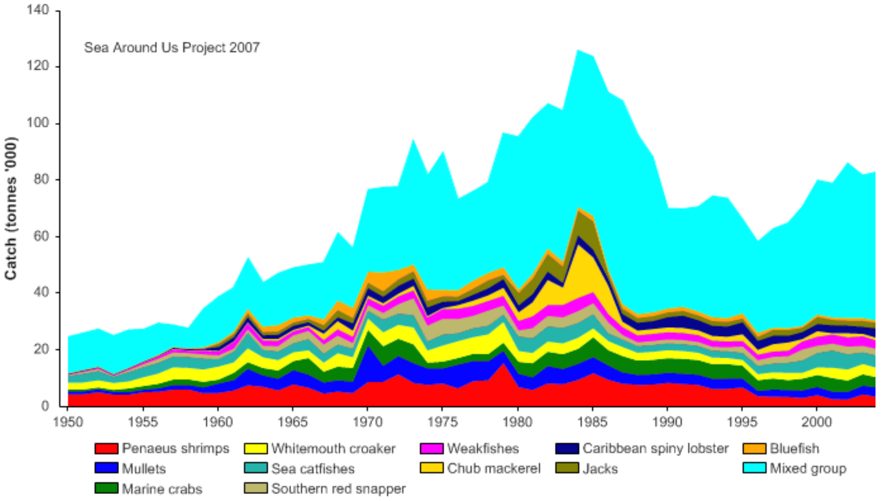

Figure XVI-53.4. Total reported landings in the East Brazil Shelf LME by species (Sea Around Us 2007).

The value of the reported landings peaked at US$400 million (in 2000 US dollars) in 1986, with landings of crustaceans accounting for the largest share (Figure XVI-53.5).

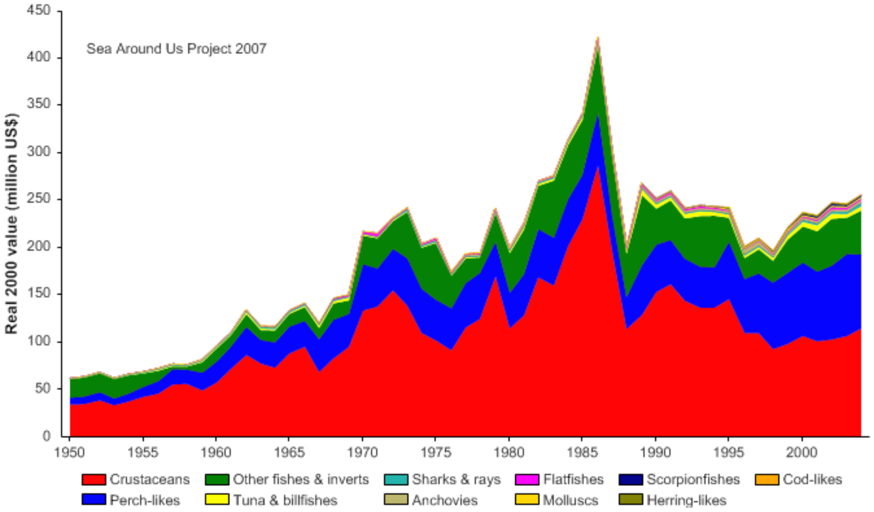

Figure XVI-53.5. Value of reported landings in the East Brazil Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings for the LME approached 5% of the observed primary production in the early 1970s, and has fluctuated between 3 to 5% in recent years (Figure XVI-53.6). This is probably an underestimate due to the large under-reporting of catch in the region (see above). Brazil accounts for almost all of the ecological footprint in this LME, which has little foreign fishing (Figure XVI-53.6).

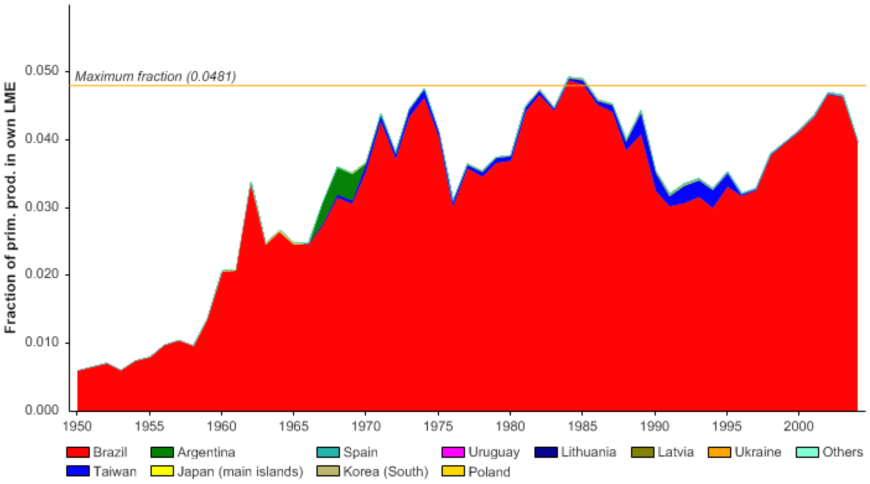

Figure XVI-53.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the East Brazil Shelf Sea LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI, Pauly & Watson 2005) has increased steadily (with variation) from around 3.2 in the early years to 3.4 in recent years (Figure XVI-53.7, top). As for the FiB index, the expansion of the fisheries in the

1950s and 1960s is represented by an increase in the FiB index, though it has since been on a generally flat trend (Figure XVI-53.7, bottom).

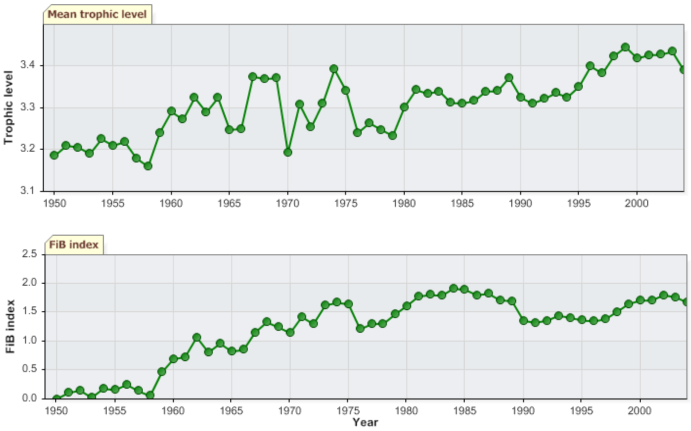

Figure XVI-53.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the East Brazil Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that over 70% of commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XVI-53.8, top). With regard to the contribution to the reported landings biomass, approximately 60% of the landings are supplied by overexploited and collapsed stocks (Figure XVI-53.8, bottom). However, given the quality of the underlying catch statistics (see text), this diagnosis is tentative.

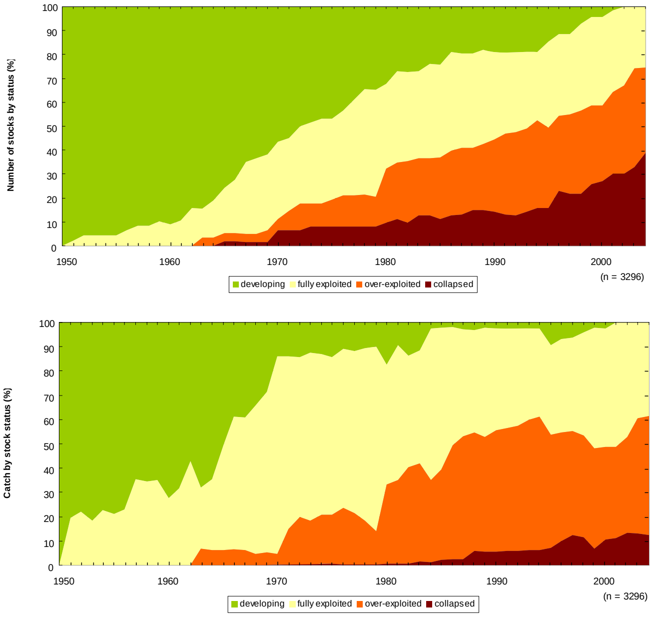

Figure XVI-53.8. Stock-Catch Status Plots for the East Brazil Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.*, this volume, for definitions).

Overexploitation is considered to be severe in this LME, with both artisanal and commercial fishing contributing to the significant decrease of the region's fish stocks. Several valuable species (e.g., shrimp, lobster, tuna, crabs and mussels) are fully exploited or exploited above MSY (FAO 1997, UNEP 2004. As a result, declining fish catches are evident in several areas (e.g., Paiva 1997, Hilsdorf & Petrére 2002) and overfishing has drastically reduced the stocks of some commercially important fish or eliminated them from the catches. In fact, marine and estuarine fisheries for red snapper, prawns and mangrove crabs have declined as a result of overfishing.

Excessive bycatch and discards range from slight to severe (UNEP 2004. Non-selective fishing methods are used extensively and up to 30% of fisheries catches in the northeast areas consists of accidental captures and/or discards. In the oceanic fisheries, bycatch comprises 80% of the catch (on the Sergipe and Alagoas coast this can reach 90%) with discards amounting to 60% of the catch. Small-meshed nets used in commercial shrimp trawling capture a number of non-target species, such as finfish, lobster, crab and turtle. This bycatch, which is normally returned dead to the sea, can reach up to 8 kg for each kilogram of shrimp captured. Destructive fishing practices are moderate to severe (UNEP 2004). Trawling has also destroyed many habitats. The use of bombs and poison is seen in most estuaries in the state of Sergipe while the use of explosives is common along the entire Bahia coast.

Measures aimed at recovery and sustainability of the principal species may help to address overexploitation in the LME (FAO 2005). However, improved fisheries statistics are necessary for the development of fisheries management plans. Fisheries statistics continue to be a difficult issue in Brazil, due to several factors including the lack of institutional stability among the regulatory agencies in charge of the fisheries sector (Freire 2003), the multitude of common names used for reporting landings (Freire & Pauly 2005), the large geographical extension of the coast, the uneasy coexistence of artisanal and commercial fisheries and the large number of species and landing sites related to the artisanal fisheries (Paiva 1997).

III. Pollution and Ecosystem Health

Pollution: Pollution is a growing concern, especially around densely populated and industrialised coastal areas where hotspots have been identified. In general, pollution was found to be moderate in this LME, but severe in localised hotspots (UNEP 2004, UNEP unpubl). The main sources of marine pollution are linked to land-based activities, especially unplanned coastal development and tourism and recreation centres, as well as ocean transport and industrial activities (e.g., Suape industrial port complex in the State of Pernambuco) and agriculture. As a result of the disposal of untreated sewage in coastal areas, microbial contamination is evident in the estuaries and coastal waters near major cities. In fact, beaches located downstream of densely populated urban centres are likely to be contaminated by faecal coliform bacteria in concentrations above the threshold limit (FEMAR 1998). Estuaries, bays and lagoons encircled by large urban areas show varying degrees of eutrophication from sewage and other organic pollution, increased sediment loads and limited water circulation (FEMAR 1998, Kjerfve *et al*. 2001). Low oxygen levels (<3 mgl^{-1}) occur in estuaries and coastal lagoons and significantly affect coastal embayments (Lacerda *et al*. 2002). As a result, fish kills due to low concentration of dissolved oxygen associated with the proliferation of harmful algal blooms are not uncommon in some areas (Sierra de Ledo & Soriano-Serra 1999).

Chemical pollution arises mainly from industry and agricultural plantations. Mercury concentrations reach about 2-5 times baseline levels in some hotspots (Seeliger & Costa 1998). Deforestation, coastal plantations and mining have facilitated soil erosion, which has resulted in increasing suspended solids in estuaries and other coastal areas (Knoppers *et al*. 1999a, 1999b).

Oil exploitation and shipping in the coastal zone, although on a lesser scale than offshore oil and gas activities, represent one of the greatest pressures on the coastal environment of this LME (IBAMA 2002). Several small-, medium- and large-scale spills of oil, grease and a number of hazardous substances have been detected in coastal and marine waters (UNEP 2004). Oil spills are becoming more frequent along the northeast coast of Brazil. The refuelling of boats and the washing of ship tanks is normally carried out a few kilometres from the coastline, resulting in the occurrence of tar and sometimes weathered oil slicks in coastal habitats such as sandy beaches and coral reefs.

Habitat and community modification: Human activities in the coastal zone have resulted in moderate to severe habitat modification in this LME, with the East Atlantic Basins and NE Brazil Shelf being the most affected (UNEP 2004, UNEP unpubl). Destruction of mangrove forests for charcoal production, timber, urban and tourist developments, salt production, agriculture and shrimp farms is widespread throughout the region. It is estimated that the area of mangrove swamp on the entire Brazilian coast has been reduced by up to 30% of its original area, with the probability of further reduction (UNEP unpubl). Only in the state of Piauí can significant areas of non-impacted mangrove forest be found. The conversion of the mangrove to shrimp farms has drastically changed the natural and ecological balance of the region’s estuaries. The highest rate of mangrove deforestation and conversion to aquaculture occurs on the coast of Rio Grande do Norte, which has lost about 2,000 ha of its original area. The states of Paraíba and Pernambuco are no exception, with almost all of its estuaries having shrimp farms of various sizes. This industry is expanding in Piauí, where the total loss of mangrove has already reached 600 ha.

The coral reefs of Brazil are mostly spread over a distance of 2,000 km between $0^{o}50'$ and 19° S latitude from the state of Maranhão in the North Brazil Shelf LME to southern Bahia. They are the southernmost reefs in the Atlantic Ocean and are characterised by relatively low species diversity and the endemism of the hard coral species, with six endemic species (Castro 1994). The largest and richest reefs of Brazil occur on the Abrolhos Bank in the southern part of the state of Bahia. In the past, the coral reefs of the North Brazil Shelf LME were mined for construction material, but at present they come under a growing number of threats. These include increased sedimentation due to unsustainable land use as well as coastal erosion, pollution from domestic sewage and pesticides from sugar cane plantations, overfishing and use of explosives for fishing, tourism, as well as port and oil/gas terminals development (Amado-Filho *et al*. 1997, Maida & Ferreira 1997, Leão 1999).

In the state of Bahia, an acceleration of generally unplanned urbanisation and indiscriminate use of septic tanks in urban centres have resulted in contamination of groundwater (Marques *et al*. 2004). As a consequence, nutrient enrichment through groundwater seepage has resulted in eutrophication of adjacent coastal areas (Costa *et al*. 2000). This has affected the trophic structure of the reefs in these areas, with increasing turf and macroalgae growth, reduction of available light to coral colonies and competition for space preventing the settlement of new coral larvae. Coral bleaching resulting from high sea surface temperature has also affected the reefs in this LME (Leão 1999). There was extensive coral bleaching in 1998 in North Bahia and the Abrolhos region, with levels of 80% reported in important species such us *Agaricia agaricites*, *Mussismilia hispida* and *Porites astreoides* (Garzón-Ferreira *et al*. 2002). However, all corals recovered after six months. The reefs of the Abrolhos Archipelago have been impacted by coastal zone development, tourism, overexploitation of natural resources and pollution from urbanisation as well as industrial activities, including the exploitation of fossil fuel in deep waters (Amado Filho *et al*. 1997, Coutinho *et al*. 1993, Leão 1996, 1999).

Changes in sediment transport dynamics due to land-based activities are considered one of the most serious environmental issues in this region (IBAMA 2002). The lower São Francisco River and its estuary have suffered significant morphological changes as a consequence of the construction of dams. Significant reduction of sediment/nutrient transport has caused sediment deficit in coastal areas, erosion and modification of ecological niches (Marques 2002). Some marine turtles, such as the green, loggerhead, hawksbill, Pacific ridley and leatherback, marine mammals such as the humpack whale, as well as the marine manatee have suffered significant reductions in their populations and are in danger of extinction (Fundação CEPRO 1996).

IV. Socioeconomic Conditions

The East Brazil Shelf LME is bordered by the Brazilian states of Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia and Espírito Santo. It shows an extremely high social, cultural and economic diversity (UNEP 2004). The estimated population is about 53 million inhabitants, with a large percentage living in urban areas (IBGE 2000). In most states, the increasing concentration of the population and economic activities in coastal cities is notable. For example, the state of Pernambuco has the highest coastal population density in the country (over 800 persons km^{-2}). This is ten times greater than the population density of the rest of the state and twice above the national average (Costa & Souza 2002). A large number of the inhabitants of this region are among the poorest in the country, with a wide social and economic gap separating the few rich and the mass of poor people (UNEP 2004).

The main economic activities are linked to agriculture, livestock farming, fisheries/aquaculture and tourism. The LME's fisheries represent an important source of food and income for coastal communities, although they make a small contribution to the country's GDP. Shrimp farming is also an important economic activity, with farms in the northeastern part representing 75% of the national total. Tourism is one of the most important drivers of coastal development in Brazil, and is expected to expand further during the coming years.

Artisanal fisheries are an important subsistence activity not accounted for in the formal economy of Brazil. Fishing represents a labour-intensive activity, responsible for about 800 000 direct jobs. Approximately four million people depend on this sector. The decline in marine fisheries in the region has been accompanied by reduced economic returns over the years. Severe impacts are seen on the fisheries sector economy, affecting the population that is directly dependent on the sector. Several fishing associations have been closed and the labour force diverted into other sectors, such as tourism. As a consequence of the declining stocks and interruption of industrial fishing activities, unemployment in the seafood processing sector has increased.

The socioeconomic impacts of pollution and habitat modification and loss in the East Brazil Shelf LME include loss of revenue and employment opportunities from tourism and fisheries, loss of property value, increased cost of surveillance, restoration of degraded areas as well as penalties against companies responsible for accidents (UNEP 2004). More frequent are the health impacts related to water-borne diseases such as microbiological and parasitic diseases (Governo do Estado de São Paulo 2002). Increasing gastrointestinal symptoms related to exposure to polluted beaches were described by Ciência e Tecnologia a Serviço do Meio Ambiente (CETESB) (Governo do Estado de São Paulo 2002). Among the social and other community impacts are the loss of recreational and aesthetic value of many coastal areas. Pollution and habitat modification are also thought to cause reduction of fish stocks, leading to loss of sustainable livelihoods in hundreds of fishing communities along the coast of this LME. Habitat and community modification have also resulted in increased costs for coastal areas maintenance due to higher vulnerability to erosion and lower coastline stability. This concern has also created generational inequity and loss of scientific and cultural heritage through the disappearance of aquatic species (UNEP 2004).

V. Governance

The Brazilian Government became involved in coastal preservation and management during the 1970s when habitat degradation increased due to industrialisation and urban growth (Lamardo *et al*. 2000). Coastal management is supported by the Federal Constitution in Brazil, which defined the coastal zone as national property (UNEP 2004). In 1988, the government implemented the National Coastal Management Plan. In 1995 the National Programme of Coastal Management (Programa Nacional de Gerenciamento Costeiro, GERCO) proposed decentralisation, with the objective of stimulating initiatives by the states and municipalities, according to the local conditions and demands. The main objective of GERCO is to realign public national policies, which affect the coastal zone, in order to integrate the activities of the states and municipalities and incorporate measures for sustainable development (UNEP 2004). In parallel with the Ecological-Economic Diagnosis, the Ministry of the Environment has coordinated the implementation of the National Programme for Coastal Management involving all 17 coastal states and their municipalities. The programme's main objective is the assessment and diagnosis of the coastal zone uses and conflicts for better planning and management of its living and non-living resources.

Some of the requirements for sustainable development in Brazil include the alleviation of poverty, innovative development strategies, technological improvements as well as sound conservation policies. The greatest constraints are the lack of harmonised legal instruments and financial mechanisms, as well as discrepancies in the capabilities of national and regional experts and managers. The Centre of Fisheries Research and Development of Northeast (CEPENE) is a regional department of the Brazilian Institute of Environment and Natural Renewable Resources and is responsible for the northeastern and eastern coast from Rio Parnaíba to north of Abrolhos Bank. CEPENE has played an important role in supporting research and technological development and promoting technical and social assistance to the local labour force.

The East Brazil Shelf LME, along with the South Brazil Shelf LME and the Patagonian Shelf LME, forms the Upper South-West Atlantic Regional Sea Area. In 1980 UNEP's Governing Council launched a programme for the marine and coastal environment of Argentina, Brazil and Uruguay. In 1998, in cooperation with the UNEP/GPA Coordination Office and the UNEP Regional Office for Latin America and the Caribbean (ROLAC), a Regional Programme of Action (POA) on Land-based Activities and a regional assessment for the Upper South-West Atlantic were prepared and endorsed by representatives of the three governments. The first steps in implementing the programme, which covers the coast from Cape São Tomé in Brazil to the Valdés Peninsula in Argentina, are under development. Under this regional POA, the Brazilian National Programme of Action for the Protection of the Marine Environment from Land-based Activities in the Brazilian Section of the Upper South-West Atlantic has been developed. This national POA covers the area from São Tomé Cape to Chuí, in Rio Grande do Sul state.

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XVI-54 South Brazil Shelf LME

S. Heileman and M. Gasalla

According to the re-definition of the Brazilian LMEs, the South Brazil Shelf LME extends from 22°-34°S along the South American southeast coast and is bordered by the Brazilian states of Rio de Janeiro, São Paulo, Paraná, Santa Catarina and Rio Grande do Sul (Ekau & Knoppers 2003). This LME has a surface area of about 565,500 km^2, of which 1.47% is protected (Sea Around Us 2007), with a wide continental shelf that reaches 220 km in some areas. Another feature is its mixed climate and composite structure of environmental conditions that imprints a warm-temperate characteristic (Semenov & Berman, 1977). According to Gasalla (2007), the South Brazil LME would extend over 3 sub-areas: (a) the Southern shelf (28-34°S), influenced by estuarine outflows; (b) the Southeastern Bight (23-28°S), also termed the South Brazil Bight, characterized by seasonal upwellings and cool intrusions; and (c) a slope and oceanic system at its eastern fringe, with the occurrence of meso-scale eddies. The Brazilian continental shelf lies within the path of the South Equatorial Current, which gives rise to the North Brazil Current and the southward flowing Brazil Current (Ekau & Knoppers 2003). The latter influences the South Brazil Shelf LME which is also under regional effects of the Malvinas current and the La Plata River plume edging northwards along the coast (Piola *et al.* 2008). Thus, the Brazil-Malvinas confluence system in the southwestern corner of the subtropical gyre also shapes this LME characteristics. Major rivers and estuaries include Patos-Mirim and Cananeia-Paranaguá Lagoon systems, Ribeira de Iguape and Paraiba do Sul rivers, and the Santos/São Vicente estuarine complex. Book chapters, articles and reports pertaining to the South Brazil Shelf LME include Bakun (1993), Vasconcellos & Gasalla (2001), Ekau & Knoppers (2003),UNEP (2004) and MMA (2006).

I. Productivity

The South Brazil Shelf LME is subjected to relatively intense shelf edge and wind-driven coastal upwelling of the South Atlantic Central Water (SACW), pumped by alongshore winds and by cyclonic vortexes originated from the Brazil Current, particularly in summer and at Cape Santa Marta (28° S) (Bakun 1993; Vasconcellos & Gasalla 2001). It is the most productive coast of the Brazil Current region and considered a Class II ecosystem with moderately high productivity (150-300 gCm^{-2}yr^{-1}). Productivity is higher in summer when upwelling of the SACW is frequent, and decreases towards the north (Metzler et al. 1997; Ekau & Knoppers 2003). In addition to coastal, shelf-edge and offshore upwelling, production is also sustained by various terrigenous sources such as the Patos-Mirim Lagoon system and La Plata River plume (Seeliger *et al*. 1997; Piola *et al.* 2008). This LME sustains higher production and fisheries than the East Brazil LME to the north (Ekau & Knoppers 2003).

Oceanic fronts (Belkin et al. 2009) (Figure XVI-54.1): The Brazil Current Front forms the offshore boundary of this LME. This current transports equatorial waters from off Cabo de São Roque (5° 30'S) down to 25°S, where the thermal contrast with colder shelf waters is enhanced in winter-spring by an equatorward flow of cold, fresh Argentinean shelf water reaching as far north as 23°S (Campos *et al*. 1995, 1999, Ciotti *et al*. 1995, Lima & Castello 1995, Lima *et al*. 1996). Shelf-slope fronts in the South Brazil Bight and off Rio Grande do Sul are year-round, but best defined from April through September

(Castro 1998; Belkin *et al*. 2009). The Subtropical Shelf Front off southern Brazil has been recently described by Piola *et al*. (2000), Belkin *et al*. (2009) and Campos *et al.* (2008).

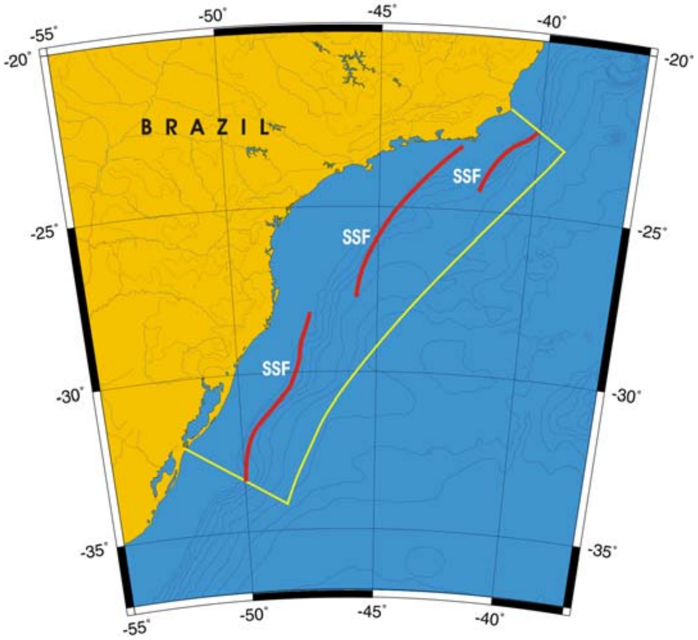

Figure XVI-54.1. Fronts of the South Brazil Shelf LME. Acronyms: SSF, Shelf Slope Front (most probable location). Yellow line, LME boundary. After Belkin *et al.* (2009).

South Brazil Shelf LME SST (Belkin 2009) (Figure XVI-54.2):
Linear SST trend since 1957: 1.12°C.
Linear SST trend since 1982: 0.53°C.

The South Brazil Shelf remained relatively cold – or cooled down – until the relatively abrupt warming by 1°C between 1981 and 1984 that commenced the modern epoch of steady warming. The post-1982 warming of 0.53°C over 25 years is moderate compared to other LMEs. The warming event of 1981-1984 was concurrent with a similar warming in the East Brazil Shelf LME. In both LMEs, the maximum warming rate was observed between 1982 and 1983. This synchronism can be explained either by large-scale forcing spanning both LMEs or by ocean currents that connect these LMEs and transport SST anomalies along shelf and shelf-slope fronts (Belkin et al. 2009).

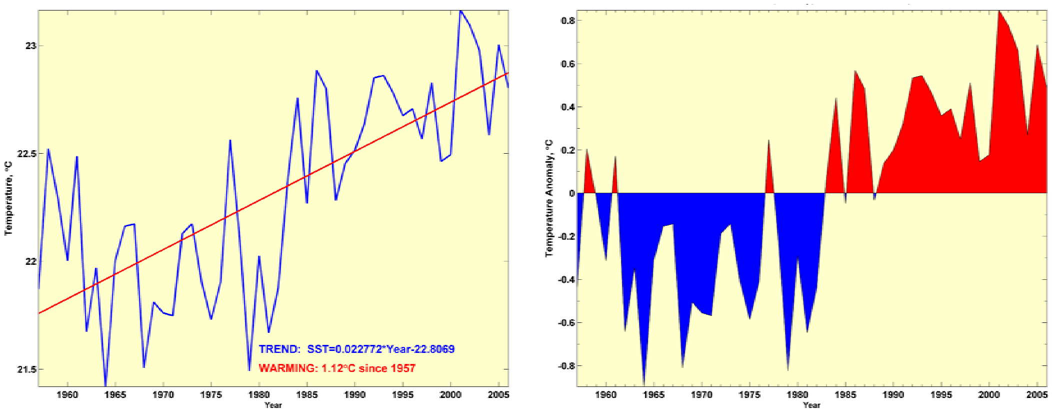

Figure XVI-54.2. South Brazil Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

South Brazil Shelf Chlorophyll and Primary Productivity

This LME is a Class II ecosystem with moderately high productivity (150-300 gCm^{-2}yr^{-1}) (Figure XVI-54.3).

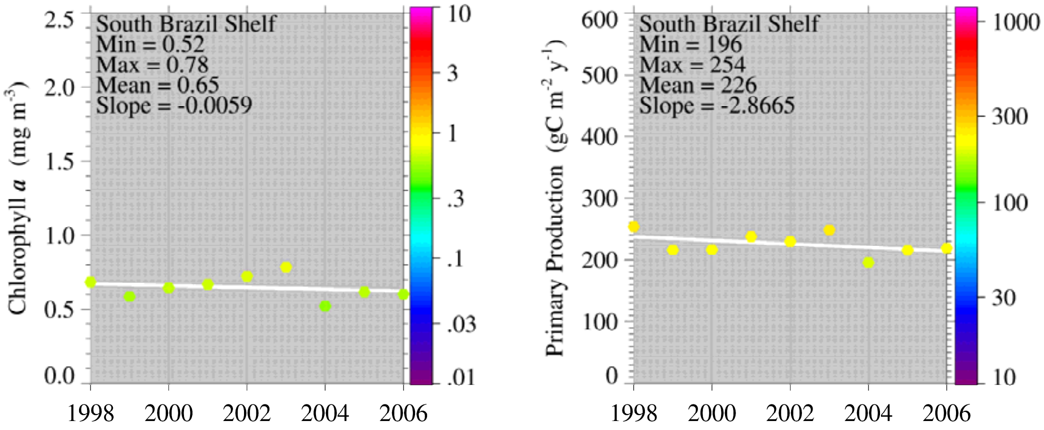

Figure XVI-54.3. South Brazil Shelf trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery; courtesy of J. O'Reilly and K. Hyde.

II. Fish and Fisheries

The South Brazil Shelf contributes about half of Brazil's commercial fisheries yield. In 2002, artisanal fisheries accounted for about 22 % of the total commercial catch in this LME (IBAMA 2002). Sardines represent the most important group in shelf catches (FAO 2003), while the important demersal species are the whitemouth croaker (*Micropogonias furnieri*), the argentine croaker (*Umbrina canosai)* and other sciaenids, the skipjack tuna *Katsuwonus pelamis*, and penaied shrimps (Paiva 1997; Valentini & Pezzuto, 2006). There is increasing expansion and importance of the oceanic fisheries in Brazil, particularly for tuna (FAO 2005a). In 2002, 23,128 tonnes of skipjack and 3,116 tonnes of yellowfin tuna were landed (IBAMA 2002). Deep fisheries initiated in the late 1990s including serranids, Aristaid shrimps, crabs and monkfish have become unsustainable (MMA 2006).

Total reported landings showed an increase up to the early 1970s, when landings peaked at 356,000 tonnes, but declined to 160,000 tonnes in 2004 (Figure XVI-54.2). Historically, catches have been dominated by the Brazilian sardinella (*Sardinella brasiliensis*). Overexploitation as well as oceanographic anomalies are believed to have accounted for the fluctuations of the sardine and anchovy fisheries in this LME (Bakun & Parrish 1991, Paiva 1997, Matsuura 1998). Some recent changes in fishing strategies and their ecosystem effect has been investigated by Gasalla & Rossi-Wongtschowski (2004).The value of the reported landings reached nearly US$600 million (in 2000 US dollars) in 1986, with crustaceans accounting for a significant fraction (Figure XVI-54.3).

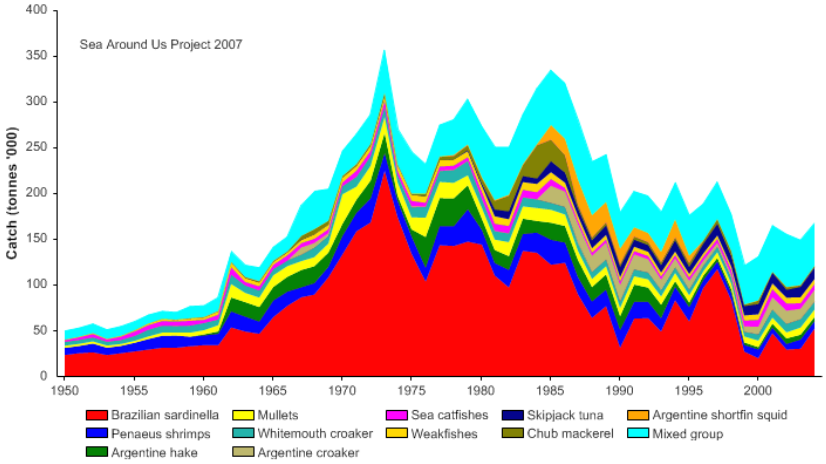

Figure XVI-54.4. Total reported landings in the South Brazil Shelf LME by species (Sea Around Us 2007). Note: Argentine shortfin squid and Whitemouth croaker trends are being reviewed.

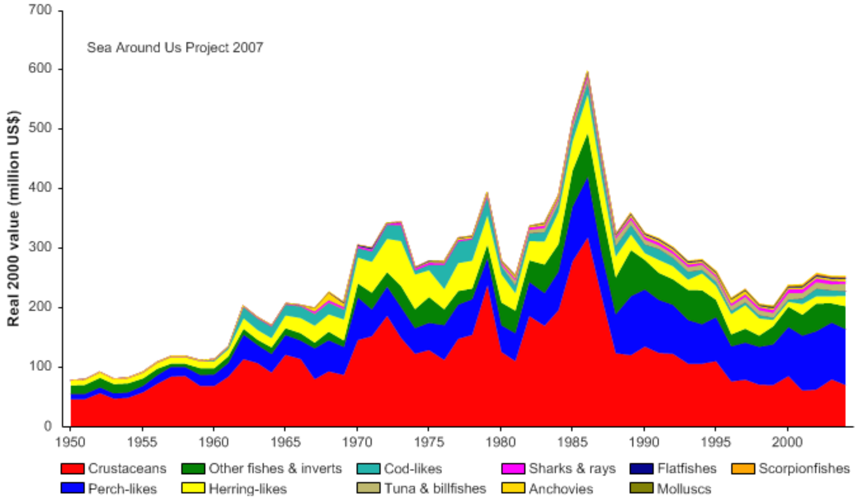

Figure XVI-54.5. Value of reported landings in the South Brazil Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 8% of the observed primary production in the mid 1980s, and has fluctuated between 4 to 6% in recent years (Figure XVI-54.6). However, Vasconcellos and Gasalla (2001) estimated that fisheries utilize 27 and 53% of total primary production in the southern most shelf and in South Brazil Bight regions, respectively. Brazil seems to account for almost all of the ecological footprint on this LME, with very small fisheries by foreign fleets.

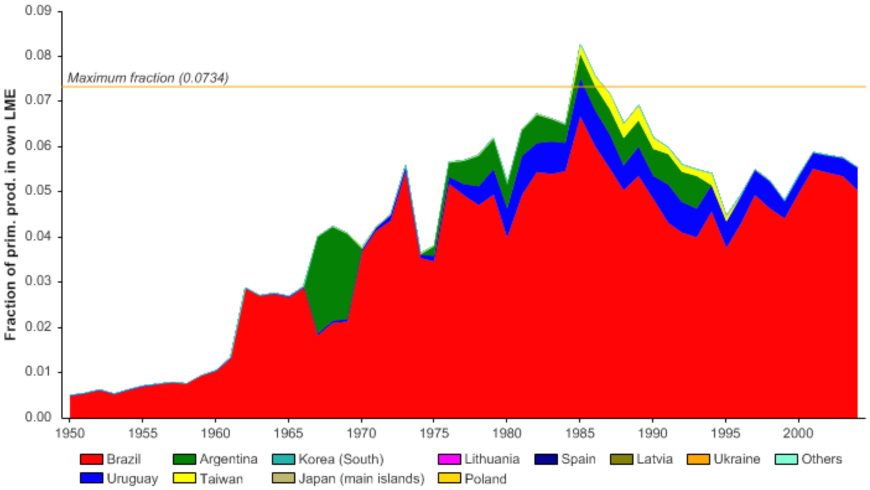

Figure XVI-54.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the South Brazil Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Both the mean tropic level of the reported landings (i.e., the MTI, Pauly & Watson 2005; Figure XVI-54.7 top) as well as the FiB index (Figure XVI-54.7 bottom) show an increase from the late 1950s, somehow consistent with what was previously found by Vasconcellos and Gasalla (2001). This pattern is indicative of the geographical expansion of the fisheries, the collapse of the sardine fishery and an increase of offshore fishing for higher trophic levels in the LME (Vasconcellos and Gasalla, 2001).

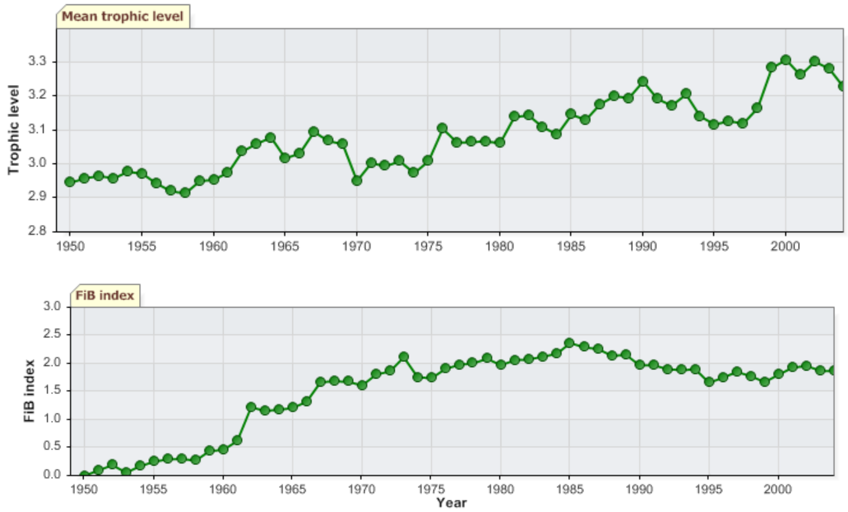

Figure XVI-54.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the South Brazil Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots indicate that about 80% of commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XVI-54.8 top) with only 20% of the reported landings biomass supplied by fully exploited stocks (Figure XVI-54.8, bottom).

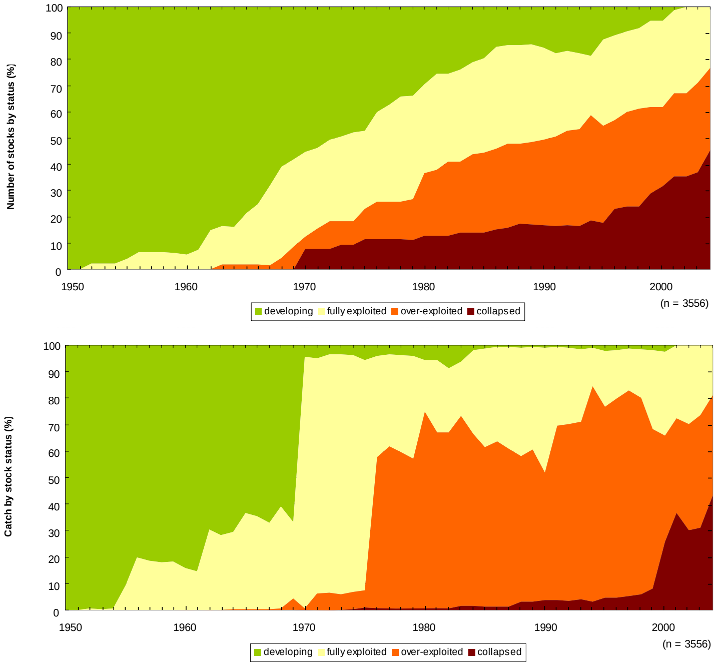

Figure XVI-54.6. Stock-Catch Status Plots for the South Brazil Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Overexploitation of fisheries, excessive bycatch and discards and destructive fishing practices were found to be severe, particularly for the inshore fisheries (UNEP 2004). In some coastal areas, the stocks have been particularly overfished. For example, fish stocks in Sepetiba Bay have declined by 20% during the last decade (Lacerda *et al*. 2002). In the mangrove areas of Babitonga Bay, crab, shrimp and mollusc have also been overexploited (UNEP 2004). Recently, national evaluations showed that this LME is the Brazil's most impacted by overfishing, with 55% of fishery resources overexploited and 29%, totally exploited (MMA, 2006). On the other hand, the oceanic fisheries for migratory species such as tuna are not yet very significant in Brazil's EEZ and could have some potential for further development (FAO 2005b). Bycatch and discards are currently important problems being faced in the coastal areas. Trawlers fish illegally in shallow waters and apart from the capture of juvenile and adult fish during spawning periods, they discard enormous quantities of small and low-value fish (UNEP 2004). Also pelagic gillnets and driftnets are still allowed to operate in this LME, and finning also has been contributing to the depletion of sharks stocks (MMA, 2006). Measures aimed at recovery and sustainability of the principal species may help to address overexploitation (FAO 2005b). However, improved fisheries statistics and stock assessments are still needed (Gasalla and Tomás, 1998), as well as fishery management programs, as in the other two Brazilian LMEs,.

III. Pollution and Ecosystem Health

Pollution: The pollution issues of great importance are usually associated with the process of coastal urbanisation observed in Latin America (Hinrichsen 1998), as well as industries, tourism and recreation centres, agriculture and shipping (UNEP 2004). Air and water pollution stem mainly from the presence of Brazil's two largest metropolitan areas that are situated in or close to the coastal area: São Paulo, the world's 7th largest city with a population of 10.9 million in 2007 (IBGE 2007) with a concentration of petrochemical and fertiliser industries, and Rio de Janeiro, with 6 million inhabitants. Megacities either affect the coastal waters or estuaries directly or contribute to coastal change through their location in catchments which carry the urban waste load. Overall, pollution was found to be severe in localised areas (UNEP 2004).

Sewage pollution is of concern downstream of densely populated metropolitan areas, with microbiological pollution and eutrophication being severe in some coastal hotspots. Several bays, estuaries and lagoons downstream of urban centres show different degrees of eutrophication due to the discharge of untreated domestic sewage and industrial effluents (Rorig *et al*. 1998, Knoppers *et al*. 1999, Braga *et al*. 2000). As a result, anoxia seriously affects some coastal embayments (Lacerda *et al*. 2002). Fish kills due to low concentration of dissolved oxygen associated with the proliferation of algae or algal toxins are not uncommon in some areas such as Conceição Lagoon (Sierra de Ledo & Soriano-Serra 1999) and Patos Lagoon estuary. Dredging and deforestation have resulted in increased soil erosion and siltation of coastal zones. Pollution by suspended solids is severe in many areas (Torres 2000).

Guanabara Bay represents one of the most severely polluted and eutrophic bays of Brazil (UNEP 2004). This and Sepetiba Bay are highly polluted as a result of discharge of domestic effluents, the petrochemical industry, trace elements, changes in sediment loading generated by river basin activities and port operation. There is no marine life in many parts of Guanabara Bay. Fishing has decreased by 90% during the last 20 years and several beaches are not recommended for swimming. The construction of Sepetiba Port and dredging of the shipping channel have caused re-suspension of heavy metals accumulated in the sediments. Cadmium, zinc, lead and chromium have been found in suspended material, sediments and in mussels, oyster and macroalgae of both Sepetiba and Guanabara Bays.

Coastal areas receive effluents with concentrations above threshold limits of heavy metals, such as zinc, mercury, chromium, copper and lead. High concentrations of heavy metals have been found in the water column, sediments and fish and shellfish tissues (Lamardo *et al*. 2000, UNEP 2000). Agricultural run-off is a significant cause of pollution in some areas such as the Patos Lagoon (Lacerda *et al*. 2002). Organochlorine compounds in tissue of molluscs were detected in Guanabara, Santos and Paranaguá Bays and Patos Lagoon. Association between water pollution and water-borne diseases such as microbiological and parasitic infections, poluted beaches, and microbiological infection were found, such as in the Paraiba do Sul river municipalities (UNEP 2004).

The country's main sea terminal, accounting for around 55% of all oil transported in Brazil, is situated on the São Paulo coast. A large number of accidents, including leaks and accidental oil spills, have been recorded during routine operations (Poffo *et al*. 1996) contributing to chronic pollution in nearby areas. Large spills have also occurred, with serious impacts on the region's coastal habitats (IBAMA 2002). From January 1980 to February 1990, 71 accidents involving spills of oil and its derivatives along the São Paulo coast occurred, causing serious damage to estuarine communities (CETESB 2001). Sea outfall monitoring showed also nutrient enrichment and increase of organic matter content in sediments of the São Paulo coast (CETESB 2003).

Recent global research on hypoxia in coastal zones showed the occurrence of dead zones in 4 regions of the South Brazil Shelf LME, as being the Patos Lagoon, Guanabara Bay, Rodrigo de Freitas and Conceição lagoons (Diaz & Rosenberg 2008). This suggests that this LME is the most impacted of Brazil.

Habitat and community modification: Urbanisation, petroleum exploitation, port operations, agriculture, tourism, fishing and aquaculture exert significant pressures on the coastal habitats, which has led to severe habitat degradation throughout this LME (UNEP 2004). Estuaries and bays have been particularly degraded. For example, drainage for rice culture, catching of shrimp and mullets, hunting as well as land speculation in beach areas have had negative impacts in the Patos Lagoon (Diegues 1999). Between 1956 and 1996, 10% of the marshland in this estuary was lost (Seeliger & Costa 1997, Seeliger *et al*. 1997). The filling of intertidal and shallow water flats in the lower Patos Lagoon estuary for port construction and residential and industrial development has destroyed or reduced seagrass beds (Seeliger *et al*. 1997). Estuaries and bays located around the cities in the states of Rio Grande do Sul, Santa Catarina have been impacted by river discharge of organic pollutants and increasing oxygen demand.

In Ilha Grande Bay in Rio de Janeiro, only 50% of the original mangrove remains (UNEP 2004). One of the largest natural fish breeding grounds, Sepetiba Bay, has been under severe impacts due to silting, pollution and mangrove destruction. Intensive soil excavation and transport for construction of the Rio-São Paulo highway, as well as increasing urbanisation have caused intense erosion and a significant increase in suspended solids in coastal waters and subsequent smothering of benthic species. The construction of decks, walls and land reclamation has destroyed rocky foreshores and modified beaches in this LME.

In Guanabara Bay, the mangrove system has been reduced by landfilling with solid waste, illegal exploitation of mangrove wood and occupation by low-income population. Changes in the sediment transport dynamics due to land-based activities on the coast are considered one of the most serious environmental issues in this region (IBAMA 2002). For example, the sediment transport and sedimentation rates in Sepetiba Bay have changed dramatically because of civil engineering works during the 1950s and water transfer from the Paraíba do Sul River for the purpose of supplying the Rio de Janeiro Metropolitan area (UNEP 2004). Coastal erosion is expected to become worse due to sea level rise, which may also eliminate mangrove habitats at an approximate rate of 1% per year (IPCC 2001).

The health of the South Brazil Shelf LME may come under greater threat in the future as a result of pollution and habitat and community modification becoming severe in the absence of any strong responses to address these concerns (UNEP 2004). These responses should include new and creative strategies to promote integrated environmental management and increasing investment in education and recovering.

IV. Socioeconomic Conditions

The population of the states bordering this LME is about 82 million, 20% of whom live in the coastal areas and are responsible for for more than 75% of the Brazilian GDP (IBGE 2007). In addition, the population of the megacity of São Paulo, about 80 km from the coast, is about 11 million people and Rio de Janeiro, the second, is about 6 million (IBGE, 2007). In most states, the increasing concentration of the population and economic activities in coastal cities is evident. The LME's major marine harbours annually move about 214 million tons of goods (UNEP 2004). The region shows an extremely high social, cultural and economic diversity. Artisanal and commercial fishing, agriculture, tourism and shipping are important activities. The aquaculture sector (mainly for shrimp, oysters, mussels and clams) is developing rapidly, particularly the state of Santa Catarina with an annual production of more than 20,000 tonnes (Poli *et al*. 2000). This state is the largest mussel producer in Latin America, producing about 12,000 tonnes in 2000 (FAO 2005a).

Fisheries are of great social, cultural and economic importance and sustain a large number of traditional fishers who have lived for generations off fishing. Small-scale and artisanal fisheries are declining as a result of overexploitation in coastal areas and competition from large fishing fleets, but there are around 110,000 artisanal fishers registered (IBAMA 2003). Traditional fishing communities have almost disappeared in some coastal areas due to real estate speculation, coastal degradation and urban-industrial expansion, and workers have moved to other activities (IBAMA 2007). Commercial fishing and the fish processing industry are important economic activities for export. Falling sardine production has led to the closure of many salting and canning companies and loss of employment. Social and community impacts in the region include reduced capacity of local populations in meeting basic human needs when fish stocks are reduced. The socioeconomic impacts of overexploitation are overall moderate in the LME (UNEP 2004) but they seem to be still underevaluated.

The economic impacts of pollution are severe in the LME (UNEP 2004). Coastal areas have already experienced economic losses, mostly in tourism and moderate to severe economic impacts in the fisheries sector because of pollution and habitat degradation. Impacts also include loss of property value, costs of remediation of polluted areas as well as penalties against companies responsible for accidents (e.g., major spills events). Health impacts due to water pollution include the incidence of water-borne microbiological and parasitic diseases. Increasing gastrointestinal symptoms related to exposure to polluted beaches have been reported (Governo do Estado de São Paulo 2002). Economic impacts of habitat and community modification are similar to those of pollution and also include increased costs for coastal area maintenance due to higher vulnerability to erosion and reduced coastline stability.

V. Governance

Brazil is party to several environmental conventions and agreements and has specific dated agreements with Uruguay relating to fisheries, the use of natural resources and environmental issues. Brazil, Uruguay, Argentina and Paraguay form the Common Market MERCOSUR. The Brazilian Government became involved in coastal preservation and management during the 1970s when degradation of ecosystems increased due to industrialisation and urban growth (Lamardo *et al*. 2000). Coastal management is supported by the Federal Constitution in Brazil (1998), which defines the coastal zone as national property. Brazil has expended great efforts to assess the state of the living and non-living resources within its EEZ. The greatest constraints include inadequate harmonised legal instruments and financial mechanisms and limited human resources. This country also has an ongoing coastal zone management programme, as well as a significant number of institutions such as universities, research institutes and foundations dedicated to fisheries research. The Centro de Pesquisa e Gestão de Recursos Pesqueiros do Litoral Sudeste e Sul (CEPSUL) is a regional department of the Instituto Brasileiro do Meio Ambiente (IBAMA) that is responsible for fisheries management of overexploited species in the area from Cape Frio to the Uruguayan border. Important protected areas include the Ecological Station of Taim and the National Park of Lagoa do Peixe-PARNA, as well as several APAs (Area de Proteção Ambiental) along the coast. Also, the so-called new “extractive reserves” have been created by fishers associations for fisheries conservation. By the other hand, since 2003, the Secretaria Especial de Aquicultura e Pesca (SEAP) with a Ministry status, have been responsible for the management of underexploited fishery resources, aquaculture and fishing development, including incentives and subsidies. There is a clear disconnection between agencies for fisheries, ICZM and conservation issues. See the North and East Brazil Shelf LMEs for additional information on governance.

The South Brazil Shelf LME, along with the East Brazil Shelf LME and the Patagonian Shelf LME, forms the Upper South-West Atlantic Regional Sea Area. See the East Brazil Shelf LME for information on the POA on Land-based Activities and on the Brazilian National Programme of Action for the Protection of the Marine Environment from Land-based Activities in the Brazilian Section of the Upper South-West Atlantic.

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XVI-55 Patagonian Shelf LME

S. Heileman

The Patagonian Shelf LME extends along the southern Atlantic coast of South America from the Río de la Plata (La Plata River) to southern Patagonia and Tierra del Fuego, covering an area of about 1.2 million km^2, of which 0.18% is protected (Sea Around Us 2007). The continental shelf is one of the widest in the world, and encompasses the Falkland Islands/Malvinas some 760 km east of the mainland. Two major wind-driven currents influence the LME: the cold, northward flowing Falkland/Malvinas Current and the warm, southward flowing Brazil Current (Bakun 1993). The Falkland/Malvinas Current provides the LME with a distinctive ecological boundary to the east. This LME is also influenced by low salinity coastal waters (principally outflow of the Río de la Plata) and upwelling of cold Antarctic waters caused by the prevailing westerly winds. Major estuaries include the Rio de la Plata, Rio Colorado, Rio Negro and Chubut. LME chapters and reports pertaining to this LME include Bakun (1993), Bisbal (1995) and UNEP (2004).

I. Productivity

The Patagonian Shelf LME is one of the world's most productive and complex marine systems, and is a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). Extensive mixing of the Falkland/Malvinas Current and the Brazil Current in the La Plata region results in a highly productive confluence zone. This mixing has biological, physical, and meteorological consequences that impact the entire LME. The outflow from the Río de la Plata, the second largest drainage basin (3.2 million km^2) in South America, also contributes to the high biological productivity on the continental shelf and slope. The waters of the sub-tropical Brazil Current show lower productivity. Phytoplankton species are dominated by dinoflagellates, coccolithophorids, and cyanophyceans, with few diatoms. The zooplankton community shows a high abundance of calanoid copepods, chaetognaths, salps and hydromedusa.

Biological diversity is rich, with species from warm, temperate and cold waters. Some endemic species such as the migratory Plata dolphin (*Pontoporia blainvillei*) are also found in this region. The coastal area has favourable reproductive habitats for small, pelagic-spawning clupeoids (Bakun & Parrish 1991). Some species (e.g., tuna and marine mammals) are migratory and are of outstanding global ecological, economic, and social importance. The LME supports significant seabird and marine mammal populations as well as fish and invertebrates (Bakun 1993, DRIyA 2001), and is particularly rich in fisheries resources.

Oceanic Fronts (Belkin et al. 2009) (Figure XVI-55.1): Three year-round fronts are distinguished over the Patagonian Shelf: Valdes Front (VF) at 42°S, San Jorge Front (SJF) at 46°S, and Bahia Grande Front (BGF) at 51°S. The origin of VF and SJF might be related to intense tidal mixing (Glorioso 1987, Glorioso and Flather 1995, 1997). Two seasonal fronts are the Bahia Blanca Front (39°S) and Magellan Front (MF), the latter consisting in fall (April-June) of two branches, the Patagonian-Magellan Front and Tierra del Fuego Front. The origin of MF and its branches is related to the influx of cold, fresh Pacific water via the Strait of Magellan. The offshore boundary of this LME coincides with the Falkland (Malvinas) Front/current that extends along the Patagonian shelf break and upper continental slope of the Argentinean Sea.

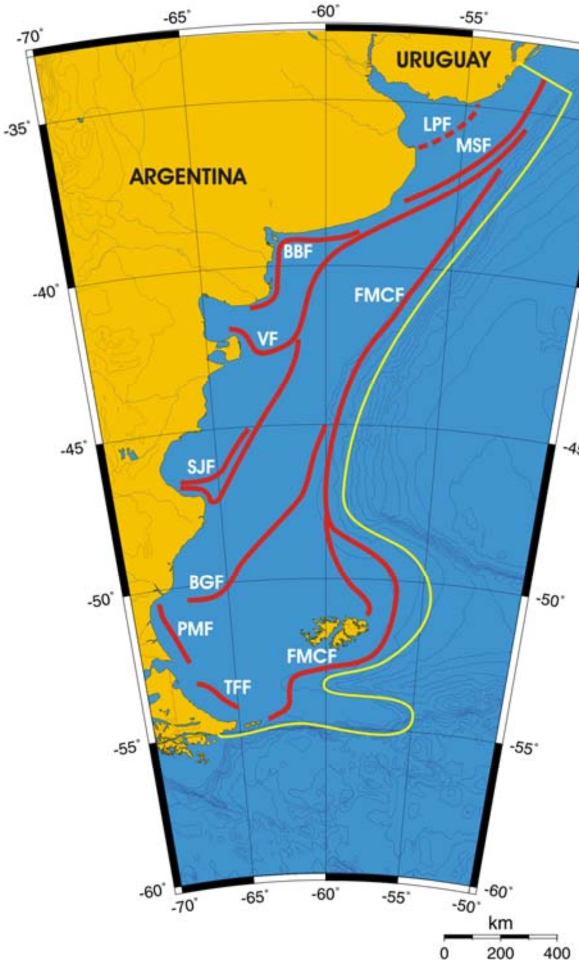

Figure XVI-55.1. Fronts of the Patagonian Shelf LME. BBF, Bahia Blanca Front; BGF, Bahia Grande Front; FMCF, Falkland/Malvinas Current Front; LPF, La Plata Front; MSF, Mid-Shelf Front; PMF, Patagonian-Magellan Front; SJF, San Jorge Front; TFF, Tierra del Fuego Front; VF, Valdes Front. After Belkin et al. (2009).

Patagonian Shelf LME SST (Belkin, 2009) (Figure XVI-55.2):
Linear SST trend since 1957: 0.15°C.
Linear SST trend since 1982: 0.08°C.

The Patagonian Shelf experienced a very gradual, steady warming over the last 50 years. The most dramatic event occurred in 1961-62, when SST rose from the all-time minimum of 10.3°C to the all-time maximum of >11.3°C. The most likely cause of the observed stability of the Patagonian Shelf is the constant influx of sub-Antarctic waters with the Falkland/Malvinas Current (see the Falkland/Malvinas Current Front, FMCF, associated with the namesake current. These waters in turn are stabilized by the Antarctic Circumpolar Current. Another possible cause of the Patagonian Shelf thermal stability is an extremely rich and well-defined frontal pattern; this pattern persists, albeit constantly evolving, year-round. Many fronts are tidal mixing fronts separating vertically mixed areas from vertically stratified areas. Naturally, SST in tidally mixed areas is more stable than elsewhere.

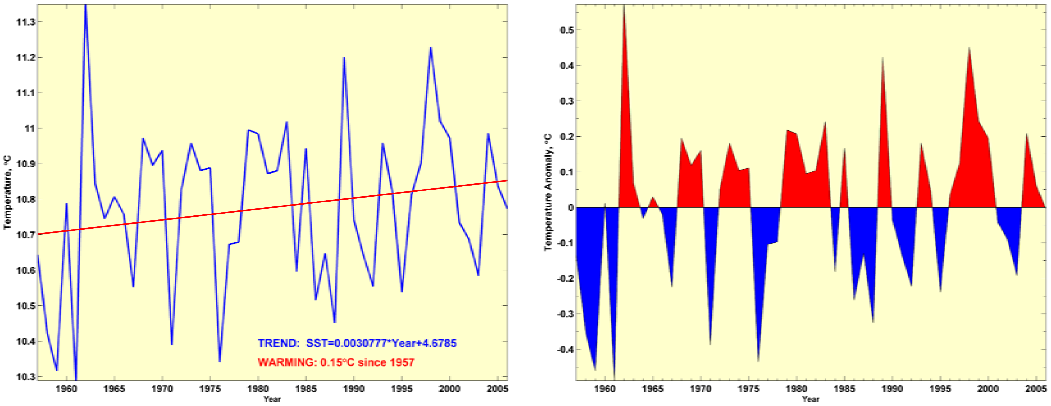

Figure XVI-55.2. Patagonian Shelf LME annual mean SST (left) and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Patagonian Shelf LME Chlorophyll and Primary Productivity

This LME is a Class I, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}) (Figure XVI-55.3).

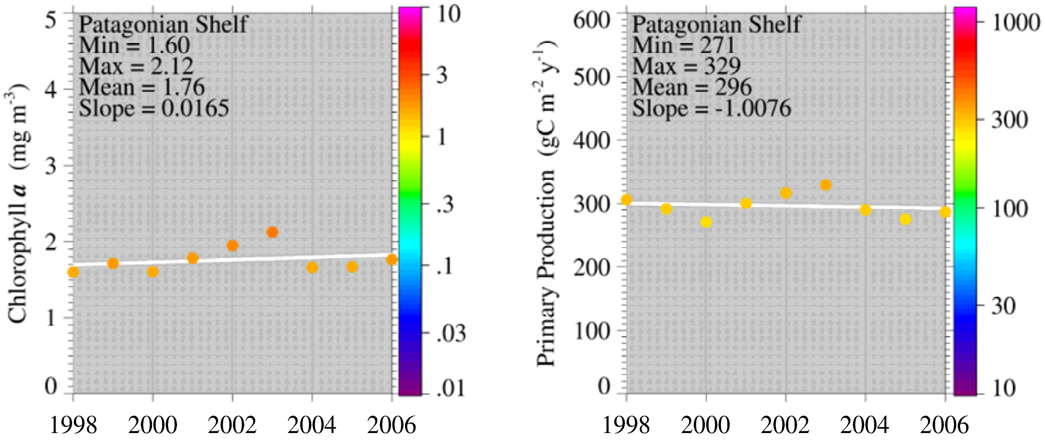

Figure XVI-55.3. Patagonian Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume

II. Fish and Fisheries

Fisheries in the Patagonian Shelf LME have undergone accelerated growth in the last decades involving mostly Argentine hake (*Merluccius hubbsi*), Argentine shortfin squid (*Illex argentinus*), southern blue whiting (*Micromesistius australis*), Patagonian grenadier (*Macruronus magellanicus*), and prawns (*Pleoticus muelleri*). Total reported landings have increased over the past three decades, recording 1.5 million tonnes in 1997 with Argentine hake and shortfin squid accounting for the majority share (Figure XVI-55.4). The landings have since declined to 970,000 tonnes in 2004 (Figure XVI-55.2). The value of the reported landings has been over US$1 billion (in 2000 real US dollars) since the mid-1980s with a peak of US$1.6 billion recorded in 1987 (Figure XVI-55.5). However, the value has been declining in recent years.

The Secretariat of Agriculture, Livestock, Fisheries, and Food (SAGP&A) reports landings of hake by the Argentinian fleet for the 2008 January through 4 September 2008 at 180,051.1 tonnes of common hake landed in Argentine ports, down 6% from the same period the previous year. (SAGP&A). The Joint Technical Commission for the Argentine-Uruguay Maritime Front (CTMFM) has banned *Merluccius hubbsi* fishing in the Common Fishing Area from 6 October through 31 December, 2008, to protect juvenile hake concentrations and "encourage rational exploitation of the resource" (www.fis.com/fis/worldnews, Tuesday, 7 October 2008).

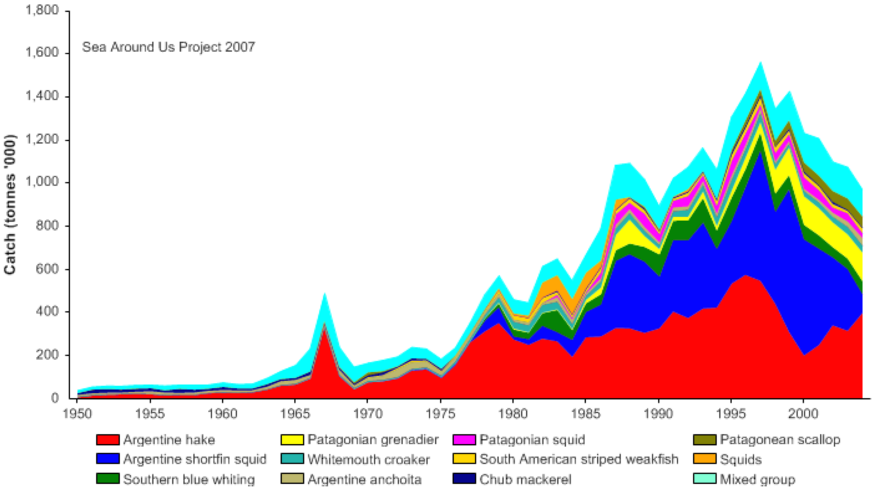

Figure XVI-55.4. Total reported landings in the Patagonian Shelf LME by species (Sea Around Us 2007).

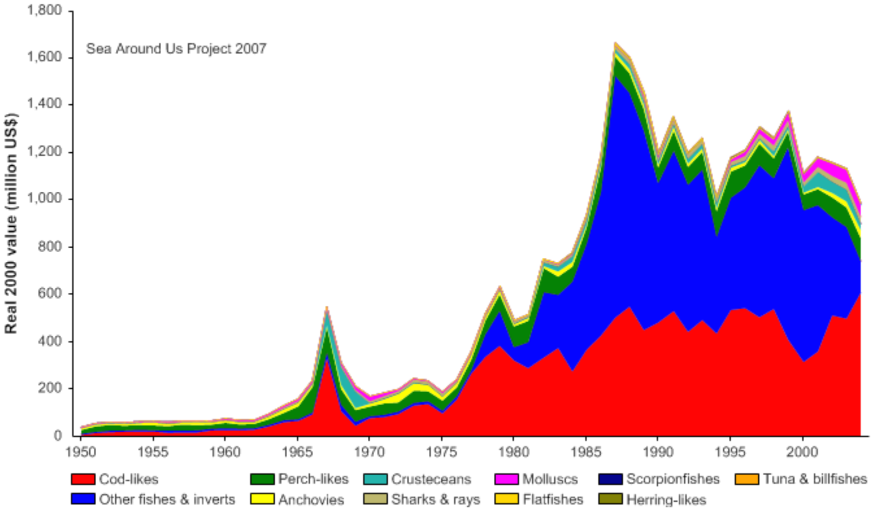

Figure XVI-55.5. Value of reported landings in the Patagonian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME reached 25% of the observed primary production in the mid-1990s, but has declined to 20% in recent years (Figure XVI-55.6). Argentina accounts for the largest share of the ecological footprint in this LME (Figure XVI-55.6).

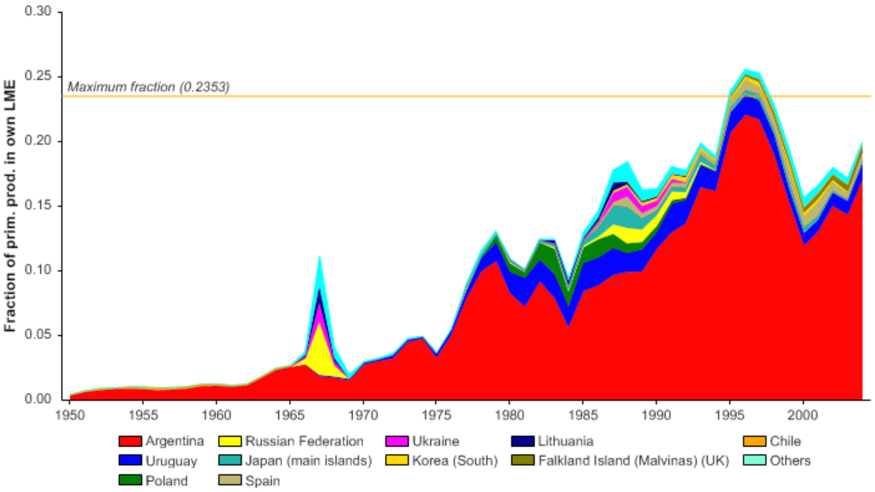

Figure XVI-55.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Patagonian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) shows a decline since the late 1970s (Figure XVI-55.7, top), an indication of a 'fishing down' of the food web in the LME (Pauly *et al*. 1998). Over the same period, the FiB index has remained flat (Figure XVI-55.7, bottom), implying that the increasing reported landings in Figure XVI-55.4 were due not only to ecological compensation, but also to a geographic expansion of the fishery. These compensatory mechanisms worked until the mid-1990s, at which points the number of overexploited and collapsed stocks increased (see Figures XVI-55.8, top and XVI-55.8, bottom).

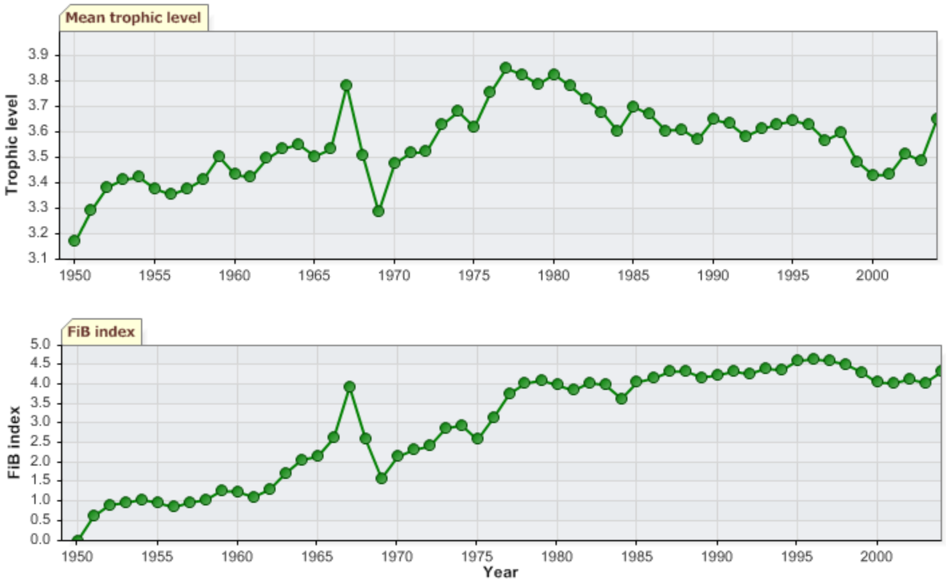

Figure XVI-55.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Patagonian Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots shows that over 70% of commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XVI-55.8, top), with 70% of the reported landings supplied by overexploited stocks (Figure XVI-55.8, top). However, the transition from fully exploited to overexploited stocks in the early 2000s was rather abrupt.

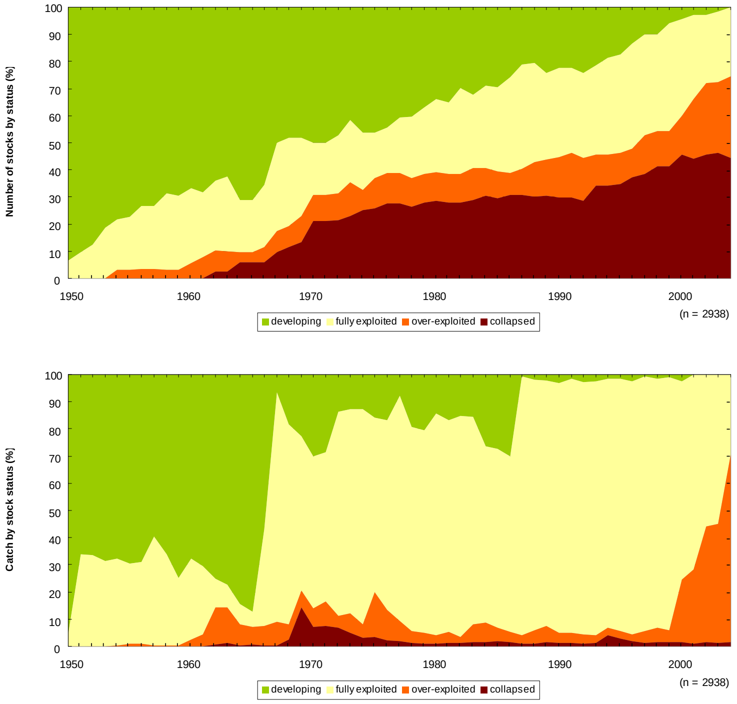

Figure XVI-55.8. Stock-Catch Status Plots for the Patagonian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Despite the low exploitation levels of some species (e.g., Atlantic anchovy and southern blue whiting), intensive exploitation of other species by Argentina and Uruguay has resulted in moderate to severe overexploitation in the LME (UNEP 2004). This is particularly serious in the Buenos Aires coastal system and Common Argentine-Uruguayan Fishing Zone. Overexploitation of hake in the Mar del Plata area became evident in 1997, with increased fishing effort (Bertolotti *et al*. 2001) and catching of large quantities of juvenile and spawning fish (DRIyA 2001). Between 1988 and 1999, the proportion of hake in the total landings fell from 62 to 31% (DRIyA 2001). Subsequently, catch limits and other controls were implemented to allow recovery of the stocks. In 2000, the hake reproductive stock south of 41ºS was the lowest since 1986 (Pérez 2001). Total biomass of the northern and southern hake stocks decreased, reproductive biomass was lower than the biologically acceptable level, and the fishery was sustained by a few year classes (Aubone 2000, Pérez 2000). This led to the collapse of the hake stocks, which may have caused important changes in productivity and community structure as shown by a decrease in trophic levels of the catch and an increase in anchoita stocks between 1993 and 1996 (DRIyA 2001).

A number of other fish and invertebrate species are also overfished. The squid fishery was established in the 1980s, with catches by both Argentina and Uruguay off the Río de la Plata. In 1987, there were indications that squid stocks were being maximally exploited and probably overfished (Csirke 1987). However, this fishery has been highly variable in subsequent years and this has probably been driven by environmental variability. Most species of bony fish targeted in the multi-species coastal fishery show a decreasing trend in biomass. The estimated population of the southern blue whiting (*Micromesistius australis*) was found to be about 77% lower than previous levels, and its exploitation rate relatively high (Wöhler *et al*. 2001). Biomass of mackerel (*Scomber japonicus*), corvina (*Micropogonias furnieri*) and shore ray species have decreased since 1996. The cod (*Genypterus blacodes*) stock is near its maximum sustainable limit of exploitation (Cordo 2001, Perrota & Garciarena 2001).

The use of non-selective fishing gear results in the capture of large quantities of bycatch and discards (DRIyA 2001). Bycatch rates of the freezer and factory fleet vary between 9.9-24.3%, and 2.3-7.2% respectively (Cañete *et al*. 1999). The high seas fleet discards about 25%-30% of its catch, while the coastal fleet discards about 25% (Caille & González 1998). From 1990-1996, between 20 and 75 thousand tonnes per year of young hake (under two years old) that represented between 80 and 300 thousand tonnes of adult fish were caught as bycatch. The cod fishery has been declining since 1999 because of high levels of bycatch of this species in the hake fishery (Cordo 2001). Trawl fishing also affects mammals such as sea lions and dolphins, as well as penguins, albatross, petrels, and seagulls. Incidental capture of macrobenthic organisms is also a common occurrence in the San Jorge Gulf and Chubut coastal areas (Roux 2000). Some species historically discarded in Argentina, such as *Myliobatis* spp., are possibly ‘keystone species’ (Power *et al*. 1996).

III. Pollution and Ecosystem Health

Pollution**:** The coastal areas of the Patagonian Shelf LME face accelerating development pressures. Although pollution is generally slight, its occurrence in several localised areas is cause for concern (UNEP 2004). The effects of pollutants from land-based sources are exacerbated in large river basins such as the La Plata, which contains important urban centres as well as agricultural and industrial activities. The Rio De La Plata and coastal areas are sinks for substantial urban, agricultural and industrial wastes. Pollution of the water and sediments of the Rio De La Plata and its maritime front from land-based and aquatic activities is a key transboundary issue. Some pollution problems arise from the coastal cities of Buenos Aires and Montevideo, which are densely populated and have a high concentration of economic and industrial activities.

Raw sewage is commonly discharged into coastal areas mainly in the vicinity of cities due to the general lack of sewage treatment facilities. This has led to serious microbial pollution in some localised areas. Pathogens, which in some cases have exceeded international recommended levels for recreational water, have been detected in coastal areas (Fundación Patagonia Natural 1999). Toxic red tides are becoming more frequent and of longer duration in the outer La Plata River and maritime front.

The Patagonian coastal zone experiences slight to moderate toxic chemical pollution. For example, lead, zinc and copper concentrations in sediments were registered in San Antonio Bay and in San Matías Gulf. Cadmium was also found in these two localities, affecting local flora and fauna, and threatening migratory birds. High cadmium concentrations were detected in the kidneys and livers of Commerson’s dolphins and dusky dolphins, and in kidneys of kelp gulls. Persistent organic pollutant (such as pp'-DDE) was detected in penguins and kelp gulls. Significant halogenated residues have been found in dead new-born cubs of sea lions, suggesting maternal transmission (Fundación Patagonia Natural 1999).

A sharp increase in turbidity has been observed in localised marine areas due to mining and alteration of the natural vegetation cover of extensive sedimentary areas in Southern Patagonia. About 30% of the Patagonia region is experiencing desertification, basically caused by overgrazing by sheep and cattle (SAyDS 2003). This has increased water runoff and soil losses and in many cases, has resulted in an increase in suspended solids, which cause moderate pollution in coastal areas. Pollution from solid wastes is concentrated mainly in urban areas near the coast where disposal of solid wastes in open dump sites is common.

The LME is subject to heavy shipping and oil tanker traffic. Chronic oil pollution is a problem in the vicinity of ports and oil terminals that have become pollution ‘hot spots’. Ecologically sensitive areas are potentially at risk when winds and marine currents transport these persistent pollutants beyond the port facilities. Beaches are often affected by the presence of tarballs and marine birds are frequently covered with oil. Occasional major oil spills occur in the Patagonian Shelf LME, with significant impact at local levels. Petrogenic hydrocarbons in sediments show the highest concentrations in oil shipping locations where oil and ballasts washing are discharged.

Habitat and community modification: The Patagonian Shelf LME coastal areas have been under pressure from population and industrial growth over the last 15 years, with attendant habitat degradation, fragmentation and loss (Gray 1997). Although this occurs in localised areas, some impacts, for example on migratory species, may be transboundary. Overall, habitat and community modification is moderate, but is expected to worsen in the future (UNEP 2004). Physical alteration and destruction of habitats in the coastal areas occur mainly through mining, dredging, port activities, urban and coastal development, tourism, and destructive fishing methods (DRIyA 2001). Urban and industrial pollution also contribute to this problem. The operation of harbours and oil shipping facilities in some areas along the shore results in localised pollution ‘hot spots’ that harm coastal habitats and associated communities.

Sediments from the continuous dredging of the La Plata River alter marine benthic communities and re-suspend sediments and pollutants. Human-induced erosion is another cause of habitat modification. Most beaches of Buenos Aires have suffered significant erosion and consequent altered coastline. For instance, in Mar Chiquita beach, the rate of the beach retreat reaches 5 m/year in some localities (Bonamy *et al*. 2002). Coastal erosion has also degraded sand dunes, salt marshes and coastal lagoons. In spite of the severe erosion problems that affect the coastline, sand extraction for construction purposes continues.

There is evidence of fragmentation of sandy foreshores, the littoral belt system, and coastal fringes, mainly in the province of Buenos Aires. The La Plata estuary is a highly impacted system because of land use practices in the drainage basin. Modification of the structure of coastal communities and mortality of fauna, mainly on the Buenos Aires coast, has been attributed to habitat degradation. Biodiversity is seriously endangered (Fundación Patagonia Natural 1999); this situation is aggravated by the accidental introduction of exotic species, such as brown alga (*Undaria pinnatifida*), Asian clam (*Corbicula fluminea*) and acorn barnacle (*Balanus glandula*), in some areas. The brown alga, introduced in ballast water, has quickly spread in the Nuevo Gulf area (Casas & Piriz 1996). The persistence of brown alga in this LME is thought to be a consequence of sewage, oil spills and wastes discharged from ships (Fundación Patagonia Natural 1999). Other species such as brown trout, rainbow trout (*O. mykiss*), pacific oyster (*Crassostrea* *gigas*), Chilean oyster (*Tiostrea chilensis*), Chinook salmon (*Onchorhynchus tshawystcha*) and beavers were intentionally introduced.

In the long-term, a slight improvement is expected due to governmental action, the influence of environmental NGOs, enhanced community awareness and commitment and increased self-regulation of industry. However, improvements in pollution control will require major investments by the private and public sectors.

IV. Socioeconomic Conditions

This LME includes the entire coastlines of Argentina and Uruguay. The combined population of the coastal cities of Montevideo and Buenos Aires is close to 16 million inhabitants. Both countries have a high urbanisation rate, with the urban population significantly exceeding the rural population. Fisheries contribute less than 1% to the GDP of these countries. Other marine-related economic activities include tourism and offshore oil exploration. The overall socioeconomic impact of unsustainable exploitation of fisheries in the Patagonian Shelf LME is moderate, and could become worse in the future if regulations are not implemented and enforced (UNEP 2004). In particular, overfishing of hake has resulted in severe social problems, loss of employment, and the closure of fishing enterprises. Since 1997, employment has decreased by about 22%, while more recently it decreased by about 13% in the Patagonian region (Bertolotti *et al*. 2001). Between 1999 and 2000, employment by the high seas fleet decreased by about 9%. Likewise, in the same period, employment by the freezer and factory fleets decreased by up to 14% (Bertolotti *et al*. 2001). Argentine fish exports decreased in 2002, mainly due to international and national market conditions, but also to reduced hake landings, which led to the closure of many fish plants (Bertolotti *et al*. 2001). Of the 38 established plants only 26 were operative in 2001. Since 1998 there has been an ongoing trend towards poorer working conditions and lower incomes. The likelihood of conflicts among different sectors also increases as a result of overfishing.

Toxic algal blooms have a negative economic impact on the private sector engaged in fisheries exploitation and seafood production, when harvests and sales are prohibited due to toxic algal blooms. Algal blooms and oil spills demand major economic investment in contingency measures. Toxic algal blooms together with shellfish toxicity have serious consequences for public health, and have caused some deaths in the Patagonian Shelf LME region. Habitat and community modification have significant economic and social impacts on coastal populations, particularly those related to fisheries exploitation. Generally, the impacts on local communities are quite harsh. Economic losses and elevated costs associated with this issue affect both the State and private sectors comprised mainly of small enterprises, cooperatives, and individuals, who are most vulnerable. Damage to urban infrastructure and disruption of coastal activities by coastal erosion has strongly affected tourism revenues and promoted conflicts among different users (tourism, aquaculture, and fishing). Many affected municipalities are now executing projects to address problems created by coastal degradation.

V. Governance

Argentina and Uruguay have national and local environmental authorities and have developed national policies and programmes aimed at the protection and management of the natural environment. The two countries are in the process of strengthening the regulatory capacity of their national environmental authorities with support from the Inter-American Development Bank. The environmental action plans of Argentina and Uruguay have set as goals the conservation and rehabilitation of the coastal habitats of the Rio de la Plata and Atlantic Ocean and strengthening the management of common resources and boundary areas.

An area held in common by both Argentina and Uruguay is the Rio de la Plata and its maritime front. The Treaty of the Río de la Plata and its Maritime Front, signed in 1973 by both countries, established the legal framework for the bi-national management of this area. This framework includes two bi-national governmental Commissions responsible for the preservation, conservation and rational use of living resources and the prevention and elimination of pollution. The Argentine-Uruguayan Technical Commission for the Rio de la Plata Maritime Front has jointly managed the shared hake stock since 1975.

The Patagonian Shelf LME, along with the East and South Brazil Shelf LMEs, forms the Upper South-West Atlantic Regional Sea Area. In 1998, in cooperation with the UNEP/GPA Coordination Office and the UNEP Regional Office for Latin America and the Caribbean, a Regional Programme of Action on Land-based Activities and a regional assessment for the Upper South-West Atlantic were prepared and endorsed by representatives of the three governments. The first steps in implementing the programme, which covers the coast from Cape São Tomé in Brazil to the Valdés Peninsula in Argentina, are under development. The Argentine Federal Fisheries Council (CFP) has requested that the National Fisheries Research and Development Institute (INIDEP) implement a mechanism that provides updated scientific information on the status of the resource [www.cfp.gov.ar/funciones_ing.htm].

Argentina and Uruguay have embarked on a joint project supported by GEF and implemented by UNDP: ‘Environmental protection of the Rio de la Plata and its Maritime Front: Pollution Prevention and Control and Habitat Restoration’. The project will contribute to the mitigation of current and emergent transboundary threats to the water body by assisting Argentina and Uruguay to prepare a Strategic Action Plan (SAP) as a framework for addressing the most imminent transboundary issues. Preparation of the SAP would be preceded by finalisation of a TDA, building on assessments already completed by prioritising issues, filling data gaps, and performing an in-depth systems analysis of cause/effect variables, including socioeconomic and ecological factors.

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XVII SOUTH EAST PACIFIC

XVII-56 Humboldt Current LME

XVII-56 Humboldt Current LME

S. Heileman, R. Guevara, F. Chavez, A. Bertrand and H. Soldi

The Humboldt Current LME extends along the west coast of Chile and Peru. It has a surface area of 2.5 million km^2, of which 0.11% is protected, and contains 0.42% of the world's sea mounts and 24 major estuaries (Sea Around Us 2007). The LME's circulation patterns are described by several authors including Wyrtki (1967), Alheit & Bernal (1993) and Wolff *et al*. (2003). Ekman offshore divergence due to the southerly trade winds gives rise to the world's largest coastal upwelling system that characterises this LME. This system shows high climatic as well as oceanographic variability associated with seasonal, interannual, decadal and longer-term changes. Considerable interannual variability occurs when the normal seasonal upwelling is interrupted by ENSO, which results in intrusions of warm, clear oceanic waters from the west and north (Wolff *et al*. 2003, Alheit & Ñiquen 2004). Book chapters and reports pertaining to this LME are by Alheit & Bernal (1993), Wolff *et al*. (2003), UNIDO (2003) and UNEP (2006).

I. Productivity

The upwelling of cold, nutrient-rich waters promotes high primary production in the Humboldt Current LME. Intense upwelling cells are located along the coast. However, the average level of primary productivity is estimated as moderate (150-300 gCm^{-2}yr^{-1}), Class II. Climatic variability is thought to be the primary driving force of biomass change in this LME, promoting marked regime shifts (Alheit & Bernal 1993, Alheit & Ñiquen 2004, Cubillos et al. 2002; Sifeddine et al., in press). Four species of pelagic schooling fish dominate this LME: anchoveta (*Engraulis ringens*), sardine (*Sardinops sagax*), jack mackerel (*Trachurus murphyi*) and chub mackerel (*Scomber japonicus*). The long-term dynamics of this LME are defined by shifts between alternating anchovy and sardine regimes that restructure the entire ecosystem from phytoplankton to the top predators, often under the influence of El Niño (Alheit & Ñiquen 2004; GTE IMARPE 2003; Klyashtorin 2001; Bouchón et al. 2000). Valdés et al. (2008) have shown that sardine and anchovy do not always vary synchronously. Phases with mainly negative temperature anomalies parallel anchovy regimes while the warm periods have been characterised by sardine dominance. Planktonic food sources for juvenile and adult anchovies are reduced because of decreased plankton production due to restricted upwelling in warm years and the diminution of the abundance of large copepods, their main food source (Alheit & Ñiquen 2004, Ayón et al. 2004, Ayón et al. in press; Yañez et al. 2003). Devastating consequences arise for the pelagic fisheries off Chile and Peru (see Fish and Fisheries) as well as for the marine fauna that rely on these normally highly productive areas. The coincidence in the fluctuations of small pelagic fish in the Humboldt, Kuroshio and California Current systems suggests teleconnections among them (Kawasaki 1991, Lluch-Belda *et al*. 1992). See Serra et al. (2002) for an extended discussion of climate change and the variability of pelagic fish stocks in the Humboldt Current Ecosystem.

Oceanic fronts (Belkin et al. 2009; Belkin & Cornillon 2003): The most important front off Peru is caused by wind-induced coastal upwelling (Figure XVII-56.1). The Peruvian Upwelling Front (PUF) extends along the shelf break from 5°S to 19°S. Farther south, the coastline sharply changes its orientation and is no longer favorable to wind upwelling. A new summertime front has been described from satellite data, called the Nasca Front (NF) because of its proximity to the Nasca Ridge (Belkin & Cornillon 2003). The Nasca Front (NF) departs from the Chilean coast at 25°S-27°S and extends northwestward, best developed in March. This front is a major tuna fishing ground, especially important for the yellowfin tuna fishery. The Subtropical Frontal Zone, bounded by the North and South Subtropical Fronts (NSTF and SSTF respectively), crosses the South Pacific zonally between 35°S-40°S, impinges Chilean coast and bifurcates, with its branches flowing meridionally but in opposite directions along Chilean coast. The attendant fronts between the Subtropical Frontal Zone waters and Chilean coastal waters are observed year-round. South of 40°S, the Chilean Archipelago low-salinity waters form a salinity front at the contact with oceanic waters.

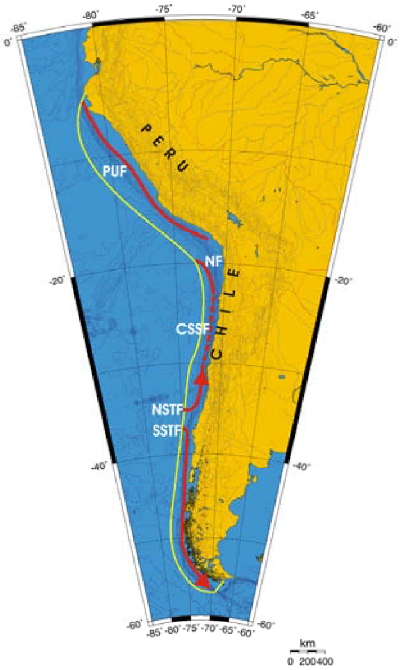

Figure XVII-56.1. Fronts of the Humboldt Current LME. Acronyms: CSSF, Chilean Shelf Slope Front (most probable location); NF, Nazca Front; NSTF, North Subtropical Front; PUF, Peruvian Upwelling Front; SSTF, South Subtropical Front. Yellow line, LME boundary. After Belkin et al. (2009).

Humboldt Current LME SST (Belkin 2009)
Linear SST trend since 1957: 0.41°C.
Linear SST trend since 1982: -0.10°C.

The thermal history of this LME (Figure XVII-56.2) can best be interpreted in the El Niño-Southern Oscillation (ENSO) framework. The northern part of this LME is strongly affected by El Niños and La Niñas (National Weather Service/Climate Prediction Center, 2007). The southern part of this LME is not directly impacted by these events. The El Niños of 1983 and 1997 were pronounced in this LME; other El Niños are barely noticeable in our time series, partly because of the area-weighed averaging over this exceptionally long LME, most of which is not affected by El Niños. In the long-term, the Humboldt Current warmed by 0.41°C since 1957. The long-term warming trend was not uniform. In fact, the Humboldt Current experienced a 1°C cooling in 1957-1973, followed by a decade-long warming that culminated in 1983. These opposite trends represent two major oceanic regimes. Biologically, these regimes manifest as “alternating anchovy and sardine regimes that restructure the entire ecosystem from phytoplankton to the top predators” (Alheit and Niquen, 2004, p. 201). Except for the warm events of 1983 and 1997 linked to El Niños, there was hardly any long-term warming in the Humboldt Current over the last few decades. Moreover, the linear trend over 1982-2006 yields a slight cooling of -0.10°C.

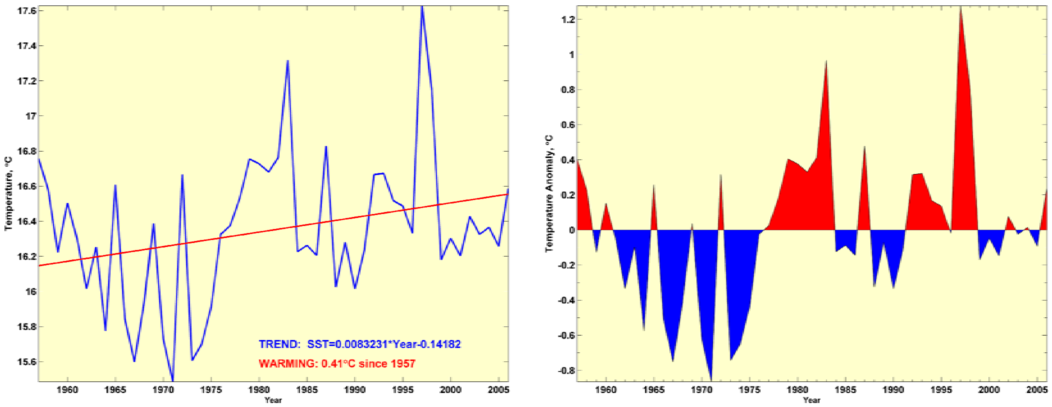

Figure XVII-56.2. Humboldt Current LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

The Humboldt Current LME and the California Current LME are the two LMEs that experienced ***cooling*** over the last 25 years. Both LMEs are located in the East Pacific coastal upwelling zones, where the upwelling intensity is near its global maximum. In these zones, equatorward alongshore winds cause offshore transport of warm surface waters and upwelling of cold subsurface waters. The observed cooling in these areas suggests an increase in the upwelling intensity, likely caused by an increase in the strength and/or persistence of the upwelling-favorable alongshore equatorward winds. This hypothesis is supported by observed data and numerical modeling experiments (for the California Current, see Schwing & Mendelssohn 1997). The fact that California and Peru both show decreasing SST trends is clearly related to a multi-decadal shift that occurred in the mid-1990s. Chavez et al., 2003 provide a conceptual model of what happens in the Pacific during these shifts and a preliminary description of the mid 1990s shift). This shift led to shallower than average thermocline in the eastern Pacific, cooler SSTs and higher chlorophyll and primary productivity. Note that Pennington and others (2006) found significant variations in monthly values for chlorophyll and primary productivity of sub-systems of the Humboldt Current.

Humboldt Current LME Chlorophyll and Primary Productivity: The average level of primary productivity is estimated as moderate (150-300 gCm^{-2}yr^{-1}), Class II.

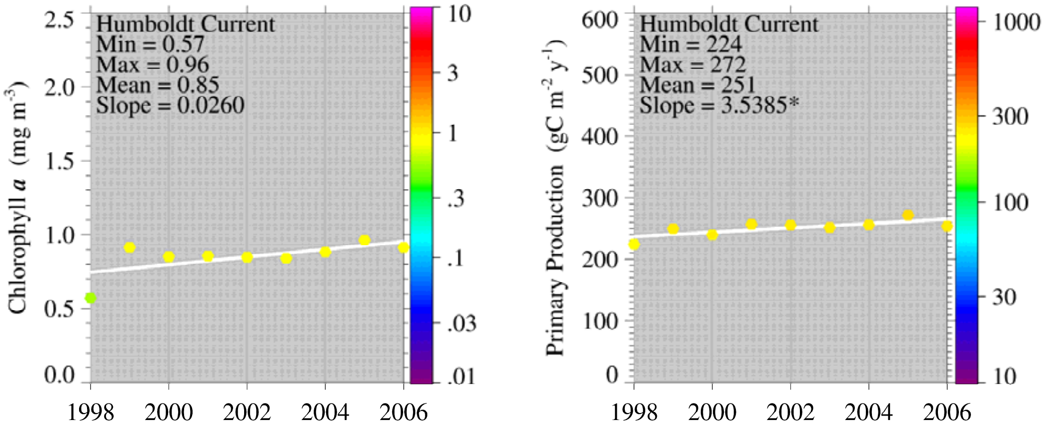

Figure XVII-56.3. Humboldt Current LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The Humboldt Current LME's high productivity supports the world's largest fisheries. In 1994, fisheries catches by Peru and Chile amounted to 12 million tonnes. These two countries account for between 16% to 20% of the global fish catch--mostly small schooling pelagic fish such as sardines, anchovies (especially the 'anchoveta', *Engraulis ringens*), jack mackerel, chub mackerel and hake, whose dynamics off Peru was reviewed in contributions in Pauly & Tsukayama (1987), Pauly *et al.* (1989), Barría et al. 2003 and Bertrand et al (In Press-a). Highly migratory resources shared between Chile and Peru (UNIDO 2003) include tuna, sword fish, shark, and giant squid. Tropical and temperate molluscs, crustaceans and sea urchins are also important resources. Total reported landings fluctuate, with two major peaks at over 11 million tonnes in 1970 and 1994 (Figure XVII-56.4) but actual catches may be much higher. For example, Castillo & Mendo (1987) estimated a maximum catch of 18 million tonnes from the Northern-Central stock of Peruvian anchoveta. The VMS control system implemented by the government in Peru in 2004, and the SGS report control system have reduced the underreporting of catches. The value of the reported landings also fluctuates, reaching about US$10 billion (in 2000 US dollars) in 1970 (Figure XVII-56.5).

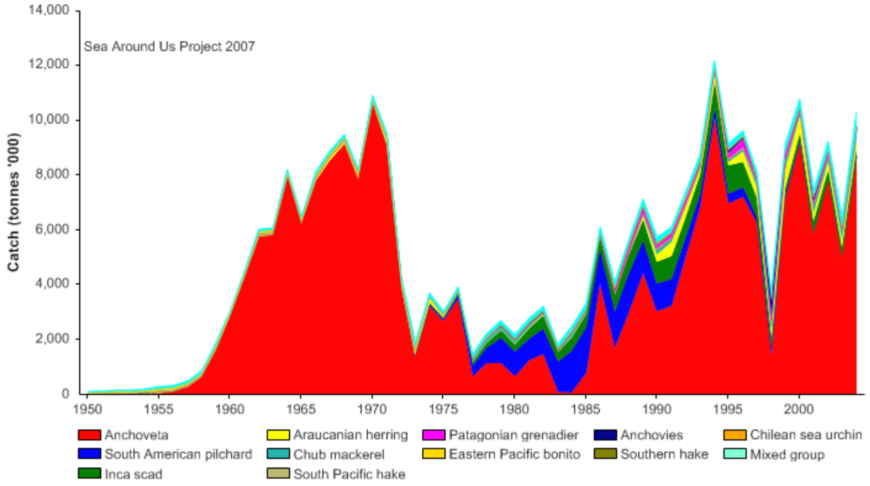

Figure XVII-56.4. Total reported landings in the Humboldt Current LME by species (Sea Around Us 2007).

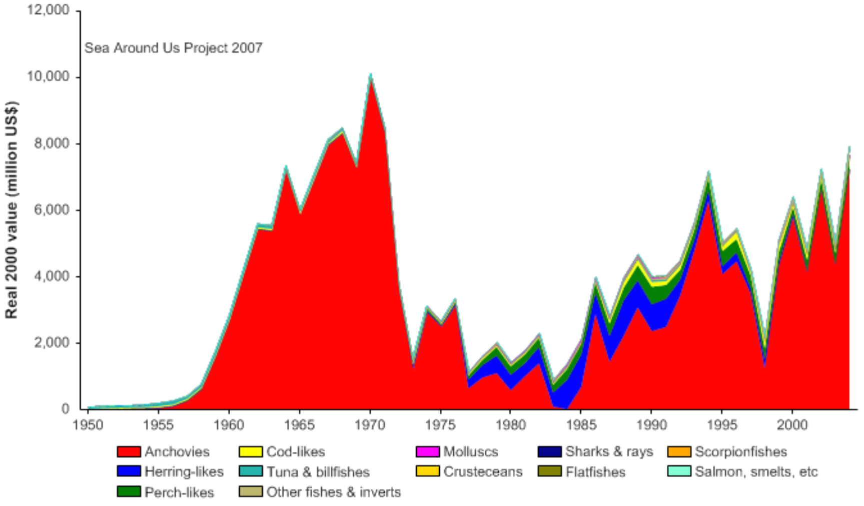

Figure XVII-56.5. Value of reported landings in the Humboldt Current LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings reached 20% of the observed primary production in the LME in the mid 1990s, and has fluctuated at this level in recent years (Figure XVII-56.6). Peru and Chile account for almost the entire ecological footprint in this LME.

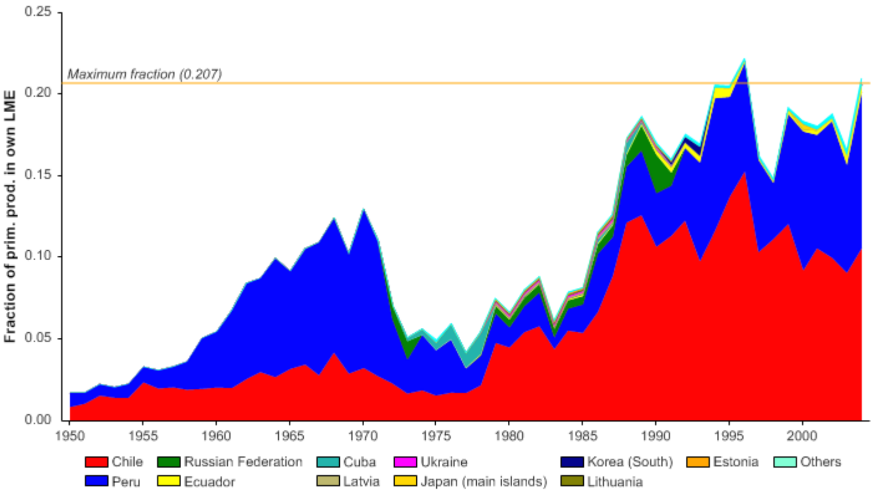

Figure XVII-56.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Humboldt Current LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of reported landings (i.e., the MTI, Pauly & Watson 2005) in this system, which in the early 1950s looked like most other LMEs (MTI of about 3.4), plunged as soon as the fisheries for anchoveta, a low-trophic level species, took off (Figure XVII-56.7, top). Indeed, for two decades, this fishery was the largest single-species fishery in the world, with some of its fluctuations in landings reflected in the FiB index (Figure XVII-56.7, bottom). Because of the dominance of anchoveta in the landings of the LME, Figure XVII-56.8 is not informative as to the status of the ecosystem. Note that in the 1940s and 50s, the Peruvian fishery was based on species like Bonito and Tuna (due to the high demand of the liver oil of these species in the US market during the II WW and Korean wars). The Anchoveta fishery started around 1955 and became the most important species during the 1960´s. This explains why the MTL diminishes in such a way during the 50´s and the FIB increases.

Pauly & Palomares (2005) studied a time series of these indices for the Peruvian segment of this LME and found that the fish assemblages exploited by coastal fisheries show strong signs of 'fishing down' (as in Pauly *et al.* 1998). Such trends can also be examined at www.seaaroundus.org, by computing the indices without anchoveta landings.

The Stock-Catch Status Plots indicate that over 80% of commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XVII-56.8 top). The plots also indicate that collapsed stocks contribute over 80% of the reported landings (Figure XVII-56.8, bottom). This is, at least in part, a definitional artefact, because of the classification of anchoveta as an overexploited stock, having experienced its maximum catch in the early 1970s, even though its catches have recovered in recent years. Here again, the analysis may benefit from being conducted without the anchoveta catch (see www.searoundus.org).

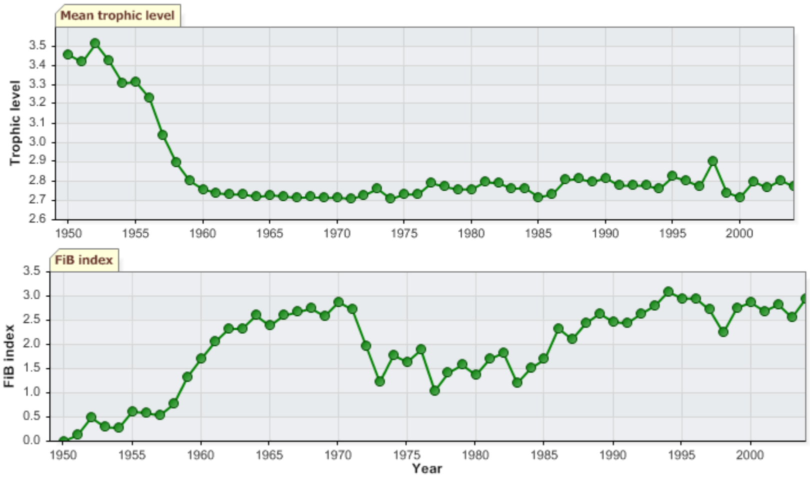

Figure XVII-56.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Humboldt Current LME (Sea Around Us 2007).

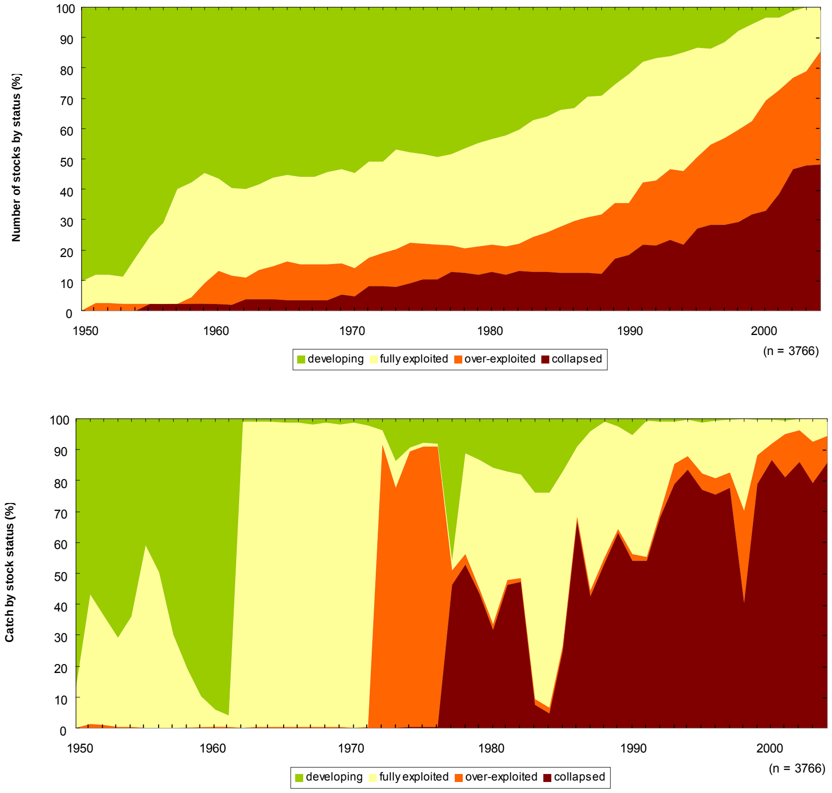

Figure XVII-56.8. Stock-Catch Status Plots for the Humboldt Current LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The marked climate-driven changes in fish biomass and distribution have a drastic impact on their fisheries. Since the early 1950s, the pelagic fishery has experienced dramatic changes in total catch as well as in the catch composition (Wolff *et al*. 2003), notably in the occurrence of anchoveta and sardine. Landings of anchoveta reached the lowest levels after the 1982/1983 El Niño. From the late 1980s, anchoveta landings recovered and remained high through 2004 except for the drop in 1998 because of El Niño (Schwartzlose *et al*. 1999, Alheit & Ñiquen 2004, Bertrand et al. 2004, Gutiérrez et al. 2007, Serra et al. 2002). The jack mackerel has also shown significant population booms and declines (Wolff *et al*. 2003). Schwartzlose et al. (1999) examine El Niño as the signal of inter-annual variation, but there are other sources of inter-decadal variation that should be mentioned in the text. For information on other sources of inter-decadal variation, review the published FAO documents and Chavez *et al.* (2003).

In addition to climatic variability, intense fishing pressure has also contributed to the changes in total catch as well as to changes in catch composition over the past decades. In fact, overexploitation was found to be the main concern in relation to fisheries in the LME (UNEP 2006). A fundamental problem is the enormous overcapacity of vessels and fish processing plants (Csirke & Gumy 1996, Fréon et al. in press). Demersal resources show a variable degree of exploitation. In Peru there are signs that the abundance, mean size caught and size at first maturity of some species have decreased. Since the beginning of the 1990s, young hake have increasingly appeared in catches as a response to overfishing, adverse climatic regime, and changes in species interactions (Wosnitza-Mendo & Guevara-Carrasco 2000, Guevara-Carrasco and Lleonart 2008, Ballón et al. in press). Catches of small hake are far above the 20% rate recommended to sustain the fishery. Furthermore, large, older females have been gradually fished out, resulting in low egg production of the stock (Wolff *et al*. 2003, Ballón et al. in press). Economic overfishing of the hake fishery occurred in 1999 as a result of increase in fishing effort by the national fleet (Wolff *et al*. 2003). The Chilean hake fishery showed a sudden decline in 2004.

An important fishery for the giant squid (*Dosidicus gigas*) occurs along the coast of Peru (Rodhouse 2001). Catches increased from 10,000 tonnes in 1989 to at least 200,000 tonnes in 1994, and have fluctuated in the past decade. Landings during 2002 and 2003 were 100,000 tonnes (Ministerio de la Producción de Perú 2004). The fishery for this species is considered to be under-to-fully exploited. Updated information on the Chile hake and giant squid fishery can be found on www.supesca.cl. Pérez and Buschmann (2003), provide analysis on the sustainability of the major Chilean fisheries; Payá (2003) and Payá et al. (2000, 2002) provide analysis on the Chilean hake fishery.

In general, excessive bycatch and discards appear to be minimal (UNEP 2006). The anchoveta and sardine fisheries have very low bycatch rates (1% - 3%). Sea turtles have been targeted and/or taken as incidental catch during the last three decades. The most common bycatch species in Peru is the common dolphin. Other species caught incidentally include the South American sea lion and marine birds. In Peru significant quantities of discards occurred in the hake fishery (20% of the total catch). Present values are much lower since the implementation of the VMS (vessel monitoring system) and direct onboard observers system in 2004.

In Peru, the decrease of fisheries resources as well as changes in the composition and abundance of species in the coastal areas are attributed to the deterioration of coastal habitats from trawling and the use of purse seine nets with small mesh size. The decreases have other causes including fishing, climate variability and coastal degradation that is largely restricted to enclosed bays and limited coastal areas. There is no specific study on the effects of trawling and pollution on coastal resources. The importance of each one of these sources in the fisheries is a matter of present research.

The use of explosives in both industrial as well as artisanal fisheries is increasing (IMARPE 2002). Substantial changes in the structure of the food web as a result of decades of intensive fishing are evident (Wolff *et al*. 2003). This has had a negative effect on the resilience of the system as a whole. The long term changes observed in the Peruvian ecosystem are also explained by environmental fluctuations. The concept of "Regime Shifts" has been argued to explain these changes and the causes have been documented by Chavez, et al (2003), Schwartzlose et al. (1999), Alheit & Ñiquen (2004), Csirke et al. (1996) and in the Bulletins of IMARPE. Not all the changes in the food web structure can be explained by the impact of the fishing activities.

Overfishing may be a major threat to the genetic integrity of fish populations and ecosystem structure in the LME (Cury & Anneville 1998, UNIDO 2003), leading to further system destabilisation through an increase in the amplitude of annual stock variations (Anderson et al. 2008). In the past, the lack of integrated fisheries management policies incorporating an ecosystem approach and natural environmental variability has had severe impacts on this LME's fisheries resources. The sustainability of the fisheries in the Humboldt Current LME is strongly dependent on the continuing combined efforts of Chile and Peru to achieve scientifically informed, adaptive, governance that takes into account the many driving forces within this important large marine ecosystem. A comprehensive vision of the fisheries of this region was published by FAO in the series: Review of the State of Marine Fishery Resources (FAO Fisheries Technical Paper 457 (2005). Chapter B.15 Southeast Pacific by Jorge Csirke).

III Pollution and Ecosystem Health

Pollution: Pollution of the coastal zone may be increasing due to population growth and concentration in the coastal zone, industrialisation, agriculture, urban development, tourism as well as maritime transport (UNIDO 2003). Most of the pollution problems are related to the lack of adequate treatment of domestic and industrial wastewater, agrochemicals and heavy metals from mining runoff. However, this issue is an important subject on the agenda of the environmental agencies of both countries and present legislation requires industries to treat liquid residuals before discharge to the environment. Pollution is not significant in the LME except for some specific hotspots (UNIDO 2003, UNEP 2006). Microbiological pollution arising from untreated sewage was identified as being a priority concern. In Peru, up to 86% of domestic wastewater is not treated (CPPS 2001) and is discharged into coastal areas (Sánchez 1996).

High levels of nutrients have been found in areas with chronic problems of pollution and continuous discharges such as Callao, Ilo and Ite in Peru and Valparaiso, Concepción, San Vicente, Bio-bio River in Chile (Zúñiga & Burgos 1996). Wastes from fish canneries as well as fishmeal factories are among the most important sources of nutrient enrichment in coastal areas, especially in some locations in the north of Chile and in Chimbote, Paita and Pisco in Peru. High values of chlorophyll *a* and low levels of oxygen with a tendency to hypoxia are typically found off these ports. The increase of organic wastes in semi-closed bays of Peru has produced HABs that have caused the mortality of fish as well as invertebrates (IMARPE[1], unpublished data).

The presence of chemicals such as DDT, DDE, and Lindane was reported in water and sediments along the coast, and in some marine species (e.g., mullet, croaker and molluscs) (Cabello & Sánchez 2003). Regional assessments of heavy metals in coastal waters, sediment and marine organisms showed that significant concentrations of copper, lead, cadmium, zinc, mercury and chromium are related to municipal wastewater discharges and mining runoff (CPPS/UNEP/IOC 1988). Despite the permanent risk of oil

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[1] The Peruvian Institute of Marine Research.

spills, levels of hydrocarbons in water are generally low except in localised areas where petroleum activity and maritime traffic are concentrated. In these areas, high concentrations of hydrocarbons have been found in water and sediments (Jacinto & Cabello 1999).

Habitat and community modification Although a large part of the coast is arid, it contains a variety of habitats such as mangroves, estuaries and sand dunes, some of which serve as important breeding as well as nursery areas for many marine species including marine mammals and turtles. These habitats are also of socioeconomic importance to the region, but their economic value is largely unknown and not integrated in coastal development (UNIDO 2003). Habitat modification was assessed as moderate in the LME and generally linked to the development of the coastal zone for infrastructure, urbanisation, tourism, aquaculture farms and industrialisation (UNEP 2006). Pollution is also a major cause of degradation of coastal habitats in localised areas. Fishing gears such as demersal trawls are among the potential causes of physical alteration of bottom habitats in the northern part of the region (UNIDO 2003).

Deforestation of mangroves is probably the most evident case of habitat loss in the region. Several mangrove areas are considered to be under a high level of threat. Peruvian mangroves have been cleared to build shrimp farms and degraded through the extraction of biological resources.

The introduction of alien species for culture purposes or through ballast waters has been of concern (CPPS 2003). Canepa *et al*. (1998) reported 14 introduced species (11 microalgae, three fish and molluscs) in the coastal environment in Peru. In Chile, Báez *et al*. (1998) reported 43 alien species in the marine environment, including algae, molluscs, crustaceans and several species of fish.

The health of this LME is expected to improve with the implementation of measures to reduce the impact of human activities and other ongoing initiatives in the region (UNEP 2006).

IV. Socioeconomic Conditions

The population of the two bordering countries, Chile and Peru, is 17 and 28 million respectively. There is increasing development and urbanisation along the coast, with almost 60% of the population of Peru's and 19% of Chile's population living in coastal areas (CPPS 2001). The economy of the two countries is mainly based on agriculture, fisheries, coastal industries, oil-related industry, ports and ocean transport (CPPS 2001). Coastal tourism is becoming increasingly important, whereas aquaculture is one of the most dynamic and important sectors of the Chilean economy (FAO 2000a).

Fisheries are of major socioeconomic importance to the two countries. In 2001, fish exports from Peru represented 16% of the total, with a value of over US$1 billion and contributing 0.49% of the GNP. Chile's fish exports (including salmon and fishmeal) in 2001 were valued at about US$1 billion or 5.5% of the total exports and contributed 1.4% to the GNP. Artisanal fisheries production makes an important contribution to the regional economy. The fisheries sector provides employment for thousands of persons in both countries. It is estimated that in 1999 more than 80,000 people worked in fishing and aquaculture (FAO 2000b).

The economic impacts of overexploitation of fish are severe (UNEP 2006). The variability in stock abundance and distribution as a consequence of environmental changes as well as high fishing pressure has had devastating consequences for the fishing industry and the economies of the two countries. For example, several hundreds of millions of US dollars in foreign currency were lost as a result of the collapse of anchovy stocks following the strong ENSO of 1972/1973 (Wolff *et al*. 2003). A TDA conducted by Chile and Peru with funding from GEF (UNIDO 2003) has identified several socioeconomic consequences of overexploitation of fisheries resources in the Humboldt Current LME. These include loss of access to potential markets, loss of investments, increase in conflicts between industrial and artisanal sectors, reduction in employment and food security, migration and occupational displacement. Overexploitation of fisheries resources will also have negative consequences on food security as well as on the eradication of poverty and hunger in the region.

The socioeconomic impacts of pollution are low but are of growing concern in the region because of its potential impact on the quality of life (UNEP 2006). Untreated domestic wastewater discharged into coastal waters poses a major health risk through direct contact.

Unsanitary conditions, as well as poverty and the eating habits of the population were associated with the 1991 cholera outbreak in some coastal areas. In addition to the risk to human health, pathogens also affect aquaculture in the region due to the reduction in quality water, e.g. in Peru the presence of the hepatitis. Other socio-economic consequences of pollution include loss of investments and employment opportunities, diminished fisheries productivity and reduced market competitiveness (UNIDO 2003).

Mangrove loss has a significant impact on the artisanal fishery, through loss of shelter and nursery areas for commercially important fish and invertebrates. Shrimp aquaculture is also affected by reduced water quality, due to the loss of the natural purification functions of coastal habitats, increase of coastal erosion as well as loss of nursery areas for shrimps. The Environmental Performance Review of Chile conducted jointly by the OECD and UN ECLAC recommended in 2005 that Chile continue to strengthen its environmental institutions to improve air, water, waste and nature management at national and regional levels, and especially in metropolitan areas. The estimated cost to replace the loss of the natural treatment ability of coastal ecotones may be comparable with that in Ecuador of one billion US$ (Hurtado *et al*. 2000).

V. Governance

Chile and Peru share the governance of the Humboldt Current LME. Each country has institutions (e.g., the Sub-Secretary of Fisheries and the Vice Ministry of Fisheries, respectively) mandated with management of its marine and coastal resources, national laws, and a national institute responsible for fisheries research: the Fisheries Research and Development Institute (IFOP) in Chile and the Marine Research Institute (IMARPE) in Peru. Both Chile and Peru have established a national environmental authority responsible for environmental conservation and natural resource management – the National Environment Commission (CONAMA) and the National Council for the Environment (CONAM), respectively. In May 2008 Peru merged the CONAM and the recently created Ministry of the Environment.

Regional frameworks for the management, including monitoring, of the LME and its resources, have been developed. Chile and Peru, along with Colombia and Ecuador, are members of the Permanent Commission for the South Pacific (CPPS 2003a; 2003b), the regional maritime organisation responsible for the coordination of the maritime policies of its Member States. The Framework Agreement for the Conservation of Living Marine Resources in the High Seas of the Southeast Pacific (Galapagos Agreement) and the Convention for the Protection of the Marine Environment and Coastal Areas of the South-East Pacific (Lima Convention) as well as other complementary agreements are the basis for a fruitful regional cooperation among Chile, Peru and other countries for the conservation of the marine environment.

The Lima Convention and its protocols provide the general legal framework of the Plan of Action for the Protection of the Marine Environment and Coastal Areas of the South-East

Pacific, which comes under the South-East Pacific Regional Sea Programme. The Plan of Action binds the contracting parties to make an effort to adopt the appropriate measures to prevent, reduce and control the pollution of the marine environment and coastal areas as well as secure adequate management of the natural resources in the South East Pacific.

Other programmes include the Tropical Ocean-Global Atmosphere, the World Ocean Circulation Experiment, the Joint Global Ocean Flux Study, the Global Ocean Ecosystem Dynamics Programme on Small Pelagics and Climate Change and an EU-sponsored project (Climate variability and El Niño Southern Oscillation: Implications for natural coastal resources and management). The GEF is supporting a project (Integrated Management of the Humboldt Current Large Marine Ecosystem) to enhance national as well as regional efforts to achieve integrated and sustainable management of the LME. The first phase of the project included the development of a TDA and a preliminary SAP to address both the threats to the LME and the gaps in knowledge essential to the sustainable management of the ecosystem. Under this project, an interim coordinating executive committee was established to implement agreements under the Bilateral Humboldt Current Compact.

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XVIII ANTARCTIC

XVIII-57 Antarctic LME

M.C. Aquarone and S. Adams

The Antarctic LME is defined by the Antarctic Convergence (or Antarctic Polar Front), the boundary oscillating between 48 and 60° S and separating the colder Antarctic surface waters from the warmer sub-Antarctic waters to the north. The boundary varies seasonally and as a result of winds, currents and sea conditions. The colder Antarctic surface waters sink beneath the warmer water masses. The LME covers a surface area of about 4.3 million km^2, of which 0.05% is protected, and contains 0.04% of the world's sea mounts (Sea Around Us 2007). The LME's geographic and climatic characteristics are characterised by extreme weather conditions and by the ice cap, holding 70% of the Earth's fresh water. Book chapters and articles pertaining to this LME include Scully *et al*. (1986), Scully (1993), Hempel (1990) and Hubold (2003). Most of the present synopsis is on the Weddell Sea where considerable focus on the study of krill (euphausiids) and their predators and prey by scientists, policy specialists and living marine resource managers has been directed by the Commission for the Conservation of Antarctic Living Marine Resources (CCAMLR) since 1985.

I. Productivity

One of the largest shelf areas around the Antarctic continent is found in the southern part of the Weddell Sea (Hempel 1990). The Antarctic Circumpolar Current flows around Antarctica and provides a partial return of water to the South Pacific, the South Indian Ocean and the South Atlantic Ocean. The Antarctic LME is a Class II, moderately productive ecosystem (150-300 $gCm^{-2}yr^{-1}$). This is linked with extreme weather conditions and limited light penetration due to the winter ice cover. In the Weddell Sea, the seasonal production cycle is strongly determined by ice formation in the fall and ice melting in the spring and summer (Hubold 2003). Upwelling and cold water currents flowing around Antarctica release nutrients that stimulate plankton blooms. The base of the marine food chain is supported by about 100 species of phytoplankton. Some 200 Antarctic finfish species are found south of the Antarctic Convergence, 25% of which are unique to the area. The species of zooplankton, fish, squid, benthic organisms, seals, whales and birds found at this latitude have sophisticated mechanisms for survival under very cold conditions. Low metabolic rates help them maintain a higher rate of protein synthesis. The food chain is often very short, with krill (*Euphausia superba*) serving as a forage species crucial to the sustainability and production of all other fisheries in the LME. Baleen whales, seals, penguins, squid, fish and seabirds all feed on krill (see contributions in Palomares *et al.* 2005). For specific information on the Weddell Sea, see Hempel (1990) and Hubold (2003). For a recent review of the circumpolar habitats of Antarctic krill, see Atkinson et al. (2008).

Oceanic fronts (Belkin *et al.* 2009)(Figure XVIII-57.1): The Antarctic Shelf-Slope Front (ASSF) is observed along most of the Antarctic shelf/slope, except for the southern Pacific Antarctic and also a part of the Weddell Sea. This front separates very cold shelf waters from warmer oceanic waters. A geostrophic current that flows westward along this front carries icebergs around the continent for thousands of kilometres, branching north into marginal Antarctic seas. This current and associated front is largely set up by strong and persistent katabatic winds that drain very cold air from the Antarctic Plateau. Local fronts exist off the Antarctic Peninsula, in the Prydz Bay, and in the Ross Sea.

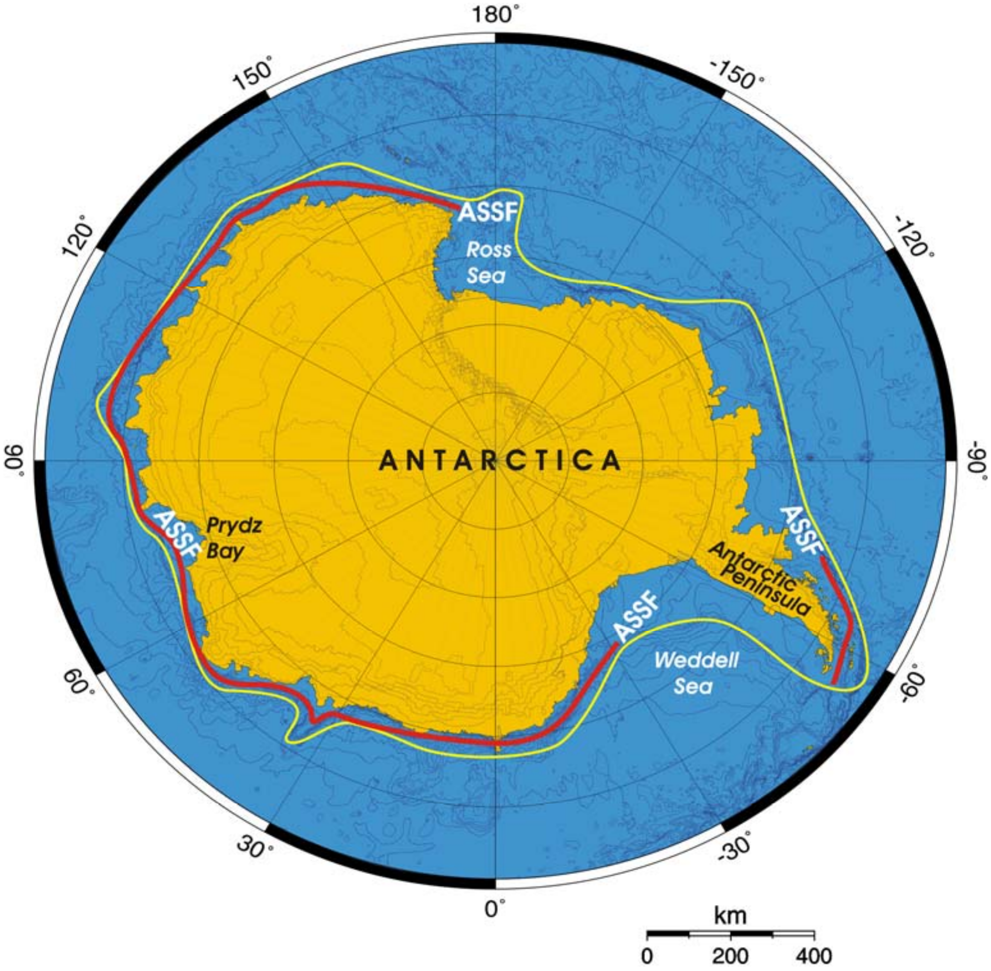

Figure XVIII-57.1. Fronts of LME the Antarctic LME. ASSF, Antarctic Shelf-Slope Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

Antarctica LME SST (Belkin 2009)(Figure XVIII-57.2):

Linear SST trend since 1957: 0.11°C.
Linear SST trend since 1982: 0.01°C.

The relatively slow warming of the Antarctic Zone may be just an appearance because of the masking effect of the perennial sea ice cover in the near-coastal zone where the Antarctic LME is largely located. This LME was excluded from the analysis since the near-coastal zone is covered by drifting sea ice, landfast ice, and icebergs almost year round; therefore, the SST data from the Antarctic LME are deemed severely contaminated by the presence of ice and therefore less reliable than elsewhere.

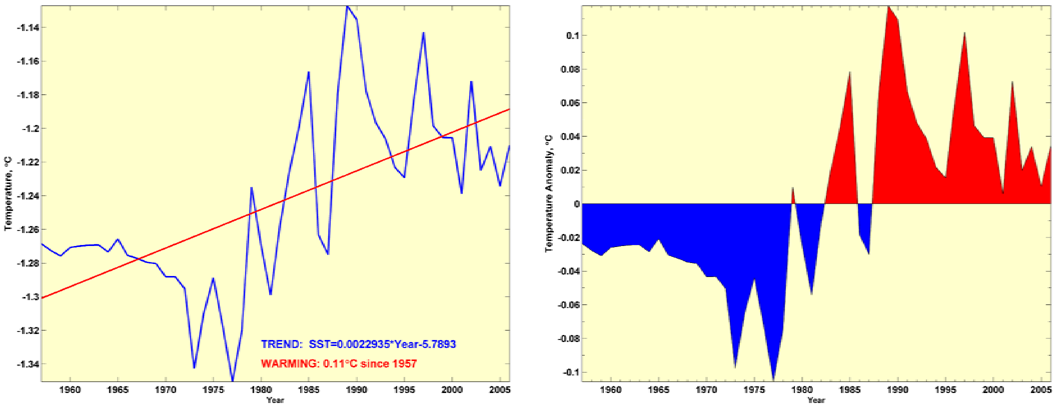

Figure XVIII-57.2. Antarctic LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Antarctic LME Chlorophyll and Primary Productivity

The Antarctic LME is a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1})(Figure XVIII-57.3).

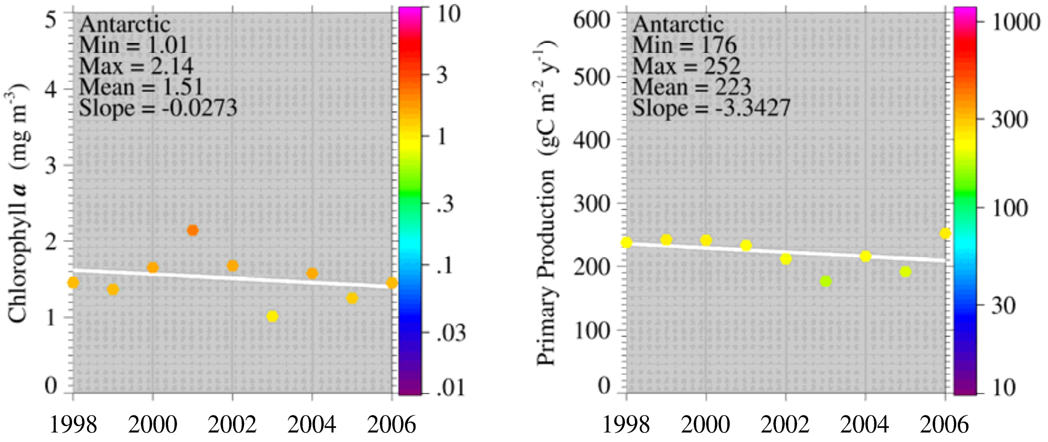

Figure XVIII-57.3. Antarctic LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

Western Antarctic Peninsula Near Surface Air Warming

The Antarctic Peninsula, the northernmost and mildest part of Antarctica, is also a hotspot of climate change, with average temperatures there having increased by more than two degrees Celsius. According to the British Antarctic Survey (BAS) reported in 2006, (Marshall et al. 2006), the westerly winds circling the pole have strengthened over the past 50 years and are the likely mechanism for the warming of the Peninsula. The stronger the westerlies, the more likely they are to cross the chain of mountains up to 2,800 m high that runs from north to south along the peninsula. As air masses move up the mountains, they lose moisture and tip into the lee side as dry, warm winds—like the föhn wind in the Alps and the Chinook in the Rockies.

II. Fish and Fisheries

Major interest in the Antarctic's marine living resources developed after the 1959 Antarctic Treaty. Species caught include krill (*Euphausia superba*), which has dominated the reported landings since early 1980s, rockcod (*Notothenia rossii*, *Lepidonotothen squamifrons*), icefish (*Champsocephalus gunnari*, *Chaenodraco wilsoni*) and toothfish (*Dissostichus mawsoni*). However, impacts on this LME by human activities go back at least to the days of peak whaling activities, where the removal of more than one million baleen whales in the 1950s and 1960s was hypothesized to have caused a huge 'krill surplus', accompanied by a parallel and concurrent massive depletion of finfish in the Southern Ocean (Ainley et al. 2007). By the early 1980s, krill accounted for more than 70% of the total catch. For information on krill and fish in the Weddell Sea, see Hempel (1990) and Hubold (2003). FAO (2003) has fisheries statistics after 1968. See FAO (2003, p. 29) for a graph of deep-water, epipelagic and total annual marine catches from 1950-1999.

There have been major fluctuations in the reported landings in this LME, with two major peaks at 112,000 tonnes in 1972 and 79,000 tonnes in 1978 (Figure XVIII-57.4). When the Soviet Union dissolved in 1991, the new republics drastically reduced their fishing activities in the Antarctic. Nevertheless, the decreasing total landings in recent years can be attributed to stock depletions. There is concern for the Patagonian toothfish (see Lack & Sant 2001). Antarctic cod and icefish are now in a depleted state. The countries that have been involved in the commercial fishing of krill are Japan, Russia, Chile, Taiwan, Korea, Spain, Poland and Germany. The potential for overfishing has grown significantly over the last two decades. These resources are subjected to fisheries management under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR 1980). Unregulated fishing is said to account for five to six times reported catch data. A major stock of squid is thought to exist in this region, and there is interest in commercial fishing for squid by the nations catching krill in the Antarctic.

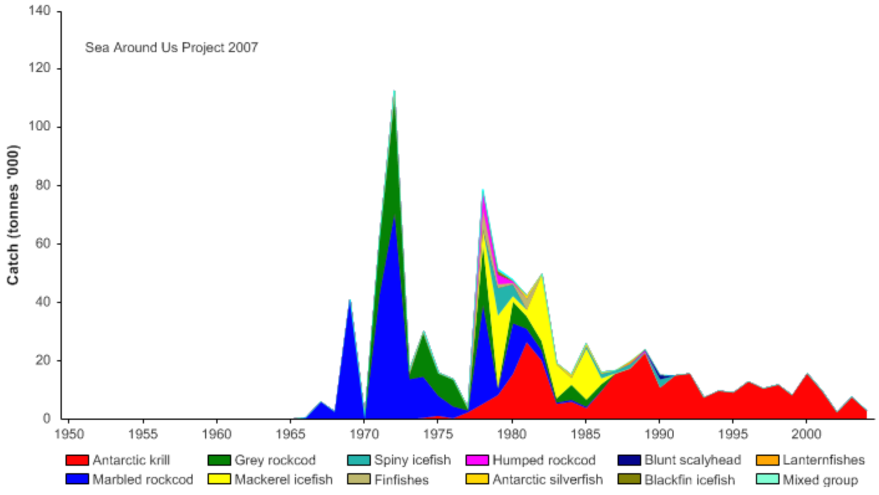

Figure XVIII-57.4. Total reported landings in the Antarctic LME by species (Sea Around Us 2007).

The trend in the value of the reported landings closely mirrored that of the landings, with two major peaks at just under US$120 million and US$80 million between early 1970s and early 1980s (Figure XVIII-57.5). However, it must be stressed that given the large amounts of unreported catch from this LME (see above), the estimates given in Figure XVIII-57.5 express only a small fraction of the value of Antarctic fisheries.

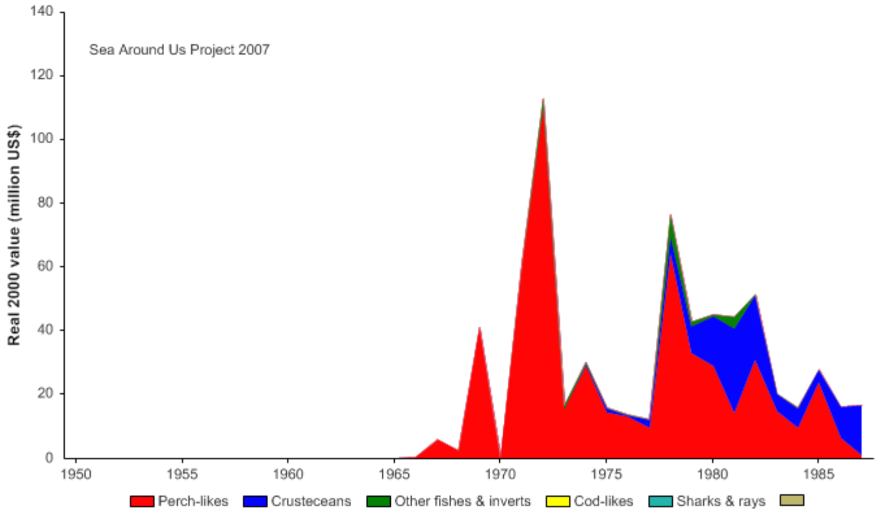

Figure XVIII-57.5. Value of reported landings in in the Antarctic LME by major commercial groups (Sea Around Us 2007).

Although based on partial catches, Figure XVIII-57.6 (top), which shows the mean trophic level of reported landings (i.e., the MTI, Pauly & Watson 2005), shows a rapid and strong decline in the 1970s and 1980s, reflecting the transition in landings from fish (mainly rockcod) to krill. Indeed, Figure XVIII-57.6(top) resembles Figure 4B in Pauly *et al.* (1998), in reference to Antarctica (defined by FAO areas 48, 58 and 88), which documented a case in which, fishes being depleted, fisheries turned to the forage species (i.e., krill) one full trophic level lower. Figure XVIII-57.6 may be seen, therefore, as a contribution to the contemporary discussion on the respective roles, in this LME, of bottom-up control (e.g., fluctuation of ice cover) vs. top-down control (e.g., depletion of the higher trophic levels) (see Ainley 2007). Note that the present MTI account (as are all MTI figures in this volume) is exclusive of marine mammals, and thus ignores the mass removal of baleen whales in Antarctic waters (Ainley et al. 2007).

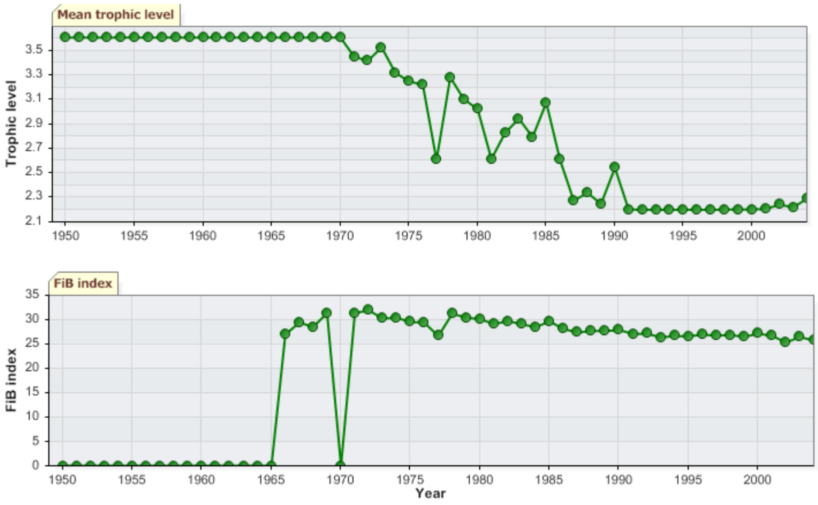

Figure XVII-57.6. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Antarctic LME (Sea Around Us 2007).

III. Pollution and Ecosystem Health

Overfishing is becoming an issue in the Antarctic LME. While the LME is remote and has no native coastal populations, it is a fragile environment in which there is growing pressure from human activity. Strict regulation is needed to maintain its relatively untouched and pristine condition. The impacts of human activities are examined on the Ohio State University, Byrd Polar Research Center, Polar Meteorology Group site at http://polarmet.mps.ohio-state.edu/. The Group examines the effects of tourists and scientists at laboratory stations, and the potential impacts of oil exploration and mining activities. According to an Australian abc.net report in 2000, an Antarctic Division study of the now abandoned Wilkes and Casey stations has found chemical contaminants (copper, lead, zinc and cadmium) leaching from rubbish dumped in old tip sites, machinery parts and fuel drums during the summer melt. Efforts for site clean-up are underway. Tourists are now required to follow a strict code of environmental conduct. For human impacts in the Antarctic Weddell Sea, see Hubold (2003).

There are other impacts on this LME due to anthropogenic environmental change. Depletion of the ozone layer has increased UV radiation that has a negative impact on surface phytoplankton productivity and on other taxa. In 1997 the NY Times reported UV damage in the eggs and larvae of icefish, the Antarctic fish that lack hemoglobin (http://topics.nytimes.com). As the ocean becomes more acidic when CO_2 increases in the atmosphere and becomes carbonic acid when dissolved into sea water (Plymouth Marine Laboratory 2006), impacts to the food web in the Antarctic are likely to be disruptive. Policy document 12/05 (2005), a report from The Royal Society, UK, outlines the impacts of increased acidity on the Southern Ocean.

Since 1974, 5,213 square miles of ice shelves have disintegrated in the Antarctic Peninsula (Zabarenko 2007). Professor Chris Rapley, director of the British Antarctic Survey and VP of the Committee for Antarctic Research, says that ice shelves may have an important role in stabilizing the ice sheet in Antarctica and that future loss of the largest ice shelves in the Antarctic could eventually cause accelerated and dramatic sea level rise (ENS 2005).

Negri et al. reported in 2004 for the first time, butylin contamination of near-shore sediments in the Ross Sea, Antarctica. The high concentration of 2290 µg Sn kg^{-1} sediment was recorded in one sample (Negri et al. 2004), likely caused by antifouling paints from ice-breaker ship hulls.

Long range atmospheric transport by global distillation is thought to be the main mechanism for moving POPS to high latitudes. Roosen et al.(2007) have reported concentrations of pesticides in soils from Adélie penguin colonies at Hop Island, 10 to 100 times higher than in reference locations.

IV. Socioeconomic Conditions

Pirate fishing has doubled in the 10 years from 1991 to 2001 as reported by P. Brown in the Guardian (2001). Lloyd's Maritime Information Services shows around 1,300 industrial fishing vessels flying flags of convenience. Among the species being depleted by pirate boats is the Patagonian tooth fish, marketed as Antarctic ice fish and caught on long lines which also kill albatross and other sea birds. Patagonian tooth fish are worth £8 a kilo for sushi and sashimi and the illegal trade in this catch alone is worth £300m annually (Brown 2001).

Whaling activities took place between the 1930s and the 1980s. See the Fish and Fisheries for information on foreign fishing fleets harvesting marine resources and specifically krill in the Antarctic LME. For more information on the commercial fishing of krill, see Hubold (2003).

The Antarctic continent has no indigenous inhabitants, but a history of researchers at various stations and, recently, tourists (abc.net 2000). Scientists live in research stations on a seasonal basis or year round to study weather and climate, oceanography, geology and glaciology. In 1999, over 10,000 tourists visited Antarctica, nearly all of them on commercial cruise ships. The International Association of Antarctica Tour Operators reports 37,522 tourists visiting Antarctica plus 2,430 staff and 19,890 crew members in 2006-2007 (www.iaato.org). No other economic activities are taking place in the LME. Iron ore, chromium, copper, gold, nickel, platinum, coal and hydrocarbons have been found in this region but are not being exploited (see Governance). The continent holds 70% of the Earth's freshwater.

V. Governance

Antarctica and the surrounding waters have a special status that required international cooperation. Seven countries originally made claims on Antarctica: England (1908), (New Zealand (1923), France (1924), Australia (1933), Norway (1939), Chile (1940) and Argentina (1943). There are special agreements pertaining to Antarctica's resources and its environmental protection. The Antarctic Region comes under an independent Regional Seas Programme. International cooperation takes place within the framework of the Antarctic Treaty, which covers the region south of 60° S latitude. The Treaty came into force in 1961 after ratification by the twelve countries then active in Antarctic science. Today 44 countries have ratified the Treaty. Its objectives are unique in international relations: to demilitarise Antarctica and establish it as a nuclear-free zone; to use it for peaceful purposes only; and to promote international scientific cooperation. In 1991, the Protocol on Environmental Protection to the Antarctic Treaty was signed, which *inter alia*, establishes the Committee for Environmental Protection. The Protocol entered into force 1998 and is aimed at ensuring the continued health of the Antarctic environment as a whole. It also includes an annex on waste disposal and waste management, but these restrictions could be difficult to enforce.

The Commission for Conservation of Antarctic Living Marine Resources (CCAMLR) was established to manage the LME's living marine resources using an ecosystems approach. Its international and ecological approach is a milestone in the conservation and management of living marine resources (see Scully *et al*. 1986, Scully 1993). Measures have been adopted by this convention to monitor and assess the level of marine debris from fishing vessels and the impact on marine living resources. There is a ban on oil exploration. Other conventions affecting Antarctica are: Agreed Measures for the Conservation of Antarctic Fauna and Flora (1964); the Convention for the Conservation of Antarctic Seals (1972); the Convention on the Regulation of Antarctic Mineral Resource Activities (1988); and the Convention on the Regulation of Mineral Resource Activities (CRAMRA 1991), which bans oil and mineral exploration for 50 years. The internationally coordinated CCAMLR-2000 Krill Synoptic Survey took place in January-February 2002 to determine krill pre-exploitation biomass in the west Atlantic subareas 48.1, 48.2, 48.3, and 48.4 in order to set precautionary catch limits for the krill fisheries in that region (Hewitt et al. 2004)

The Antarctic region is an international science laboratory where scientists study weather and climate, oceanography, geology and glaciology. Reporting of data for the Antarctic LME started in 1966.

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XIX NON-REGIONAL SEAS LMES

XIX-58 West Greenland Shelf LME
XIX-59 Newfoundland-Labrador Shelf LME
XIX-60 Scotian Shelf LME
XIX-61 Northeast U.S. Continental Shelf LME
XIX-62 Hudson Bay LME
XIX-63 Insular Pacific-Hawaiian LME
XIX-64 Southwest Australian Shelf LME

XIX-58 West Greenland Shelf LME

M.C. Aquarone and S. Adams, D. Mikkelson and T.J. Pedersen

The West Greenland Shelf LME extends along Greenland's west coast in the Atlantic Ocean, and encompasses a number of banks, including the Fyllas Bank. It has an area of 375,000 km^2, of which 1.37% is protected, and contains one major estuary, the Tasersuaq (Sea Around Us 2007). It is characterised by its subarctic climate, as well as by ice cover for parts of the year. For a map of sea currents and geography, see Pedersen & Rice (2002). Climate is the primary force driving this LME, with intensive fishing as the secondary driving force. Nutrient enrichment and mixing depend on changes in sea and air temperature. Book chapters and articles pertaining to this LME include Hovgård & Buch (1990), Blindheim & Skjoldal (1993), Pedersen & Rice (2002) and UNEP (2004).

I. Productivity

The West Greenland Shelf LME is a Class III, low productivity (<150 gCm^{-2}yr^{-1}) ecosystem. The waters of the West Greenland Current come from Greenland's south coast, the Labrador Sea and from East Greenland's strong Irminger Current. For a map of surface currents in the northern part of the Atlantic Ocean, see Hovgård & Buch (1990, p. 39). Hydrographical conditions seem to be changing in the Irminger Sea to the east. For more information on variations in climate, see Hovgard & Buch (1990). There is a relatively long time series of plankton and hydrographic samples allowing an exploration of the links between climate, physical oceanography and abundance of major zooplankton and ichthyoplankton species (see Pedersen & Rice 2002). Investigations on selected fish larvae and zooplankton in relation to hydrographic features are currently undertaken as part of the monitoring programme NuukBasic. The marine component of the monitoring program was initiated in 2005, and is managed by the Center of Marine Ecology and Climate Effects at Greenland Institute of Natural Resources. Results from the monitoring programme are published in annual reports, as well as in peer-reviewed scientific papers when appropriate. Currents carry cod eggs and larvae in a clockwise direction around the southern part of Greenland, but there is a need to learn more about the patterns of occurrence of selected fish larvae and zooplankton over time and space and how those patterns relate to hydrographic features. For more information on the variable inflow of cod larvae from Iceland, see Hovgard & Buch (1990). Studies showed a decreasing trend in zooplankton abundance. Information on current velocity is scarce. For a study of factors affecting the distribution of Atlantic cod, Greenland halibut, redfish, long rough dab, wolf fish, sandeel and northern shrimp, see Pedersen & Rice (2002). The decline of cod, redfish and long rough dab stocks can be seen mostly as consequences of changes in climate, temperature and salinity. NORWESTLAND has conducted surveys along 3 transects in the West Greenland coast, Store Hellefiske bank, Sukkertop bank and Fyllas bank, where sea temperatures and salinities have been measured.

Oceanic fronts (Belkin et al. 2009) (Figure XIX-58.1): The West Greenland Current Front (WGCF) closely follows the shelf break and the steep upper slope until 52°W, where the slope becomes notably less steep and therefore no longer stabilises the WGCF. The front instability results in eddy generation that enhances cross-frontal exchange of heat, salt and nutrients as well as larvae and juvenile fish. The WGCF waters originate partly in the cold, fresh East Greenland Current and partly in the warm and salty Irminger Current. The Mid-Shelf Front (MSF) runs over mid-shelf roughly parallel to the coast and carries very cold, low-salinity polar water originated in the East Greenland Current augmented by melt water from the Greenland Ice Sheet.

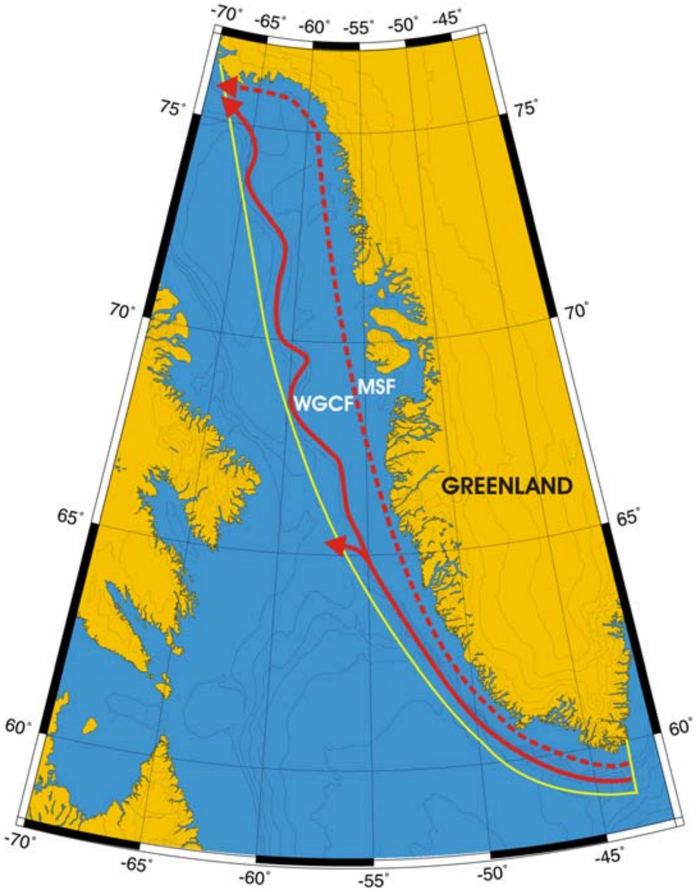

Figure XIX-58.1. Fronts of the West Greenland Shelf LME. MSF, Mid-Shelf Front (most probable location); WGCF, West Greenland Current Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

West Greenland Shelf SST (Belkin 2009) (Figure XIX-58.2):

Linear SST trend since 1957: 0.42°C.
Linear SST trend since 1982: 0.73°C.

The long-term 50-year warming of the West Greenland Shelf was interrupted by cold events that peaked in 1970, 1983-84, and 1996. These cold anomalies were associated with low-salinity, high-sea-ice cover anomalies dubbed "Great Salinity Anomalies" or GSAs since they are best detected in the salinity time series (Dickson et al., 1988; Belkin et al., 1998; Belkin, 2004). The GSAs form in the Arctic and are transported by oceanic currents into the northern North Atlantic either through Fram Strait between Greenland and Svalbard or through the straits of the Canadian Arctic Archipelago; some GSAs could also form locally in the Labrador Sea. The West Greenland Shelf is one of a few LMEs where the GSAs are conspicuous in temperature records as well as in salinity time series. As the GSAs travel along the Subarctic Gyre, they affect spawning and fishing grounds; generally, their impact is detrimental to fish stocks. The first anomaly (GSA'70s) led to a collapse of cod stock in this area, ultimately replaced by shrimp. The ensuing cod-to-shrimp transition of local fisheries has had profound societal ramifications at the regional level (Hamilton et al., 2003). The cold episodes of the early 1980s and early-to-mid 1990s have been caused by the harshest climatic conditions ever recorded in this area since the beginning of meteorological observations at Godthab (now Nuuk) in the mid-19th century. During these events, enhanced export of cold and fresh Arctic waters to the Baffin Bay and Labrador Sea (through Canadian straits and also through Fram Strait) likely contributed to the formation of the GSA'80s and GSA'90s. The all-time maximum SST of >1.4°C in 2003-2004 may have been advected from the upstream-located East Greenland Shelf LME where SST peaked at >2.6°C in 2003.

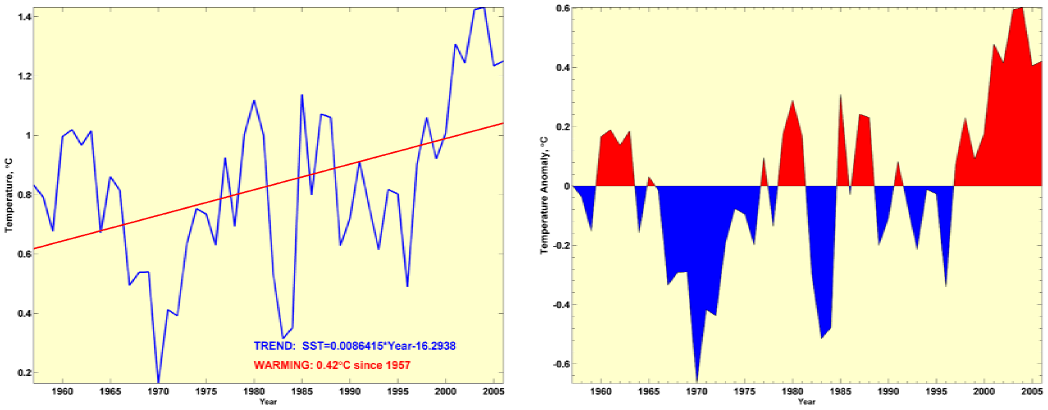

Figure XIX-58.2. West Greenland Shelf LME annual mean SST (left) and SST anomalies, 1957-2006, based on Hadley climatology. After Belkin (2009).

West Greenland Shelf LME Chlorophyll and Primary Productivity

This LME is a Class III, low productivity (<150 gCm^{-2}yr^{-1}) ecosystem (Figure XIX-58.3).

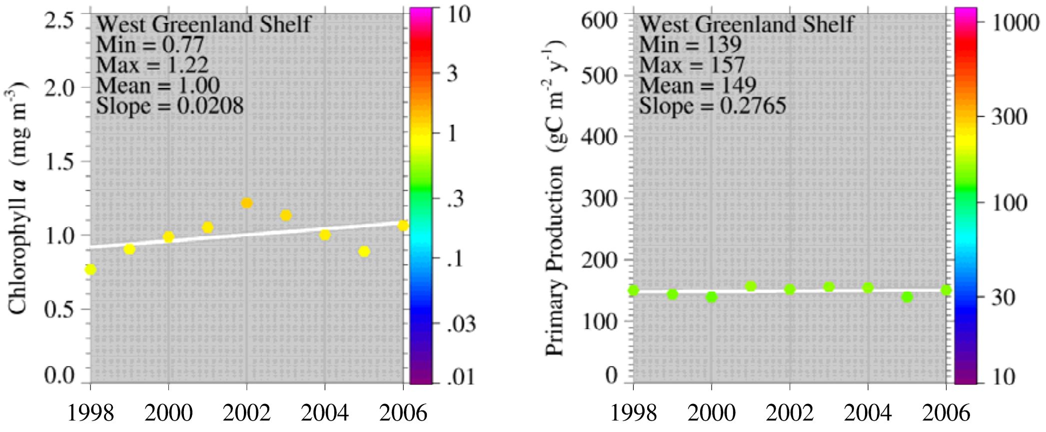

Figure XIX-58.3. West Greenland Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The most important species group in terms of shelf catches for recent years is the northern prawn (*Pandalus borealis*), representing more than two-thirds of the total catch. Another important species group is flatfish. For a study of changes in the West Greenland fisheries, see Pedersen & Rice (2002). Reported landings of commercial fish species show major changes over the past century, from a system dominated by Atlantic cod landings to one defined by prawn landings Reported landings were at a historical peak of over 350,000 tonnes in the 1960s (Figure XIX-58.4). They subsequently showed significant declines to under 100,000 tonnes, with the decline in cod landings, but have shown an increasing trend over the last few years (Figure XIX-58.4). As northern prawn now contributes the majority of the reported landings, a potentially large amount of fish bycatch can be assumed to remain unreported. The value of the reported landings reached US$400 million (in 2000 US dollars) in the 1950s and 1960s, but has since reduced to US$163 million in 2004 (Figure XIX-58.5).

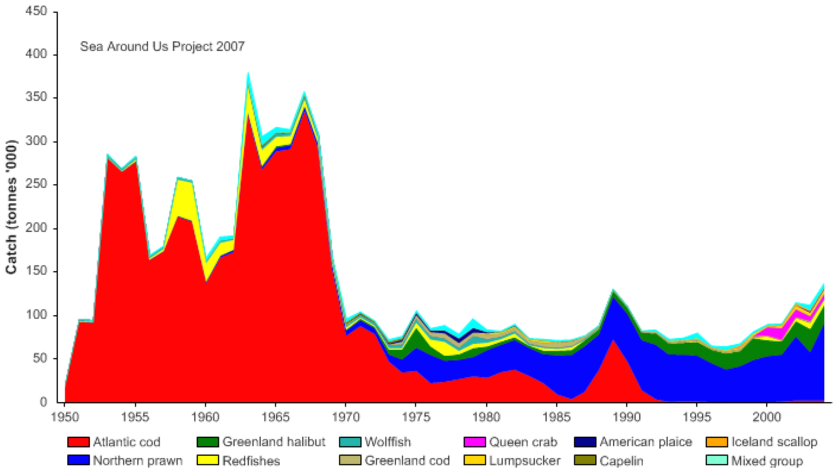

Figure XIX-58.4. Total reported landings in the West Greenland Shelf LME by species (Sea Around Us 2007).

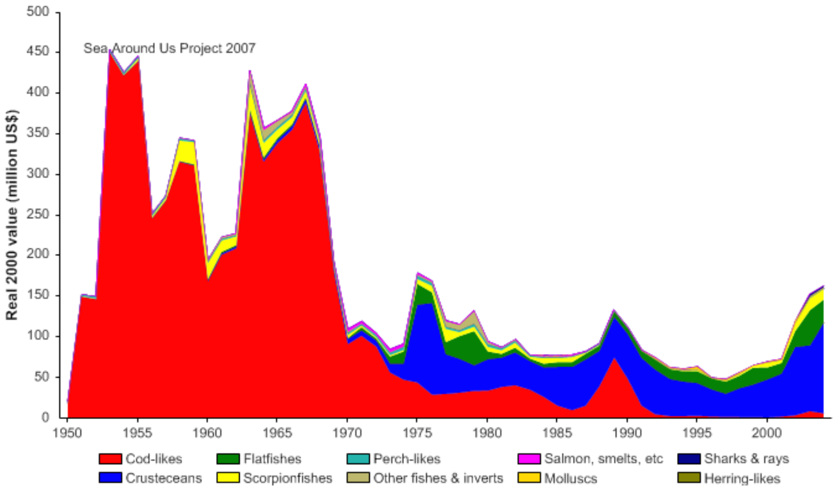

Figure XIX-58.5. Value of reported landings in the West Greenland Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME was over 70% of the observed primary production in the 1960s before declining to less than 2% over the last three decades. The extremely high PPR recorded in the 1960s is likely a result of the high level of accumulated biomass of cod stocks being exploited, not due to the exploitation of annual surplus production.

Greenland accounts for the largest share of the ecological footprint in this LME, although European countries accounted for the majority of the footprint in the 1950s and 1960s.

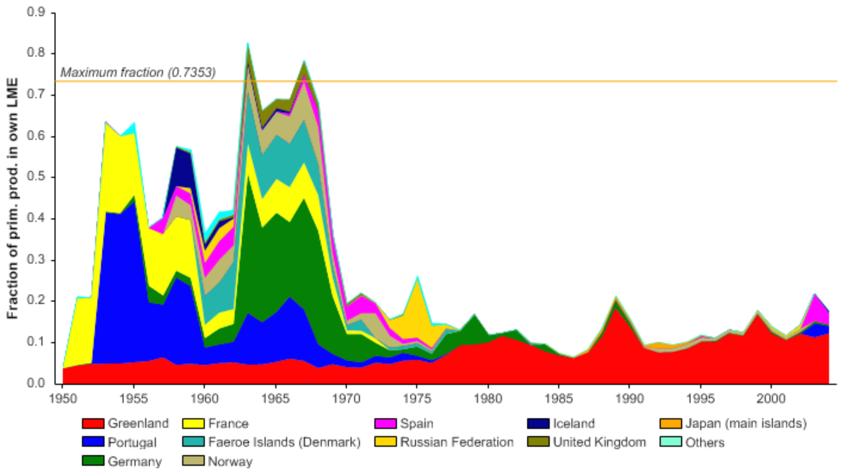

Figure XIX-58.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the West Greenland Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

From 1950 to 1970, cod was dominant in the reported landings in this LME and as a result, the mean trohic level (i.e., the MTT, Pauly & Watson 2005) remained high. It then showed a decline with the change from cod to prawn dominance in the ecosystem (Figure XIX-58.7, top).

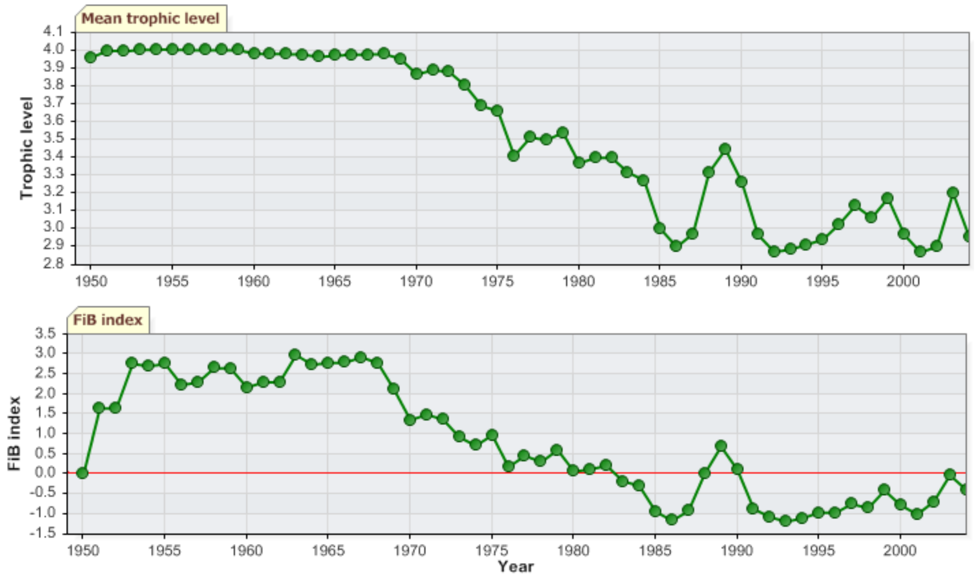

Figure XIX-58.7 Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the West Greenland Shelf LME (Sea Around Us 2007).

This trend, by its definition, implies a ‘fishing down’ of the food web (Pauly *et al*. 1998). The FiB index showed a similar trend (Figure XIX-58.7, bottom), suggesting that the reported landings did not compensate for the decline in trophic levels during that period. However, it must be noted that inclusion of bycatch may alter the trends in the indices observed here. Furthermore, it is known that the system shift from cod to prawn was to a large extent driven by environmental changes (see, e.g., Pedersen & Zeller 2001).

The Stock-Catch Status Plots indicate that more than 70% of commercially exploited stocks in this LME have collapsed (Figure XIX-58.8, top), however, with 90% of the landings still from fully exploited stocks, more specifically from the northern prawn (Figure XIX-58.8, bottom). Considering the decrease in the reported landings over the past three decades (Figure XIX-58.4), the observed trends in these plots present a stark reminder that they must be examined as a pair, not in isolation from each other.

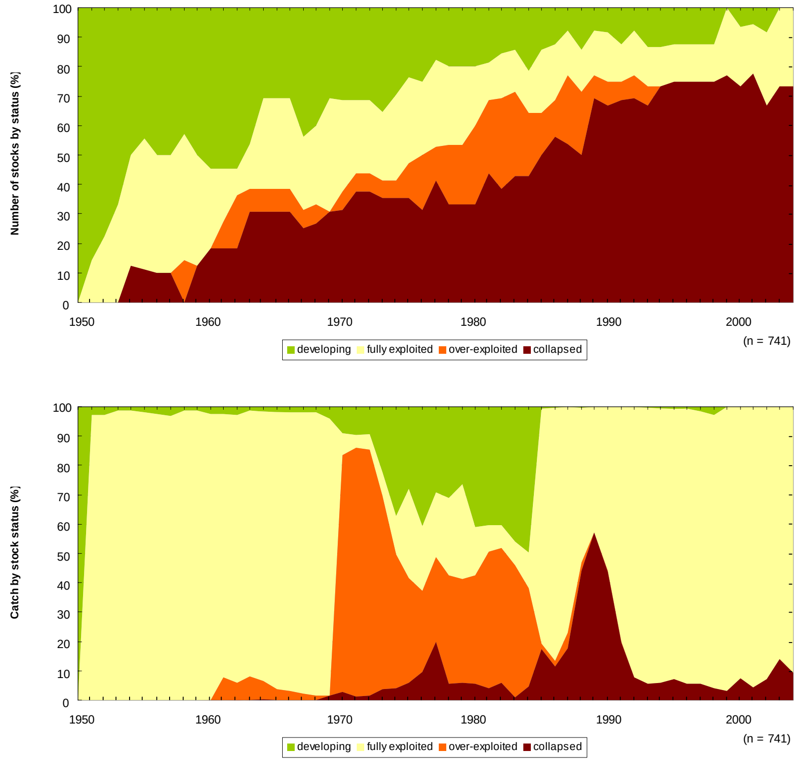

Figure XIX-58. 8. Stock-Catch Status Plots for the West Greenland Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

Landings of cod, redfish and long rough dab have declined. Low recruitment played an important role in the collapse of the cod fishery. The periodic fluctuations of cod stocks have been linked to changes in sea and air temperature (see Hovgård & Buch 1990). These authors also examine the southern displacement of the cod fishery, and provide information on the development of the cod stock since 1956. For more information on the biological effects of the temperature and salinity anomaly on the West Greenland cod, see Blindheim & Skjoldal (1993). In the same period, catches of Greenland halibut and northern shrimp increased. For nominal catches of Atlantic cod, redfish, Greenland halibut and northern shrimp, see Pedersen & Rice (2002, p. 153). The present abundance of shrimp in this LME may partly be the result of a lower abundance of cod and redfish (see Horsted 2000). Large numbers of redfish, Greenland halibut, polar cod, cod and others are caught and discarded in the West Greenland shrimp fishery (see Pedersen & Kanneworff 1995). It is important to also consider the added influence of changes in fishery technology and effort on cod stocks. The International Cod and Climate Change Programme (ICCC) studies the response of different cod populations to climate changes in various regions of the cod's North Atlantic range. Pedersen, Madsen and Dyhr-Nielsen (2004) report that fishing mortality on cod has been too high due to by-catch in the shrimp fishery and due to unregulated fishery directed for cod in the fjords (GIWA 2004).

III. Pollution and Ecosystem Health

The waters of the West Greenland Shelf LME are little polluted. Information about pollutants and their transport vectors in the Arctic region including Greenland is available from the Arctic Marine Assessment Program (AMAP) (www.amap.no). Larsen et al. (2001) reported in Environmental Pollution (2001) that elevated levels of lead and zinc have been found in sediments and biota in the fjord at Maarmorilik, West Greenland—a legacy from the mining once done in the area. Bindler et al. (2001) concluded that the lead in Søndre Strøfjord (W. Greenland) sediments dated since WW II bears isotopic signatures suggesting W European sources as well as Russian sources. Larsen et al. (2001) conclude that this has important implications for future depositions of eco-toxicologically important pollutants such as Hg and POPs. Pedersen et al.(2004) cite studies showing that the cold Arctic climate creates a sink for Hg and POPs, and that the already high levels of mercury in the Arctic are not declining despite significant emissions reductions in Europe and North America.

IV. Socioeconomic Conditions

Greenland made the transition from a nation of hunters to a nation of fishers, primarily for cod, over the course of the last century. A rich Atlantic cod fishery started in the 1920s after a general warming of the Arctic. It developed from a local, small-boat fishery to an international offshore fishery of primarily trawlers. Today the fishery is dominated by shrimp, crab and halibut. The industries of West Greenland include fish processing, gold, uranium, iron and diamond mining, handicrafts, hides and skins, and small shipyards. Pedersen et al. (2004) suggest that economic diversification is not yet sufficient to offer alternative income possibilities to professional fishermen and hunters.

V. Governance

Both Canada and Greenland share jurisdiction over this LME. After 1945 Canadian fisheries were regulated under the International Commission for the Northwest Atlantic Fisheries (ICNAF), consisting of all the industrialised fishing nations of the world operating in that area (see www.nafo.ca/about/icnaf.htm). ICNAF's effectiveness, however, was limited by the voluntary nature of compliance to its rules. With the increase in foreign fishing fleets after World War II, the cod fishery expanded greatly. The limited development of Canada's domestic fleet prompted Canada to establish a 200-mile EEZ in 1977. The Greenland Institute of Natural Resources is responsible for providing scientifically sound management advice to the Government of Greenland. Pedersen et al. (2004) point out that chemical contamination of the waters and ecosystems of Greenland come there from Europe, Asia and North America. Concerted international effort should be focused on control of these emissions and to enforce existing agreements.

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XIX-59 Newfoundland-Labrador Shelf LME

M.C. Aquarone and S. Adams

The Newfoundland-Labrador Shelf LME extends some distance off the eastern coast of Canada, encompassing the areas of the Labrador Current and the Grand Banks. It has an area of about 896,000 km^2, of which 0.44% is protected, and contains 14 major estuaries (Sea Around Us 2007). The seabed of the shelf is structurally complex. As in some other LMEs, overexploitation is the principal driver of changes within this LME, although fluctuations in the ocean climate have also been implicated. The ability to explain the dynamics of this LME is severely limited by the lack of time series of data on living components of the system, except for a few species of fishes and seals. A description of the changing conditions of the fish and fisheries of this LME is given in Rice (2002).

I. Productivity

The Newfoundland-Labrador Shelf LME is considered a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}). For productivity information, see the GLOBEC Working Group Summary of the Newfoundland and Labrador Shelves (1993). Harsh environmental conditions, extensive and persistent sea ice, extreme cold anomalies, changes in distribution of the area occupied by a Cold Intermediate Layer water mass (CIL), as well as overfishing, have all contributed to fish population collapses (see Fish and Fisheries module) in the 1990s. The crab and shrimp that have increased the most are the favoured prey of cod and other major predators that have collapsed. The new population densities that have appeared may have redistributed energy flows in ways that have made it difficult to return to earlier system configurations. There have been several local studies on plankton dynamics (see Prasad & Haedrich 1993). There was a continuous plankton recorder transect through this area in the 1950s to the early 1970s.

Oceanic fronts (Belkin et al. 2009) (Figure XIX-59.1): The Labrador Shelf-Slope Front (LSSF) extends along the shelf break and upper slope. The Labrador Mid-Shelf Front (LMSF) recently identified from satellite data runs inshore of the LSSF, parallel to Labrador. Farther downstream, the LMSF hugs Newfoundland and merges with the LSSF south of Newfoundland, near 45°N and 55°W. The Flemish Cap, a shallow bank that supports important fisheries, is surrounded by the Flemish Cap Front (FCF) that isolates on-bank waters from direct contact with off-bank oceanic waters. The FCF can be considered an offshore branch of the LSSF. The main branch of the LSSF continues south via Flemish Pass between the Grand Banks of Newfoundland and Flemish Cap.

Newfoundland Labrador Shelf SST (Belkin 2009) (Figure XIX-59.2):
Linear SST trend since 1957: 0.77°C.
Linear SST trend since 1982: 1.04°C.

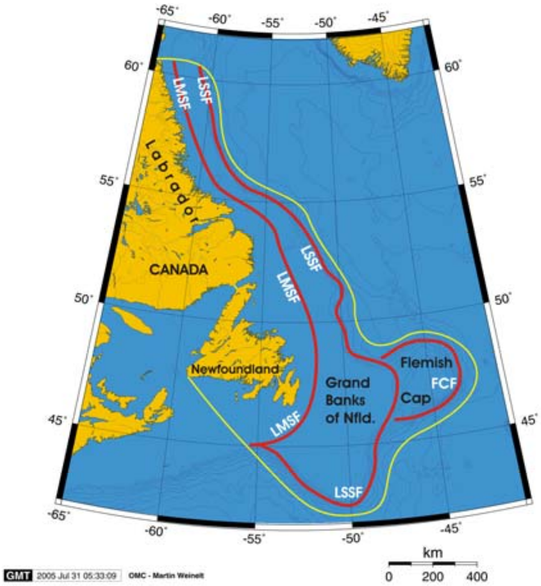

Figure XIX-59.1. Fronts of the Newfoundland-Labrador Shelf LME. FCF, Flemish Cap Front; LMSF, Labrador Mid-Shelf Front; LSSF, Labrador Shelf-Slope Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

The thermal history of the Newfoundland-Labrador Shelf LME is different from that of the adjacent Scotian Shelf LME. There was no cold spell in the 1960s. Instead, long-term steady warming has been observed since 1957, punctuated by strong interannual variability with a magnitude of ~1°C. This warming has accelerated since the mid-1990s. Since the near-all-time minimum of 4.6°C in 1991, the SST has risen to 6.4°C in 2006, a 1.8°C increase in just 15 years. Despite a single large reversal in 2000-2002, this increase was one of the fastest regional warming events of the last 25 years. The minima of 1972, 1985 and 1991 may have been associated with large-scale cold, fresh anomalies called "Great Salinity Anomalies" or GSAs (Dickson et al., 1988; Belkin et al., 1998; Belkin, 2004). These anomalies form in the Arctic Ocean; enter the northern North Atlantic either via Fram Strait or through the straits of the Canadian Archipelago; and propagate around the Subarctic Gyre, where they profoundly affect regional ecosystems. The GSAs could also form in the Labrador Sea (Belkin et al., 1998; Belkin, 2004).

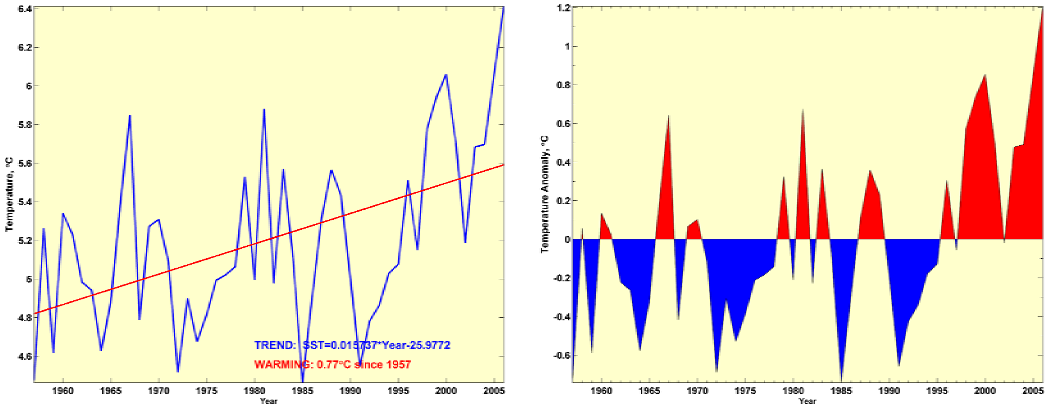

Figure XIX-59.2. Newfoundland-Labrador Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Newfoundland-Labrador Shelf LME Chlorophyll and Primary Productivity
This LME is a Class II, moderately productive ecosystem (150-300 gCm^{-2}yr^{-1}) (Figure XIX-59.3).

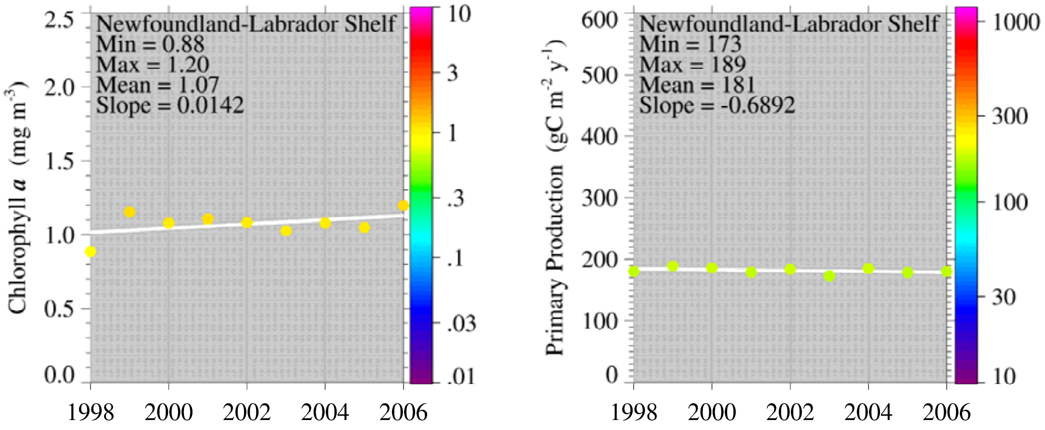

Figure XIX-59.3. Newfoundland-Labrador Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Commercially exploited fish species in this LME include cod, haddock, salmon (see salmon stock assessment for 1997), American plaice, redfish, yellowtail and halibut. Also harvested are lobster, shrimp and crab. Historic records of catches of Atlantic cod can be reconstructed back to 1677 (see Forsey & Lear 1987, for a time series of cod catches). For a stock by stock assessment and recommendation, see Canada's Department of Fisheries and Oceans website.

Total reported landings, dominated by cod until the 1990s, exceeded 1 million tonnes from 1967 to 1970, but declined to 525,000 tonnes in 2004 (Figure XIX-59.4).

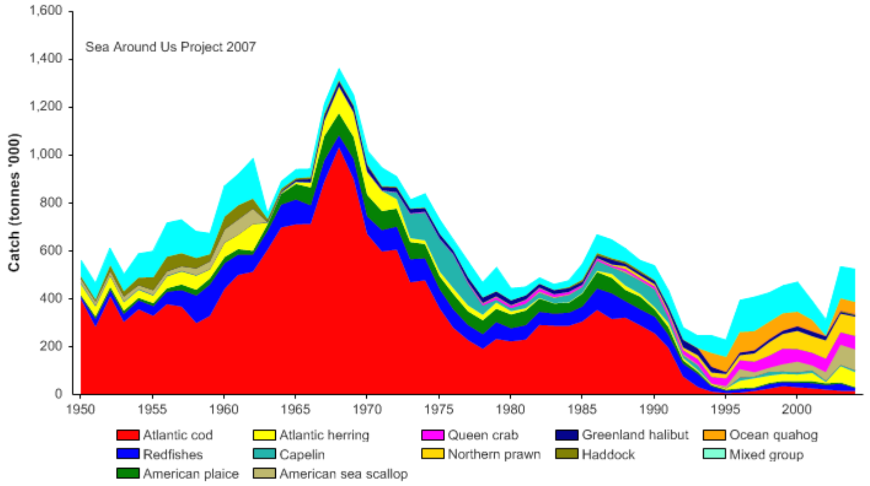

Figure XIX-59.4. Total reported landings in the Newfoundland-Labrador Shelf LME by species (Sea Around Us 2007).

The cod landings, in particular, declined from a historic high of over 1 million tonnes in 1968 to 16,000 tonnes in 2004 with landings of less than 10,000 tonnes recorded in 1995 and 1996. With the collapse of the cod stock, landings in more recent times are dominated by invertebrates (crabs, prawns and scallops) and herring (Figure XIX-59.4). The reported landings of the LME were valued at over US$1.2 billion (in 2000 US dollars) in the late 1960s, most of which was attributed to cod landings, while in recent years similarly high values are produced by its invertebrate landings (Figure XIX-59.5).

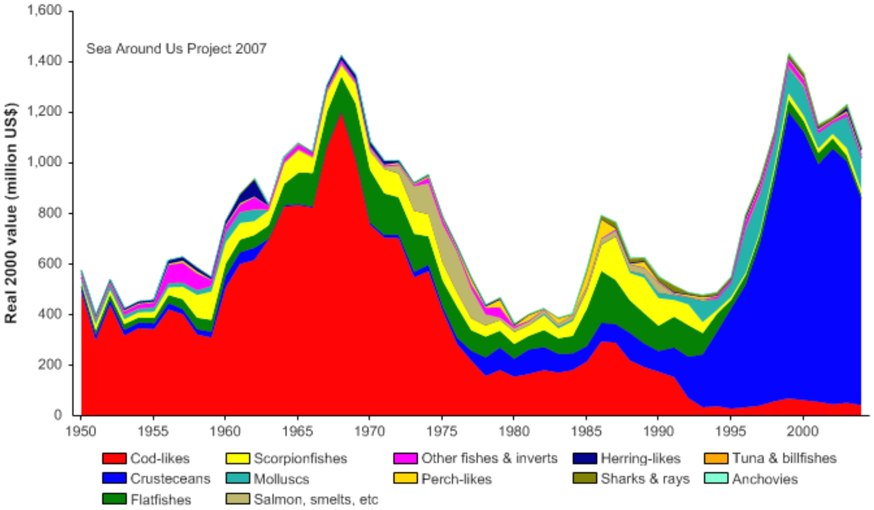

Figure XIX-59.5. Value of reported landings in the Newfoundland-Labrador Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in the LME reached 60% of the observed primary production in the mid 1960s, but has declined in recent year (Figure XIX-59.6). The peak level achieved in the 1960s is likely a result of the high level of accumulated biomass of cod stocks being exploited, not due to the exploitation of annual surplus production.

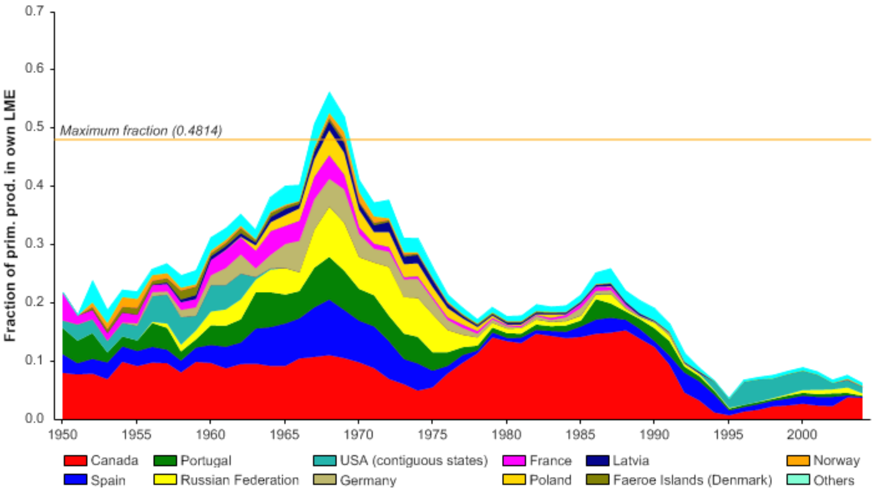

Figure XIX-59.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Newfoundland-Labrador Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

Since the late 1970s Canada accounts for the largest share of the ecological footprint in this LME, although in the 1960s, a number of European countries also had a large share.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) remained high until the 1990s, when the cod stock began to collapse (Figure XIX-59.7, top), a clear case of 'fishing down' the food web in the LME (Pauly *et al*. 1998, 2001). The FiB index shows a similar trend (Figure XIX-59.7, bottom), indicating that the reported landings did not compensate for the decline in the MTI over that period. However, these landings do not account for the discarded bycatch from the shrimp fishery, which now accounts for half of the value of the landings (Figure XIX-59.5).

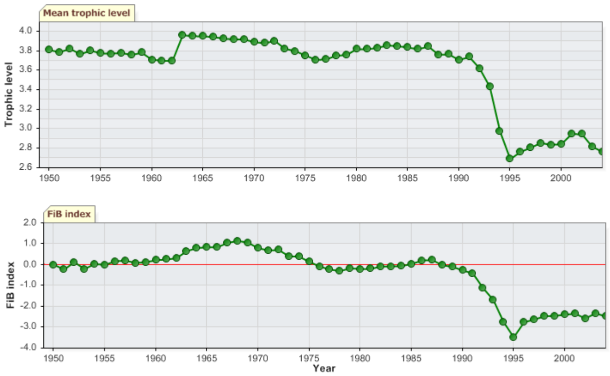

Figure XIX-59.7 Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Newfoundland-Labrador Shelf LME (Sea Around Us 2007)

The Stock-Catch Status Plots show that over 60% of commercially exploited stocks in the LME have collapsed, with another 20% overexploited (Figure XIX-59.8, top). Over 50% of the reported landings biomass is now supplied by fully exploited stocks (Figure XIX-59.8, bottom).

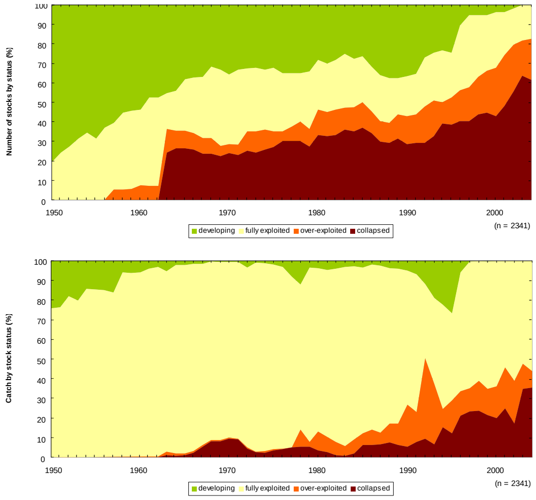

Figure XIX-59.8. Stock-Catch Status Plots for the Newfoundland-Labrador Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.*, this volume, for definitions).

Instability, variability and overexploitation have characterised the entire history of fisheries off the coast of Newfoundland and Labrador. Over time, the LME has shown major changes, which have been greater in recent decades than in any other period in history. There was a rapid expansion of distant water fleets during the late 1950s, as well as an intensification of fishing effort. This affected the major fish stocks of the shelf (Murawski *et al*. 1997). Overfishing of cod, haddock, redfish and major flatfish in the 1960s and 1970s led to fisheries collapses. There were also declines in the abundance of broadhead wolffish and thorny skate. These collapses led to a fishing moratorium for cod in 1992 (Walters & Maguire 1996), and the eventual closure of the fishery a decade later. At the same time, other fisheries (notably for crab and shrimp, formerly prey of cod) experienced record high yields.

III. Pollution and Ecosystem Health

Given the low population density of Newfoundland, pollution from land-based sources is mostly limited to urban coastal areas. However, there is an increasing threat to the region from the oil and gas industry's exploitation of the Hibernia, Terra Nova, White Rose, and the Hebron Complex oil reserves, for example. The Canadian Wildlife Federation (CWF) reported three spills in November of 2004 at the Terra Nova oil field off the coast of Newfoundland and Labrador, the first spill releasing 170,000 litres into the ocean. Additionally, CWF asserts that deliberate dumping, the primary source of oil pollution in Atlantic Canada, is a chronic problem that is both illegal and preventable (2004). The Economic Research and Analysis Division of the Government of Canada (2007) reports that oil production in the province is expected to increase by 30%, that prices will remain high, and more exploratory drilling will likely occur in 2008 and 2009.

There have been *Oikopleura* blooms in this LME. The International Cod and Climate Change Programme studies the response of different cod populations to climate changes in various parts of the cod's North Atlantic range. Canada is a key participant in the Scientific Committee on Ocean Research (www.jhu.edu/~scor/) and the International Council for Exploration of the Sea (www.ices.dk).

IV. Socioeconomic Conditions

The Grand Banks of Newfoundland and Labrador have been fished since the 1400s, with fleets arriving annually from several of Europe's fishing nations. The banks and coastal areas, being rich and productive, formed the basis for human settlement. The Atlantic cod fishery was the base of the economy. About 30,000 people have been adversely affected by the collapse of the cod fishery and its associated economy. However, the value of the annual fisheries catch is approaching that of the cod fishery, with recent increases in the crab and shrimp landings (Rice 2002). Hamilton and Butler (2001) caution that the cod to crustaceans transition, while roughly an even exchange for the Newfoundland economy, should not be taken for a new stable state. They point out that shrimp size has been decreasing, depressing catch value and raising uncertainty about the stock's future. Gear has been changed to prevent the female snow crab from being caught, but the biomass of snow crab declined in 1999 and 2000. Greenland halibut, are slow-growing, long-lived deepwater fish that cannot support intensive exploitation and are thought to be on the verge of collapse (Hamilton and Butler 2001).

Newfoundland's population has been declining and no longer compensates for outmigration. If this trend continues, it will be difficult for the province to provide services to those who remain. Department of Finance Canada (2004) points to high economic growth rates because of the development of offshore oil and gas projects--growth that helps the Government of Newfoundland and Labrador to provide essential public services in the face of a high provincial debt burden and the declining population in the region (www.fin.gc.ca). The Minister of Natural Resources, Gary Lunn, addressed the Newfoundland Offshore Industry Association on 19 June 2007 and urged increased oil and gas investment in the Newfoundland and Labrador province. He cites 2,800 people directly employed by the oil and gas projects and another 14,000 employed in support industries and businesses—8% if all the people employed in Newfoundland and Labrador. Tim Appenzeller (2004) in "The End of Cheap Oil," quotes Thomas Ahlbrandt, the geologist who led the USGS 2000 study asserting 50% more world oil remaining than feared, as saying "Oil and gas are limited; my personal feeling is, we have a concern in the next couple of decades."

Hamilton and Butler point out that Rural Newfoundland hosts a strong informal economy (Felt and Sinclair 1992) including country foods such as moose meat or fish and local firewood cut for heating. Barter or cash-based exchanges of goods and services such as home-building and vehicle maintenance are common.

V. Governance

Canada and France (the islands of St. Pierre and Miquelon) share jurisdiction of this LME. The establishment by Canada of a 200-mile EEZ in 1977 effectively excluded foreign fleets from most of the Grand Banks. The Government of Canada has guaranteed that Newfoundland and Labrador will receive 100 percent of royalties from its offshore oil and gas production, some offset benefits per the Atlantic Accord, and some protection from reductions in revenues.

Single species quota management continues. The Fisheries Resource Conservation Council (FRCC) was created in 1993 with a mandate to contribute to a more comprehensive approach to the management of the Atlantic fisheries on a sustainable basis, to integrate stock assessments at the ecosystem level and recommend to the Minister and industry appropriate action to ensure sustainable fisheries. While there is a stated desire to change to an ecosystem level approach, there are no explicit objectives within fisheries management plans for the ecosystem. This ambiguity in management objectives underscores the need for the many single function management agencies to be integrated. See the West Greenland Shelf LME for further information on the International Commission for the Northwest Atlantic Fisheries.

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XIX-60 Scotian Shelf LME

M.C. Aquarone and S. Adams

The Scotian Shelf LME is bordered by the Canadian province of Nova Scotia and extends offshore to the shelf break, more than 200 nautical miles from the coast. The area of this LME is 283,000 km^2, of which 0.87% is protected, and contains one major estuary, the St. Lawrence (Sea Around Us 2007). To the north the LME is separated from the Newfoundland Labrador Shelf LME by the Laurentian Channel, while to the south it extends to the Fundian Channel (Northeast Channel). The Scotian Shelf LME has a complex topography consisting of numerous offshore shallow banks and deep mid-shelf basins. It can be divided into eastern and western subsystems. The eastern Scotian Shelf LME includes Emerald Bank. The Nova Scotia Current hugs the coastline in a southwestward direction and enters the Gulf of Maine through the Northeast channel (Zwanenburg *et al*. 2002, Zwanenburg 2003). Book chapters pertaining to this LME are by Zwanenburg *et al*. (2002) and Zwanenburg (2003).

I. Productivity

The Scotian Shelf LME is considered a Class II, moderately high productivity ecosystem (150-300 gCm^{-2}yr^{-1}). Productivity is influenced by changes in environmental conditions and temperature. A decrease in ambient temperature is noted on the eastern Scotian Shelf for the period 1980-1992 (Zwanenburg *et al*. 2002). The recent changes to research vessel survey protocols broaden the collection of ecosystem monitoring data to include abundance and distribution of phytoplankton, zooplankton, as well as an increased suite of physical oceanographic parameters. A monthly Continuous Plankton Recorder Survey is being conducted in collaboration with the Allister Hardy Foundation, Plymouth, England. There has been an exponential increase in grey seal abundance since the 1960s. Harp, hooded and harbour seals are found in the Gulf of St. Lawrence and so are Beluga whales.

Oceanic fronts (Belkin *et al.* 2009) (Figure XIX-60.1): The Shelf-Slope Front (SSF) along the Scotian Shelf/Slope bounds this LME and is associated with the southward cold, fresh Labrador Current, augmented by fresh discharge from the Gulf of St. Lawrence. The Gulf component is strongly seasonal and reflects in the SSF characteristics (Linder & Gawarkiewicz 1998). The newly-identified Gully Front (GF) is observed at 43.5°N over the Gully, the largest canyon that incises the Scotian Shelf and Slope. Medium-scale thermohaline fronts in the southern Gulf of St. Lawrence are generated seasonally by spring freshet, followed by summertime warming. The Cabot Strait Front (CSF) is also related to the Gulf of St. Lawrence fresh outflow. The Cape North Front (CNF) develops north of Cape Breton Island.

The Scotian Shelf LME SST (Belkin 2009) (Figure XIX-60.2):
Linear SST trend since 1957: 1.15°C.
Linear SST trend since 1982: 0.89°C.

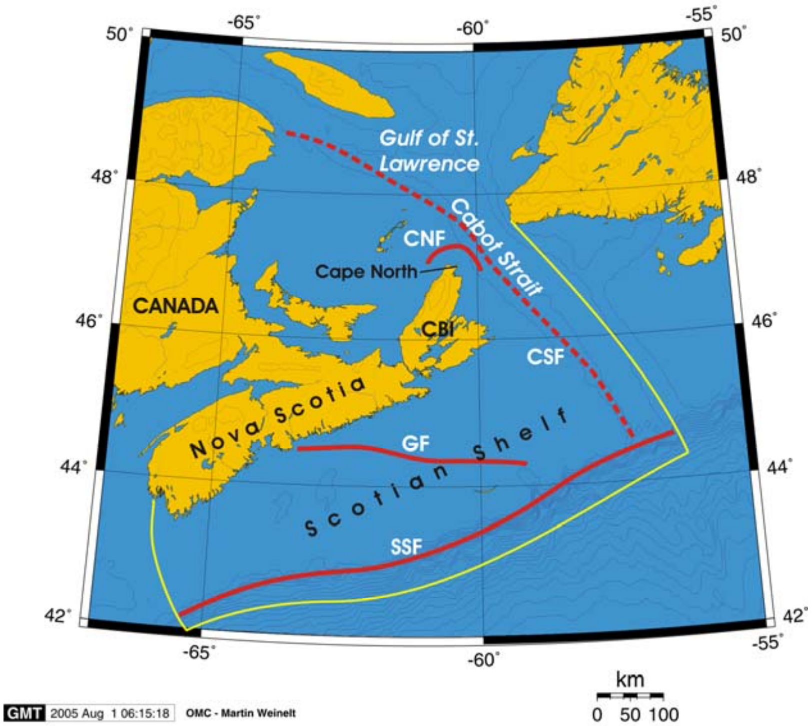

Figure XIX-60.1. Fronts of the Scotian Shelf LME. CNF, Cape North Front; CSF, Cabot Strait Front (most probable location); GF, Gully Front; SSF, Shelf-Slope Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

The thermal history of the Scotian Shelf LME is similar to that of the Northeast U.S. Continental Shelf LME. These LMEs are connected by the Slope Current, which flows southwestward along the shelf break and upper continental slope. This connection explains the observed similarities between thermal histories of these LMEs: first of all, the cold spell of the mid-1960s, with the all-time minimum of 6.7°C in 1965 and the subsequent steady warming until the present. As in the Northeast Shelf LME, 1965 can be taken as a true breakpoint between two regimes characterized, respectively, by long-term cooling before 1965 and long-term warming after 1965. The post-1965 warming amounted to approximately 2°C over 40 years, making the Scotian Shelf as a geographic whole, one of the fastest warming LMEs. Note that smaller processes like the rapid cooling of the eastern Shelf during the 1980s, drive significant changes in the biota. Generalizations about the entire Scotian Shelf do not examine important differences between the eastern and western sections of this LME.

Over the late 1990s, the Scotian Shelf interannual variability was in sync with the Northeast U.S. Continental Shelf LME as evidenced by the simultaneous minimum in 1997, maximum in 1999, minimum in 2004, and the sharp increase in 2004-2006, in both LMEs. The most recent SST increase in 2004-2006 led to the all-time maximum of >9.0°C in 2006 over the Scotian Shelf, consistent and concurrent with the near-all-time maximum of 13.0°C over the Northeast U.S. Shelf Continental LME and the all-time maximum of 6.4°C over the Newfoundland-Labrador Shelf LME, both in 2006. The above simultaneity suggests large-scale forcing on the order of 2,000 km as a dominant factor over these distinct but adjacent ecosystems.

The minima of 1986 and 1997 may have been related to passages of the decadal-scale Great Salinity Anomalies (GSA) associated with low temperatures (Belkin et al., 1998; Belkin, 2004).

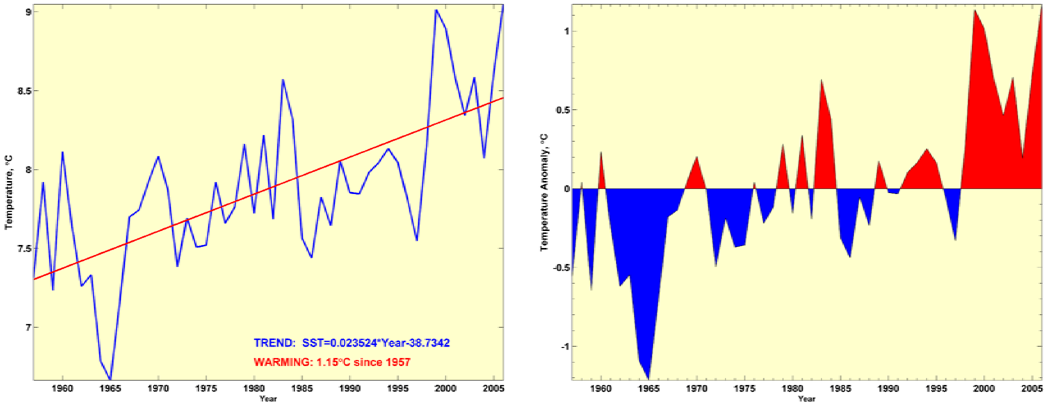

Figure XIX-60.2. Scotian Shelf LME annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Scotian Shelf LME Chlorophyll and Primary Productivity

This LME is a Class II, moderately-high productivity ecosystem (150-300 gCm^{-2}yr^{-1}) (Figure XIX-60.3).

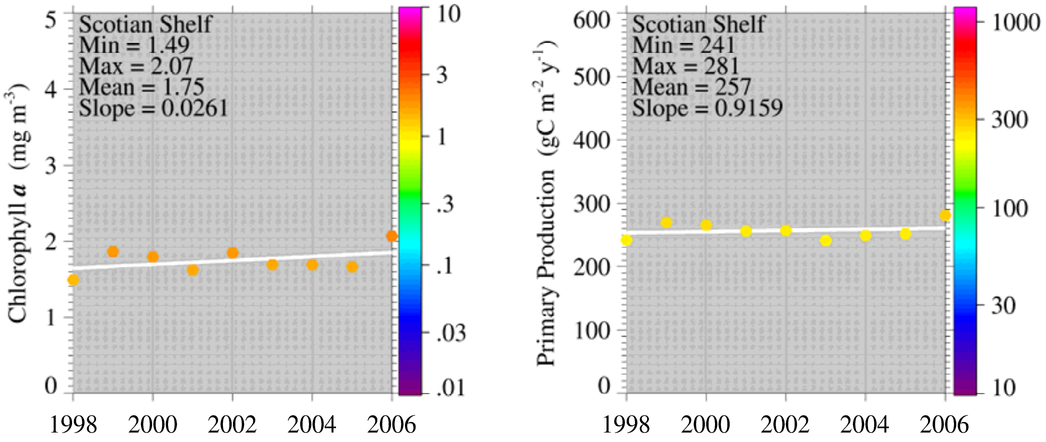

Figure XIX-60.3. Scotian Shelf LME annual trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Commercially exploited species include cod, haddock, pollock, silver hake, halibut, white hake, and turbot. Pelagic species include the Atlantic herring and the Atlantic mackerel. Invertebrates include snow crab, northern shrimp and short fin squid. Both snow crab and northern shrimp prefer cold water and the increased landings for both those species coincide with the cooling of the eastern shelf (Zwanenburg 2003). Systematic fishery surveys of the shelf made between the 1960s and the present are the most consistent source of information available concerning this LME.

Total reported landings recorded a peak of 889,000 tonnes in 1970 and declined to less than a quarter of this level or 213,000 tonnes in 2004 (Figure XIX-60.4). Major changes include a dramatic decline in landings of cod, silver hake and redfish. However, the value of the reported landings reached its peak of US$1.2 billion (in 2000 US dollars) in 2000, as a result of high value commanded by its landings of crustaceans (Figure XIX-60.5).

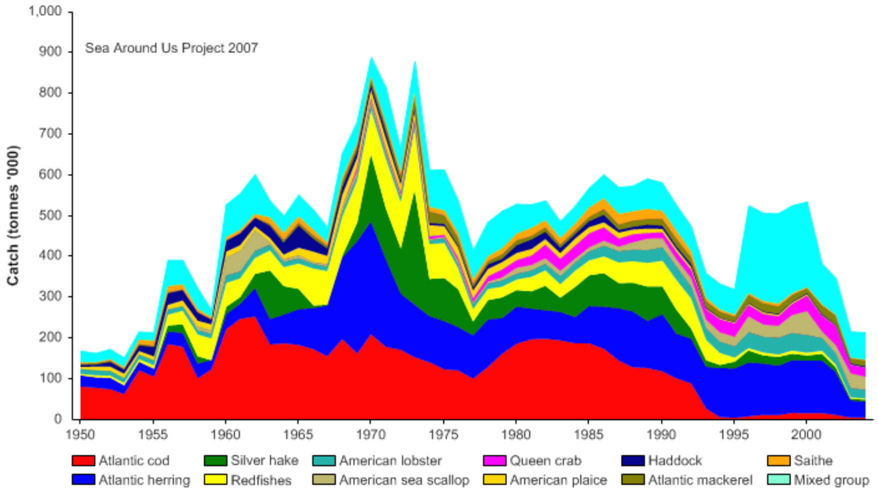

Figure XIX-60.4. Total reported landings in the Scotian Shelf LME by species (Sea Around Us 2007).

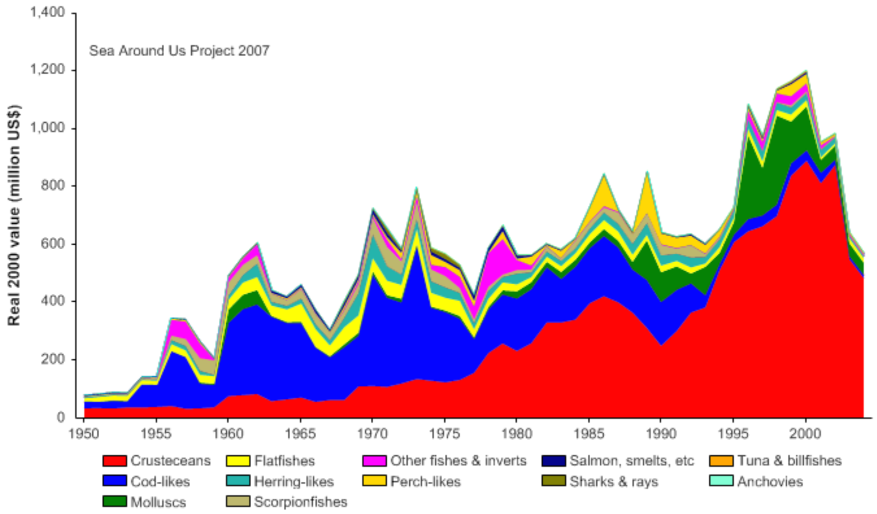

Figure XIX-60.5. Value of reported landings in the Scotian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly & Christensen 1995) to sustain the reported landings in this LME exceeded the observed primary production in the mid 1970s, but has declined in recent years (Figure XIX-60.6). The extremely high PPR recorded in the mid 1970s was likely due to the accumulated biomass of cod stocks being exploited and not from exploitation of annual surplus production. Canada accounts for almost all of the ecological footprint in this LME (Figure XIX-60.6), although in the 1960s and 1970s, a number of European countries also had a large share.

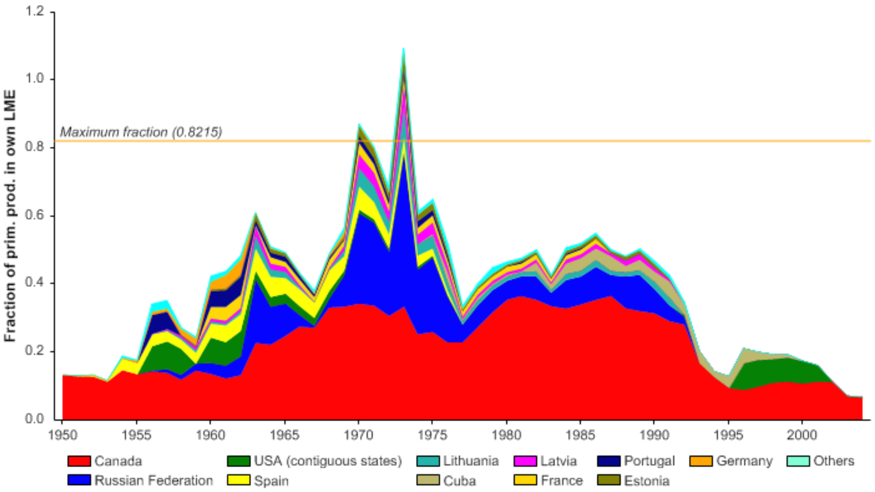

Figure XIX-60.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Scotian Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (i.e., the MTI; Pauly & Watson 2005) remained high until the early 1990s, when the cod stock collapsed (Figure XIX-60.7, top), a clear case of 'fishing down' of the food web (Pauly *et al*. 1998, 2001). The FiB index showed a similar trend (Figure XIX-60.7, bottom), suggesting that the reported landings did not compensate for the decline in the MTI over that period.

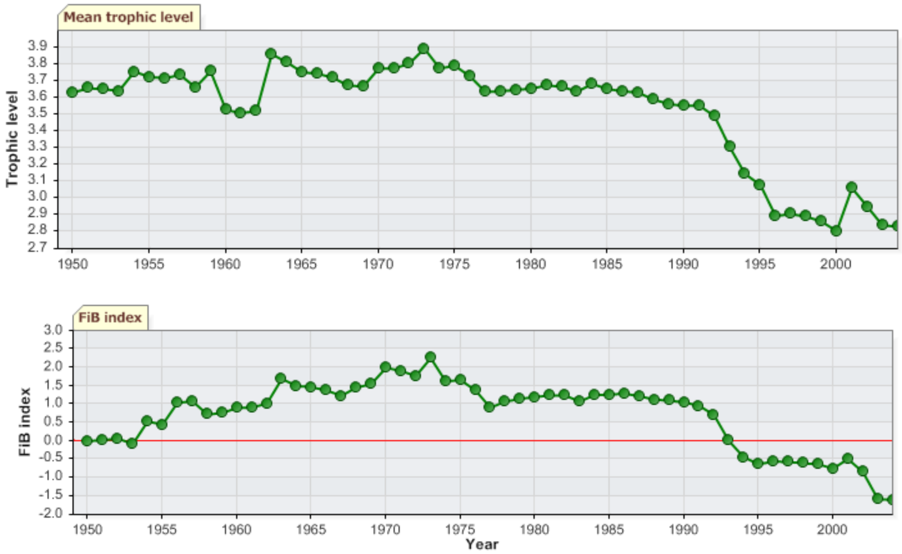

Figure XIX-60.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Scotian Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plot shows that over 90% of commercially exploited stocks in the LME are either overexploited or have collapsed (Figure XIX-60.8, top) with less than 30% of the reported landings biomass supplied by fully exploited stocks (Figure XIX-60.8, bottom).

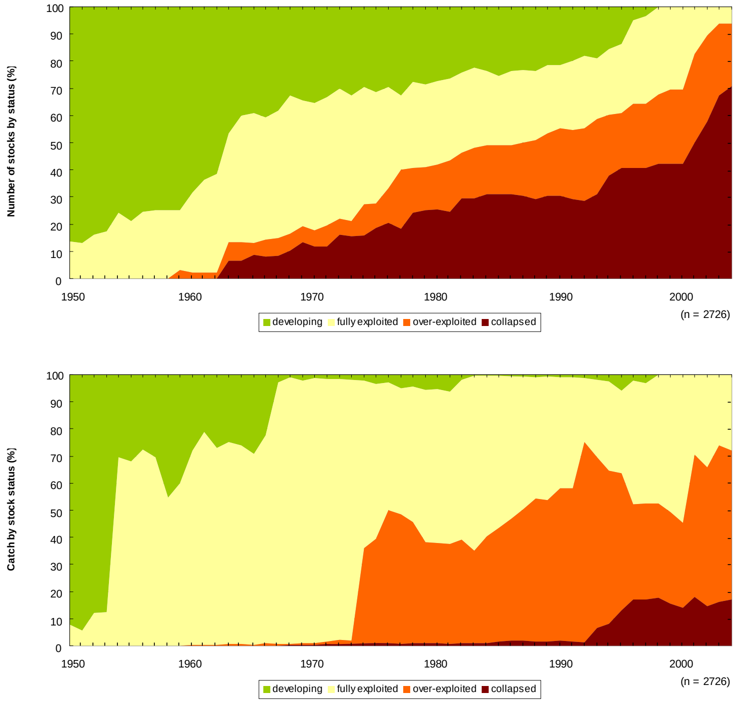

Figure XIX-60.6. Stock-Catch Status Plots for the Scotian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al.*, this volume, for definitions).

There have been significant declines in abundance and sizes for many commercially exploited fish species (Zwanenburg 2000), indicating that the limits of exploitation had been reached (Pauly *et al*. 2001). The decrease in size, related to fishing effort, occurred both on the eastern and western shelves. Fishing effort increased rapidly with the establishment of Canada's 200-mile EEZ in 1977. Recent analyses of changes in the productivity and biomass yields of the Scotian Shelf LME revealed the consequences of the removal of top predators on the trophic structure of an ecosystem (Choi *et al*. 2004, Frank *et al*. 2005). The dominant change in the biomass yield was a sharp decline in groundfish landings and biomass from the mid-1980s through the mid-1990s. The trawlable demersal biomass declined from 450,000 tonnes in 1973 to less than 15,000 tonnes in 1997. Coincident with this decline was an increase of pelagic fish as well as of shrimp and snow crab. At the lower trophic levels, increases were observed for a 40-year period from 1960 to 2000 in phytoplankton concentrations based on colour index values from CPR, and in the increase in numbers of zooplankters, less than 2 mm in length. The principal fisheries are now directed toward pelagic fish and macroinvertebrates, and are dominated by herring, shrimp and snow crab.

A management scheme taking into account species interaction and biomass production is being initiated to address the overexploitation of the LME's main fisheries (cod, haddock, flounder, and other demersal fish). When the cod fishery collapsed on the Eastern shelf, a cod moratorium was imposed in 1993 and remains in effect. Overfishing led to a number of fishery closures in the early 1990s.

III. Pollution and Ecosystem Health

For information on marine pollution and the protection of this LME's offshore environment, consult the Fisheries and Oceans Canada site at www.mar.dfo-mpo.gc.ca. The report section on Ocean Disposal and Marine Environmental Quality, Scotian Shelf: An Atlas of Human Activities (2005), lists illegal spills and discharges such as the chronic introduction of oil from vessel traffic, marine debris, chemical contaminants from vessels and offshore hydrocarbon development activities, and the introduction of invasive species and pathogens through ballast water as significant ongoing environmental concerns. Also listed are shipwrecks and post-war chemical and unexploded ordinance dump sites that need new assessments for risk. There have been several large-scale environmental emergencies, including the wreck of the Arrow oil tanker and other vessel sinkings. The DFO reports no concentrations of heavy metals above the PEL (probable effects level) on the Scotian Shelf.

Hollingworth recognized the need to assess the wider ecological costs of over exploitation of the fisheries resource (2000). The International GLOBEC Cod and Climate Change Programme studies the response of different cod populations to climate changes in various regions of the cod's North Atlantic range, including the Scotian Shelf. The ESSIM project (Eastern Scotian Shelf Integrated Management Project) described in its first Ecosystem Status Report for the Eastern Scotian Shelf (DFO 2003) the shift in the ecosystem from groundfish to pelagic species and invertebrates (see also Zwanenburg et al. 2006). O'Boyle and Jamieson (2006) point to an ongoing paradigm shift in ocean management, exemplified by explicit consideration of the impacts of all ocean sectors on the marine environment, both separately and in aggregate. The authors recommend adaptive management, and include both conceptual and operational level management goals to achieve ecosystem-based management. Climate change is a priority issue, and on 12 December 2007 the Government of Canada announced at the UN Climate Change Conference in Indonesia new mandatory regulations for industry for emissions reduction. Industries must submit air emissions data to the Government of Canada within the next six months as part of the "toughest plan in Canadian history" to clean up air, tackle climate change and protect our environment" said Environment Minister John Baird. The air emissions action is part of Canada's "Turning the Corner: An Action Plan to Reduce Greenhouse Gases and Air pollution launched in April 2007.

IV. Socioeconomic Conditions

The Nova Scotia Department of Finance, Economics and Statistics, reports that the population of Nova Scotia on 1 October 2007 was 935,106 persons of whom 452,000 were employed and per capita income in 2006 was $29,459. Health Canada posts a report by Dr. Ronald Colman (2005) on the socioeconomic gradient in health in Atlantic Canada based on evidence from Newfoundland and Nova Scotia 1985-2001 finding high socioeconomic inequality in health in Newfoundland and Glace Bay and Kings County, Nova Scotia compared to Canada as a whole, Europe and Australia. Income was found to be the most important contributor to socioeconomic inequality in health; education and economic status also contributed to health status (Colman 2005).

The trophic cascade changed the structure of the Scotian Shelf LME from an economic perspective, with the recent value of shrimp and crab landings exceeding the previous value of the demersal fishery. With regard to other marine resources, the Canada-Nova Scotia offshore petroleum Board is responsible for the regulation of petroleum affairs in the province. The presence of oil raises issues of multiple uses of the marine environment.

V. Governance

Federal jurisdiction over Canada's coastal and inland fisheries dates to the Constitution Act of 1867. In 1979 the federal government established the Department of Fisheries and Oceans. However, the provinces are responsible for certain areas of fisheries jurisdiction, including fish processing and the training of fishermen (The Canadian Encyclopedia at www.thecanadianencyclopedia.com). In November 2007 the DFO announced a new framework for the management of fisheries resources. Drivers for the new management framework include the need to certify that Canadian seafood products are sustainably harvested, domestic legislation including Bill C-45, and International agreements and protocols signed by Canada. The Framework and the international agreements emphasise the Precautionary Approach, the Ecosystem Approach, and Sustainable Development.

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XIX-61 Northeast U.S. Continental Shelf LME

M.C. Aquarone and S. Adams

The Northeast U.S. Continental Shelf LME extends from the Gulf of Maine to Cape Hatteras in the Atlantic Ocean. It is characterised by its temperate climate. Structurally, this LME is complex, with marked temperature and climatic changes, winds, river runoff, estuarine exchanges, tides and multiple circulation regimes. It is historically a very productive LME of the Northern Hemisphere. The LME has an area of 310,000 km^2, of which 1.96% is protected, and has 28 major estuaries and river systems (Sea Around Us 2007), including Casco Bay (Kennebec), Chesapeake (including the Potomac River), Delaware, and Long Island Sound (Connecticut River). Four major sub-areas are the Gulf of Maine, Georges Bank, Southern New England, and the Mid-Atlantic Bight. Book chapters and articles pertaining to this LME include Falkowski (1991), Sissenwine & Cohen (1991), Sherman *et al.* (1996a, 1996b, 2002, 2003) and Murawski (1996, 2000). A Northeast Shelf Ecosystem volume, edited by Sherman *et al.*, was published in 1996. A trophodynamic energy network model has recently been published (Link et al. 2008).

I. Productivity

This LME is bounded on the seaward side by the Gulf Stream, with its circulation and seasonal meanders and rings influencing the LME. The gyre systems of the Gulf of Maine and Georges Bank, and the nutrient enrichment of estuaries in the southern half of the LME contribute to the maintenance on the shelf of relatively high levels of phytoplankton and zooplankton prey fields for planktivores including menhaden, herring, mackerel, sand lance, butterfish, and marine birds and mammals. For a map of surface circulation, see Sherman *et al.* (2003). For an overview of the physical oceanography of the shelf, see Brooks (1996). The Northeast U.S. Continental Shelf LME is a Class I, highly productive ecosystem (>300 gCm^{-2}yr^{-1}), and is one of the world's most productive LMEs. Since 1977, the NOAA Northeast Fisheries Science Centre (NEFSC) has monitored this LME for primary productivity, chlorophyll-*a,* zooplankton biomass and species diversity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance. Productivity varies in the 4 major sub-areas, and from season to season. Zooplankton is used as an indicator of major changes in stability of the lower levels of the food web and of biofeedback responses to oceanographic changes (Durbin & Durbin 1996). Over the past two decades, zooplankton has been stable with regard to biomass. Relatively high biodiversity and abundance of zooplankton within the ecosystem contributed to the recovery of herring and mackerel from their low levels in the mid-1970s and supported the recovery of several demersal fish stocks beginning in the mid-1990s (Sherman *et al.* 2003).

Oceanic fronts (Belkin *et al.* 2009)(Figure XIX-61.1): The Shelf-Slope Front (SSF) is associated with a southward flow of cold, fresh water from the Labrador Sea. The Mid-Shelf Front (MSF) follows the 50-m isobath (Ullman and Cornillon, 1999). The Nantucket Shoals Front (NSF) hugs the namesake bank/shoals along 20-30-m isobaths. The Wilkinson Basin Front (WBF) and Jordan Basin Front (JBF) separate deep basins from Georges Bank and Browns Bank and are best defined in winter. Georges Bank is surrounded by a tidal mixing front, GBF (Mavor and Bisagni, 2001). The Maine Coastal Front (MCF) and Cape Cod Front (CCF) are seasonal (Ullman and Cornillon, 1999).

Northeast U.S. Continental Shelf LME SST (Belkin 2009)(Figure XIX-61.2):
Linear SST trend since 1957: 1.08°C.
Linear SST trend since 1982: 0.23°C.

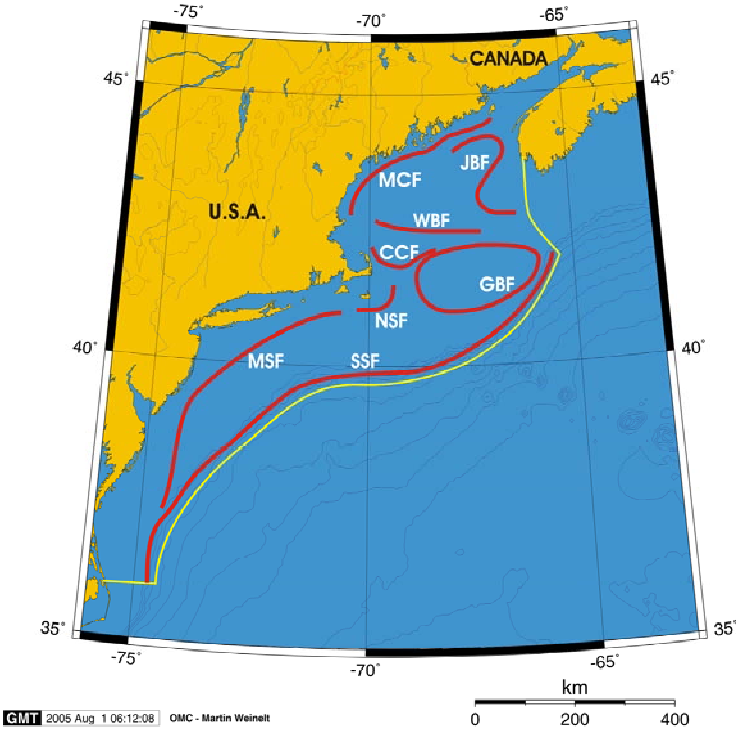


Figure XIX-61.1. Fronts of the Northeast U.S. Continental Shelf LME. CCF, Cape Cod Front; GBF, Georges Bank Front; MCF, Maine Coastal Front; MSF, Mid-Shelf Front; NSF, Nantucket Shoals Front; SSF, Shelf-Slope Front. Yellow line, LME boundary; after Belkin et al. (2009).

The Gulf Stream brings warm waters from the Gulf of Mexico into the Southeast U.S. Shelf, creating oceanographic conditions dramatically different from those of the Northeast U.S. Continental Shelf LME. The Southeast U.S. Shelf is protected from northern influences by the convergence of the Gulf Stream with the coast near Cape Hatteras, which leaves very little opening for the leakage of shelf/slope waters from the Mid-Atlantic Bight into the South Atlantic Bight. Subarctic influences can reach the Mid-Atlantic Bight of the NE Shelf LME but not the South Atlantic Bight of the SE Shelf LME (Greene and Pershing, 2007). Additionally the Gulf Stream, deflected offshore past Cape Hatteras, indirectly impacts the Northeast U.S. Shelf by warm-core rings, whereas the Southeast U.S. Continental Shelf is directly affected by the meanders of the Gulf Stream.

A cold spell in the 1960s resulted in a 2°C SST drop down to 10.5°C by 1965; the recovery took four years. From 1969 on, the Northeast U.S. Continental Shelf experienced a gradual warming with substantial interannual variability. The linear trend for 1957-2006 yields a warming of 1.08°C, whereas the linear trend for 1982-2006 yields a much smaller warming of 0.23°C.

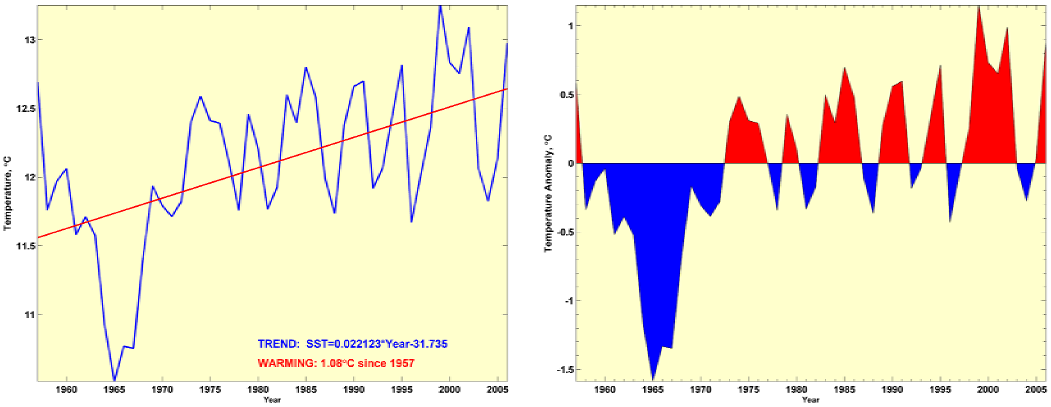


Figure XIX-61.2. Northeast U.S. Continental Shelf annual mean SST (left) and SST anomalies (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Northeast Shelf LME Chlorophyll and Primary Productivity

The Northeast U.S. Continental Shelf LME is a Class I, highly productive ecosystem (>300 $gCm^{-2}yr^{-1}$)(Figure XIX-61.3),

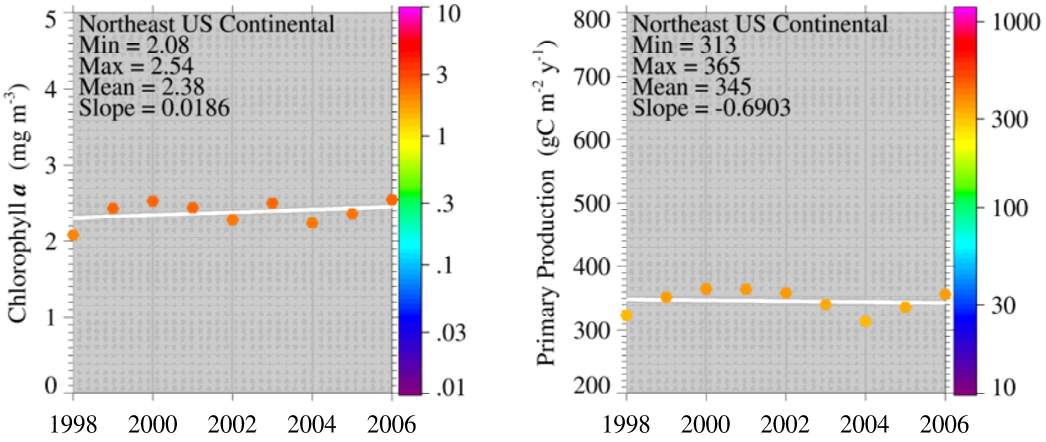


Figure XIX-61.3. Northeast U.S. Continental Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Much has been published on Northeast U.S. Shelf LME fisheries, including population assessments (Sherman *et al.* 1996c; Kenney *et al.* 1996; Mavor & Bisagni 2001) and the status of living marine resources in Our Living Oceans (NOAA 1999) and in the NEFSC Status of Stocks reports. The catch composition of this LME is diverse, and is comprised of demersal fish (groundfish) dominated by Atlantic cod, haddock, hakes, pollock, flounders, monkfish, dogfish, skates and black sea bass, pelagic fish (mackerel, herring, bluefish and butterfish), anadromous species (herrings, shad, striped bass and salmon), and invertebrates (lobster, sea scallops, surfclams, quahogs, northern shrimp, squid and red crab). In the late 1960s and early 1970s there was intense foreign fishing within the

LME. The precipitous decline in biomass of fish stocks during this period was the result of excessive fishing mortality (Murawski *et al.* 1999). Total reported landings declined from more than 1.6 million tonnes in 1973 to less than 500,000 tonnes in 1999, before increasing to just under 800,000 tonnes in 2004 (Figure XIX-61.4). The value of the reported landings reached US$1.8 billion (in 2000 US dollars) in 1973 and in 1979, and has maintained a level above US$1 billion except for the three-year period between1998 and 2000 (Figure XIX-61.5). Among the most valuable species are lobster, sea scallops, monkfish and summer flounder.

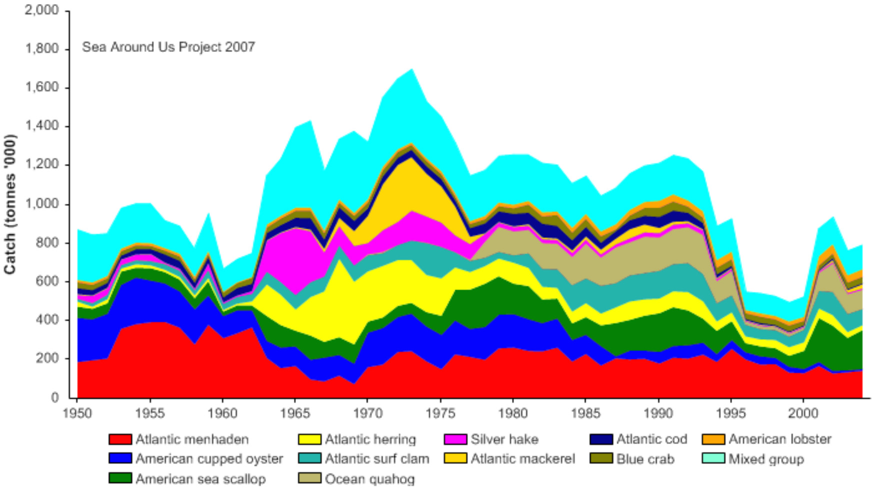


Figure XIX-61.4. Total reported landings in the Northeast U.S. Continental Shelf LME by species (Sea Around Us 2007).

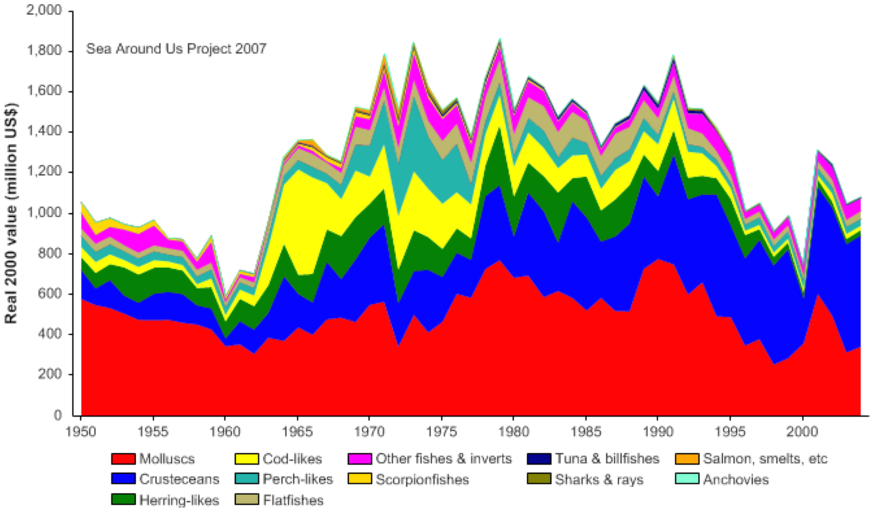


Figure XIX-61.5. Value of reported landings in the Northeast U.S. Continental Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR) (Pauly & Christensen 1995) to sustain the reported landings in the LME reached 90% of the observed primary production in the mid 1960s, but has declined to less than 20% in recent years (Figure XIX-61.6). The extremely high PPR recorded in the 1960s and 1970s was likely due to the exploitation of the accumulated biomass of cod stocks rather than from the exploitation of annual surplus production in the LME. The USA accounts for most of the ecological footprint in this LME, and Canada for some, although European countries also had a major share in the 1960s and 1970s.

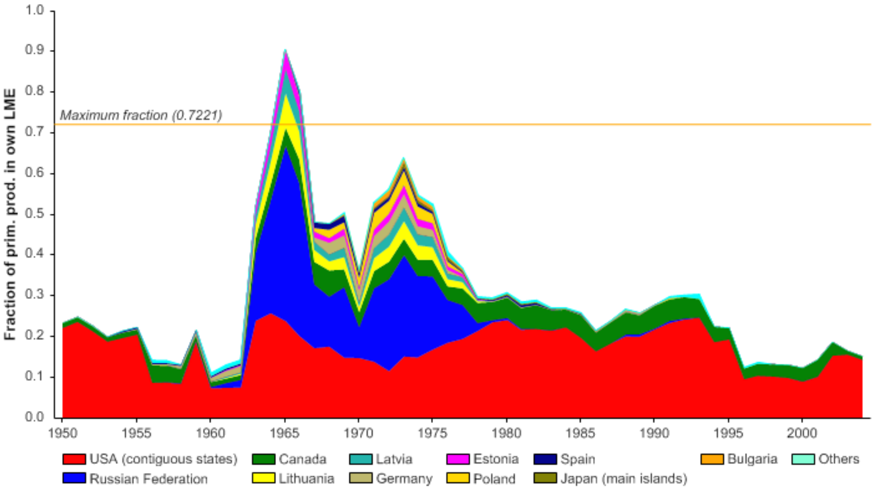


Figure XIX-61.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Northeast U.S. Continental Shelf LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (Pauly & Watson 2005) has declined since the early 1960s, when the rate of exploitation of demersal fish in the LME was high (Figure XIX-61.7, top), the consequence of a clear case of 'fishing down' of the food web (Pauly *et al.* 1998). The Fishing in Balance index showed a similar decline (Figure XIX-61.7, bottom), implying that the increase in reported landings in the 1970s did not compensate for the decline in the Marine Trophic Index over that period.

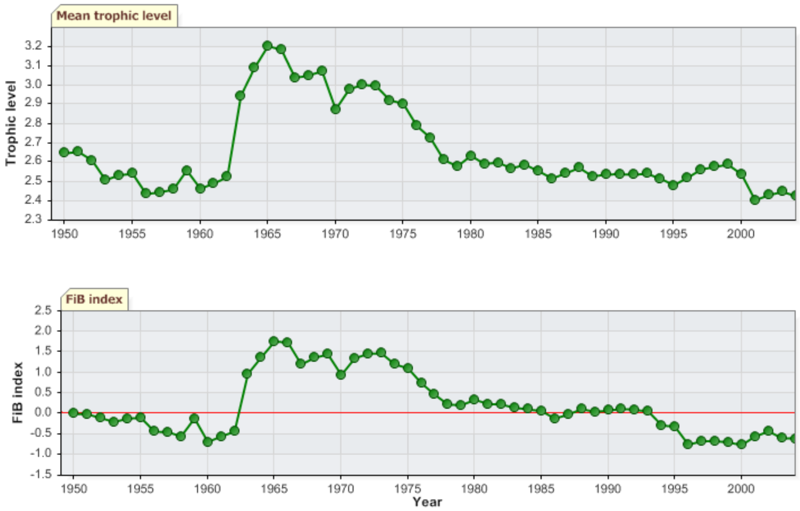
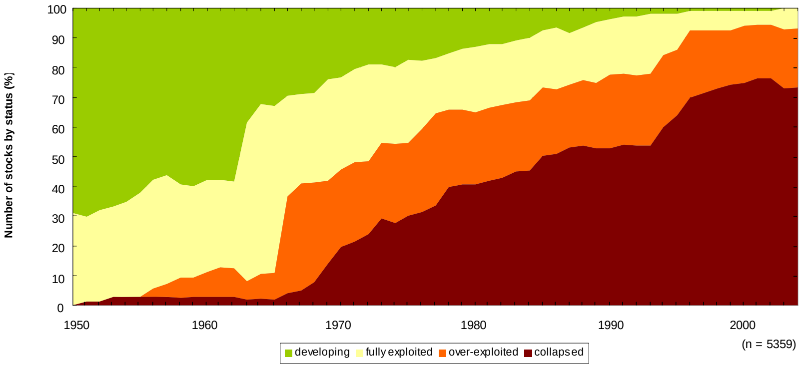


Figure XIX-61.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Northeast U.S. Continental Shelf LME (Sea Around Us 2007).

The Stock-Catch Status Plots show that over 70% of commercially exploited stocks in the LME have collapsed, with another 20% being overexploited (Figure XIX-61.8, top). Slightly over 30% of the reported landings biomass is supplied by fully exploited stocks (Figure XIX-61.8, bottom). The US National Marine Fisheries Service (NMFS) includes “overfished” but not “collapsed” in its stock status categories. Currently overfished are several demersal stocks (NMFS 2009).



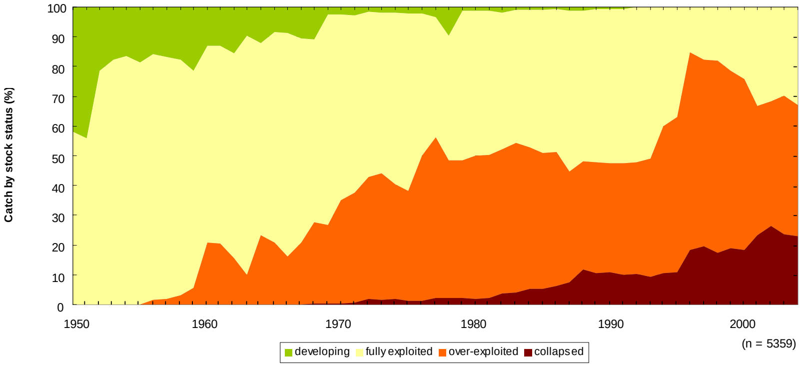


Figure XIX-61.8. Stock-Catch Status Plots for the Northeast U.S. Continental Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of ‘stocks’, i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The status of demersal fisheries can be found in Our Living Oceans (NMFS 1999; 2009), Anderson et al. (1999a and 1999b), EPA 2004 and NMFS 2009. The Northeast Shelf groundfish complex supports important recreational fisheries as well (summer flounder, Atlantic cod, winter flounder, and pollock). Many demersal stocks are considered overfished and are currently rebuilding. Groundfish partially recovered because of reduced fishing effort and restrictive management in the late 1970s. The recovery trend of George’s Bank yellowtail and haddock observed in the late 1990s is linked to reductions in the exploitation rate when, in 1994, there was an emergency closure of portions of Georges Bank, and severe restrictions were placed on the fishing of demersal species by the New England Fishery Management Council Sherman et al 2003). The measures to reduce fishing effort included the reductions of days at sea and a moratorium on new vessel entrants (NMFS 1999). Landings of most groundfish species, however, were low in the mid 1990s as a result of poor recruitment and continued restrictions on effort. In a biomass flip, dogfish and skates increased in abundance in the 1970s, as groundfish and flounder declined. However, a decrease of dogfish and skates has been observed more recently, after a peak in the 1990s (NMFS 1999; Anthony 1996). Some of the Northeast Shelf LME's demersal stocks are among the best understood and assessed fishery resources in the US (EPA 2004, NMFS 2009). Abundance of pelagic mackerel, herring and bluefish has increased since the late 1970s and is presently above average. The virtual elimination of foreign fishing on Atlantic herring and mackerel stocks has resulted in the recovery of both species to former abundance levels, as neither species is a high priority table fish for the U.S. consumer. The herring stock is somewhat underutilized. Northeast pelagics are an important link in many marine food chains as they are utilized as prey by a variety of predatory fish, marine mammals and birds. Some anadromous species (shortnose sturgeon, Atlantic salmon) are listed as endangered and landings are generally low for Atlantic anadromous fisheries but for the recently observed increase in landings of striped bass following several years of management restrictions (NMFS 2009). The alteration of river migration routes blocking access to historic spawning grounds, pollution and coastal development have played a major role in the decline of Atlantic salmon, sturgeon, river herring, and shad. The only remaining Atlantic salmon populations occur in 8 small rivers in eastern Maine. In the face of declining natural populations, a small salmon aquaculture industry in Maine has grown to fill the production void and averages approximately 10,000 t annually. Invertebrate fisheries (American lobster, sea scallops) are the most valuable in the Northeast Shelf. The lobster fishery has become increasingly dependent on small and young lobsters that reach a legal size just prior to capture. There are efforts to reduce the currently high fishing mortality on lobsters. Both the closure of half of the U.S. portion of Georges Bank to scallop harvesting to protect groundfish stocks and the increase in the ring diameter of scallop dredges in 1994 contributed to an increase in sea scallop stock biomass (Anderson *et al.* 1999). A system of rotational closures for sea scallop management is in place to allow small scallops to grow to a larger size. Landings are presently at high levels.

The long-term potential yield for this LME was set at about 1.6 million tonnes (NMFS 1999). The long-term sustainability of high economic yield species depends on the rebuilding of fish stocks through the application of adaptive management strategies (Murawski 1996). Agencies involved in the complex management of Northeast fisheries include the New England Fishery Management Council, the Mid-Atlantic Fishery Management Council, the Atlantic States Marine Fisheries Commission, individual states, and Canada. Information on fishery management plans is available in Our Living Oceans (NMFS 1999; NMFS 2009). The NEFSC compiles information on the distribution, abundance and habitat requirements for the 38 commercially valuable species managed by the New England and Mid-Atlantic Fishery Management Councils (NMFS 1999).

III. Pollution and Ecosystem Health

The Northeast Coast is the most densely populated coastal region in the United States. The ratio of watershed drainage areas to estuary water areas is relatively small (EPA 2004). Hypotheses concerned with the growing impacts of pollution, overexploitation and environmental changes on sustained biomass yields in the Northeast Shelf LME are under investigation. Efforts to examine changing ecosystem states and the relative health of this LME are underway in the four sub-areas of the Northeast Shelf ecosystem. Major rivers systems (Hudson, Delaware, Chesapeake) contribute nitrates to estuaries and coastal systems from agriculture fertilisation, atmospheric deposition and sewage. The estuaries and near-coastal waters of the LME are under considerable stress from increasing coastal eutrophication resulting from high levels of phosphate and nitrate discharges into drainage basins (Jaworski & Howarth 1996). Whether the increases in the frequency and extent of nearshore plankton blooms are responsible for the rise in incidence of biotoxin-related shellfish closures (White & Robertson 1996) and marine mammal mortalities remains a question of considerable concern to state and federal management agencies. For this LME as a whole, water clarity is good, dissolved oxygen and coastal wetlands are fair, while the increasing extent of eutrophication is cause for concern). The water quality index is fair to poor (EPA 2004). About 60% of estuarine areas have a high potential of increasing eutrophication or existing high concentrations of chlorophyll-*a*. High levels of sediment contamination are found near urban centres, reflecting current discharges and the legacy of past industrial practices (EPA 2004). Over 25% of sediments exceed the EPA guidelines for contaminants. Nearly 40% of wetlands along the coast were eliminated between 1780 and 1980. About 10% of fish sampled by EPA have elevated levels of contaminants in their edible tissues (EPA 2001). Benthic community degradation, fish tissue contamination and eutrophication are increasing. Coastal contamination is especially high along the urbanised and densely populated areas along the northern part of the coast and in poorly flushed waters. Flux levels of zinc, cadmium, copper, lead and nickel are highest in the southern New England region, reflecting the level of urbanisation and industrialisation (O'Connor 1996). Heavy metal concentrations in demersal fish, crustaceans and bivalve molluscs are monitored as biological indicators (Schwartz *et al.* 1996). The Virginia Oyster Heritage Program highlights the critical role oysters play in keeping coastal waters clean and providing habitat for other marine life (EPA 2004). Of the 826 beaches in the Northeast Coast that reported information to the EPA, 18% were closed or under advisory for a period of time in 2002 due to elevated bacteria levels, rainfall events or sewage related problems (EPA 2004).

IV. Socioeconomic Conditions

The population of the coastal counties of the northeast coast, from northern Maine to the tidewaters of Virginia, is estimated at 54.3 million people for 2008, representing 78% of the total population of all the Northeast coastal states (NOAA 2005). Four of the nation's largest metropolitan areas, New York, Washington DC/Baltimore, Philadelphia and Boston, are located along the coast of this region. On average, 13 to 23 percent increases in coastal population were expected in Maryland and Virginia between 2003 and 2006. The economic centres in the region include New York City, the largest financial market in the world. Northeast economic activities include agriculture, resource extraction (forestry, fisheries, and mining), major service industries highly dependent on communication and travel, recreation and tourism, manufacturing and transportation of industrial goods and materials (USGCRP 2004).

In 2006, the Northeast Shelf ecosystem supported over 1,100 active fishing vessels in both federal (3-200 miles) and state waters. These vessels produced fish and shellfish (and other invertebrates) landings worth over US$1.2 billion. In the late 1960s and early 1970s, the intense involvement of foreign fishing fleets and overfishing led to marked declines in fish abundance (Sherman & Busch 1995). Analyses of catch per unit effort and fishery independent bottom trawling survey data were critical sources of information used to implicate overfishing as the cause of the shifts in abundance. Northeast fishermen were adversely affected by the collapse of the groundfish fishery in the late 1980s. A groundfish vessel buyout program (1995-1998) was designed to provide economic assistance to fishermen who voluntarily chose to remove their vessels permanently from the fishery. This resulted in a 20% reduction in fishing effort (NOAA 1999). The fishing culture is traditional in the region and fishermen have struggled to remain solvent and engaged in the fishing industry in the face of mandated declines in fishing effort as part of a groundfish stock rebuilding program. Fishing effort reductions led to curtailed revenues for fishermen (NMFS 1999, Hennessey & Sutinen 2005; Heinz 2000)). The reduction in fishing effort since 1994 has resulted in an initial recovery of several demersal fisheries, including stocks of sea scallops, haddock and Georges Bank yellowtail flounder. The Northeast has a low rate of projected future warming compared to other regions of the U.S. The U.S. Global Change Research Program report on the potential consequences of climate variability and change in the Northeast (USGCRP 2004) has projected increasing trends in precipitation of as much as 25% by 2100 with increased flooding from storms, rising sea levels, and coastal land loss. At risk are transportation, communication, energy, water sources and waste disposal systems, particularly in major Northeast cities presently characterized by insufficient capacity and deferred maintenance. Sea level rise in the Northeast coastal zone will also exacerbate stresses to estuaries, bays and wetlands from increasing pollutants, temperature and salinity and the inundation by sea water of wetlands and marshes.

V. Governance

The Northeast Shelf includes the coastal waters of Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Pennsylvania, Maryland and Virginia. Governance in this LME is shared among several stewardship agencies and there is a complex layering of management agencies. The 1976 Magnuson Fishing Management Act established the U.S. 200-mile EEZ, which led to reduction of fishing effort on herring and mackerel stocks and the recovery of their biomass. But the Act's single species focus neglected predator-prey relationships and other interactions. This focus has often resulted in conflicting goals and bycatch mortality (Murawski 1996). A Council system for fisheries management in the region was introduced in 1976 where co-managing stakeholders are responsible for developing regulations which are enforced by the National Marine Fisheries Service. Civil societies participating in this process include fishing groups and environmental organizations. The New England and mid-Atlantic Fishery Management Councils (Federal Fisheries) and the Atlantic States Marine Fisheries Commission (State water fisheries) regulate the region's fisheries through over 35 fishery management plans (FMPs). Regulatory measures since 1994 have been aimed at a managed recovery of depleted fish stocks through reductions in days at sea, increased minimum mesh sizes, expanded closed areas, trip limits, and now limited access privileges including individual transferable quotas (ITQs). Together with decentralized co-management, these measures have led to good recruitment and recovery of the spawning biomass of sea scallops and haddock stocks. One issue is the management of transboundary stocks of Atlantic cod, haddock, yellowtail flounder and pollock in Canadian waters on Georges Bank and in the Gulf of Maine. Another is the management of transboundary stocks and jurisdiction over Atlantic anadromous fisheries, along with Canada and West Greenland (NMFS 2009). Conservation tools are implemented through the North Atlantic Salmon Conservation Organization (NASCO). In terms of pollution and ecosystem health, the Chesapeake Bay Programme's partnership with the bordering states has set specific targets for improving the water quality of the Bay (EPA 2001). Wetlands protection regulations have reduced the loss of wetlands. Coordinated programmes with participation from states, academic institutions, the private sector and federal government are underway to improve monitoring strategies aimed at mitigating habitat loss, coastal pollution, eutrophication and fisheries overexploitation.

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XIX-62 Hudson Bay LME

M.C. Aquarone, S. Adams and R. Siron

The Hudson Bay LME is a vast, shallow, semi-enclosed LME, bordered by the Canadian provinces of Quebec, Ontario, Manitoba and Nunavut and with a surface area of about 1,743,895 km², of which 0.42% is protected (Sea Around Us 2007). It is connected to the Davis Strait, Labrador Sea and Atlantic Ocean through the Hudson Strait, and to the Arctic Ocean by the Foxe Basin and the Fury and Hecla Straits. The LME receives Atlantic and Arctic marine waters, and freshwater from a vast watershed extending from the Northwest Territories to Saskatchewan and Alberta. The coastal zone geomorphology (low-lying areas, cliffs and headlands, and bottom topography) is still rebounding from the great weight of the Laurentide Ice Sheet that once covered the entire region. A unique oceanographic feature of this LME is its Arctic climate and variety of ecoclimatic zones, ranging from humid high boreal in the south to low Arctic. The LME has long, cold winters and short, cool summers. It is the largest body of water in the world that seasonally freezes over in the winter and becomes ice-free in the summer and it is significantly colder than other marine regions situated on the same latitude. Strong winds during the open water season, persistent low temperatures and the influx in the spring and summer of fresh water from numerous rivers and melting sea ice characterise the LME. Annual ice cover fluctuates with oscillatory changes in the climate system produced by the North Atlantic Oscillation and the Arctic Oscillation. There is extreme variation in the range of average temperatures and average total precipitation, both seasonally and annually, throughout the LME. Book chapters and articles pertaining to this LME include Stewart & Lockhart (2004, 2005).

I. Productivity

Three key features characterise productivity of the Hudson Bay LME: (1) the extreme southerly penetration of Arctic marine water; (2) a very large volume of freshwater runoff; and (3) the dynamic geomorphology of the coastal zone, with its low-lying marshes and wide tidal flats. Polynyas (open water areas in the ice, which are known to be biologically important throughout the Arctic) are found predominantly along the north-west and east coasts of the LME, in the James Bay and in the vicinity of the Belcher Islands, situated in the Southeast of the LME. The areas of ice cover and polynyas strongly affect the LME’s physical and biological oceanography, the surrounding land, and human activities. In summer there is a strong vertical stratification of the water column, particularly offshore. This slows vertical mixing, precludes the transfer of nutrients to surface waters and limits biological productivity. In winter, reduced runoff, ice cover and surface cooling weaken this vertical stratification. The large volume of freshwater influences the timing and pattern of the ice cover breakup, the surface circulation, water column stability, species distribution, and biological productivity. Areas to the North of James Bay are characterised by complete winter ice cover and summer clearing, moderate semidiurnal tides of Atlantic origin, a strong summer pycnocline, and lower biological productivity (Stewart & Lockhart 2004).

The Hudson Bay LME is considered a Class II (150-300 $gCm^{-2}year^{-1}$) productivity ecosystem. Productivity appears to be lower than that of other LMEs at similar latitudes, and is enhanced in coastal waters, near embayments and estuaries, and near islands where there is periodic entrainment or upwelling of deeper, nutrient-rich water. A remarkably diverse microalgal community, consisting of over 495 taxa, exists despite the northerly latitude, Arctic character, and low productivity of the Hudson-James Bay system

(Stewart and Lockhart 2005). Migratory fish, marine mammals and birds use the varied range of habitats year-round or seasonally. The ability to exploit the brackish zone is an important ecological adaptation for both the Arctic freshwater and marine species. Fewer species are found toward the North where Arctic species predominate. The LME and its ice habitats are used by five species of seals (bearded, ringed, hooded, harbor and harp), and by whales, including bowhead, beluga, narwhals, killer whales, minke, sperm whales and northern bottle-nose whales. There are walruses, Arctic foxes and polar bears in the LME coastal areas and ice habitats. The quality, extent and duration of the sea ice cover determine the seasonal distribution, movements and reproductive success of all these mammals. The polar bear population in the Hudson Bay region is at risk as ice cover recedes and seal prey are less available.

A precautionary approach to setting catch limits for polar bear in a warming Arctic was adopted at the 14th meeting of the IUCN Polar Bear Specialist Group in 2005. Knowledge gaps on the structure and function of the food web make it difficult to identify and understand trends of change and to discern whether they result from natural environmental variations or from human activities. The seasonal ice cover effectively prevents year-round, bay-wide research. Taxonomic coverage is uneven or incomplete, with few studies examining trophic relationships, biological productivity, and seasonal or inter-annual variation in the LME's physical and biological systems. Stewart and Lockhart (2005) who listed species that frequent Arctic marine waters: at least 689 invertebrate species, 61 fish species, marine mammals (5 species of whales, 5 species of seals, walrus, polar bear), and 133 species of seabirds. In addition, it is pertinent to highlight the importance and diversity of the ice algal community in Hudson Bay,including at least 155 taxa of which most (142) are diatoms.

Oceanic Fronts (Belkin *et al.* 2009) (Figure XIX-62.1): This LME appears relatively uniform as it features just a few comparatively weak fronts, mainly around its periphery. The most robust thermal front is observed in the far south, within James Bay, probably related to the enhanced freshwater discharge into the apex of James Bay that generates a collocated salinity front.

Similar estuarine fronts are likely to exist elsewhere off the bay's eastern, southern and western shores, peaking after spring freshets. A meandering front develops in the northern part of Hudson Bay between waters that flow into the bay from the northwest and resident waters. This front develops seasonally; its location and TS-characteristics ultimately depend on the seasonal ice cover melt since the latter determines the amount of fresh water released by the melting sea ice and eventually determines the salinity differential across this front.

Hudson Bay LME Sea Surface Temperature (Belkin 2009) (Figure XIX-62.2):
Linear SST trend since 1957: 0.59°C.
Linear SST trend since 1982: 0.28°C.

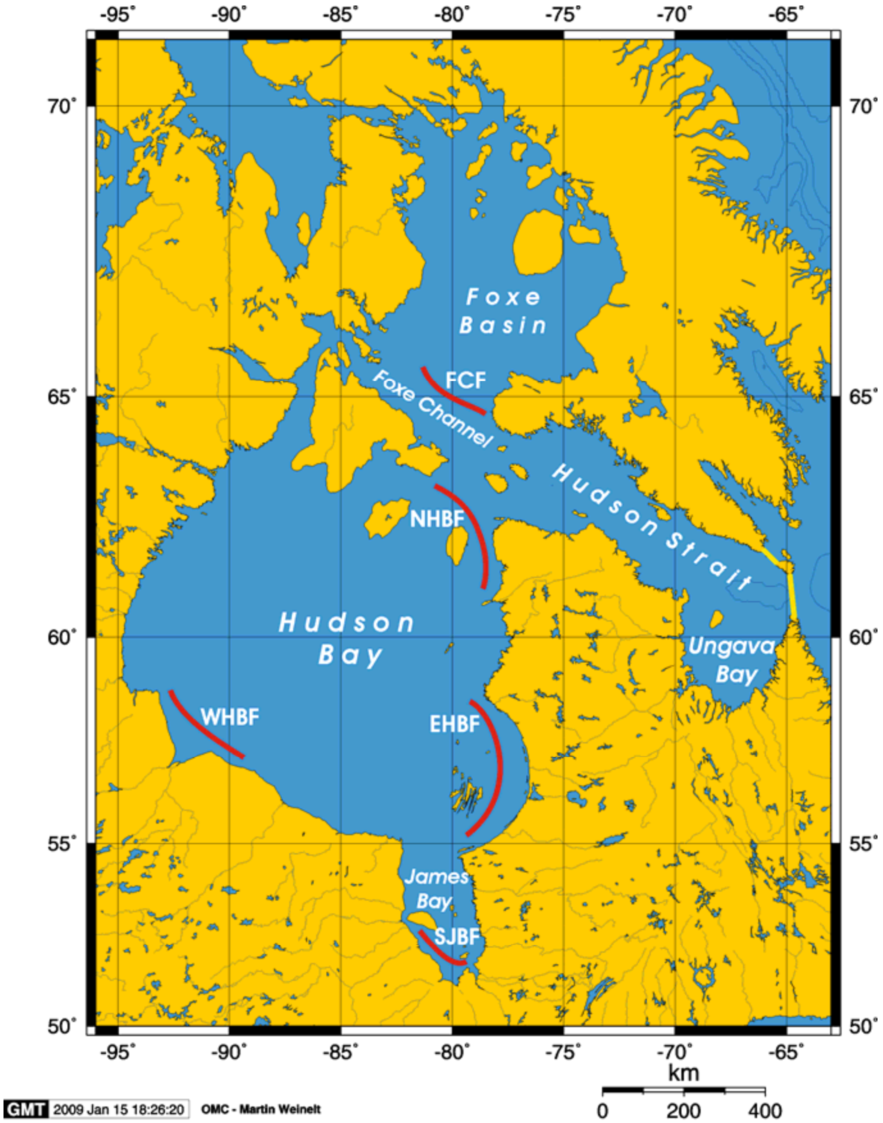

Figure XIX-62.1. Oceanographic fronts of the Hudson Bay LME. EHBF, East Hudson Bay Front; FCF, Foxe Channel Front; NHBF, North Hudson Bay Front; SJBF South James Bay Front; WHBF, West Hudson Bay Front. Yellow line, LME boundary. After Belkin *et al.* (2009).

The Hudson Bay warming was steady but moderate-to-slow. The all-time minimum of -0.1°C was achieved in 1972, in the end of a long-term cooling epoch. The post-1972 long-term warming resulted in an SST increase of >1°C over the next 20 years. The all-time maximum of 1.6°C in 1999 was an isolated event. The long-term decrease of river freshwater discharge into the Hudson Bay caused salinization of the upper ocean (Déry et al., 2005), so that there are two modern trends – warming and salinization – that have opposite effects on water density, which decreases with rising temperature and increases with rising salinity. Circulation in Hudson Bay flushes melt water out of the Bay into Hudson Strait and eventually onto the Newfoundland Shelf. Therefore the continuing warming of the Hudson Bay is bound to affect the Newfoundland Shelf. Significant asymmetry was found in temporal trends of landfast ice thickness between western and eastern sides of the Bay (Gagnon and Gough, 2005). First, "significant thickening of the ice cover over time was detected on the western side …., while a slight thinning … was observed on the eastern side" (Gagnon and Gough, 2005). Second, "this asymmetry is related to the variability of air temperature, snow depth, and the dates of ice freeze-up and break-up" (Gagnon and Gough, 2005). These results contradict numerical models of general circulation and field results obtained in other areas of the Arctic.

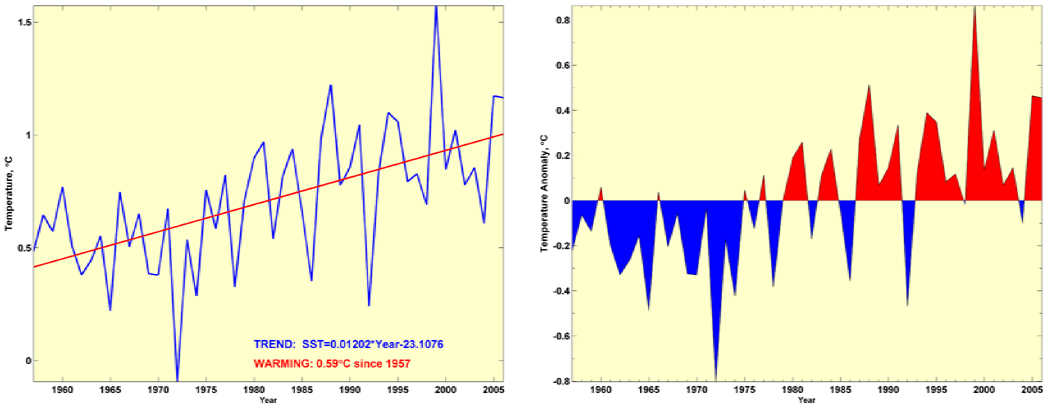

Figure XIX-62.2. Hudson Bay LME annual mean SST (left) and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

Hudson Bay LME Chlorophyll and Primary Productivity

This LME is a Class II moderate-high (150-300 gCm^{-2}year^{-1}) productivity ecosystem (Figure XIX-62.3).

It is difficult to measure the contributions of phytoplankton, ice algae, benthic algae and benthic macrophytes to primary production in the marine ecosystem. Stewart and Lockhart (2005) point out the difficulty of sampling at breakup when the main phytoplankton bloom likely occurs.

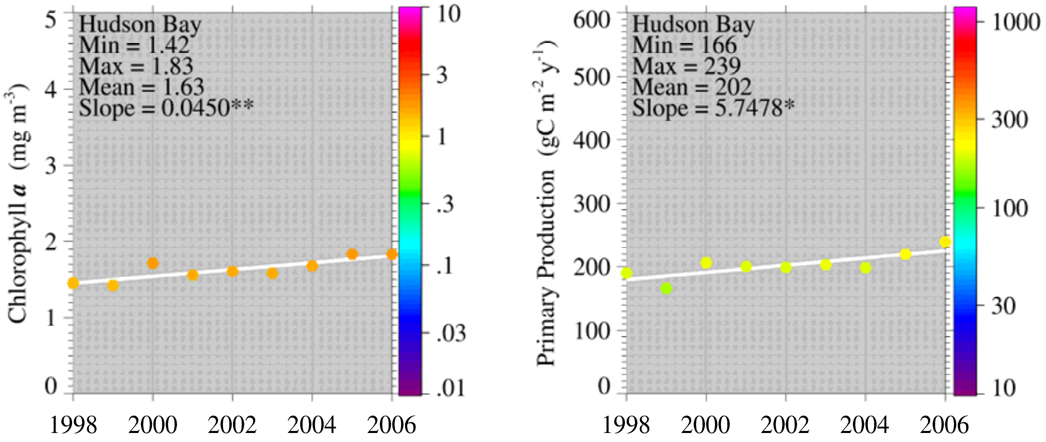

Figure XIX-61.3. Hudson Bay LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

A subpycnocline chlorophyll ***a*** maximum occurs in the offshore waters of Hudson Bay in the summer (Stewart and Lockhart 2005).

II. Fish and Fisheries

The Hudson Bay LME supports around 60 species of fish, consisting of a mix of Arctic marine, estuarine and freshwater species. This shallow LME lacks the deepwater species that inhabit the Hudson Strait. The typically Arctic mollusk species are more common and abundant offshore. The more significant marine resources are to be found in Foxe Basin, near the Fury and Hecla Strait. The Cree and Inuit catch most fish from estuarine or coastal waters during the open water season. Fishing is mainly for food, and as a traditional social and cultural activity. Exploited species include anadromous cisco, whitefish, longnose sucker, brook trout, capelin, cod, sculpin and blue mussels (*Mytilus edulis*). Indigenous peoples also catch seals, walrus and whales, and trap muskrat and beaver. Migratory waterfowl are a significant portion of the Cree and Inuit diet in the eastern Hudson Bay.

Of importance in this LME are largely unreported subsistence fisheries of the local Inuit and Indian populations, as described in Booth & Watts (2007). Twenty-four communities situated around the Hudson and James Bays make use of its resources, and the human population of these communities has grown from approximately 4,000 in 1950 to over 19,000 in 2001. Catches mainly target Arctic charr (*Salvelinus alpinus*) and Arctic cod (Boreagadus saida), although some other species are also taken, notably Atlantic salmon (*Salmo salar*) and Fourhorn sculpin (*Triglopsis quadricornis*). Estimated subsistence catches in 1950 were approximately 362 tonnes, and peaked in 1962 at 897 tonnes before declining to approximately 290 tonnes by the early 2000s (Figure XIX-62.4). A large portion of the decline over the last few decades is attributed to the fact that the snowmobile has replaced the dog sled as the major form of transportation, thus reducing the need for marine fish as dog food (Booth & Watts 2007).

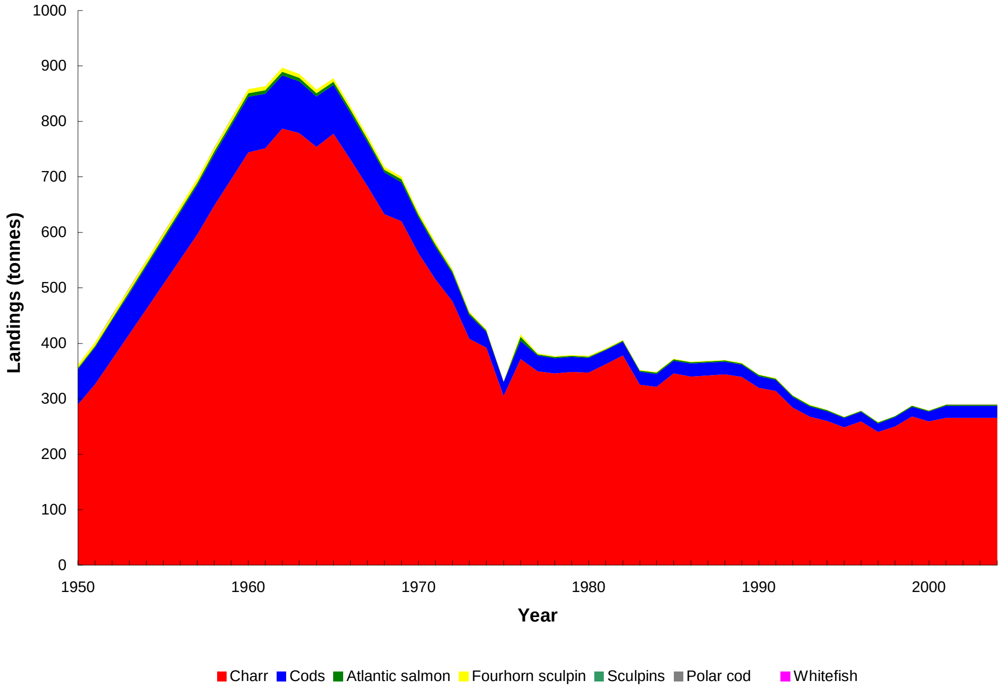

Figure XIX-62.4. Total estimated catches (subsistence fisheries) in the Hudson Bay LME by species (Sea Around Us 2007).
[No Figures 5, 6, 7, or 8]

Due to the tentative nature of these catch estimates, no indicators based on these data will be presented (but see Sea Around Us 2007).

III. Pollution and Ecosystem Health

Pollution: The Hudson Bay LME is relatively pristine. The human activities that can affect the natural environment of the LME are resource exploitation, marine transportation, mining, hydrocarbons, sewage disposal and the diversion of freshwater for industrial and agricultural purposes. The polynyas are thought to be affected by pollution as a result of the alteration in freshwater input to the southern Hudson Bay. Mercury levels in the La Grande River system rose considerably when a hydroelectric project began, but they are now declining. Slightly elevated mercury levels have been found in marine fish within 10 km to15 km of the La Grande River mouth. Marine mammals high on the food chain have the highest levels of mercury. Many Hudson Bay communities lack sewage and wastewater treatment facilities, and as a result, bacterial and chemical contaminants can be directly discharged into the sea. This is, however, offset by low temperatures and high salinity, which kill most pathogenic organisms. The impacts of marine ecotourism, while at present slight, are increasing. Visitors come to the port of Churchill (Manitoba) during the summer to see the beluga whales, polar bears and migratory birds. Cruise ships visit the northwestern Hudson Bay in the summer. Although there is a regular flow of ship traffic through the region, little has been altered along the coast except for the port of Churchill and for some small docking facilities. There is a risk of spills (oil, contaminants), and of introducing exotic species when bilges are cleaned.

Overall, the Hudson Bay LME is a relatively pristine environment. However, there is some evidence of the impacts of human activities on Hudson Bay with the presence in biota and sediments of synthetic persistent organic pollutants (POPs) which can reach the Arctic, and Hudson Bay, via long range transportation with moving air masses. Among the most toxic products found in Hudson Bay ecosystem, there are PCBs and radionuclides which result exclusively from human activities (Stewart and Lockhart, 2005). High levels of both DDT and PCBs have been reported from eastern part of Hudson Bay relative to other parts of the Arctic. High levels of PCBs were measured in human milk in coastal communities of northern Quebec (Cobb et al., 2001). In addition to POPs, toxic heavy metals have been found in this region. For example, a significant proportion of people living in coastal communities of northern Quebec has levels of blood mercury over the normal range (Cobb et al., 2001), whereas high levels of mercury have been observed in animals that are the highest in food chains, particularly some birds and marine mammals such as belugas and polar bears (Stewart and Lockhart, 2005)

Habitat and community modification: Low-lying rocky islands, tidal flats, tundras, salt marshes, eelgrass beds, coastal cliffs and open water polynyas are important habitats, used seasonally by migratory fish, marine mammals, migratory waterfowl and shore birds. The islands and coasts of James Bay provide critical habitats for breeding, feeding and moulting for a wide variety of species near the limits of their breeding distributions. Watersheds around the Hudson Bay LME are being altered as a result of population growth, business activity, agriculture, hydroelectric development and climate change. The pace of ecological change in the region seems to be accelerating if one draws upon the observations of indigenous populations who, for generations, have hunted and fished in this LME.

Hydroelectric installations have altered the timing and the rate of the flow of the La Grande and Eastmain Rivers, which drain into James Bay from the Province of Quebec, and of the Churchill and Nelson Rivers, which drain into southwest Hudson Bay from Manitoba. The long-term impacts of these diversions on the marine environment are currently unknown. Today the natural spring freshet into James Bay does not occur at the La Grande or Eastmain Rivers. The Eastmain River plume is significantly reduced, with saline intrusions occurring upstream over a distance of 10 km. The La Grande River now discharges 8 times more freshwater into James Bay, with the plume extending 100 km into the bay. Impacts might include changes in the duration of the ice-cover; changes in the habitats of marine mammals, fish, and migratory birds; changes in the system of currents flowing in and out of the Hudson Bay LME; changes in anadromous fish populations and in the seasonal and annual loads of sediments and nutrients; and changes in the biological productivity of estuaries and coastal areas.

There are concerns about probable climate change and sea level rise caused by global warming. Changes in air temperature, precipitation, stream flow, sea ice and biota are observed in the Hudson Bay LME, with evidence of warming in the western part, cooling in the eastern part, and an increasing trend of annual precipitation in the spring, summer and fall. The ice cover record (Stewart & Lockhart 2004) shows evidence of climate change. The loss of seasonal ice cover has major implications in the Hudson Bay LME: (1) an initial increase and subsequent reduction or elimination of polynyas and ice edge habitats that are important areas for the exchange of energy fluxes between ecotones; (2) an increase of surface salinity; (3) the dilution of surface waters by freshwater inputs from melting sea ice; (4) wind mixing, making more nutrients available to primary producers in the upper water column; (5) more surface light available to primary producers; (6) a decrease of damage to plants and bottom habitats caused by freezing; and (7) a reduction of ice habitats and their associated biota. Climate change has the potential to alter the spatial distribution of biota in and around the Hudson Bay LME, affecting ice-adapted species. However, the direction and degree of change is impossible to predict given the complexity of the ecosystem.

IV. Socioeconomic Conditions

The Hudson Bay LME is characterised by its remote location and by the non-commercial nature of its marine resources. European occupation began in the 1600s, with the exploration of the southeastern Hudson Bay and James Bay in search of a northwest passage to Asia. Today, the coastal areas of the Hudson Bay LME are populated by approximately 10,000 people living in 17 communities. Much of the local economy is based on subsistence hunting, trapping and fishing. Land settlement agreements with the Canadian government have given the Cree and Inuit title to large stretches of coast. Nunavut is the new Inuit territory, created in 1999. Many Inuit continue to harvest bowhead whales for food and as part of their cultural heritage. Ringed seals for the Inuit and the Cree, and bearded seals for the Inuit, are another very important natural resource. Waterfowl are also important to the regional economy, for subsistence and for sport hunting. The common eider is harvested year-round for its meat, feathers, skin, eggs and down. Some of the down is exported. Quotas exist for the number of bears that can be harvested. The sharing of the proceeds of hunting and gathering continues to be of great social, cultural and economic significance to both Inuit and Cree. There is a small fish smoking plant at Puvirnituq (Quebec). None of the Kivalliq fish processing operations has received enough fish consistently to meet operating expenses. The commercial exploitation of coastal marine and estuarine fish is conducted along the Quebec coast, and the fish is marketed through local cooperatives. Climate change could effect major changes in the lifestyle and resource use of the native peoples living in coastal areas, such that their traditional knowledge would no longer be applicable.

Several hydroelectric projects are in operation, or are planned, to divert or impound the renewable energy of the numerous rivers flowing into the Hudson Bay LME. At present there is no offshore mineral or hydrocarbon development, although exploration has taken place in the southwestern part of the bay. The region has a known potential for hydrocarbons, precious metals, diamonds, phosphates, gypsum and limestone. Construction, some tourism and government services are the other principal activities. A Hudson Bay shipping route is being envisaged to open up the Canadian prairies.

Churchill Harbor plays an important role in shipping, which is one of the most important activity that sustains the socio-economy of this region, along with tourism (e.g. polar bear watching).

V. Governance

The Hudson Bay LME waters are under Canadian federal jurisdiction. There is a federal responsibility to protect the integrity of the marine and fresh water ecosystems of the region. Under Canada's Oceans Act, the Department of Fisheries and Oceans (DFO) has a mandate to lead and facilitate the integrated management of all of Canada's estuarine, coastal and marine environments. The DFO is taking an ecosystem-based approach to integrated oceans management. In addition to the Oceans Act, several pieces of relevant federal legislation that apply to Arctic marine waters contribute to the conservation and protection of the Hudson Bay LME: the Fisheries Act, Canada Water Act, Canada Shipping Act, Arctic Water Pollution Prevention Act (up to 60°N), Species at Risk Act, Canadian Environmental Assessment Act, Canadian Environmental Protection Act. Main federal responsible authorities are Fisheries and Oceans Canada, Transport Canada, Environment Canada, Indian and Northern Affairs Canada.

The Nunavut Wildlife Management Board (NWMB) makes decisions relating to fish and wildlife in Nunavut. This includes setting quotas, fishing and hunting seasons and regulating harvesting methods, and approving management plans and the designation of endangered species (www.gov.nu.ca/nunavut/). Under the Northern Quebec Agreement (1976), Inuit and Cree are guaranteed certain levels of harvest which are to be maintained unless their continuation is contrary to Canadian principles of conservation. As opposed to the commercial and sport fisheries, subsistence fisheries by registered native peoples are not restricted by fishing area, season or harvest. The Cree and the Inuit may harvest migratory birds, and their eggs and down, year round. The NWMB has instituted a flexible quota system for polar bear hunts by Kivalliq communities and a community-based management of the Repulse Bay narwhal hunt, to provide communities with more responsibility in the management of their renewable resources. The NWMB relies on government departments for scientific research and advice, with scientists providing their research and interpretive skills. The local people contribute their on-site observations over time.

Wapusk National Park, Manitoba's Cape Churchill and Cape Tatnam Wildlife Management Areas, and Ontario's Polar Bear Provincial Park provide protection for marine mammals, birds and coastal wetland habitats along the south coast of the LME. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) provides assessment and makes recommendations about the status of species. Actually, species at risk are designated as such under the Species at Risk Act which is under the responsibility of Environment Canada (in general) and DFO (for marine species). The Committee on the Status of Endangered Wildife in Canada has designated the bowhead whale as endangered in the Hudson Bay LME and the beluga whale as threatened in the eastern part of the LME. There is ‘special concern’ for the Lac des Loups Marins subspecies of harbour seal and for the polar bear. The Ivvavik National Park and the Tuktut Nogait National Park include a marine component. The Canadian Arctic Resources Committee has proposed a Hudson Bay Programme, in an attempt to implement sustainable development policies in the region.

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XIX-63 Insular Pacific-Hawaiian LME

M.C. Aquarone and S. Adams

The Insular Pacific-Hawaiian LME includes a range of islands, atolls, islets, reefs and banks extending 1,500 miles from the Main Hawaiian Islands (MHI) of Hawaii, Maui, Lanai, Molokai, Oahu, Kauai and Nihau to the outer Northwest Hawaiian Islands (NWHI) from Nihoa to Kure Atoll and their near-shore boundaries. The LME has an area of about one million km², of which 35.59% is protected, and contains 0.38% and 1.00% of the world's coral reefs and sea mounts, respectively, and four major estuaries (Sea Around Us 2007). Equatorial currents and predominant northeasterly trade winds influence the region, which has a tropical climate. Sea surface temperature (SST) ranges from 21 - 29° C, with the LME area-averaged SST ranging between 24.5 and 25.3 ° C. The Hawaiian Islands were formed by successive periods of volcanic activity, and are surrounded by coral reefs. More information on environmental conditions influencing the Hawaiian Islands (climate, temperature, salinity, waves, currents and tides) can be found in the Ocean Atlas of the University of Hawaii. NOAA's Western Pacific Region includes the Hawaiian Islands and the U.S. affiliated islands of American Samoa, Guam and the Northern Marianas (NMFS 1999). Book chapters and articles pertaining to this LME include Morgan (1989).

I. Productivity

NOAA's Climate Studies Group has investigated decadal-scale changes in ecosystem-wide productivity in the Northwestern Hawaiian Islands (NWHI), the 1,500 km chain of islands reefs and atolls that stretches northwest of the main Hawaiian Islands (MHI). In the late 1980s a change in ocean conditions and ocean productivity occurred along the NWHI. The effects were seen at several trophic levels, from seabirds and monk seals to reef fishes and spiny lobsters. The Aleutian Low Pressure System was more intense and located more to the south as compared with 1977 - 1988. As conditions changed in the mid-1980s the winter storm winds weakened, resulting in lower vertical mixing, fewer nutrients in the photic zone, and thus reduced productivity in the open ocean (Pacific Fisheries Environmental Laboratory (**PFEL)** online at www.pfeg.noaa.gov).

The Insular Pacific-Hawaiian LME is considered a Class III, low productivity ecosystem (<150 $gCm^{-2}yr^{-1}$). It has a high diversity of marine species but relatively low sustainable yields due to limited ocean nutrients (NMFS 1999). The LME has a high percentage of endemic species: about 18% - 25% of its shore fishes, molluscs, polychaete worms, seastars and algae exist only in this LME. It is a major habitat for the North Pacific humpback whale. The algal habitats and coral reef ecosystems are used by a variety of organisms for food, shelter and nursery grounds. A study of coral disease in this LME, a collaborative effort among the Hawaii Institute of Marine Biology, USGS, the Hawaii Department of Land and Natural Resources Division of Aquatic Resources and the Bishop Museum, is available at the University of Hawaii website. The US National Assessment of Climate Change Overview of Islands in the Caribbean and the Pacific (2000) outlines potential effects of climate change on freshwater resources, public health, ecosystems, biodiversity and sea-level variability.

Oceanic fronts: This is the only mid-ocean LME (Belkin et al., 2009). Meteorological and oceanographic conditions are relatively uniform and can be characterised as subtropical. This relative uniformity is interrupted by the Subtropical Front (STF) that cuts across the LME at 25°-26°N in winter and 28°-29°N in summer (Figure XIX-63.1). This seasonal shift of the STF is caused by a corresponding meridional shift of the wind field convergence, which is ultimately responsible for the STF formation. The STF sometimes consists of two nearly parallel fronts a few degrees of latitude apart that form the double Subtropical Frontal Zone, similar to the double frontal zones found in other subtropical oceans (Belkin 1988, 1993, 1995, Belkin and Gordon 1996, Belkin *et al*. 1998). The STF plays an important role in ocean ecology as it defines a major trans-ocean migration path and feeding ground of various fish species, including apex predators such as tuna, and also turtles (e.g., loggerheads).

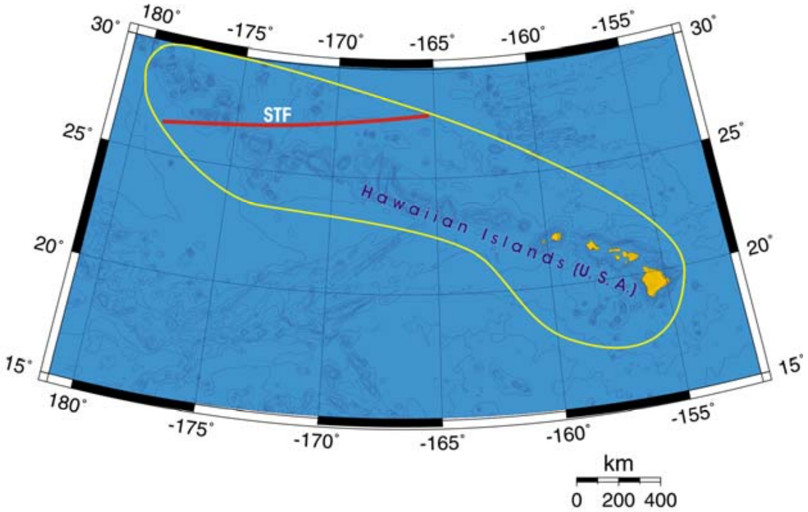

Figure XIX-63.1. Fronts of the Insular Pacific-Hawaiian LME. STF, Subtropical Front. This front is shown with a single line: on many occasions the STF appears as a double front zone (STFZ), with two nearly parallel fronts, North STF and South STF, 300-500 km apart (Belkin 1995; Belkin et al., 1998). Yellow line, LME boundary. After Belkin et al. 2009.

Insular Pacific-Hawaiian LME SST **(Belkin 2009)**
Linear SST trend since 1957: 0.03°C.
Linear SST trend since 1982: 0.45°C.

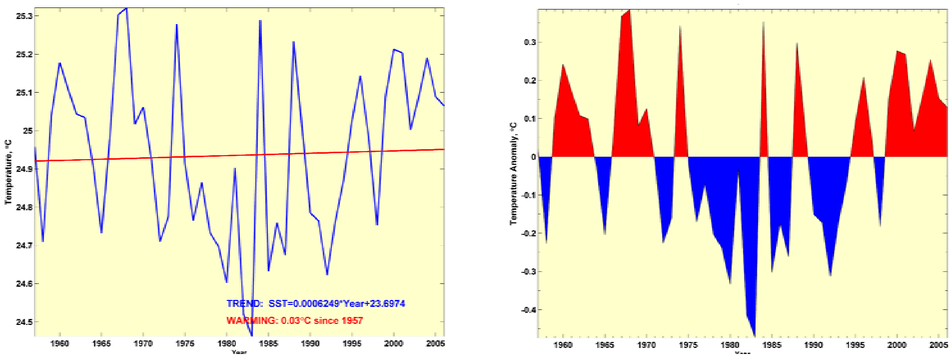

Figure XIX-63.1. Insular Pacific-Hawaiian LME annual mean SST and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin 2009.

The Hawaiian LME is a relatively stable oceanic environment within a large-scale anticyclonic subtropical gyre. This stability leads to the most striking feature of the Hawaiian SST time series: the lack of significant long-term warming over the last 50 years. Indeed, linear trend warming since 1957 was only 0.03°C. However, after the minimum observed in 1982-83, the SST rose significantly: the linear trend warming since 1982 was 0.45°C. Interannual variability is not substantial in absolute terms, usually <0.5°C. The LME area-averaged annual SST varies little from one year to another, usually <0.5°C. However, in some locations, interannual variability may be of a larger order of magnitude: in the northern Hawaiian islands, interannual variations up to 8.0°C have been recorded. The relative long-term thermal stability of the Hawaiian LME is confirmed by the *in situ* monitoring data from the Hawaii Ocean Time-Series (HOT) station off Hawaii, which monitors productivity and biomass variables.

Insular Pacific-Hawaiian Chlorophyll and Primary Productivity: The Insular Pacific-Hawaiian LME is considered a Class III, low productivity ecosystem (<150 $gCm^{-2}yr^{-1}$).

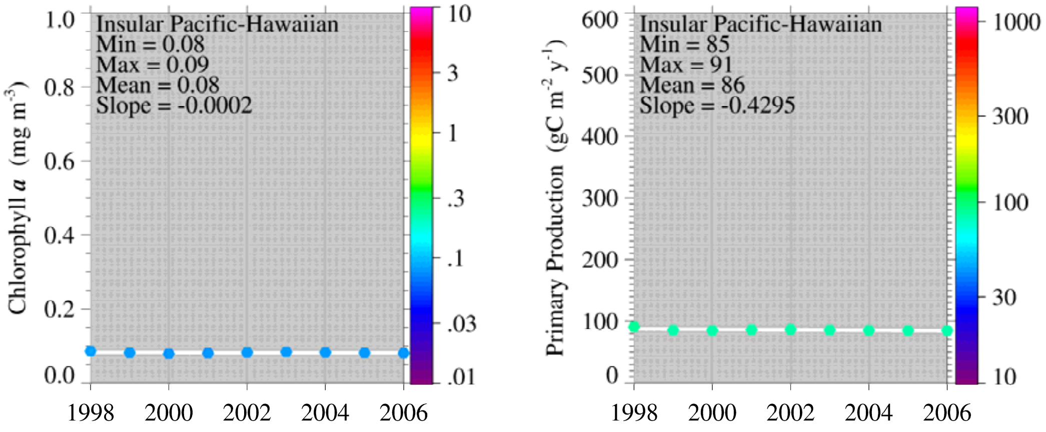

Figure XIX-63.3. Insular Pacific-Hawaiian LME trends in chlorophyll *a* (left) and primary productivity (right), 1998 to 2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

The LME supports a variety of fisheries in both the NWHI and the MHI. The resources include invertebrates, precious coral, bottomfish, armorhead fisheries, highly migratory pelagic fisheries, and nearshore fisheries. The fisheries are on a relatively small scale compared to mainland U.S. fisheries (NMFS 1999). Most fisheries (bottomfish, nearshore reef fish, and invertebrates) are concentrated in the coastal waters of the narrow shelf areas surrounding the islands, except for the fishery for highly migratory pelagic species (NMFS 1999). Tuna (bigeye, yellowfin, skipjack, and albacore) is the LME's most valuable resource. Transboundary fishery resources are of value to the Pacific Rim nations and to the U.S. fleets fishing within and beyond the U.S. EEZ.

The lobster fishery harvests both spiny and slipper lobsters in the NWHI and MHI, and is governed by the Western pacific Regional Fishery Management Council under a Fisheries Management Plan (FMP). Spiny lobster is the primary target of a commercial lobster trap fishery in the NWHI and a small scale, primarily recreational fishery in the MHI (NMFS 2009). Evidence that slipper lobsters have taken over certain areas previously defined as spiny lobster habitats might indicate an increase in abundance and spatial distribution of slipper lobsters due to the "fishing down" of spiny lobsters and the availability of lobster habitat formerly occupied by spiny lobster. Statistics for 1983-1997 showed a decline in lobster landings which is attributed to the combined effect of a shift in oceanographic conditions affecting recruitment and fishing mortality in the mid-1980s

(NMFS 1999). In response to the continuing decline in CPUE the fishery was closed in 1993 and the fishing seasons were shortened in 1994 and 1995. An FMP was implemented in 1983, with amendments designed to eliminate lobster trap interactions with the endangered Hawaiian monk seal (EPA 2004). Other invertebrates harvested are shrimp, squid, and octopus. Precious deepwater corals including pink, gold and bamboo are harvested with set quotas. Black coral is a shallow water species. Bottomfish landings and CPUE have declined since 1948 (NMFS 1999). To determine whether the causes are environmental, biotic (e.g., habitat and competition), or anthropogenic requires more catch data, assessments and research. Bottomfish fisheries (snappers, jacks, and grouper) employ full time fishermen on relatively large vessels in the NWHI. Bottomfish fisheries are managed jointly by the Western Pacific Fishery Management Council and state authorities and are presently overfished. Armorhead fisheries are targeted in the numerous seamounts of the LME, described in Kitchingman et al. 2007, and were exploited in the late 1960s and 1970s by Japanese trawlers and by trawlers from the components of the ex-USSR (especially Russia). Partial estimates of pelagic armorhead (*Pseudopentaceros wheeleri*) and alfonsin (*Beryx* spp.) catches are presented in Zeller et al. (2005). For the present account, they were estimated from the catch of seamount species reported to FAO by Japan and the components of the ex-USSR (Zeller and Rizzo 2007), and from the distribution of seamounts in that LME (from the global seamount map in Kitchingman and Lai 2004).

An issue for the armorhead seamount fishery is how to implement a form of international management that is conducive to stock recovery. Reports on Hawaiian pelagic fisheries (tuna, albacore, marlin, swordfish, dolphinfish and sharks) and gear types are available at NOAA's Pacific Islands Fisheries Science Center website (www.pifsc.noaa.gov). Tropical tunas and dolphinfish are important to subsistence fisheries. Others, especially marlins, yellowfin tuna, and albacore, support important recreational fisheries, as in Kona, Hawaii. Nearshore fisheries are defined as those coastal and estuarine species found in the 0-3 nautical mile zone of coastal state waters. The more highly populated islands receive the heaviest inshore fishing pressure (NMFS 2009). Total reported landings in this LME reached 100,000 tonnes in 1973, when the seamount fishery was at its peak, but have since declined to 5,000 tonnes in 2004 (Figure XIX-63.4).

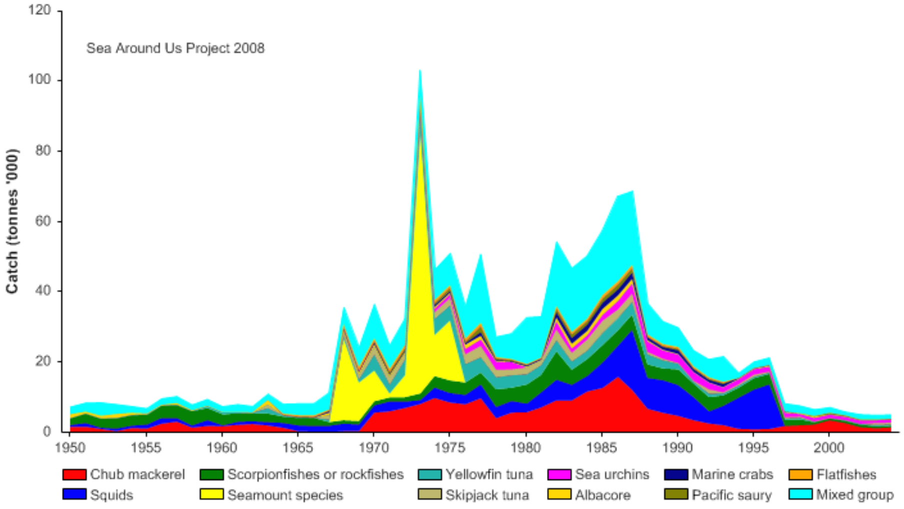

Figure XIX-63.4. Total reported landings in the Insular Pacific-Hawaiian LME by species (Sea Around Us 2007).

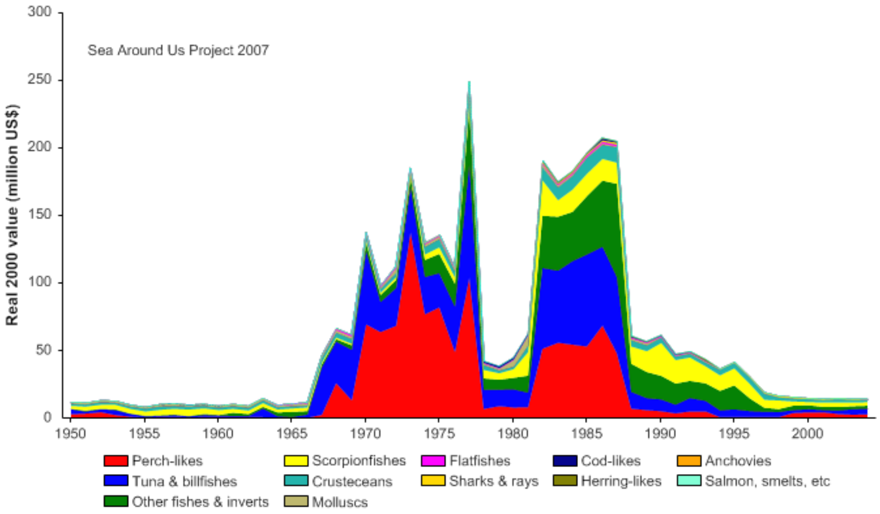

Figure XIX-63.5. Value of reported landings in the Insular Pacific-Hawaiian LME by commercial groups (Sea Around Us 2007).

Catches of inshore fish by small-scale and recreational fishery are high, however, and were they to be included in our analysis, the trend in the reported landings would change considerably (Zeller *et al.* 2005, 2007). Some key issues in Hawaiian fisheries are: (l) the management of highly migratory species, (2) shark finning, (3) longline fisheries bycatch of sea turtles, and (4) longline fisheries bycatch of sea birds. Increasingly, climate change is an issue for ecosystem dynamics and fisheries management (Polovina and Haight 1999). Reported landings were valued at near US$ 250 million (in 2000 US dollars) in 1977 and over $US 200 million in 1986 and 1987 (Figure XIX-63.5). The primary production required (Pauly & Christensen 1995) to sustain the reported landings in the LME reached 7% of the observed primary production in the late 1980s, but has declined to below 1% in recent years (Figure XIX-63.6). The USA accounts for the largest share of the ecological footprint in this LME, although a large share by foreign fleets from Japan and South Korea was reported in the 1970s and 1980s.

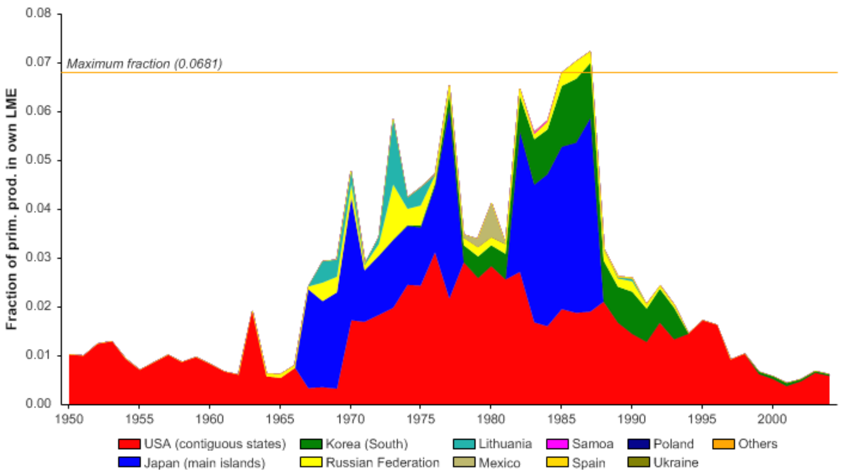

Figure XIX-63.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Insular Pacific- Hawaiian LME (Sea Around Us 2007). The 'Maximum fraction' denotes the mean of the 5 highest values.

The mean trophic level of the reported landings (Pauly & Watson 2005) shows a steady decline (Figure XIX-63.7 top), an indication of a 'fishing down' of the food web in the LME (Pauly *et al*. 1998). The Fishing-in-Balance (FiB) index also showed an initial increase, followed by a decline since the late 1980s (Figure XIX-63.7 bottom). The true patterns of these indices, however, are likely masked by the underreporting of catches in the LME (Zeller *et al* 2005, 2007).

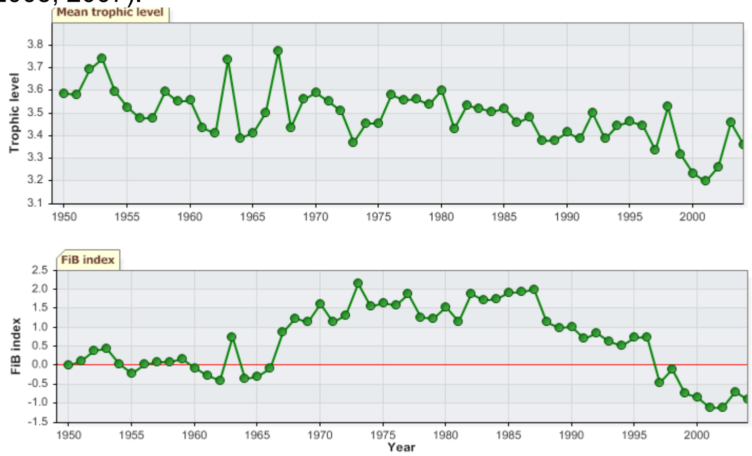

Figure XIX-63.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Insular Pacific-Hawaiian LME (Sea Around Us 2007).

The problem of misreporting probably also affects the Stock-Catch Status Plots, which indicate that over 80% of commercially exploited stocks have collapsed (Figure XIX-63.8, top), with less than 10% of the reported landings biomass supplied by fully exploited stocks (Figure XIX-63.8 bottom). The US National Marine Fisheries Service (NMFS) includes "overfished" but not "collapsed" in its stock status categories (NMFS 1999). Currently overfished are bottomfish fisheries (snappers, jacks, and grouper).

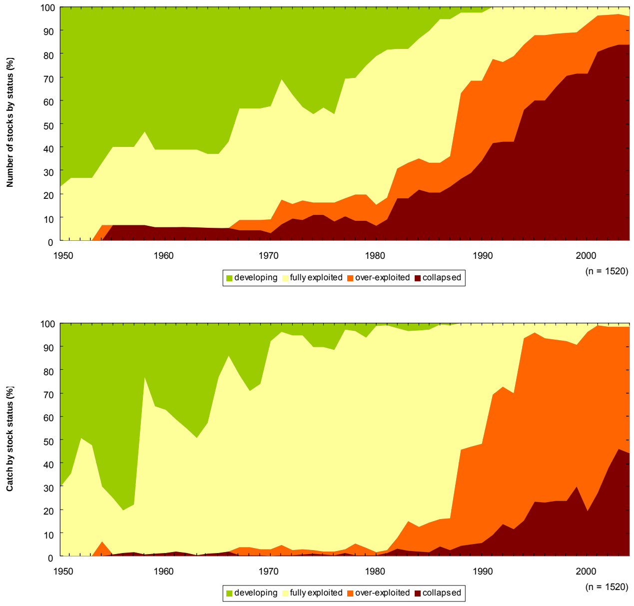

Figure XIX-61.8. Stock-Catch Status Plots for the Insular Pacific-Hawaiian LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

III. Pollution and Ecosystem Health

Some mangroves have been destroyed to make way for aquaculture (Farewell and Ostrowski 2001. For a chapter on marine mammals of the U.S. Pacific Region and Hawaii, see NMFS (1999). This provides data for Hawaii of the Hawaiian monk seal, and various species of dolphins and whales. Mammals are possible indicators of ecosystem health. For a list of endangered species, see http://hbs.bishopmuseum.org/endangered/. The LME has a high percentage of endemic species and Hawaii has the highest extinction rate of biodiversity of any state in the nation according to the U.S. National Assessment (2000). This LME does not have a comprehensive coastal monitoring programme. Issues needing to be addressed in specific bays are non point source runoff and offshore discharges. The State of Hawaii assessed 99% of its estuarine square miles and 83% of its 1052 miles of shoreline. Fifty-seven percent of Hawaiian estuaries are classified as impaired (EPA 2004). Only 3% of the assessed shorelines are threatened for one or more uses by some form of pollution or habitat degradation (EPA 2001 and 2004). The primary causes of estuarine impairment are increased concentrations of suspended solids and nutrients. For marine pest invasions, see Hutchins et al. 2002. For information on the Kaneohe Bay coral reef system, data on water column and sediments, chlorophyll and nutrients, see www.hawaii.edu/cisnet. Kaneohe Bay is the focus of a long term project initiated in 1998 to monitor water quality and sediment processes as part of a nationwide project cooperatively funded by EPA, NOAA and the National Aeronautics and Space Administration (NASA), termed 'CISNet' (Coastal Intensive Site Network). Recent surveys of the Au'au channel have documented an infestation by the invasive species *Carijoa riisei*, which smothers black coral colonies. The ongoing Hawaii Coral Reef Assessment and Monitoring Programme was created in 1997 by leading coral reef researchers, managers and educators in Hawaii to understand the ecology of Hawaiian coral reefs (http://cramp.wcc.hawaii.edu/). The initial task was to develop a state-wide network of over 30 long-term coral reef monitoring sites, and its associated database. The focus has been expanded to include rapid quantitative assessments and habitat mapping on a state-wide spatial scale. The EPA has developed biological criteria for coral reef ecosystem assessment (Jameson et al 1998). Coral reef ecosystems are biologically critical to this LME and are being impacted by sedimentation, eutrophication and pollution from intensified human activity in some areas. A question needing further study is the effect on fish habitat of the harvesting of precious corals. Some habitat-destructive fishing techniques are coral tangle-netting and dredging.

In addition to unidentified metallic debris buried behind the seawall along most of the northern shore of Tern Island, revealed in the USCG field survey in 1997, elevated levels of PCBs have been detected in the biota around the island (Miao et al., 2001). Elevated levels of copper in crabs, arsenic in eels, and lead in coral were found in the study, suggesting bioaccumulation of those metals. Former military activity in the area did not appear to be a factor in the accumulation of metals, with the possible exception of lead. Teams led by NOAA collected more than 125 tons of debris in the Northwestern Hawaiian Islands in 2004. An estimated 40 tons of marine debris washes up on Hawaiian reefs and beaches each year according to the NOAA Coral Reef Ecosystem Division in Honolulu (www.pifsc.noaa.gov/cred/). Of 87 coastal beaches reporting information to the EPA, only 8% (7 beaches) were closed or under an advisory for any period of time in 2002 (EPA 2004). The Hawaiian Islands are stressed by rapid human population growth, increasing vulnerability to natural disasters, and degradation of natural resources. Droughts and floods are among the climate extremes of most concern as they affect the amount and quality of water supplies in island communities and thus can affect health. Many islands already face chronic water shortages and problems with waste disposal.

IV. Socioeconomic Conditions

The U.S. Census Bureau (http://factfinder.census.gov) estimated the population of Hawaii at 1,285,498 in 2007. A diverse economy provides employment for 610,394 persons in mining, utilities, construction, manufacturing, trade, transportation, information, finance and insurance, real estate, professional scientific and technical services, administration, waste management, education, health care, arts and recreation, food and other services. The Bureau of Labor Statistics (www.bls.gov) estimates that 6,243 of the current labour force works in farming, fishing, and forestry occupations. Tourism is the economic mainstay of Hawaii. The Hawaii Tourism Report (1999) reported that the travel and tourism industry produced an estimated $6.3 billion in 1998. The Hawaii State Department of Business, Economic Development and Tourism (DBEDT) reported that Hawaii received a total of 6,452,834 visitors in 2002 (www.hawaiitourismauthority.org). The people of Hawaii have traditionally used the LME for fishing, aquaculture, trade and transportation. US fishermen have a long history of fishing for Pacific highly migratory species in Hawaii. For the economic contributions of fisheries in Hawaii, see Sharma et al. 1999. Tourism, agriculture, fish processing, financial and other service industries all depend on adequate water supplies. Coral reef ecosystems and fisheries have major cultural and economic importance. Fisheries are partially artisanal and geared towards subsistence while a portion is focused towards large pelagic species for profit. Aquaculture is an important historical activity in the marine environment. The wide range of temperature in the water allows the culture of a wide diversity of species all year: tropical fish, trout, salmon, carp, milkfish, mullet, *mahi mahi*, shrimp, seaweed and shellfish.

V. Governance

This LME is governed by the U.S. and by the State of Hawaii. The Western Pacific Fishery Management Council manages fisheries in the State of Hawaii and in the Territories of American Samoa and Guam, the Commonwealth of the Northern Mariana Islands and US Pacific Islands possessions—an area of nearly 1.5 million square miles (http://www.wpcouncil.org/). Coral reefs are managed under a plan implemented in 1983. The Western Pacific Fisheries Coalition is a partnership between conservationists and fishers to promote the protection and responsible use of marine resources through education and advocacy. For information on the North Pacific Marine Science Organization (PICES), which promotes and coordinates marine research in the northern North Pacific and adjacent seas, see Chapter X - Northwest Pacific. Recent international consultations with Japan, Korea, Russia and the US have begun, to establish new mechanisms for the management of high seas bottom fisheries by vessels operating in the North Western Pacific Ocean. A management concern is the problem of illegal, unreported, and unregulated (IUU) fishing by vessels operating outside the control of regional management regimes (NMFS 2009).

In 2000, President Clinton established the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve. In 2006, President Bush designated the Papahānaumokuākea Marine National Monument, an area larger than all US national parks combined and the second largest area in the world dedicated to the preservation of a unique coral reef area (NMFS 2009). Pacific whales are protected under the International Whaling Commission (IWC), which prohibits non-subsistence hunting by member nations (http://www.iwcoffice.org). With increasing awareness that whales should not be considered apart from their habitat, and that detrimental environmental changes may threaten whale stocks, the IWC decided that the Scientific Committee should give priority to research on the effects of environmental changes on cetaceans. The IWC has adopted Resolutions encouraging the Scientific Committee to increase collaboration and cooperation with governmental, regional and international organisations. Related research will be carried out under the IWC's SOWER programme (www.iwcoffice.org/other/site_map.htm). Humpback whales are classified as an endangered species under the U.S. Endangered Species Act. A Hawaiian Islands Humpback Whale National Marine Sanctuary was designated in 1992 (www.sanctuaries.nos.noaa.gov/oms/omshawaii/omshawaii.html). The Hawaiian Islands National Marine Sanctuary Act aims to protect humpback whales and their habitat within the sanctuary, educate the public, and manage human uses within the sanctuary.

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XIX-64 Southwest Australian Shelf LME

T. Irvine, J. Keesing, N. D'Adamo, M.C. Aquarone and S. Adams

The Southwest Australian Shelf LME extends from the estuary of the Murray-Darling River to Cape Leeuwin on Western Australia's coast (~32°S). It borders both the Indian and Southern Oceans and has a narrow continental shelf until it widens in the Great Australian Bight. The LME covers an area of about 1.05 million km^2, of which 2.23% is protected, with 0.03% and 0.18% of the world's coral reefs and sea mounts, respectively, as well as 10 major estuaries (Sea Around Us, 2007). This is an area of generally high energy coast exposed to heavy wave action driven by the West Wind Belt and heavy swell generated in the Southern Ocean. However, there are a few relatively well protected areas, such as around Albany, the Recherche Archipelago off Esperance, and the Cape Leeuwin / Cape Naturaliste region, with the physical protection facilitating relatively high marine biodiversity. Climatically, the LME is generally characterised by its temperate climate, with rainfall relatively high in the west and low in the east. However, rainfall is decreasing and Western Australia is getting warmer, with a 1°C rise in Australia predicted by 2030 (CSIRO, 2007) and an increase in the number of dry days also predicted. The overall environmental quality of the waters and sediments of the region is excellent (Environmental Protection Authority, 2007).

The LME is generally low in nutrients, due to the seasonal winter pressure of the tail of the tropical Leeuwin Current and limited terrestrial runoff (Fletcher and Head, 2006). However, the continental slope of this region comprises some of Australia's most complex networks of submarine canyons and some of the largest areas of abyssal plains within Australia's Exclusive Economic Zone, and thus contains some of the most extensive deepwater benthic environments (Commonwealth of Australia, 2007). Pattiaratchi (2006) identified six such regions that at localised scales, and set against a regionally oligotrophic background, can produce areas of high productivity. The coastal environments include spectacular granite reefs, long pristine sandy beaches, embayments, sponge gardens and communities of filter feeders in deeper waters of the shelf.

There have been few ecological studies to describe the marine flora and fauna over the shelf with any great detail. Some notable exceptions include significant research undertaken to characterise the fish habitats of the Recherche Archipelago (Kendrick *et al.*, 2005), marine biological workshops resulting in publication of a number of papers on the taxonomy, ecology and physiology of local marine flora and fauna (e.g. Wells *et al.* 1991, 2005), marine protected area (MPA) planning studies for State MPAs (see www.dec.wa.gov.au and Department of Environment and Conservation, 2006) and Federal bioregional marine planning studies (see Commonwealth of Australia, 2007).

The LME contains areas of extensive seagrass beds, dominated by genus *Posidonia*, with seagrass found as deep as 45m and diverse kelp habitats dominated by the relatively small *Ecklonia radiata* rather than larger kelps expected in these latitudes where waters are typically colder and have higher nutrients (CALM, 1994). In addition, the area is of global significance as breeding or feeding grounds for a number of threatened marine animals, including Australian sea lions, southern right whales and white sharks (Commonwealth of Australia, 2007). Furthermore, islands off the coast are home to colonies of New Zealand fur seals, penguins and other seabirds, all dependent on the sea for survival.

Some northern species of tropical origin have distributional ranges within this LME due to the influence of the Leeuwin Current. Five tropical coral species extend their distribution into this area (specifically at King George Sound and the Recherche Archipelago) and there are four species endemic to southern coast of Australia (Veron and Marsh, 1988; CALM, 1994). To date, the range of ecological research undertaken in the region reveals a significant number of southwest endemic species. For example, in the Great Australian Bight, one of the world's most diverse soft sediment ecosystems, approximately 85% of fish species, 95% of molluscs and 90% of echinoderms are thought to be endemic (Commonwealth of Australia, 2007). The near shore and archipelago regions are characterised by areas of relatively highly marine biodiversity, many of which have been selected as worthy of representation in national and State-based marine conservation reserve networks, as described in Commonwealth of Australia (2006) and CALM (1994), respectively. Some of these areas are currently undergoing assessment for statutory MPA reservation, such as the proposed Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet Marine Park and Walpole/Nornalup Inlet Marine Park (see www.dec.wa.gov.au) and many others are embedded in Western Australia's aspirational frameworks for a Statewide system of MPAs, such as the Recherche Archipelago (CALM, 1994).

Reports which provide good general reference material pertaining to the ecology and environmental status of this LME include CALM (1994), UNEP (2003), Commonwealth of Australia (2006), Department of Environment and Conservation (2006), Department of the Environment and Water Resources (2007) and Environmental Protection Authority (2007).

I. Productivity

The Southwest Australian Shelf LME is considered a Class III, low productivity ecosystem (<150 $gCm^{-2}yr^{-1}$). With the Leeuwin Current extending into this southwest region, it carries nutrient poor water and generally suppresses upwelling (see the West-Central Australian Shelf LME review for more information). However, there are deep chlorophyll maxima peaking in late autumn/early winter, in phase with the seasonal strengthening of the Leeuwin Current, and the formation of eddies which can generate large productivity pulses (Koslow *et al*., 2006; Feng *et al*., 2007). In addition, counter currents close to coast do allow for upwelling increasing nutrients in a localised sense. In turn, primary productivity is increased when these counter currents are active in spring and summer.

Overall, the LME's waters are oligotrophic and characterised by broad-scale inhibition of upwelling due to the presence of the Leeuwin Current. However, as Pattiaratchi (2007) describes, at localised scales and set against a regionally oligotrophic background, sub-regional effects due to the surface and sub-surface current systems, strong coastal winds, and a combination of topographic features (eg headlands, islands, submarine canyons) can produce areas of relatively high productivity. Pattiaratchi (2007) highlighted six such features: the Perth Canyon; the Albany Canyon group (including the Leeuwin Canyon); the Kangaroo Island canyons and adjacent shelf break; the Kangaroo Island 'Pool'; the predictable large scale eddy field emanating from the main neck of the Leeuwin Current; and Cape Mentelle upwelling. Pattiaratchi (2007) describes these regions as being characterised by high productivity which attracts intense feeding aggregations of large animals such as deep diving mammals, dolphins, seals and sea lions, large predatory fish and seabirds. Some of these areas are also important as pupping zones for school sharks. The areas associated with large eddies are thought to be important for "uplifting" deep ocean water, which is cooler and richer in nutrients, towards the surface where it can embrace the production of plankton communities, which in turn attract larger marine life in an extended food chain.

This LME is a haven to a wide diversity of fish and marine species including scallop, shrimp, trevally, humpback whale, sea lion, penguin and dolphin. Zonation is evidenced by shallow-water reef fish. Three ecological barriers appear to inhibit dispersal: a sharp temperature gradient around Albany near the seasonal cessation of the Leeuwin Current, and two interruptions in the nearshore rocky reef area: in the centre of the Great Australian Bight, and at the mouth of the Murray River. There are numerous rivers and estuaries fed by winter flowing rivers, however the number of rivers and estuaries decreases towards the east of the LME, as the coastline becomes more arid, with limited runoff from rainfall combining with the effect of the Leeuwin Current to limit the nutrients available and hence the productivity of the waters. The waters within this LME are generally clear with low turbidity levels. As a result, light penetrates to greater depths allowing a number of light-dependent species and associated communities to be found in waters deeper than those in which they live in other parts of Australia. For instance, macro-algae and seagrass can be found at depths of up to 120m (Commonwealth of Australia, 2007). The indication from recent and current research programs within the LME is that there is much yet to discover in respect to marine biodiversity in the area. For example, when marine biologists recently surveyed the Recherche Archipelago, some 300-400 species of sponges were collected, of which nearly half were new to science and six new fish species were recorded. Islands off the coast in the Recherche Archipelago area are home to colonies of New Zealand fur seals, Australian sea lions, penguins and other seabirds, all dependent on the sea for survival (http://rmp.naturebase.net/south-coast).

For a general understanding of oceanographic processes affecting nutrient dynamics and the productivity of Australian marine ecosystems, see the Western Australian government's State of the Environment Reports. For more information on productivity, an associated general marine biodiversity, hydrodynamic characteristics and environmental health of the region see, http://rmp.naturebase.net/south-coast (general regional marine planning studies); Department of Environment and Conservation (2006) and www.dec.wa.gov.au (general MPA studies); Australian Fisheries and Research Development Corporation Project 2001/060 (led by Dr Gary Kendrick, University of Western Australia); CALM (1994); Furnas (1995); D'Adamo and Mamaev (1999); UNEP (2003); Commonwealth of Australia (2006); Goldberg *et al*. (2006); Pattiaratchi (2006, 2007); Department of the Environment and Water Resources (2007); Environmental Protection Authority (2007) and Sea Around Us (2007).

Oceanic fronts (Belkin *et al.* 2009)(Figure XIX-64.1): The warm and saline Leeuwin Current (originated within the West-Central Australian Shelf LME) rounds Cape Leeuwin to enter the Great Australian Bight. After rounding Cape Leeuwin, the Leeuwin Current generally flows along the outer continental shelf in its passage eastwards, at least as far as Cape Pasley near 124°E, when it tends to move offshore again because of the distinct northwards kink in the coastline. As on the west coast, large meanders can carry the warm water over 100 kilometres offshore. The Leeuwin Current and the associated TS-front (Leeuwin Current Extension Front, LCEF) continue eastward generally along the shelf edge all the way up to Spencer Gulf. An estuarine front exists across the entrance to Spencer Gulf (SGF). Two inner shelf/near-coastal fronts are observed in the western and eastern parts of the Great Australian Bight (WGABF and EGABF) (Belkin *et al*. 2009).

A series of counter currents exist, moving westward below the Leeuwin Current or existing at times when the Leeuwin Current flow is weakened (spring/summer). The Flinders Current, a westward slope current, exists at depths of 400m or more and is the dominant feature along the southern coast of Australia extending from Tasmania to Cape Leeuwin. It is the only northern boundary current in the Southern Hemisphere. The Flinders Current is driven largely by persistent, deep equator-ward transport across the

Southern Ocean that is turned west due to vorticity constraints. It can result in favourable conditions for upwelling as it flows past the mouths of the Murray Canyons (Arthur, 2006). The Cresswell Current (Pattiratchi, 2006) is a seasonal coastal wind-driven counter-current in the south of Western Australia, just east of the Capes areas, occurring in the summertime.

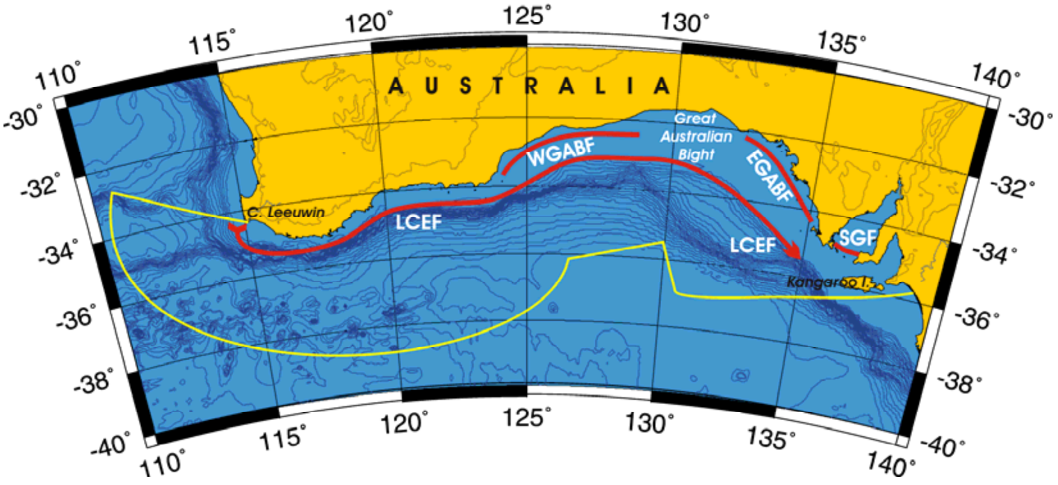

Figure XIX-64.1. Fronts of the Southwest Australian Shelf LME. LCEF, Leeuwin Current Extension Front; LCF, Leeuwin Current Front; EGABF, East Great Australian Bight Front; SGF, Spencer Gulf Front; WGABF, West Great Australian Bight Front. Yellow line, LME boundary; after Belkin *et al.* (2009).

Southwest Australian Shelf LME SST (Belkin 2009)(Figure XIX-64.2):
Linear SST trend since 1957: 0.42°C.
Linear SST trend since 1982: 0.09°C

The moderate, steady warming of the Southwest Australian Shelf was punctuated by several events. The most conspicuous warm events occurred in 1961-63, 1976, 1983 to 1985, and 2000. Three cold events peaked in 1960, 1968, and 1986-87. Most events correlate with similar episodes south and north of Australia. The 2000 warm event can be tentatively linked to a similar event of 1999-2001 in the Southeast Australian Shelf LME.

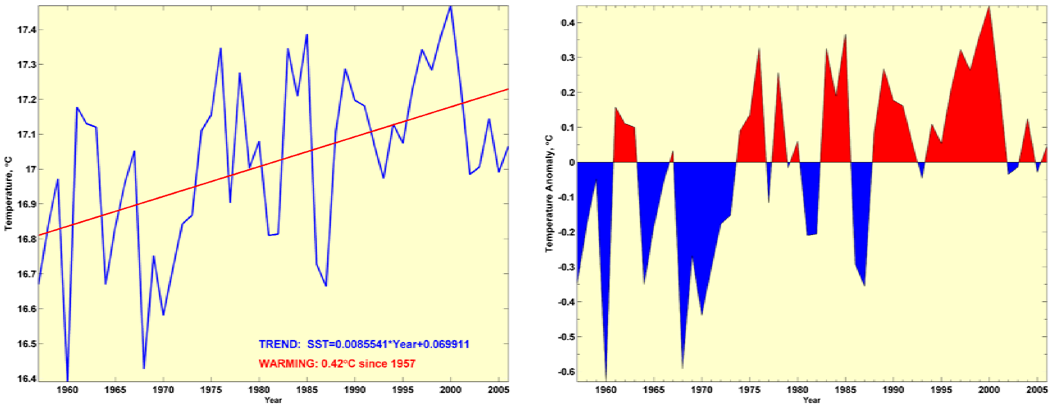

Figure XIX-64.2. Southwest Australian Shelf LME annual mean SST (left) and SST anomaly (right), 1957-2006, based on Hadley climatology. After Belkin (2009).

These two LMEs are the only two areas where the El Niño 1997-98 manifested much later than elsewhere. The two-year delay can be explained by the dampened influence of the Southern Ocean. The warm event of 1983-85 occurred simultaneously in the West-Central Australian Shelf LME. The observed synchronism between West-Central, Southwest, and Southeast Australian Shelf LMEs can be explained by the existence of the Leeuwin Current that carries warm tropical waters from the Southeast Indian Ocean around Cape Leeuwin into the Great Australian Bight and eventually toward Tasmania and into Bass Strait (Ridgway and Condie, 2004).

Southwest Australian Shelf LME Chlorophyll and Primary Productivity

The Southwest Australian Shelf LME is considered a Class III, low productivity ecosystem (<150 gCm^{-2}yr^{-1})(Figure XIX-64.3).

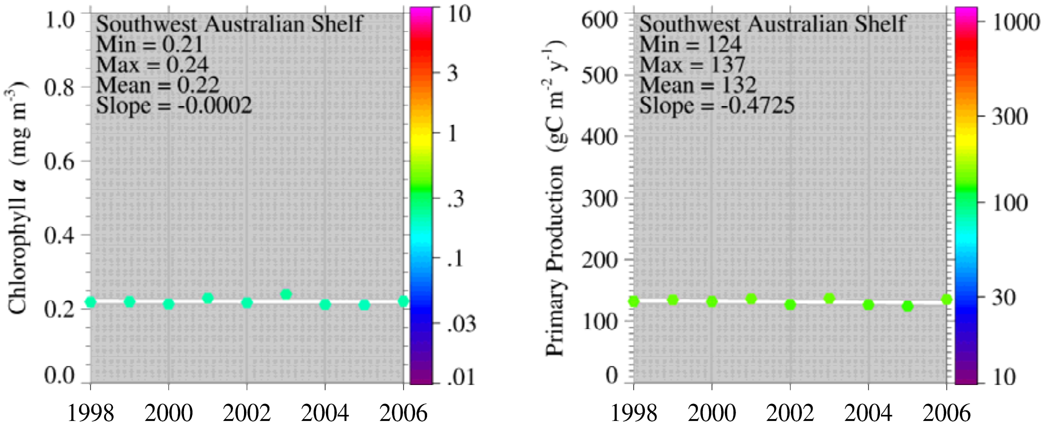

Figure XIX-64.3. Southwest Australian Shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998-2006, from satellite ocean colour imagery. Values are colour coded to the right hand ordinate. Figure courtesy of J. O'Reilly and K. Hyde. Sources discussed p. 15 this volume.

II. Fish and Fisheries

Australian waters are relatively nutrient-poor and although not productive by world standards, there are numerous commercial and recreational fisheries based in the waters of this LME. Production is limited by low levels of nutrient-rich upwellings. Fish stocks are predominantly temperate, with most species distributions extending the length of the LME. Many species are endemic to Australia. Under the Australian Constitution, jurisdiction over Australia's fisheries resources is a complex mix of Australian Government and State or territory government responsibilities. Relevant legislation has established the Australian Fisheries Management Authority (AFMA) as the Australian Government statutory body empowered to manage fisheries. Within this LME there are Western Australian and South Australian State managed fisheries, and Commonwealth managed commercial fisheries. For details relating to Western Australia see Fletcher and Head (2006), for South Australia see Primary Industries and Resources South Australia (2007) and for Commonwealth fisheries see Larcombe and McLoughlin (2007).

Major Western Australian State commercial fisheries in this region are abalone, purse seine fishery targeting pilchards and other small pelagics, and demersal gillnet fishery for sharks. Other smaller fisheries are beach seine fishery for Australian salmon and herring, a trap fishery targeting southern rock lobster and deep water crabs and the intermittent scallop fishery in the Recherche Archipelago (Fletcher and Head, 2006). The South Australian Government has responsibility for four fisheries, these are the Northern Zone

Rock Lobster, the Giant Crab, the Sardine and the Marine Scalefish fisheries. In 2004/05, the four fisheries' combined catch was over 43000 tonnes of fish, worth around US$55 million. The most important of South Australian-managed fisheries by value was the Sardine Fishery with a catch value of over US$27 million and landings of over 39000 tonnes (Commonwealth of Australia, 2007). South coast commercial fishing vessels operators often hold a number of licenses to create a viable year round operation.

Commonwealth managed fisheries in the area are the Southern Bluefin Tuna Fishery, Western Tuna and Billfish Fishery, Southern and Eastern Scalefish and Shark Fishery (SESSF), Western Australian Southern Demersal Gillnet and Longline Fishery and Western Skipjack Fishery (see Larcombe and McLoughlin, 2007). The total global catch of Southern Bluefin Tuna in 2005 was 21686 tonnes, of which Australia's share was 5244 tonnes, worth A$140 million (Larcombe and McLoughlin, 2007). The Southern Bluefin Tuna Fishery is an international fishery and listed as globally overfished. It has been managed since 1994 through the Commission for the Conservation of the Southern Bluefin Tuna (CCSBT), which is advised by a scientific committee of member-country scientists and independent international scientists. The Australian Government is party to a number of international conventions or agreements for the management of highly migratory tunas and billfishes that range far beyond the Australian Fishing Zone – see Larcombe and McLoughlin (2007). Responsibility for management of these stocks is shared by multiple governments through Regional Fisheries Management Organisations.

As much of the coast is remote or difficult to access, recreational boat and beach fishing is concentrated around main population and holiday centres. The major target species for such fishing are salmon, herring, whiting, trevally, pink snapper, queen snapper, Bight redfish, shark, samson fish and King George whiting (Fletcher and Head, 2006) The predominant aquaculture activity undertaken in the area is the production of mussels and oysters from Oyster Harbour at Albany. Other forms of aquaculture (e.g. sea cage farming) are restricted on the south coast by the high-energy environment and the very limited availability of protected deep waters typically required by this sector (Fletcher and Head, 2006)

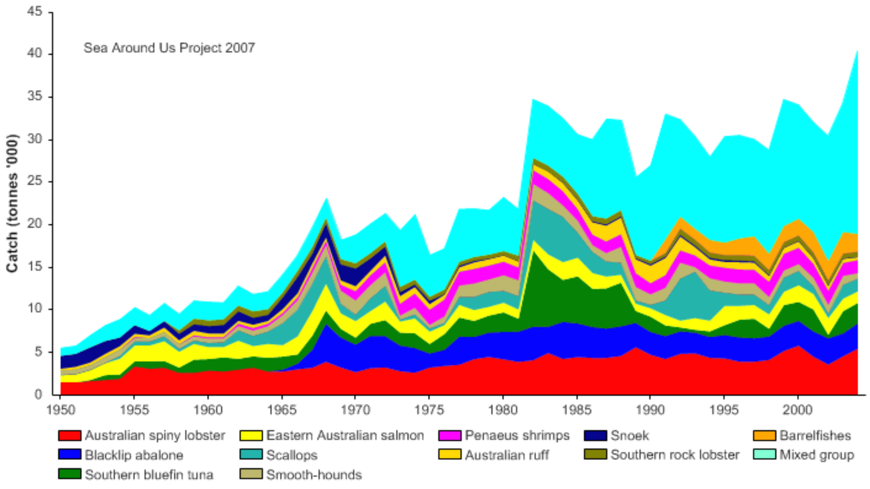

Figure XIX-64.4. Total reported landings in the Southwest Australian Shelf LME by species (Sea Around Us 2007).

The total of reported landings in the LME is still growing with 40,000 tonnes recorded in

2004 (Figure XIX-64.4). However, there is, presumably, a significant fish bycatch from the shrimp fishery which is not included in the reported landings. The reported landings were valued at US$ 333 million in 2000, due to the high value commanded by spiny lobsters (crustaceans) and abalone (molluscs), and US$ 292 million in 2004 (Figure XIX-64.5).

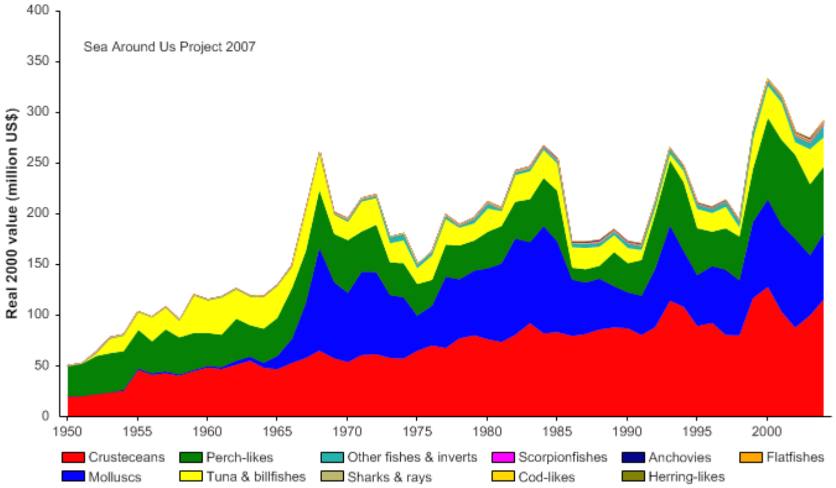

Figure XIX-64.5. Value of reported landings in the Southwest Australian Shelf LME by commercial groups (Sea Around Us 2007).

The primary production required (PPR; Pauly and Christensen 1995) to sustain the reported landings in this LME has been increasing but is still below 2% of the observed primary production (Figure XIX-64.6). Australia accounts for the majority of the ecological footprint in this LME.

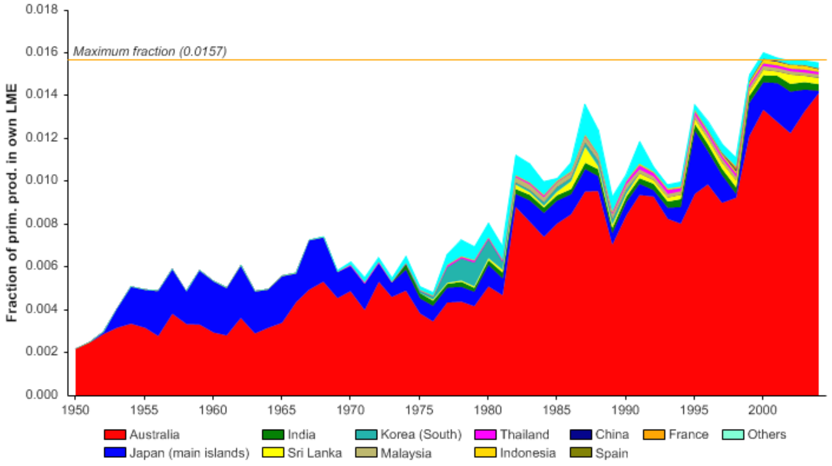

Figure XIX-64.6. Primary production required to support reported landings (i.e., ecological footprint) as fraction of the observed primary production in the Southwest Australian Shelf LME (Sea Around Us 2007). The ‘Maximum fraction’ denotes the mean of the 5 highest values.

During the 1950s and the 1960s, the mean trophic level of the reported landings (MTI, Pauly and Watson 2005) declined steadily (Figure XIX-64.7 top), indicating a 'fishing down' of the food web in the LME during this period (Pauly *et al*., 1998). The subsequent increase of the mean trophic level, as well as the FiB index (Figure XIX-64.7 bottom), imply a possible geographic expansion of the fisheries (Figure XIX-64.6.)

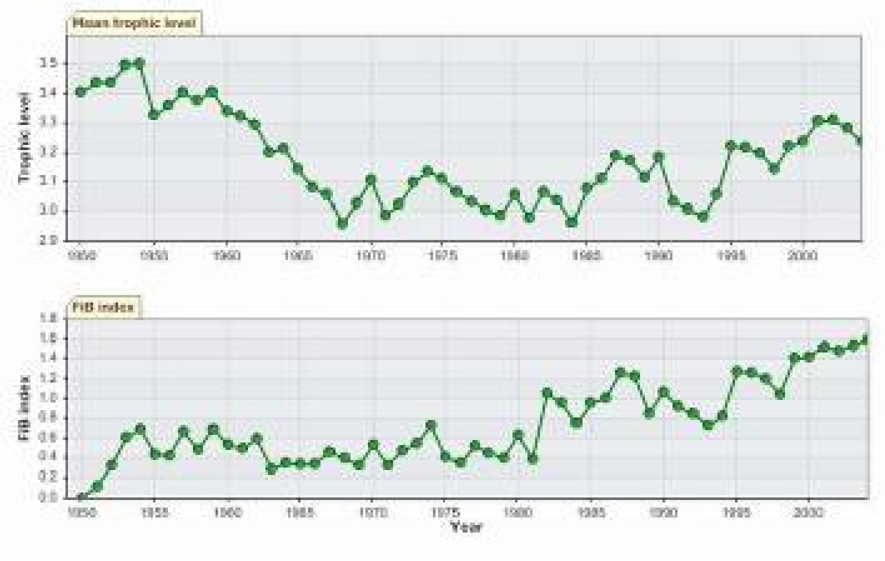

Figure XIX-64.7. Mean trophic level (i.e., Marine Trophic Index) (top) and Fishing-in-Balance Index (bottom) in the Southwest Australian Shelf LME (Sea Around Us 2007).

Until recently, fisheries resources were usually managed in separate fishery units. Under the Environment Protection and Biodiversity Conservation Act 1999 (the EPBC Act), the Commonwealth Government has a framework that helps it to respond effectively to current and emerging environmental problems, and to ensure that any harvesting of marine species is managed for ecological sustainability. All fisheries in the area are subject to management plans which embrace the principles of Ecosystem Based Fishery Management (EBFM) as opposed to single target species management approaches (Smith *et al*., 2007). State commercial fisheries are managed primarily through input controls such as limited entry, catch numbers, size limits and seasonal closures, and stock assessments are undertaken to assess breeding stock levels and exploitation status undertaken for most fisheries. Management includes assessment of bycatch species impacts, protected species interactions, food chain effects and habitat effects (Fletcher and Head, 2006).

The Stock-Catch Status Plots indicate that about 30% of commercially exploited stocks in the LME have collapsed and another 30% are overexploited (Figure XIX-64.8, top). About half of the reported landings appear to be supplied by fully exploited stocks (Figure XIX-64.8 bottom). However, the editors and Australian contributors wish to acknowledge and advise caution that there are several reasons possible for the apparently reduced status of some species. Among them, Australian management authorities have in many cases limited catches and effort to protect the species from overfishing. Landings of these stocks are therefore lowered, giving the appearance of an overfished condition status in Figure 8. In addition, productivity of some of these fisheries is tightly coupled to environmental variability, in particular ENSO, and this also reduces catches in some years in ways not due to exploitation rate. Catches of all species are subject to annual active management intervention and often include temporally and spatially explicit adaptive management measures to prevent overfishing.

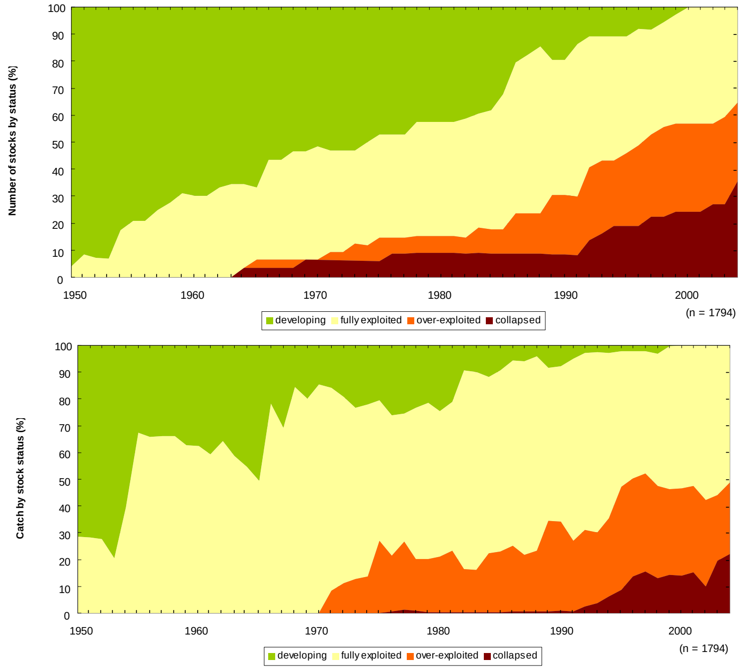

Figure XIX-64.8. Stock-Catch Status Plots for the Southwest Australian Shelf LME, showing the proportion of developing (green), fully exploited (yellow), overexploited (orange) and collapsed (purple) fisheries by number of stocks (top) and by catch biomass (bottom) from 1950 to 2004. Note that (n), the number of 'stocks', i.e., individual landings time series, only include taxonomic entities at species, genus or family level, i.e., higher and pooled groups have been excluded (see Pauly *et al*, this vol. for definitions).

The FAO provides additional information on Australia's fisheries and the characteristics of the industry (www.fao.org).

III. Pollution and Ecosystem Health

The SW Australian Shelf LME is sparsely populated except for the areas of the cities of Perth in Western Australia and Adelaide in South Australia. Thus, the inshore marine habitats of the coast are largely unaffected by human activities, the exceptions being some estuaries and marine embayments (e.g. Princess Royal Harbour, Oyster Harbour and Wilson Inlet) where significant eutrophication associated with nutrient inputs from landbased activities has occurred (Fletcher and Head, 2006). The most visible result of such nutrient enrichment is the seagrass loss or degradation in South Australia (Shepherd *et al*., 1989). In addition, increased nutrient loads to coastal waters have also been directly implicated in the increased frequency of algal blooms, particularly 'Red Tides', and more recently, in the loss of mangroves (Connolly, 1986; Edyvane, 1991). Of the limited environmental threats that exist for this LME as a whole, of particular concern is an increase in shipping-related releases of ballast water, which has been shown to contain harmful bacteria, viruses and algae as well as non-indigenous plankton, and the larval forms of many invertebrates and fish. Other concerns in this LME are ocean dumping, marine debris, new exploration for offshore oil and the risk of oil spills from resulting production. There is also is the potential for environmental impacts caused by tourism and by the provision of infrastructure to support tourism (airports, power generation facilities, accommodation, sewage treatment and disposal facilities, moorings, and marine transport).

In respect to the area surrounding Adelaide, including the Spencer Gulf, pollution derives from mining, manufacturing, petroleum, chemical, agricultural, food processing, gas and power, and sewerage waste water industries. The main discharges are chemical from the industrial plants at the northern end of Spencer Gulf, at the various sewerage outfalls and saline discharges from salt and chemical works at Dry Creek and Osborne (Port Adelaide) (Zann, 1995). In general, the levels of heavy metals in seawater appear relatively low and the levels of contamination of aquatic species are considered within defined limits (Zann, 1995). To name only one of the many local South Australia ongoing water quality improvements, the EPA is currently negotiating with industry in the Northern Spencer Gulf area to curb the discharges of heavy metals into the Gulf.

The condition of WA's coastal and shelf waters, including this southwest region, has historically been poorly monitored, with the exception of certain highly pressured areas, such as Albany harbours (Environmental Protection Authority, 2007). Relevant reports are available through the Western Australian Department of Conservation and Environment (www.dec.wa.gov.au) and the Environmental Protection Agency (www.epa.wa.gov.au). Western Australia's overall marine and coastal monitoring framework is undergoing a significant expansion as part of the State's marine protected area (MPA) implementation and management programs, as discussed in Section V (Governance, p.849 ff.).

The State of the Environment Report for Western Australia 2007 (Environmental Protection Authority, 2007) lists two fundamental pressures of high concern and "likely to deteriorate": first, rainfall is decreasing in the south-west with severe implications as ocean levels are rising and all of Western Australia is getting warmer; and second, population and consumption are of concern. It is noted that Western Australians have among the largest ecological footprints in the world.

With respect to benthic disturbance by fishing, methods which can impact on marine habitats such as trawling are naturally restricted due to the relatively low productivity and abundance of species capable of trawl capture. A small, limited-entry scallop trawl fishery focused in the Esperance region is the only state-managed fishing activity which can have any significant physical interaction with the marine habitat (Fletcher and Head, 2006). Trawling in deep waters off the edge of the continental shelf is managed by the Commonwealth Government. This area, particularly the western part of the Great Australian Bight, was subject to significant exploratory trawling by locally based and international vessels prior to the 1980s, but is only sporadically fished now. There is a coastal trawling closure of state waters along the western Bight sector, enacted under Commonwealth Government fisheries legislation, to ensure deep-sea trawlers do not venture into sensitive coastal areas (Larcombe and McLoughlin, 2007). For more information on pollution and ecosystem health, see Pogonoski *et al*. (2002) and for marine disturbances and coastal pollution see www.ea.gov.au.

IV. Socioeconomic Conditions

Most of South Australia's population of 1.4 million is situated on the coast, with major towns and cities concentrated on the Fleurieu Peninsula (including Adelaide) and northern Spencer Gulf (Whyalla, Port Pirie, Port Augusta). The coastal fringe of the Great Australian Bight from Ceduna to Esperance has a low population density, and few towns with more than 200 persons listed in the 2001 census. The South Australian portion of the region is characterised by substantially older median ages and high elderly dependency, and is more dependent on agriculture, fisheries and forestry industries with lower employment diversification outside regional centres (http://adl.brs.gov.au). The Australian Government reports that major marine industries associated in the area include commercial fishing, marine-based tourism, shipping, oil and gas exploration, boat and ship-building, defence activities and aquaculture (Department of the Environment and Water Resources, 2007). Marine based tourism is not well developed in the area, and focuses on diving and fishing; there is however scope for future development. There is no current oil and gas production in the region, but exploration has identified two frontier basins with petroleum potential - the Naturaliste Plateau and Bight Basin.

Commercial fishing employment, including aquaculture, is largely concentrated across most of the Eyre Peninsula where almost all coastal towns have strong linkages to commercial fishing activities. For example, Port Lincoln has the largest number and proportion of people employed within the fishing sector of any coastal town in Australia (Bureau of Rural Sciences, 2006). In 2003, fishers active within Australian Government-managed fisheries in the LME caught around US$135 million worth of fish. In the WA and SA State-managed fisheries, rock lobster, abalone, scallop, shark, King George Whiting and prawn mostly caught in State waters, have a gross value of production nearing $385 million a year. More than 3,600 people are directly employed by the fishing industry in the area with a further 800 employed in the aquaculture sector. Of increasing economic importance is the developing mariculture industry which is primarily based in the coastal inlets and bays of Eyre Peninsula. Recreational fishing is particularly important in regional and local economies, especially in the towns on the far-west coast and on Yorke and Eyre Peninsulas. Recreational fishers are increasingly moving further offshore to target a range of deep-sea species. Despite the vastness of the South Australian coastline, human activities tend to be concentrated near centers of population and here most conflict or competition occurs. The region is becoming of increasing interest for general coastal and marine tourism and associated water based recreational activities, and this trend is likely to continue as the region continues to receive greater focus for its ecological values through marine conservation under State and Commonwealth instruments.

V. Governance

For a fuller overview of the history, current status and underpinning principles of respective Commonwealth and Western Australia marine biodiversity conservation frameworks refer to the West-Central Australian Shelf LME section (this series).

Australia has a federal system of government with the States forming the Australian Commonwealth federation. The LME is bordered by the States of South Australia and Western Australia. The States are responsible for the marine environment for the first three nautical miles from the shore. Australia declared a 200 nautical-mile EEZ in 1978. Refer to the West-Central LME section for more details of the Commonwealth and State zones and responsibilities. The Australian State and Commonwealth governments identified a need to protect representative examples of the full range of marine ecosystems and habitats in marine protected areas. A spatial framework was established, the Integrated Marine and Coastal Regionalisation of Australia (IMCRA), for classifying Australia’s marine environment into bioregions that make sense ecologically and are at a scale useful for regional planning (Commonwealth of Australia, 2006). The Southwest Australian Shelf LME encompasses 8 IMCRA meso-scale bioregions. The Commonwealth’s IMCRA framework provides a platform for the development of a National Representative System of Marine Protected Areas (NRSMPA), which is a comprehensive, adequate and representative system of marine protected areas that will contribute to the long-term ecological viability of marine and estuarine systems, maintain ecological processes and systems and protect Australia's biological diversity at all levels.

The establishment of the Commonwealth’s MPA network is being progressed as part of the marine bioregional planning process being conducted by the Department of the Environment, Water, Heritage and the Arts under the *Environment Protection and*

Biodiversity Conservation Act 1999. IMCRA bioregions are pooled to form Marine Bioregional Planning Regions (www.environment.gov.au/coasts/mbp). These bioregions are large areas of ocean, considered to be ecologically similar, compared to other similarly sized areas. See the West-Central Australian Shelf LME section for more information on the bioregionalisation schemes developed in Australia and how these provide a framework for a representative system of marine reserves. The Commonwealth's South-west Marine Bioregion comprises 7 provincial bioregions, 5 of which fall into this LME. A Bioregional Profile identifying the important ecological, conservation and socio-economic values of the region for this region has been released (Commonwealth of Australia, 2007). Within this LME, the Western Australian and South Australian State-based marine conservation reserve frameworks are being progressed so as to be aligned and consistent with the federal framework.

Australian fisheries resources are managed under both Commonwealth and State/Territory legislation. The jurisdiction and responsibilities among these various governments has been agreed to under the Offshore Constitutional Settlement (OCS). Under OCS, the states and territories have jurisdiction over localised, inshore fisheries. The Commonwealth has jurisdiction over offshore fisheries, transboundary fisheries (extending to waters adjacent to more than one state or territory) and foreign fisheries. Each government has separate fisheries legislation and different objectives. An important goal is to ensure that the exploitation of fisheries resources is conducted in a manner consistent with the principles of ecologically sustainable development. This includes the need to assess the impact of fishing activities on non-target species and the long-term sustainability of the marine environment. For more information on the governance of Australia's fisheries, see the FAO website.

Coastal development proposals are presently regulated under various State and local Government planning legislation. In South Australia, coastal development is regulated by the Planning Commission and overseen by the Coast Protection Board; however coastal management is often uncoordinated, fragmented and prone to jurisdictional and administrative overlap. Human activities such as mining, fishing, shipping, or tourism, which may detrimentally affect marine or coastal habitats, are generally regulated through conditions on the permits or licenses issued under the respective controlling legislation.The marine tourism industry has produced a code of conduct that covers issues such as anchoring, dropping of rubbish, fish feeding and preservation of world heritage values.

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