22.03.02

Exxon Valdez Oil Spill Trustee Council

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MEMORANDUM

TO: Trustee Council

FROM: Molly McCammon
Executive Director

DATE: July 30, 2001

RE: GEM follow-up

Enclosed is the latest draft of the GEM Program Document. We have had two recent review sessions – one with the Public Advisory Group and one with the Trustee agency liaisons. These were very helpful and resulted in us re-organizing the whole document in order to improve readability. Overall, both groups were very positive about the direction of the document, and most comments were easily accomodated. Because of the recent organizational changes however, we have only been able to review each individual chapter, and not the revised document as a whole, until now. Consequently, there are still minor revisions that need to be made, in addition to final proofing and editorial word-smithing. Attached you will find a working list of the changes we will be incorporating into the next version.

At the August 6 meeting, I will be asking for your approval to move forward with this draft as the "NRC review draft". Our plan is to make the final edits and revisions by August 15, send the draft to the printer, and submit the draft to the NRC by September 1, 2001. Phil Mundy and I will be meeting with the NRC review committee in Seattle September 18-19 to discuss the latest draft. The committee meets again in November in a closed-door meeting to begin drafting their final report, which we should receive in March 2002.

22.05.01

REVISIONS TO GEM PROGRAM DOCUMENT

July 30, 2001

Content

1 Need to add section on community involvement, stewardship and TEK Somehow these did not get incorporated into the latest draft
2 Volume I, Chapter 2 – Human Activities and their Impacts – still needs revision In addition, we will be contracting with someone (economist, social scientist?) to expand this to the level of the chapters in the Scientific Background (Volume II, Chapter 3) and incorporate all, or parts, into that chapter
3 Two policy decisions –Can we use principal investigators to provide some level of peer review for other projects? Should we revisit the issue of not funding "normal agency management?"
4 Executive summaries need to be added for overall document and for Scientific Background, Volume II, Chapter 3
5 Add discussion of salmon life cycle (with figure from Sustainable Salmon Report) somewhere in Volume I as example of GEM approach with management application

Style

1 A number of figures are still being worked on
2 Final edits and proofing needs to be done
3 Possibly add acronyms & Web links appendix to Volume I also?

22.05 01

GULF ECOSYSTEM MONITORING AND RESEARCH(GEM) PROGRAM DOCUMENT

VOLUMES I & II
STRATEGIC PLAN FOR MONITORING AND RESEARCH

Volumes I and II together should be referred to as the GEM Program Document

REVIEW DRAFT- JULY 30, 2001

Gulf of Alaska **E**cosystem **M**onitoring and Research Program (GEM)

Volume I
Strategic Plan for Monitoring and Research

Volumes I and II together should be referred to as the GEM Program Document

Review Draft – July 30, 2001

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ACKNOWLEDGMENTS

The primary authors of the GEM Program Document are Molly McCammon, Phil Mundy, and Bob Spies Editors for the document were Molly McCammon, Phil Mundy, Bob Spies, and Judy Griffin

Credit goes to the following authors in Volume II Chapter 3 - Ted Cooney, Jim Bodkin, Anne Hollowed, Lloyd Lowry, Phil Mundy, Peter Olsson, Charles Peterson, Bob Spies, Alan Springer, Tom Weingartner, Chapter 4 - Phil Mundy and Bob Spies, Chapter 5 - Gretchen Oosterhout, Chapter 6 - Charles Falkenberg, Appendix A - Michael H Martin, Appendix B - Kerim Ayden, Appendix C - Joe Sullivan, Dede Bohn, Veronica Christman, and Sandra Schubert, Appendix D and E, Phil Mundy Cherri Womac has been instrumental in preparing the entire document

Many people made material or intellectual contributions to the GEM Program Document Because the number of contributors and advisors is so large, we apologize if we inadvertently left your name off this list

The efforts of the following are gratefully acknowledged Alisa Abookire, Ken Adams, Vera Alexander, Fred Allendorf, Paul Anderson, Peter Armato, Shannon Atkinson, Jim Ayres, Torie Baker, Kris Balliet, Hal Batchelder, Bill Bechtol, Catherine Berg, Brock Bernstein, Chris Blackburn, Jim Blackburn, John Blaha, Jim Bodkin, Dede Bohn, James Brady, Stephen Braund, Evelyn Brown, Patty Brown-Schwalenberg, Al Burch, Vern Byrd, Robert Clark, Dave Cobb, Ken Coyle, Ted Cooney, Seth Danielson, Tom Dean, Robert DeVelice, Jane DiCosimo, Gary Drew, Janet Duffy-Anderson, Doug Eggers, Dave Eslinger, Gary Fandrei, Bob Foy, Steve Frenzel, Carol Fries, Fritz Funk, Dan Gillikin, David Goldstein, Andy Gunther, Gary Gury, Ed Harrison, Bill Hauser, Robert Henrichs, Ken Holbrook, Anne Hollowed, Brett Huber, Gary Hufford, Charlie Hughey, Dan Hull, Joe Hunt, Henry Huntington, David Irons, Lisa Ka'aihue, Tom Kline, Gary Kompkoff, Jan Konigsberg, Gordon Kruse, Kathy Kuletz, Pat Lavin, Pat Livingston, Lloyd Lowry, Allen Macklin, Tom Malone, Suzanne Marcy, Michael H Martin, Paul McCollum, Walter Meganack, Jr , Jennifer Nielsen, Gordon Nelson, Pat Norman, Phil North, Worth Nowlin, Peter Q Olsson, Gretchen Oosterhout, Ted Otis, Paul Panamarioff, Kent Patrick-Riley, Charles Peterson, John Piatt, Josie Quintrell, Terry Reed, Stanley Rice, Evan Richert, Monica Riedel, George Rose, Dave Roseneau, Susan Saupe, Andy Schmidt, Carl Schoch, Sandra Schubert, Marianne See, Stan Senner, Bob Shavelson, Hugh Short, Jeff Short, Claudia Slater, Bob Small, Alan Springer, Stacy Studebaker, Arliss Sturgulewski, Joe Sullivan, Kevin Summers, Gary Thomas, Glenn VanBlaricom, Shari Vaughan, Gale Vicki, Jia Wang, Sarah Ward, Tom Weingartner, Steve Weisberg, David Welch, Kent Wohl, Bruce Wright, Kate Wynne

OVERVIEW OF THE GEM DOCUMENT

The Gulf Ecosystem Monitoring (GEM) Program Document has been prepared in two volumes to more easily describe the basic monitoring and research program (Volume I) while providing access to the factual basis for the program (Volume II) Volume I explains the basic motivations for the program, information needs, and the strategies for meeting these information needs (see Table O 1 below) Volume II presents the factual basis for the program, including the detailed descriptions of two important components of the program (1) modeling and (2) data management and information transfer Table O 1 identifies the question addressed by each chapter and the products provided The Overview Figure, following the table, illustrates the structure of the GEM Program Document

Table O 1 Contents of the GEM Program Document

Chapter	Title & Question Addressed	Products
Volume I—Strategic Plan for Monitoring and Research		
1	Vision *Why do this and what do we hope to achieve?*	Mission and goals Program context
2	Human Uses and Activities *What are the human activities in the region and their potential impacts?*	Issues of concern to the Trustee Council and public
3	GEM Information Needs *What information do we need?*	Specific questions and information needs
4	Program Components and Strategies *How can we get the information we need?*	Key components and implementation strategies
5	Monitoring Plan & Research Agenda *What are we going to do to get the information, when will we do it, and with whom?*	Starting point for implementation process
6	Program Management *What are the processes and policies for monitoring and research?*	The Gulf Ecosystem Monitoring and Research Program
Volume II—The Historical Legacy Building Blocks for the Future		
1	Building on Lessons of the Past *What do other regional marine science programs have to teach us?*	Past experience Hypotheses and strategies
2	Lingering Effects of the Oil Spill *What does experience from the oil spill teach us?*	Past experience
3	Scientific Background *What is published that can help us?*	Current knowledge of the Gulf of Alaska General research questions

Table O 1 Contents of the GEM Program Document

Chapter	Title & Question Addressed	Products
4	Conceptual Foundation *How do we think the ecosystem works?*	Central hypothesis and questions
5	Modeling *What is the role of modeling in GEM implementation?*	Modeling definitions and options for program implementation
6	Data Management and Information Transfer *What are the roles of data management and information transfer in GEM implementation?*	Data management and information transfer options for program implementation
A	Appendix A Fish and Invertebrate Species from 1996 Trawl Survey of the Gulf of Alaska	
B	Appendix B North Pacific Models of the Alaska Fisheries Science Center and Selected Other Organizations	
C	Appendix C Gulf Ecosystem Monitoring and Research (GEM) Database	
D	Appendix D Glossary of Existing Agency Programs and Projects	
E	Appendix E Acronyms and Web Links	

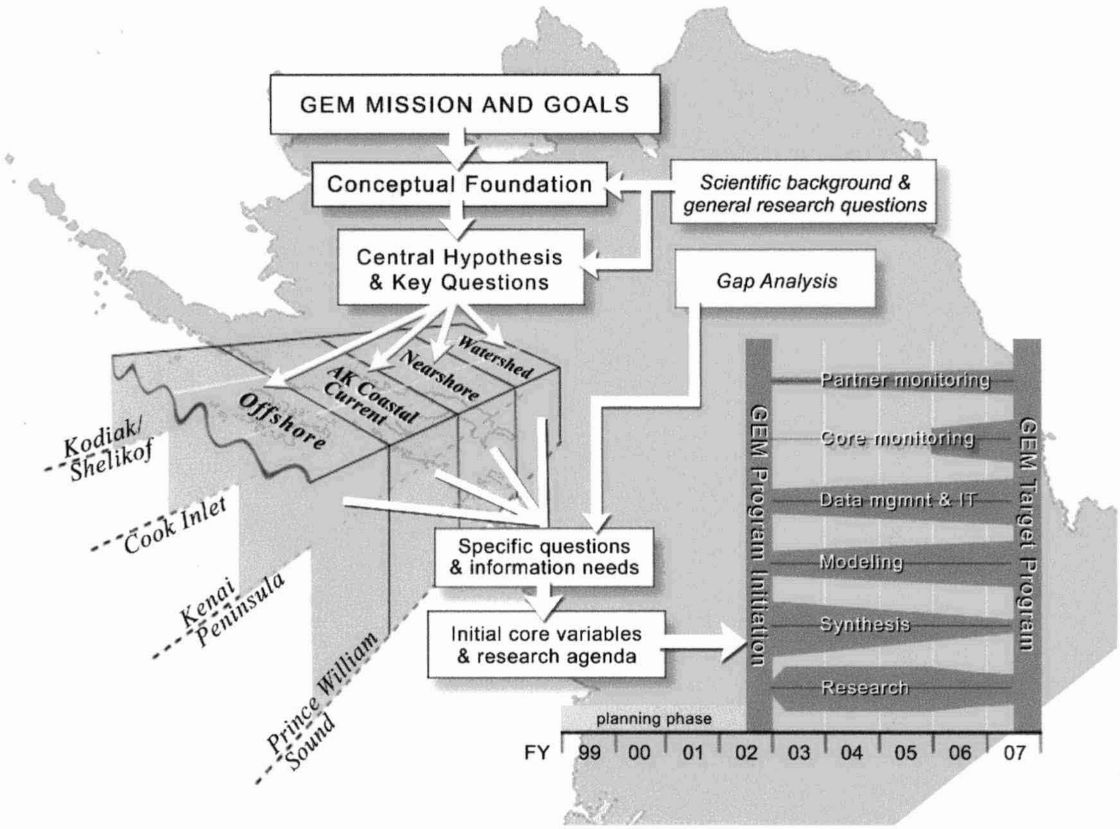

Figure O.1. An overview of the structure of the GEM program document showing the relation of key concepts to the habitat types and the schedule of implementation

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1. VISION FOR GEM IN THE NORTHERN GULF OF ALASKA

In This Chapter

- Origin of the GEM program
- Explanation of the mission identified for the program
- Identification of goals, geographic scope, and funding

1.1 Introduction

A program rooted in the science of a large-scale ecological disaster is uniquely suited to form the foundation for ecosystem-based management. The knowledge and experience gained during 10 years of biological and physical studies in the aftermath of the *Exxon Valdez* oil spill (EVOS) confirmed that a solid historical context is essential to understand the sources of changes in valued natural resources Toward this end, in March 1999 the *Exxon Valdez* Oil Spill Trustee Council (Trustee Council) dedicated approximately $120 million for long-term monitoring and research in the northern Gulf of Alaska (GOA) The new fund will be in place by October 2002 and will function as an endowment, with an annual program funded through investment earnings, after allowing for inflation-proofing and modest growth of the corpus

In making the decision to allocate these funds for a long-term program of monitoring and research, referred to herein as the Gulf Ecosystem Monitoring and Research (GEM) program, the Trustee Council explicitly recognized that complete recovery from the oil spill may not occur for decades and that through long-term observation and, as needed, restoration actions, the injured resources and services are most likely to be fully restored The Trustee Council further recognized that conservation and improved management of these resources and services would require substantial ongoing investment to improve understanding of the marine and coastal ecosystems that support the resources, as well as the people, of the spill region Improving the quality of information available to resource managers should result in improved resource management. In addition, prudent use of the natural resources of the spill area without compromising their recovery requires increased knowledge of critical ecological information about the northern GOA This knowledge can only be provided through a long-term monitoring and research program that will span decades, if not centuries There are both immediate, short-term needs to complete

Prudent use of the natural resources of the spill area requires increased knowledge of critical ecological information about the northern GOA

the understanding of the lingering effects of the oil spill and long-term needs to understand the sources of changes in valued natural resources

1.2 Mission

The original mission of the Trustee Council's Restoration Program, adopted in 1993, was to "efficiently restore the environment injured by the EVOS to a healthy, productive, world-renowned ecosystem, while taking into account the importance of the quality of life and the need for viable opportunities to establish and sustain a reasonable standard of living"

Consistent with this mission and with the ecosystem approach to restoration adopted by the Trustee Council in 1994, the mission of the GEM program is as follows

> ***Sustain a healthy and biologically diverse marine ecosystem in the northern Gulf of Alaska (GOA) and the human use of the marine resources in that ecosystem through greater understanding of how its productivity is influenced by natural changes and human activities***

In pursuit of this mission, the GEM program will accomplish the following

- Sustain the necessary institutional infrastructure to provide scientific leadership in identifying research and monitoring gaps and priorities,
- Sponsor monitoring, research, and other projects that respond to these identified needs,
- Encourage efficiency in and integration of GOA monitoring and research activities through leveraging of funds and interagency coordination and partnerships, and
- Promote local stewardship by involving stakeholders and having them help guide and carry out parts of the GEM program.

In adopting this mission, the Trustee Council acknowledges that, at times, sustaining a healthy ecosystem and ensuring sustainable human uses of the marine resources may be in conflict. In those instances, the goal of achieving a healthy ecosystem will be paramount. The Trustee Council also acknowledges that, at this time, clearly defined measures for assessing "ecosystem health" are lacking (NRC 2000) These measures will be incorporated into the program as they are developed

1.3 Goals

Five major goals have been identified as necessary to accomplish the GEM mission Attaining all five, however, will require several decades Two of these goals may be attainable within the early decades of operating the GEM program, given sufficient funding and collaboration with other partners

1 **Detect** Serve as a sentinel (early warning) system by detecting annual and long-term changes in the marine ecosystem, from coastal watersheds to the central gulf, and

2 **Understand** Identify causes of change in the marine ecosystem, including natural variation, human influences, and their interaction.

Two other goals provide an essential piece of the foundation for a long-term program Although these goals are likely to be fully realized only after the first decade of operating the GEM program, shorter-term accomplishments should be achieved sooner

3 **Inform.** Provide integrated and synthesized information to the public, resource managers, industry and policy makers in order for them to respond to changes in natural resources, and

4 **Solve** Develop tools, technologies and information that can help resource managers and regulators improve management of marine resources and address problems that may arise from human activities

The fifth goal is inherently long-term and difficult to achieve, but of considerable potential value to resource users and managers It serves more as a long-range beacon to guide the design of monitoring activities, than as a goal that may be attained within the near term

5 **Predict** Develop the capacity to predict the status and trends of natural resources for use by resource managers and consumers

During the process of learning how to detect and understand change in the northern GOA, resource managers and the concerned public should collect incremental dividends on their investment in GEM The benefits, however, will be maximized over the long run Ultimately, GEM must provide information that enables resource-dependent people, such as subsistence users, recreationalists, and commercial fishers, to better cope with changes in marine resources The data and information produced by GEM during its first decade may not totally solve problems for the public, commercial interests, resource managers, and policy makers faced with environmental change Nonetheless, as information accumulates, the ability for GEM to provide problem-solving information and tools can and must increase

Given the size and complexity of the northern GOA ecosystem and the available funding, it will not be possible to meet these goals with only the data collected by GEM Addressing the program goals will require achieving the following operational goals

- **Synthesize** monitoring and research results to advise in setting priorities,
- **Prioritize** monitoring and research needs,

- **Identify** monitoring and research gaps currently not addressed by existing programs,
- **Fund** monitoring of core variables,
- **Leverage** funds to augment ongoing monitoring work funded by other entities,
- **Track** work of other entities relevant to understanding biological production in the GOA,
- **Involve** other government agencies, non-governmental organizations, stakeholders, policy makers, and the general public in a collaborative process to achieve the mission and goals of GEM, and
- **Facilitate** application of GEM research and monitoring results to benefit conservation and management of marine resources

The substantial experience of the EVOS Restoration Program indicates that these eight operational goals are reasonable, necessary, and attainable

1.4 Geographic Scope

Consistent with the Restoration Plan, GEM program activities will occur within the area affected by the 1989 oil spill, which is generally the northern GOA, including Prince William Sound (PWS), Cook Inlet, Kodiak Island, and the Alaska Peninsula (Figure 1 1) Recognizing that the marine ecosystems affected by the oil spill do not have discrete boundaries, some monitoring and research activities may extend into adjacent areas of the northern GOA

Figure 1 1

THIS IS FIGURE 1 OF PREVIOUS REPORT NEED THE ELECTRONIC FILE

The primary geographic focus of GEM will be the four habitat types that contain the ecosystems of the area affected by the oil spill Building on the lessons of the past from the oil spill damage assessment (Natural Resource Damage Assessment), the oil spill restoration program, and other efforts (see Volume II), monitoring will occur in localities within the habitat types best suited to answer the scientific questions posed in the GEM strategic plan (see Chapter 4, Volume I) Suitability of locales will be determined by scientific and policy criteria (Chapters 4 and 5, Volume I) that are designed in accordance with the mission and goals of the Trustee Council

In defining geographic scope, it is also important to note that the ecosystems of the northern GOA encompass four habitat types–watersheds, intertidal and subtidal, Alaska Coastal Current (ACC), and offshore (the continental shelf break and the Alaska Gyre) (Section 3 1 2) Another important consideration is that the waters of the GOA are connected to adjacent waters Waters from the shelf and basin of the GOA eventually enter the Bering Sea and the Arctic Ocean (through the Bering Strait) Although GEM has a regional (GOA) outlook, the program will be of vital importance in understanding the downstream Bering Sea and Arctic Ocean ecosystems In addition to the linkages provided by the movements of ocean waters, the GOA is linked to other regions by the many species of birds, fishes, and mammals that also move through these regions It is also becoming increasingly clear that environmental conditions in the GOA, such as levels of persistent organic pollutants, as well as the temperature of GOA waters, can originate many thousands of miles away

1 5 Funding and Governance

The Trustee Council will fund the GEM program beginning in October 2002 with funds allocated for long-term monitoring and research, estimated to be approximately $120 million The Trustee Council will manage these funds as an endowment, with the annual program funded by investment earnings after inflation-proofing, thus providing for a stable program through time The Trustee Council also may choose to fund a smaller program in the early years to allow the corpus of the fund to build The Trustee Council's long-term goal is to allow for additional deposits and donations to the fund from other sources to increase the corpus Achieving this goal might require changes in state or federal legislation and possibly a change in the court-approved settlement and will be pursued at a later time

Under existing law and court orders, three state and three federal trustees have been designated by the Governor of Alaska and the President of the United States to administer the restoration fund, which includes funding for GEM, and to restore the resources and services injured by the oil spill The State of Alaska trustees are the Commissioner of the Alaska Department of Environmental Conservation, the Commissioner of the Alaska Department of Fish and Game, and the Attorney General The federal trustees are the Secretary of the Interior, the Secretary of Agriculture, and the Administrator of the National Oceanic and Atmospheric Administration, U S Department of Commerce

The trustees established the Trustee Council to administer the restoration fund The state trustees serve directly on the Trustee Council The federal trustees each have appointed a representative in Alaska to serve on the Trustee Council They currently are the U S Interior Department's Alaska Director of Fish Wildlife Service, the Alaska Director of the National Marine Fisheries Service, and the Supervisor of the Chugach National Forest for the Department of Agriculture All decisions by the Trustee Council are required to be unanimous

It is expected that the current Trustee Council will make policy and funding decisions for the GEM program It has been suggested that at some time in the future, a new board or oversight structure other than the Trustee Council be established to administer or guide the GEM fund It is also possible that an existing board, either under its current structure or with minor modifications, could take over management of the fund Use of a new governance structure, if justified, would require changes in law and the applicable court decrees Such changes would take considerable time and are not anticipated in the near future

1.6 References

NRC 2000 Ecological indicators for the nation National Academy Press Washington, D C

2. HUMAN USES AND ACTIVITIES IN THE NORTHERN GULF OF ALASKA

In This Chapter

- Discussion of the human impacts in the GOA
- Descriptions of sub-regions
- Identification of human activities occurring

NOTE This chapter is being reworked, and part or all of it will be included in the Scientific Background, Chapter 3, Volume II

The growing population of Alaska and the existing and potentially greater human use of the resources of the northern GOA are important considerations for development of GEM To achieve the GEM mission of sustaining a healthy ecosystem, as well as sustaining human use of the marine resources of the GOA, it is essential to assess and understand the impacts that human activities may have on important fish and wildlife species, their habitat, and the northern GOA ecosystem overall

The economy of Alaska depends heavily on extraction of natural resources, primarily oil, fish, and shellfish, followed by timber and minerals In the northern GOA, commercial fishing, recreation, and tourism (including sport fishing), oil and gas development, logging, roadbuilding and urbanization, marine transportation, and subsistence harvests are all activities that have the potential to affect fish and wildlife populations and habitat.

The human impact on Alaska's marine ecosystems is relatively small, compared to impacts in most of the developed world Other regions are faced with marine dead zones caused by eutrophication (decline of a water body caused by oxygen deficiency) from pesticide runoff, overfishing and depletion of fish stocks, serious industrial pollution, and degradation of important habitat such as coral reefs and coastlines Alaska is pristine in comparison Even here, however, natural resource managers have concerns about localized pollution, the potential impacts of some fisheries, extreme changes in some fish and wildlife populations, and the little known impacts of contaminants and global warming

Even in pristine Alaska natural resource managers are concerned about the impacts of pollution on marine ecosystems

State and federal laws and permitting systems are designed to identify and mitigate the direct impacts of these activities Secondary and cumulative impacts are not as routinely assessed, however There is concern that local problems, if left unidentified or unmonitored, could grow into regional problems

Experience with the EVOS Restoration Program has demonstrated that, unless an impact is very large, it is often extremely difficult to isolate the human impact from the natural variability Because GEM will be a long-term program, however, it is important to assess the potential impacts of human activities on a regular basis to determine their influence on changes in the abundance and distribution of important resources

2 1 Socioeconomic Profile of the Northern Gulf of Alaska

About 71,000 full-time residents live within the area directly affected by the oil spill (Figure 1 1), and two to three times that number use the area seasonally for work and recreation The spill area population, combined with that of the nearby population centers of Anchorage and Wasilla, totals 62% of the state's 627,000 permanent residents When the resident population is combined with more than one million tourists who visit the state each year, it becomes clear that the natural resources of the northern GOA cannot be immune to the pressures associated with human uses and activities

2 1.1 Prince William Sound

PWS lies north of the GOA and west of Cordova About 7,000 people live and make their living in this area The largest communities–Cordova, Valdez, and Whittier–are all coastal and predominantly non-Native, although Valdez and Cordova are home to Alaska Native village corporations and tribes Chenega Bay and Tatitlek are Alaska Native villages All five communities are accessible by air or water, and all have dock or harbor facilities In the north, the ports of Valdez and Whittier link the area to the state's main road system

The economic base of the five communities in PWS is heavily resource dependent. The Cordova economy is based on commercial fishing, primarily for pink and red salmon As the terminus of the Trans-Alaska Pipeline System, Valdez is dependent on the oil industry, but commercial fishing and fish processing, government, and tourism also are important to the local economy Large oil tankers routinely traverse PWS and the northern GOA to and from the Port of Valdez In addition to working as oil industry employees, Whittier residents also work as government employees, longshoremen, commercial fishermen, and service providers to tourists The people of Chenega Bay and Tatitlek augment commercial fishing, aquaculture, and other cash-based activities with subsistence fishing, hunting, and gathering

2.1.2 Kenai Peninsula

The Kenai Peninsula, on the northwest margin of the GOA, separates Cook Inlet from PWS The central peninsula is connected to the main road system, only a few hours by car from the major population center of Anchorage Homer and Kenai have jet air access from Anchorage, and Whittier has train access, both passenger and cargo Because of this road connection to Anchorage, the Kenai Peninsula is the fastest growing area in the northern GOA About 50,000 people live on the peninsula, with about two-thirds living near the cities of Kenai and Soldotna The economy of this area depends on the oil and gas industry, commercial fishing, and tourism This area was the site of the first major Alaska oil strike in 1957 and has been a center for oil and gas exploration and production since that time Seward is a seaport on the eastern Kenai Peninsula near the western entrance of PWS It is the southern terminus of the Alaska Railroad, which transports marine cargo and passengers to and from Anchorage

The southern Kenai Peninsula contains the cities of Homer and Seldovia and the Alaska Native villages of Nanwalek and Port Graham Homer, on the north side of Kachemak Bay, is the southern terminus of the state's main road system on the peninsula Seldovia, Nanwalek, and Port Graham, all located south of Kachemak Bay, are accessible only by air and sea Nanwalek and Port Graham depend largely on subsistence hunting and fishing and on village corporation enterprises, such as the salmon hatchery, cannery, and logging enterprise at Port Graham Homer is the economic and population hub of this part of the peninsula and depends on commercial fishing, tourism, and forest products

Tourism is an important and growing part of the Kenai Peninsula economy Marine sport fishing out of Seward and Homer is a major attraction for the tourist industry Cruise ships dock at the Seward harbor, and commercial vessels take passengers on tours of the nearby Kenai Fjords National Park The Kenai River and its tributary, the Russian River, are major sport fishing rivers, attracting tourists from Anchorage and all over the world

2 1 3 Kodiak Island Archipelago

The Kodiak Island archipelago lies to the west of the northern GOA This region includes the city of Kodiak and the six Alaska Native villages of Port Lions, Ouzinkie, Larsen Bay, Karluk, Old Harbor, and Akhiok About 14,000 people live in this region, although the population swells in the fishing season Communities on Kodiak Island are accessible by air and sea Approximately 140 miles of state roads connect communities on the east side of the island

The economy of the archipelago depends heavily on commercial fishing and seafood processing Kodiak is one of the world's major centers of seafood production and has long been among the largest ports in the nation for seafood volume or value of landings Village residents largely depend on subsistence hunting and fishing Kodiak Island is also home to a commercial rocket-launch facility that held its first successful launch in 1999 The U S Coast Guard Station near Kodiak is a major landowner and employer

2 1.4 Alaska Peninsula

The Alaska Peninsula is on the western edge of the northern GOA Five communities on the south side of the Alaska Peninsula lie within the area affected by the EVOS Chignik, Chignik Lagoon, Chignik Lake, Ivanof Bay, and Perryville The population of the area is about 450 year-round residents, but doubles during the fishing season All five communities are accessible by air and sea The cash economy of the area depends on the success of the fishing fleets

Chignik and Chignik Lagoon serve as regional salmon-fishing centers, and Dutch Harbor, southwest of Perryville and outside the spill area, is a major center for crab and other marine fisheries In addition to salmon and salmon roe, fish processing plants in Chignik produce herring roe, halibut, cod, and crab About half the permanent population of these communities is Alaska Native Subsistence on fish and caribou is important to the people who live in Chignik and Chignik Lagoon

Chignik Lake, Ivanof Bay, and Perryville are predominantly Alaska Native villages and maintain a subsistence lifestyle, relying on salmon, trout, marine fish and shellfish, crab, clams, moose, caribou, and bear Commercial fishing provides cash income Many residents leave during summer months to fish from Chignik Lagoon or work at the fish processors in Chignik

2.1 5 Will add section on Anchorage Basin and how it affects other parts of region

2.2 Description of Human Activities

2.2 1 Commercial Fishing

Commercial fishing is by far the predominant human activity in the northern GOA and is thought at this time to have the potential for the most significant impacts on the GOA ecosystem Within the GOA, the major commercial fisheries are salmon, Pacific herring, pollock, cod, halibut, and shellfish For the 2000 fishing season, within state waters, the total gross earnings for the GOA fishing activity were estimated to be about $127 5 million Approximately 200 people fished, using a total of 2,900 permits (Note more information is needed in this paragraph)

The period before the 1989 oil spill was a time of relative prosperity for many commercial fishermen Since 1989, these drastic changes have occurred in the commercial fishing industry

- Low prices have reduced the value of the pink and sockeye salmon fisheries
- Sharp declines in herring populations in PWS, possibly caused by disease related to the EVOS, have resulted in closures that have devastated the fishery

- The listing of the Steller sea lion under the federal Endangered Species Act has resulted in restrictions on groundfish fisheries
- GOA crab stocks have continued their plummet

A major ecological concern with all types of removals by fishing activities is the sustainability of fish stocks, which could be affected by directed fisheries or as a result of discarded bycatch in other fisheries and high seas interception Overfishing could lead to stock depletion The predominant fishery stocks historically fluctuate because of natural variability and climate cycles Setting harvest rates without a complete understanding of those fluctuations could lead to unintentional overharvest, resulting in population declines that could take years to rebound

Another ecological concern with all types of fishing is the removal of marine nutrients (nitrates, phosphates, iron) that are key to sustaining the long-term productivity of watersheds (Finney et al 2000) Fishing for a dominant anadromous species such as salmon may lower the productive capacity of a watershed not only for salmon, but for a wide range of plants, fish, and mammals that are known to depend on marine nutrients When combined with the loss of nutrients associated with development of riparian (river and other waterfront) habitats and wetlands, the loss of marine nutrients may contribute to the process known as oligotrophication or "starvation" of the watershed Unfortunately, not enough monitoring data on marine nutrients in tributaries of the GOA is available to understand the degree to which oligotrophication is occurring

A third ecological concern with fishing is the potential for degradation of habitats, and attendant losses of unintended species Sport-fishing activities in watersheds have substantially degraded some riparian habitats in Southcentral Alaska, resulting in lost vegetation, lost fish habitat, and siltation Various types of marine fishing methods and gear, such as pots and hard-on-bottom trawls (baglike nets), also have the potential for degrading sea-bottom habitat and reducing populations of sedentary species such as corals and seaweeds

More information on how to define critical marine habitats is essential to balancing fishing opportunities and protection of habitat

Protection has already been afforded to marine habitats in some cases by excluding gear types that are thought to be injurious to habitat For example, the eastern GOA is now closed to trawling and dredging in part to protect coral habitats from possible trawling impacts In addition there are numerous trawl-and-dredge closure areas near Kodiak Island, the Alaska Peninsula, and the Aleutian Islands Areas where marine mammals feed and that are adjacent to their haul-out areas also have been closed to commercial fishing in parts of the Bering Sea, Aleutian Islands, and GOA Given the amount of marine habitats already subject to closure, more information on how to define critical marine habitats, a possible role for GEM, is essential to balancing fishing opportunities and protection of habitat (Need to add impacts of drift nets)

Commercial fishing also has the potential to affect other elements of the marine ecosystem, such as bird and marine mammal populations Effects result either directly, through entanglement in fishing nets or disturbance to haul-outs and rookeries, or indirectly, through impacts on food supplies A recent National Marine Fisheries Service (NMFS) Biological Opinion concludes that lack of food is the reason why the endangered Steller sea lion is not recovering from serious declines in the GOA and Bering Sea On the basis of this opinion, NMFS has severely limited fixed-gear and trawl fishing for several groundfish species, a major food source for the Steller sea lion

Salmon fisheries in the GOA are notable because hatcheries produce the majority of some salmon species in some areas and, in specific fisheries, the majority of salmon harvested Billions of juvenile salmon are released annually from hatcheries in three areas within the northern GOA Cook Inlet, Kodiak, and PWS Within this region, 56% of the salmon in the traditional commercial harvest were of hatchery origin in 1999 The percentage is higher if cost-recovery fisheries are also included In PWS in particular, hatchery production provides a majority of the pink and chum salmon harvested and a substantial fraction of the sockeye and coho salmon harvested In 1999, hatchery pink salmon contributed 84% of the number of pink salmon harvested by commercial fisheries in PWS

Information on the interactions between hatchery and wild fish appears to be essential to long-term fishery management programs

Ecological concerns related to hatcheries include reduced production of wild fish because of competition between hatchery and wild salmon during all stages of the life cycle, loss of genetic diversity in wild salmon, and overharvest of wild salmon during harvest operations targeting hatchery salmon Information on the interactions between hatchery and wild fish in specific locations, and on the impact of salmon produced in hatcheries in both Asia and North America on food webs in the GOA, appears to be essential to long-term fishery management programs

2.2 2 Recreation and Tourism

Major recreational and tourist attractions within the spill area include Portage Glacier, Kenai Fjords National Park, Columbia Glacier, Kachemak Bay, and Katmai National Park World-class salmon fishing attracts residents and visitors alike to the Kenai River, the Russian River, and other rivers on the Kenai Peninsula Charter halibut fishing is an important and growing recreational activity, especially for Seward and Homer More than 500 vessels are active in this industry Camping, hiking, kayaking, and wildlife viewing attract visitors to the Kodiak Island National Wildlife Refuge, the Chugach National Forest, and numerous state and federal park units and refuges within the spill area

Growth of the Alaska population and increases in nonresident visitation to Alaska will increase the potential impacts of GOA resource use Between 1990 and 1998 alone, the number of nonresident visitors to Alaska increased from 900,000 to 1 35 million per year, averaging a 5% annual rate of increase during this period

Cruise ship traffic to the state has been increasing by more than 10% a year, although the rate may be slowing somewhat

Increased tourism and recreational use could result in a variety of impacts on marine fish and wildlife and their habitats Sport fishing could contribute to localized depletion of fish stocks, as well as degradation of streambank habitat in watersheds Increased recreational boat traffic can disturb wildlife on their rookeries and haul-outs, as well as increase oil and gas residue in harbors and adjacent waters Cruise ships often carry more people than populate many Alaska towns, and cause concerns about their disposal of garbage and other waste, impacts on air quality, and potential for diesel fuel spills The growing use of jet skis for recreational use and their potential for disturbing nesting waterfowl has led to a jet ski ban in Kachemak Bay by the Alaska Department of Fish and Game (ADF&G) Increased hiking and camping on coastal areas and riverbanks can lead to trampling, erosion, and related impacts on local water quality The Whittier road, opened in 2000, is expected to increase visitation to northwestern PWS, with potential impacts to shorelines, tidelands, and nearshore waters, as well as the fish and wildlife populations that rely on these habitats

2 2 3 Oil and Gas Development

The oil and gas industry is a major economic force in PWS and Cook Inlet Crude oil pumped from fields on the North Slope is transported by pipeline to Valdez, where it is loaded onto tankers and shipped to the lower 48 states Tankers traverse PWS on the journey south The number of tanker voyages from the Port of Valdez has declined from 640 in 1995 to 411 in 1999, because of the sharp reduction in North Slope crude oil production Any additional North Slope development could increase tanker traffic

Discovered in 1957, the Swanson River oilfield in the Kenai National Wildlife Refuge is the site of the first commercial oil development in Alaska Much of the oil and gas development in the Cook Inlet area occurs on offshore platforms Underwater pipelines transport product to terminals on both sides of Cook Inlet. Tankers ship crude oil and refined product to the lower 48 states

In April 1999, the State of Alaska offered for lease all available state-owned acreage (approximately 2 8 million acres) in its first Cook Inlet Areawide Oil and Gas Lease Sale As a result of the first sale, oil and gas leases have been issued on about 115,000 acres of land Sales in August 2000 and May 2001 resulted in the lease of about 205,000 acres of land Additional sales are planned in 2002 and 2003

The major concerns about oil and gas development include the potential for oil spills from vessel traffic, as happened during the 1989 EVOS, as well as small, chronic spills, pipeline corrosion and subsequent leaks, disposal of drilling wastes and potential impact on water quality, and the introduction of exotic species from ballast waters In 1995, local conservation groups negotiated a settlement with

Cook Inlet oil and gas producers for more than 4,000 violations of the federal Clean Water Act in Cook Inlet

The State of Alaska issues permits and leases that stipulate site- and activity-specific mitigation measures, and provide for monitoring of production, transport, and exploratory activities on state land and waters (The Minerals Management Service is responsible for comparable federal regulation of offshore development under the Outer Continental Shelf Act) For activities within federal jurisdiction, the National Environmental Protection Act provides for analysis of environmental oil and gas development impacts All oil producers, shippers, and refineries are required to have approved contingency plans detailing response capabilities and specific response actions in the event of a spill In addition, the Oil Pollution Act of 1990 created the regional citizens advisory groups to oversee oil and gas activities in PWS and Cook Inlet

2 2.4 Subsistence Harvest

Fifteen predominantly Alaska Native communities in the GEM region, with a total population of about 2,200 people, rely heavily on harvests of subsistence resources such as fish, shellfish, seals, deer, and waterfowl Subsistence harvests in 1998 varied among communities from 250 to 500 pounds per person, indicating strong dependence on subsistence resources Subsistence activities also support the culture and traditions of these communities Many families in other communities also rely on the subsistence resources of the spill area

Subsistence use is a form of resource exploitation and must be considered as a factor potentially affecting resource abundance and distribution It is monitored under state and federal authorities Subsistence harvest of marine mammals is probably of greatest concern because marine mammals are an important component of subsistence diets in the GEM region and because subsistence harvests are the only legal take of marine mammals, have no regulatory restrictions, and may affect species with small populations

2 2 5 Timber Harvest

No major timber operations are currently occurring in PWS, but logging continues on Afognak Island in the Kodiak archipelago and small-scale timber operations are planned for parts of the Kenai Peninsula Of the three major logging operators on Afognak Island, only Afognak Native Corporation is still logging in a major way, with 30 million board feet in 2000 and another 30 million board feet planned for 2001 Poor lumber markets, increased competition, and a dwindling timber supply have all led to decreased logging activities on Afognak Logging operations on Port Graham Corporation lands on the southern Kenai Peninsula have concluded, but some logging may take place on Native allotments near Port Graham On the Alaska Peninsula, Ninilchik Native Corporation and Cook Inlet Region Inc are preparing a major logging operation to begin in 2001 on the Crescent River, a major salmon producer in Cook Inlet.

The State of Alaska has a five-year Schedule of Timber Sales for the Kenai Peninsula and Kodiak area from 2000 through 2004 One significant factor affecting forest planning in the Kenai area is a major epidemic of the spruce bark beetle The proposed timber sales are designed to use dead and dying timber or to harvest timber with a high likelihood of infestation in the next few years During this 5-year period, the state plans to hold 31 timber sales on about 23,000 acres of state land on the Kenai Peninsula Harvest from these lands is estimated to be 115 million board feet of spruce and hemlock and 410,000 cubic board feet of birch, cottonwood, and aspen In 1999 in the Moose Pass area, one sale that totaled 153 acres occurred In December 2000, three tracts in the Ninilchik/Clam Gulch area, totaling 1,604 acres, were re-offered, however, no bids were received

Concerns about logging include water quality effects, long-term effects on the marine system of bark from log transfer facilities, and impacts on anadromous streams from siltation and habitat destruction The Alaska Department of Environmental Conservation (ADEC) reported that 24% of the water bodies on the state's list of polluted sites are due to some aspect of logging (ADEC 2000, ADEC et al 2001) A significant issue related to logging is the increased access to previously remote lands provided by logging roads Logging operations on the Kenai Peninsula alone have added more than 3,000 miles of roads in the region This increased access has encouraged all-terrain vehicle use in sensitive habitats, such as the headwaters of salmon streams

2 2.6 Other Industrial Activity

Large spills like the EVOS are rare More common are smaller discharges of refined oil products, crude oil, and hazardous substances Small spills have been caused by a variety of industries, such as oil and gas, timber, fishing, and seafood processing industries, as well as small commercial establishments such as gas stations and dry cleaners

Under state law, the release of hazardous substances and oil must be reported to ADEC In 1998 and 1999, 1,325 spills were reported in the EVOS region, resulting in a total discharge of 218,000 gallons of refined oil products, crude oil and hazardous substances Although small spills were reported throughout the spill area, by far the largest number of spills (1,037) and greatest volume of discharge (198,000 gallons) occurred in the Cook Inlet region Most spills (87%) involved refined oil products, these spills accounted for about 90% of the total volume discharged Only 6,000 gallons of crude oil were reported spilled in the region from 1998 to 1999 (ADEC 2001)

Figures reported to ADEC include spills onshore as well as discharges into the marine environment The effects of these small spills depend on such variable factors as the volume of the discharge, its toxicity and persistence in the environment, the time of year the spill occurred and the significance of the affected environment in the life history of species of concern

2.2.7 Road Building and Urbanization

Community growth and urbanization often go hand in hand with loss of water quality and fisheries habitat. The greatest concentration of roads, subdivisions, and other aspects of increased urbanization affecting the GEM region are within the Municipality of Anchorage and on the west side of the Kenai Peninsula **In Anchorage (need more information)** In 1999, the Kenai Peninsula Borough approved plats for 250 subdivisions Most of the subdivisions were small, but a few were 40 acres or more The borough recently initiated a road-permitting program that will address placement and design of new roads

Continued expansion of urban areas and resulting expansion of suburban zones inevitably degrade habitat Changes in land surfaces can change entire hydrologic systems and add to water pollution problems Urban growth leads to increasing disposal of human wastes Even treated wastes may lead to changes in species composition and productivity in watersheds, estuaries, and nearshore areas

Increased areas of impervious surfaces through new roads and subdivisions usually increase stormwater runoff Stormwater runoff is the largest single source of pollution in Alaska and is caused by runoff and erosion from pavement, parking lots and ditches, commercial and residential construction, and septic systems Thirty-eight percent of the sites on a 1998 state list of polluted water are affected by such community runoff The pollutants include chemicals, bacteria, and excess soil

Increased stormwater runoff tends to lower base flows in streams and increase peak flows Stream macroinvertebrates (large animals that lack backbones) and fish populations are sensitive to these changes As part of its stormwater discharge permit through ADEC, the Municipality of Anchorage is mapping the impervious surfaces within its area and studying the response of stream macroinvertebrates Under a U S Environmental Protection Agency (EPA) 319 grant from ADEC, the U S States Department of Agriculture Cooperative Extension Service is also studying the effects of impervious surfaces A pilot project is planned for the Anchorage area, and if successful, the methodology may be applied to other areas in the future

Increased urbanization also results in filling wetlands, which play an important ecological role in filtration for water quality and stormwater protection The Municipality of Anchorage has a wetlands plan, with high- and low-value wetlands identified There is no plan delineating the extent of wetlands and analyzing their function and values for the rest of the region, however

Human access to streams usually leads to degradation of aquatic habitat

Human access to streams increases as the number of miles of road increases Trampling of stream banks, changes in stream configuration created by culverting of roads, reduction in riparian zone vegetation, and a multitude of other problems created by road building and access lead to aquatic habitat degradation and loss of basic productivity Increased human access to small rivers and streams containing relatively large animals such as salmon and river otters also usually leads to loss of aquatic species through illegal taking, despite the best efforts of law enforcement Indeed, limitations in budgets usually lead resource management and protection agencies to focus scarce resources on sensitive areas during critical seasons, leaving degradation to take its course in less sensitive locations

2 2 8 Contaminants and Food Safety

The presence of industrial and agricultural contaminants in aquatic environments has resulted in worldwide concerns about potential effects on marine organisms and on human consumers Polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides, such as dichlorodiphenyltrichloroethane (DDT) and its derivatives, are distributed around the world in marine and coastal waters and in the rivers and watersheds that feed fresh water into these environments Such pollutants can be transported great distances by winds and ocean currents following their releases from industrial and agricultural sources, most of them far from Alaska In addition, mercury and other metals, such as inorganic arsenic, cadmium, and selenium, are naturally present in the environment at low concentrations, but man-made sources can contribute additional quantities to the environment

The remoteness of the northern GOA from centers of industry and human population might be expected to protect much of this region from deposition of environmental contaminants Nonetheless, there is limited evidence suggesting wide geographic distribution of persistent organochlorines (DDT, dichlorodiphenyldichloroethylene [DDE], PCB), other organic pollutants and heavy metals in the Arctic, Subarctic, and areas adjacent to the GOA (Crane and Galasso 1999) For example, measurable amounts of organochlorines have been found in precipitation, and fishes of the Copper River Delta, a tributary of the GOA that forms the eastern boundary of PWS (Ewald et al 1998)

A variety of geophysical pathways bring these materials into the GOA, including ocean currents and prevailing winds In particular, the prevailing atmospheric circulation patterns transfer various materials as aerosols from Asia to the east across the North Pacific (Pahlow and Riebsell 2000) where they enter the marine environment in the form of rain Some of these contaminants, such as PCBs and DDT, can bioaccumulate in living marine organisms For example, research sampling of transient killer whales that had eaten marine mammals in PWS indicated concentrations of PCBs and DDT derivatives that are many times higher than those concentrations found in fish-eating resident whales The sources of these contaminants are not specifically known It has been established, however, that these contaminants are passed from nursing female killer whales to their calves

There is also concern about the potential effects of contaminants on people, especially those who consume fish and shellfish, waterfowl, and marine mammals

At higher levels of exposure, many of the chemicals noted above can cause adverse effects in people, such as the suppression of the immune system caused by PCBs

The State of Alaska does not monitor environmental pollutants in the marine environment or in marine organisms on a regular basis There is no ongoing program for sampling food safety in subsistence resources in coastal communities, although the oil spill provided the opportunity to sample subsistence resources for hydrocarbons in the affected areas from 1989 through 1994 Federal funding for a joint federal-state-Native initiative has been requested from Congress NOAA has annually measured chemicals in mollusks and sediments since 1984 The agency also has monitored chemical concentration in the livers of bottom-dwelling fish and in sediments at the sites of fish capture since 1984 The Prince William Sound Regional Citizens Advisory Council has measured hydrocarbon concentrations and sources within areas of PWS and the GOA This program focuses on sampling of intertidal mussels and nearby sediments

2 2 9 Global Warming

Although driven by forces outside the control of Alaska's natural resource managers, global warming is an essential consideration for development and implementation of the GEM program The earth's climate is predicted to change because human activities–the combustion of fossil fuels and increased agriculture, deforestation, landfills, industrial production, and mining–are altering the chemical composition of the atmosphere through the buildup of greenhouse gases These gases are primarily carbon dioxide, methane, and nitrous oxide Their heat-trapping property is undisputed, as is the fact that global temperatures are rising Observations collected during the last century suggest that the average land surface temperature has risen 0 45° to 0 6° C Precipitation has increased by about 1% over the world's continents in the last century, with high-latitude areas tending to see more significant increases in rainfall and rising sea levels This increase is consistent with observations that indicate the northern GOA seasurface temperature has increased by 0 5° C since 1940, and that precipitation in Alaska (excluding the panhandle) increased 11% from 1950 through 1990

Increasing concentrations of greenhouse gases are likely to accelerate the rate of climate change The changes seen in the northern GOA and their relationship to other warming and cooling cycles in the North Pacific and the combined effects on global climate are important for understanding how humans affect biological production Some populations of fish and marine mammals that show longtime trends, up or down, or sharp rapid changes in abundance, are actively managed through harvest restraints The extent to which harvest restraints may be effective in establishing or altering trends in abundance of exploited species can only be understood within the context of climate change

2 3 References

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3. INFORMATION NEEDS

In This Chapter

- Summary of general gaps in marine science
- Definition of the central question in terms of the four main habitat types integral to the GEM program
- Starting points for development of information needs for each habitat type

3.1 Introduction

Appendix C summarizes the database of current and historical monitoring and research projects in the GOA and adjacent waters, and highlights a number of data sets that will be of great value in developing the GEM program This chapter provides a "gap analysis" of information needed to answer the key questions of the conceptual foundation described in Volume II, Chapter 4 Those questions are designed to promote better understanding of the origins and time-space scales of variability in marine production and fluctuations of key marine-related species in the GEM region The questions, and information needed to answer them, are still very broad To provide a more meaningful gap analysis, the key questions have been further expanded into multiple specific questions for each of the four representative habitat types watersheds, intertidal-subtidal, Alaska Coastal Current (ACC), and offshore The specific questions are then followed by a description of the information needed to answer them Critical ecological processes are also suggested for each habitat type to provide further context for the specific questions and information needs Together, these information needs will form the starting point for developing specific hypotheses and designing the monitoring and research components necessary to test them as described in Chapter 5 (Volume I)

The reader is advised to consider the questions and information needs below as the starting points for the process of implementation All concepts for specific information needs are subject to further development through the scientific advisory process described in Chapter 6 (Volume I) The advisory process is expected to include workshops and other meetings to gather the advice of experts in science, public policy, management, and user group concerns Opportunities for data acquisition and partnerships are discussed in Chapter 5 (Volume I)

3 1.1 General Information Gaps in Marine Science

Relatively little information has been gathered for species of plants and animals that are physically small and unsuitable for commerce and subsistence (see Appendix C) Consequently, substantial information gaps still exist for the basic life histories and biology of broad assemblages of species and communities that are outside the realm of human trade The rule of thumb is that the amount of scientific information available is inversely proportional to the remaining energy and biomass at each trophic level **(Need xc figure here)** An especially large gap exists for basic information on zooplankton species and benthic invertebrates that provide a vital link between primary producers and fish, birds, and mammals that constitute the higher trophic levels Additionally, how natural forces and human activities control productivities of valued living marine resources is still poorly understood, although information on the natural forces of climate and physical oceanography is steadily increasing primarily through satellite telemetry

3 1 2 Representative Habitat Types

Four habitat types, representative of the GEM region, are used to better organize the GEM program watersheds, the intertidal-subtidal areas, the ACC, and the offshore areas (the continental shelf break and the Alaska Gyre) These habitats are composed of identifiable, although not rigid, collections of characteristic microhabitats, resident and migratory species, and physical features The physical locations are described below

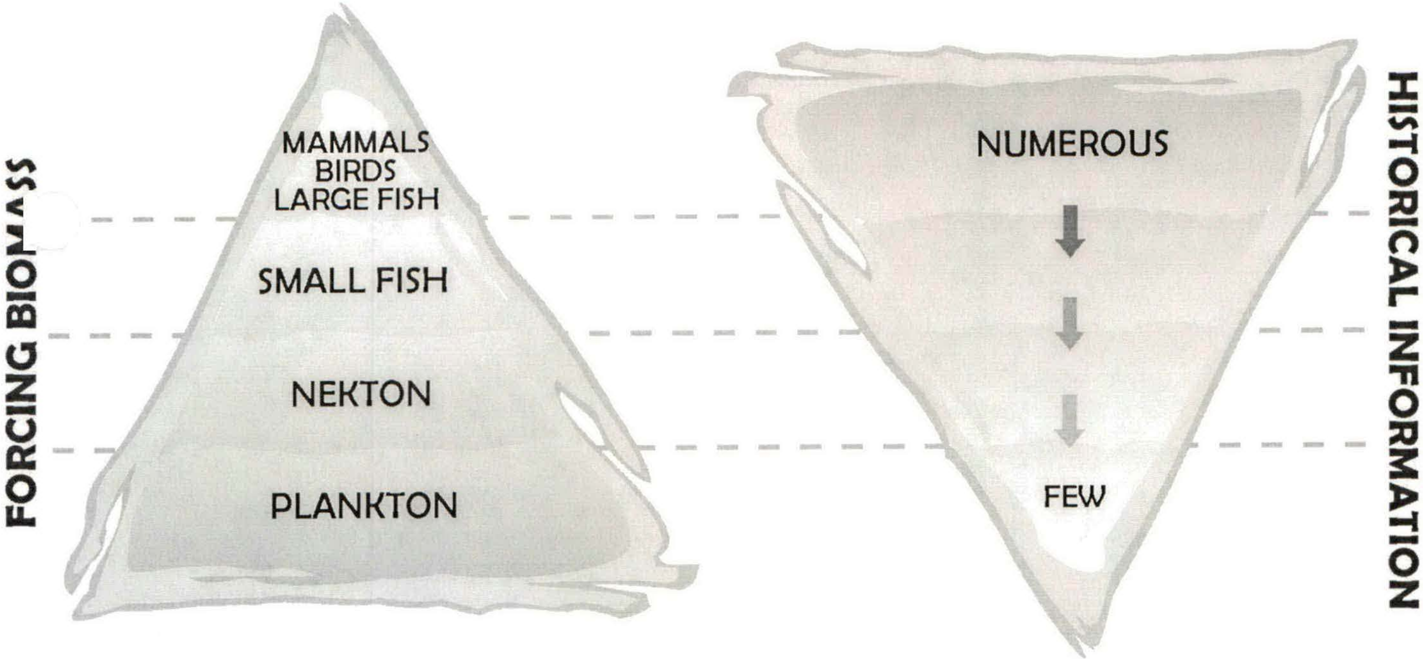
- Watersheds–freshwater and terrestrial habitats from the mountains to the extent of the rivers' plumes,
- Intertidal-subtidal areas–brackish and salt-water coastal habitats that extend offshore to the 20-m depth contour,
- ACC–a swift coastal current of lower salinities (25 to 31 psu) typically found within 35 km of the shore, and
- Offshore–the continental shelf break (between the 200-m and 1,000-m depth contour) and the Alaska Gyre in waters outside the 1,000-m depth contour

3 1.3 The Central Question by Habitat Types

The central question (Chapter 4, Volume II) seeks fundamental understanding of the degree to which changes in production of plants and animals in the four habitat types of GEM are controlled by natural environmental forces as opposed to human activities

> ***What are the relative roles of natural forces and human activities, as distant and local factors, in causing short-term and long-lasting fluctuations changes in the biological communities that support birds, fish, shellfish, and mammals in the four key habitats of the GOA?***

To identify the information needed in each habitat type, the central question is adapted to the habitat's circumstances in the following sections Information needs are identified as the answers to specific forms of the central question for each habitat type


FORCING BIOMASS
MAMMALS
BIRDS
LARGE FISH
SMALL FISH
NEKTON
PLANKTON
NUMEROUS
FEW
HISTORICAL INFORMATION

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3.2 Watersheds

3.2.1 General Watershed Information Needs

The key question for watershed habitats is

What are the relative roles of natural forces, such as climate, and human activities, such as habitat degradation and fishing, as distant and local factors, in causing short-term and long- lasting changes in marine-related biological production in watersheds?

Long-term monitoring of marine-related productivity in watersheds is needed before the long-term effects of human activities and other natural forces on productivity can be understood Current monitoring activities and historical records make it possible to detect changes in productivity of prominent species within watersheds that are subject to relatively high levels of human activities, such as the Kenai River Understanding the causes of changes is not possible, however, because a lack of basic measurements prevents separating the effects of changes in marine productivity from the effects of other factors such as human activities and natural biological and geological forces Evidence of the significant role of marine nutrients in determining the productivity of watersheds is growing, however, monitoring of these linkages in the northern GOA is nonexistent to weak, based on the information gathering projects described in the database (see Appendix C) Measurements of certain kinds of human activities such as land development and fishing in watersheds are widely available, but the actual impacts of these activities on production of natural resources are less certain Cumulative impacts such as accumulation of persistent contaminants may be of interest at some point in the future as they relate to control of plant and animal production

In addition, although there is substantial evidence of the potential role of the micronutrient iron in controlling marine productivity, the degree to which watersheds may be contributing iron to marine food webs in the GOA is not being measured The nature of flows of marine nutrients into watersheds, and the flow and distribution of freshwater micronutrients (such as iron), and carbon from the watersheds into the marine environments remain poorly understood in the GOA Filling watershed information gaps would address long-term questions about how the transport of marine nutrients, terrestrial micronutrients, carbon, and fresh water contribute to changes in productivity and community structure in watersheds and the marine environment.

3 2 2 Specific Watershed Questions and Information Needs

Three specific watershed(W) questions and the related information needs are presented below

W-1 What are levels of marine-related nutrients in watersheds and how do the annual inputs of marine nutrients vary?

Specific Information Needs Levels of nitrogen-stable isotopes in freshwater plants and animals, and feasibility of studying sources of precursors of reduced iron in watersheds with marine access

W-2 What is the annual variability in precipitation and runoff in Alaska watersheds bordering the northern GOA? (Same question applies to intertidal-subtidal and ACC habitats)

Specific Information Needs Annual precipitation and runoff for all watersheds flowing into the northern GOA In some cases, where gaps exist, it may be possible to use marine salinity data to supplement precipitation and stream flow measures in estimating total freshwater run off from land to the GOA Input of the amount of fresh water entering the GOA from northern British Columbia and Southeast Alaska would also be needed to use marine salinity as a proxy for freshwater runoff

W-3 What are the levels of persistent contaminants entering and leaving watersheds along marine-related pathways?

Specific Information Needs Levels of persistent organic pollutants such as PCBs in anadromous species as adult immigrants and as juvenile emigrants of the watersheds

3.2 3 Watershed Processes

The watershed processes identified as of interest to the GEM program are those involved in linkages between terrestrial and marine variability, such as biogeochemical cycles

3 3 Intertidal and Subtidal

3.3 1 General Intertidal and Subtidal Information Needs

The key question for intertidal and subtidal habitats is

What are the relative roles of natural forces, such as currents and predation, and human activities, such as sediment and pollutant discharge, as distant and local factors, in causing short-term and long-lasting changes in community structure and dynamics of the intertidal and subtidal habitats?

Long-term monitoring is needed to identify how human activities can change the community structure of the intertidal and subtidal areas Current monitoring activities may make it possible to detect changes in community structure that are the result of a combination of human activities and natural forces in some localities, however, no program now produces the measurements sufficient to determine the extent to which such changes are due to human activities Evidence of the increasingly important role of human activities in changing the community structure of shallow nearshore environments is growing, however, monitoring that is structured to separate human and natural effects in areas of growing human impacts is sporadic Monitoring is needed to measure the natural variability of the intertidal-subtidal areas at places and times that support detection of the effects of human activities Simultaneous monitoring of currents and nutrients, bottom substrates, species composition, and other important natural forces in areas with differing degrees of chronic human activity is needed Filling intertidal-subtidal information gaps would begin to address the long-term questions of how human activities combine with natural forces to cause changes in productivity and community structure in intertidal-subtidal environments

3.3 2. Specific Intertidal and Subtidal Question and Information Needs

One specific intertidal and subtidal (I) question and several related information needs are presented below

I-1 What is the variability of selected plant and animal populations in the intertidal and subtidal zones?

Specific Information Needs

- Variability in numbers and diversity of fixed algae and invertebrates in several regions PWS, Kachemak Bay, and Kodiak Island
- Relative availability of larval dispersal stages
- Measures of the cycling of carbon, nutrients, and contaminants in key species such as *Fucus*
- A detailed map of intertidal plant biomass during the growing season on a wide spatial scale
- Monitoring of clam populations
- Measurements of population processes of sea otters
- Identification and measurement of human impacts of concern

3.3 3 Intertidal and Subtidal Processes

Processes in the intertidal and subtidal habitat of interest to the GEM program relate to variability in community structure and plant biomass of selected populations and processes affecting populations

3 4 Alaska Coastal Current

3 4 1 General ACC Information Needs

The key question for ACC habitats is

What are the relative roles of natural forces, such as the variability in the strength, structure and dynamics of the ACC, and human

activities, such as fishing and pollution, in causing local and distant changes in production of phytoplankton, zooplankton, birds, fish and mammals?

Long-term monitoring activities to detect seasonal changes in the ACC have permitted a general, large-scale understanding of circulation and lower trophic level productivity in the ACC, but current monitoring does not permit the changes in the ACC to be related to the changes in community structure or productivities in intertidal-subtidal areas and watersheds Long-term monitoring is needed to measure the natural seasonal and interannual variability of the ACC at locations that are likely to permit evaluation of these relationships Changes in annual production of some fish stocks are highly correlated with physical changes in the ACC, but ideas about the basis for these apparent relations cannot be evaluated from current monitoring activities Filling ACC information gaps would begin to address the long-term questions of how human activities combine with the transport of marine nutrients, terrestrial micronutrients, carbon, and fresh water to contribute to changes in productivity and community structure in watersheds and the marine environment

3 4 2 Specific ACC Questions and Information Needs

Seven specific ACC (A) questions and related information needs are presented below

A-1 What is the annual variability of strength, location and dynamics of the ACC?

Specific Information Needs Measurements of variability in temperature and salinity with depth, on time scales of from days to multiple decades at locations sufficient to understand seasonal-scale variability at localities sufficiently widely dispersed to understand large-scale structure, including intrusion into bays

A-2 What is the variability in the supply of deepwater nutrients to the photic zone of the ACC and their concentrations in that zone on time and space scales appropriate to understanding annual primary production?

Specific Information Needs Measurements of, or proportional to, macronutrients and micronutrients at appropriate spatial scales

A-3 What is the variability in chlorophyll a concentrations and phytoplankton species composition in the photic zone of the ACC on time and space scales appropriate to understanding annual primary production?

Specific Information Needs

- Chlorophyll a measurements
- Information on phytoplankton species composition

A-4 What is the variability of zooplankton biomass and species composition in the ACC on time and space scales appropriate to understanding annual primary and secondary production?

Specific Information Needs Information about zooplankton biomass and species composition

A-5 What is the variability in the availability of forage fish to higher trophic levels (birds, fish, mammals) in the ACC?

Specific Information Needs

- Analyses of the diets of selected higher-trophic-level organisms (birds, mammals, large predatory fish)
- Analyses of selected higher-trophic-level organisms (birds, mammals, large predatory fish) for fatty acid composition in relation to diet.

A-6 What are the major factors affecting long-term changes in sea bird populations?

Specific Information Needs Annual colony and chick productivity counts of appropriate species in selected GOA colonies

See also information needs for Question A-5 above

A-7 What are the major factors affecting long-term changes in harbor seal populations?

Specific Information Needs

- Annual surveys of molting population in selected GOA haul-outs
- Fatty acid profiles of individual animals and scat analysis surveys in selected GOA haul-outs

3 4 3 Alaska Coastal Current Processes

Processes in the ACC of interest to the GEM program relate to variability in the current structure and dynamics, nutrient supply, and selected populations and processes affecting populations

3.5 Offshore: The Outer Continental Shelf and Oceanic Waters

3.5 1 General Offshore Information Needs

The key question for offshore habitats is

What are the relative roles of natural forces, such as changes in the strength of the Alaska Current and Alaskan Stream, mixed layer depth of the gyre, wind stress and downwelling, and human

activities, such as pollution, in determining production of carbon and its shoreward transport?

Long-term information gathering is needed on the effect of the open ocean gyre on the natural variability in seasonal and annual productivity of the continental shelf and ACC Past information gathering is sufficient to suggest that a strong relationship between gyre and inner waters has existed at times The gyre-continental shelf-ACC relationship appears to be based on movement of nutrients-detritus and plankton Current information gathering, however, does not provide the long-term data sets needed to detect changes in the gyre that may be related to changes in the ACC, intertidal-subtidal areas, or watersheds The same changes in annual production of certain fish stocks that are highly correlated with physical changes in the ACC also appear to be correlated with changes in the gyre, but ideas about the apparent relations between fish stocks, the ACC, and the gyre cannot be evaluated from current information gathering Filling information gaps on the gyre would begin to address the long-term questions of how oceanic productivities and processes in the GOA may contribute to changes in productivity and community structure in watersheds and the marine environment.

3.5.2 Specific Offshore Questions and Information Needs

Five specific offshore (O) questions and related information needs are presented below

O-1 What is the annual variability in the production of zooplankton in the offshore areas?

Specific Information Needs Abundance of zooplankton on time and space scales appropriate to understanding annual production

O-2 How are the supplies of inorganic nitrogen, phosphorus, silicon, and other nutrients essential for plant growth in the euphotic zone annually influenced by climate-driven physical mechanisms in the GOA?

Specific Information Needs Measurements of inorganic nitrogen, phosphorus, silicon, and other nutrients on time and space scales appropriate to understanding annual variability

O-3 What is the role of the Pacific High pressure system in determining the timing and duration of the movement of dense slope water onto and across the shelf to renew nutrients in the coastal bottom waters?

Specific Information Needs Synoptic information on sea level pressure and horizontal and vertical structure of density and nutrients on the outer continental shelf and Alaska Gyre in relation to the ACC on appropriate time and space scales

O-4 Is freshwater runoff a source of iron and silicon that is important to marine productivity in the offshore and adjacent marine waters?

Specific Information Needs Levels of biologically available silicon and iron from offshore water in relation to the ACC on appropriate time and space scales

O-5 Does iron limitation control the species and size distribution of the phytoplankton communities in the offshore areas?

Specific Information Needs Levels of biologically available iron and species composition and size distribution of the phytoplankton communities from offshore water on appropriate time and space scales

3.5 3 Offshore Processes

Processes of interest to the GEM program in the offshore habitat are variability in the strength and location of the Alaska Current and Alaskan Stream, gyre activity, and primary and secondary production

4. PROGRAM COMPONENTS AND STRATEGIES

In This Chapter

- Relationships and functions of tools for implementing the GEM program
- Strategies for program implementation
- The ongoing role of gap analysis

4.1 Program Components

Synthesis,research, monitoring, modeling, and data management and information transfer are the tools to be used in implementing the GEM program These tools are common to most programs for assessment of living marine resources (Myers et al 2000) For organizational purposes, retrospective analysis and process studies are treated as forms of research As a common toolset for monitoring and research, the components are closely related, and their functions sometimes overlap

4 1 1 Synthesis

The starting point for developing the GEM program is synthesis, because all good science ultimately involves synthesis In the words of biologist, E O Wilson (1998)

> We are drowning in information while starving for wisdom The world henceforth will be run by synthesizers, people able to put together the right information, think critically about it, and make important choices wisely

Synthesis builds on and updates current understanding of the northern GOA It brings together existing data from any number of disciplines, times, and regions to evaluate different aspects of the GEM program central hypothesis, key questions, and related ideas Synthesis has three broad uses First, it is used to provide direction for developing hypotheses to be tested and, combined with research and monitoring, to update and refine the conceptual foundation Second, it is used as a tool–for example, in workshops, meetings, or publications–to inform stakeholders and the public about the developing understanding of the factors responsible for change in the marine environment. And third, synthesis is used to solve resource management problems, by identifying new applications of existing information or by identifying opportunities to solve existing problems through collection of new information Synthesis is a logical place to begin the cycle of monitoring and research, but once used to initiate a project or component, it logically becomes a companion to research

For the purposes of the GEM program, synthesis is defined separately from research and from retrospective analysis, a form of research Synthesis differs from research in the requirement that synthesis be interdisciplinary or concerned with multiple habitat types, or both Synthesis brings together existing data from any number of disciplines, times, and regions to evaluate the central hypothesis, key questions, specific questions, and related ideas and is usually supported by various forms of retrospective analysis (discussed below) The results of synthesis and research are often used together to solve problems

4 1 2 Research

Research collects relatively short time series of observations to evaluate some specific aspect of the monitoring program or some testable hypothesis relating to the central hypothesis with fixed limits on project duration It may build on or use existing data and it may also build models Testing current understandings through research provides the basis for making changes to the monitoring program and associated components such as modeling, data management, and information transfer

Retrospective analysis is a specialized form of research that uses existing time series data to evaluate a testable hypothesis or other question of similar specificity relating to monitoring, often supported by statistical modeling Retrospective analysis contributes to building numerical models and to synthesis

Research, in the form of *process studies*, plays a vital role in moving beyond the correlative relationships that arise from the monitoring efforts to understand the underlying mechanisms Process studies develop information on the mechanisms through which energy and matter are transferred across varying scales of time and space This critical deeper understanding is essential to provide a framework and substance for the numerical modeling and synthesis Large-scale process studies may encompass ecosystem-level processes occurring across multiple trophic levels, water masses, and habitat types, whereas small-scale studies may deal with mechanisms as specific as the digestion rates of individual animals Processes such as predation, nutrient transport, and heat transfer are critical to understanding changes in living marine-related resources Process studies support model building by defining relationships among individuals and species and between phenomena such as primary production and physical forcing Process studies also contribute to other forms of research, such as retrospective analysis, and to synthesis

The short-term end point for GEM program synthesis and research is implementation of core monitoring activities The roles of research and synthesis in the GEM program are first to support implementation of monitoring, and second to give the monitoring program the capacity for change once it is established

The continuing roles for synthesis and research, as supported by modeling, are to promote understanding of the relationships among and within the broad habitat types of the ecosystems, plant and animal species, physical and chemical oceanographic processes, and climate in the GOA Continual refinement and testing of hypotheses, synthesis across geographic areas and species, and modeling of biological and physical processes are expected

4.1 3 Monitoring

Monitoring is the action of taking long-time-series observations at times and places designed to test hypotheses based on current understandings Monitoring is essential to detecting and understanding change, because it provides the starting point for synthesis, various forms of research, modeling, and information transfer How often and where to sample are important aspects of detection, and therefore, key considerations in the design of monitoring They must be appropriate to the hypotheses being analyzed

Monitoring in the GEM program will be organized into core monitoring and partnership monitoring Core monitoring is fully supported by the GEM program, and partnership monitoring is partially supported

The end point for monitoring is a geographically distributed network gathering data on the state of the marine ecosystem that is transformed into information for user groups through application of synthesis, research, modeling, data management, and information transfer Monitoring will use spatially structured survey methods

4 1 4 Modeling

Models are tools for organizing data and telling a story Modeling is used to make the relationships between the parts and processes of the ecosystem clear, and models can be written in a variety of media as verbal, visual, statistical, or numerical models In the GEM program, the specific purposes of modeling are to help accomplish the following

- Inform, communicate, and provide common problem definition,
- Identify core variables and relationships,
- Set priorities,
- Improve and develop experimental (monitoring) designs, and
- Improve decision-making and risk assessment

Modeling, monitoring, and data management strategies need to work in concert for each to be fully effective (Figure 4 1) Modeling is a pivotal link between monitoring and data management and information transfer on the one hand, and synthesis and research on the other Modeling feeds back information to the monitoring program in the form of recommendations on how the monitoring system can be made more effective Modeling also helps interpret data for the use

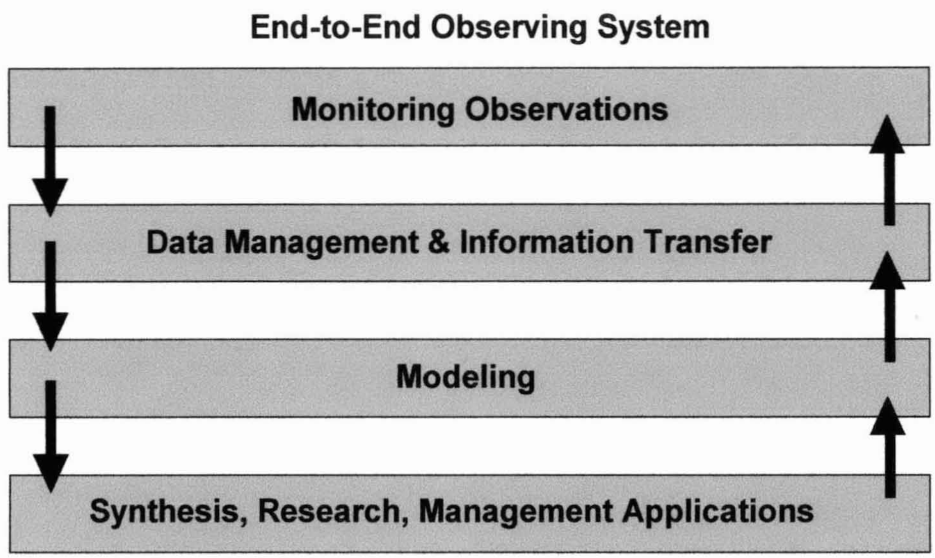

Figure 4.1 The End-to-End Observing System. This system shows the relationships among components of the GEM program (monitoring observations, data management and information transfer, modeling, synthesis and research) and management applications. (Adapted from Tom Malone [U.S. GOOS Steering Committee 2000]).

of synthesis and research activities. Current modeling efforts are considered in more detail in Chapter 5, Volume II. The discussion below provides a brief introduction to definitions and strategies for modeling in the GEM program.

As defined for the purposes of the GEM program, a model may be expressed in verbal, visual, statistical, or numerical languages. Verbal models are also known as "qualitative" and "conceptual"; statistical models are also known as "correlative" and "stochastic"; and numerical models are also known as "deterministic" and "mechanistic." Note that "prediction," "simulation," and "analysis" are not types of models, but uses of models. For example, the use of any kind of statistical or numerical model to reproduce the behavior of a process, such as population growth, is known as a simulation (see Chapter 5, Volume II). The different media for models are explained below.

- Verbal models come in different degrees of precision, from low-precision, narrative explanations of how physical and biological factors combine to produce birds, fish, and mammals (the conceptual foundation, Chapter 4, Volume II), to highly precise statements known as testable hypotheses.
- Visual models, such as **Figure 4.2 (need figure)** of the conceptual foundation, are graphic images of verbal models.
- Statistical models and related mathematical techniques promote understanding of whether verbal models are worth considering further. By comparing combinations of measurements, such as fish growth rates at

different water temperatures, statistical methods show the likelihood of relationships among phenomena, but not how or why they are related

- Numerical models are mathematical translations of verbal models describing how and why phenomena are related Numerical models often rely on established principles from physics, chemistry, and biology

All four types of models will be used in the GEM program In the near-term, however, models of biological phenomena are expected to be mostly verbal, visual, and statistical, whereas models of physical and chemical phenomena are likely to be primarily numerical, in addition to being verbal and statistical

Models are tools not only for understanding, but also for predicting change Models organize and analyze monitoring observations of plants and animals, natural forces, and human activities With the use of the mathematics of modeling, short-term predictions can be made about how a particular aspect of the ecosystem works The ultimate demonstration of understanding a phenomenon, however, is longer-term prediction Covering the vast distance between current understanding of the productivity of living marine-related resources and predicting changes on longer time scales (weeks, months, and years) will require thousands of small steps in understanding This progression will necessarily take a long time Because of the time required, identifying the relationship between current understanding and probable changes in resource productivity is a reasonable goal for a long-term program such as the GEM program

The long-term modeling end points for GEM monitoring, synthesis, and research are working biophysical models that make managers, policy makers, and resource users aware of changes in natural resources, help them understand the human and natural origins of these changes, and give them some idea of what to expect in the future

4 1 5 Data Management and Information Transfer

Data management and information transfer are the processes of acquiring in the field, receiving in the office, formatting, and storing data, providing quality control and assurance, developing and managing databases, and making the data understandable to users It includes the development of information products based on interpreted data and the delivery of these products, including development of user interfaces The short-term objective of data management and information transfer in the GEM program is to gain control of the data acquired with EVOS funds Many of these data are in danger of being lost as the passage of time leads to loss of project personnel and institutional memory

The long-term end point for GEM data management and information transfer is a system that manages the rapid and efficient flow of data and information based on core monitoring projects to end users, and that facilitates the flow of data and information between GEM partners and among GEM partners and the user community

GEM data management is a program support function intended to accomplish the following

1 Support cross-disciplinary integration of physical, biological, and traditional knowledge within a structured, decision-making framework,

2 Support synthesis, research, and modeling that evaluate testable hypotheses on the roles of natural forces and human activities in controlling biological production, and

3 Lay the groundwork for future use of distributed, Web-based analysis and management tools as the monitoring program becomes fully operational

By necessity, the data incorporated into the GEM program will derive from a variety of sources and formats, which will include retrospective data sets and traditional knowledge, may contain spatial and temporal components Synthesis and research will need to incorporate data not directly collected by the GEM program, such as satellite remote-sensing information and fishery catch data Incorporation of these data into regional models and decision-making systems will require tools for data ingestion and query, especially to facilitate modeling (see Figure 4 1) Because the output from the GEM program will be used by people from a wide variety of disciplines and backgrounds, the user interface must be easy to understand and accessible through a distributed network, such as the Internet.

Data management and acquisition policies are essential to ensure the rapid transfer of information to end users Although the data must flow through the system as quickly as possible, quality control and assurance procedures and the prerogatives of scientists to publish interpretations of the data need to be respected One approach that may prove useful is the establishment of "peer reviewed" data sets that allow the scientists involved to receive credit for their efforts in the publications of other scientists who may use the data

Information transfer products will depend on the nature of the monitoring and research activities (see Chapter 5) that are yet to be chosen Possibilities for these products, based on the experience of other monitoring and research programs, are discussed in Chapter 6, Volume II

4.2 Strategies for Implementation

The scientific strategy of the GEM program uses a central hypothesis and key questions from the conceptual foundation to establish the initial direction for the program From this starting point, the GEM program follows a path of synthesis, research, and monitoring to detect, understand, and, eventually, predict changes in living marine-related resources of the GEM region As shown in the table below, the strategy calls for modeling and data management to closely support synthesis and research

The way to achieve prediction in the long term is to build a body of knowledge on how and why the productivity of living marine-related resources changes through time Synthesis is used to build and maintain a coherent and comprehensive understanding of the current state of knowledge Research tests current understandings Monitoring activities take long-time-series observations at times and places designed to test hypotheses based on current understandings And at all stages of the program, an ongoing gap analysis demonstrates when it is possible to take advantage of the work of others **(Figure 4 3) (need figure)**

The basic sequence of activities for establishing the monitoring network is envisioned as follows

Synthesis → Research → Monitoring

Concurrent programs of modeling and data management would support the sequence of synthesis, research, and monitoring Table 4 1 illustrates this implementation strategy

Table 4 1 Strategy for Implementing a Monitoring Network

Example of building a monitoring activity for the GEM program in 5 fiscal years through synthesis and research, supported by concurrent modeling and data management

Fiscal Year	Monitoring Activity		Model	Data Management
	Core	Partners		
2003	Synthesis Research	Monitor	Verbal(c)	Prototype
2004	Synthesis Research	Monitor Research	Statistical(c)	Coordination (c) Archiving(c)
2005	Research	Monitor Research	Statistical(c) Numerical prototype (p)	Coordination (c) Archiving (c) Distribution (p)
2006	Research Monitor	Monitor Research	Statistical(c) Numerical (p)	Coordination (c) Archiving (c) Distribution (p)
2007	Monitor Research	Monitor	Numerical (p)	Archiving (c) Distribution (p)

Notes

c = core (GEM program supported) activity

p = partnership (jointly supported) activity

The implementation strategy shown in Table 4 1 uses the basic components of the program in a series of three steps that lead gradually to the identification and establishment of a long-term monitoring program The first step is increased synthesis of existing information, continuing the process started in preparing the scientific background (Chapter 3, Volume II) and in conjunction with exploratory research projects that build on current synthesis The GEM program is now at this step, with ongoing synthesis and preliminary research expected to continue through Fiscal Year (FY) 2002 The initial synthesis activities, including modeling, would support identification and development of testable hypotheses Initial research activities would explore the feasibility of measuring candidate variables at various localities in the watershed, nearshore, and offshore Initial synthesis in the nearshore and offshore areas would rely heavily on past and developing information from research and monitoring programs such as SEA, FOCI, OCC, and GLOBEC (see Appendix C), and on past and ongoing monitoring and research in the watersheds under ADF&G, USFWS, U S Forest Service (USFS), and others

The second step, to be initiated in FY 03, combines continuing synthesis with research that examines opportunities for core monitoring in PWS, the outer Kenai Peninsula, Lower Cook Inlet, Kodiak, and adjacent waters All research projects are initiated for a fixed duration, however, some of these initial projects might be considered "pilot monitoring" projects that could be extended indefinitely if results of retrospective analyses, workshops, modeling studies, synthesis, and other preparatory research show continuation is warranted

The third step is full implementation of a long-term monitoring program As identified by the preparatory synthesis, research, and modeling, each core monitoring activity would collect data on a number of core variables that support evaluation of testable hypotheses Partners may fund additional measurements at the location of core monitoring activities For example, with proper planning it is usually possible to add monitoring equipment to moorings without disrupting existing activities for data acquisition It may also be advantageous for partners to incorporate core monitoring locations into their own transects and other surveys The actual number of core monitoring activities at full implementation at the end of FY 07 will depend on how much funding is available and the needs demonstrated by the results of retrospective analyses, workshops, modeling studies, synthesis, and other preparatory research

4 3 Gap Analysis: An Ongoing Strategy for Implementation

The identification of information needs, or gap analysis, is an important part of the process of identifying the starting points for monitoring and research (Chapter 5, Volume I) It will continue to be an important part of implementation In the process of starting the GEM program, the available information (Appendix C) was compared to the information relevant to answering the key questions (Chapter 4, Volume II) to see what information was missing (Chapter 3, Volume I) This process will continue during implementation, however, the more general key questions will be replaced by increasingly specific questions

It is important to have a clear understanding of how the nature of the question determines the nature and outcome of the gap analysis The gap analysis has three essential parts

1 A question,

2 Identification of information necessary to answer the question, and

3 A survey of relevant available information

The first part, the question, is fundamental to the gap analysis and defines the survey of all relevant information needed to answer it A general question calls for a general gap analysis, and a more detailed question calls for a more detailed gap analysis The gap analysis concludes with a comparison of the information needed and the information available

As the GEM program moves from general questions about what controls biological production within habitats and the connections among production in these habitats toward testable hypotheses, the gap analysis will become highly specific Testable hypotheses will be developed during the second half of FY 02 More detailed gap analysis will be done when the process reaches the level of testable hypotheses, with highly specific questions, in FY 03

A continuing gap analysis, supported by a continuously updated database of current and historical information-gathering projects in the GOA and adjacent areas, is essential to implementing the GEM program This analysis will be key to finding new partners for monitoring activities, identifying new opportunities for research and synthesis, and providing increased opportunities for collaboration, without risking duplication

The immediate end point of the gap analysis strategy is a database that supports identifying information needs in the short term, as core monitoring variables and locations are selected In the longer term, the supporting database will become a valuable tool for resource managers, policy makers, other scientists, stakeholders, and the general public

4.4 References

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5. MONITORING PLAN AND RESEARCH AGENDA

In This Chapter

- Elements of the phased approach to monitoring
- Use of synthesis, research, modeling, and data management to develop and refine monitoring activities
- Fiscal Year 2002 agenda for activities

5.1 Introduction

The monitoring program developed by the Trustee Council and its partners is intended to be the "flagship" of the GEM program The monitoring program is the heart of the GEM program and will be maintained even if funding levels vary Synthesis, research, modeling, and data management will all be used to develop and refine monitoring activities A phased approach is envisioned during a 5-year period, from FY 03 to FY 07, and will incorporate these elements

- Use of the *key question* for each habitat as the starting point for performing the necessary synthesis and research for developing testable hypotheses
- A table showing a *proposed schedule and strategy for implementation,* FY 03 to FY 07, for core and partnership activities, models, and data management
- Lists of probable or *prospective partners* that are actively doing related monitoring or research in the broad habitat type
- *Candidate (or possible) core monitoring activities* recommended based on the conjunction of partnership opportunities and opportunities for measuring biological and physical quantities related to the key question and information gaps
- *Candidate (or possible) core variables* recommended based on approaches suggested by the literature reviewed in the scientific background (Chapter 3, Volume II)

Following a discussion of data management, this chapter discusses the above monitoring program elements for each habitat type The key questions were introduced in Chapter 3, Volume I

5 2 Data Management

Because data management functions and products are generic to all habitat types, the suggested implementation strategy provided in this section is applicable for all four habitat types Core data management will be prototyped in FY 03 as core synthesis and research projects are initiated and partnerships formed The first core function is to establish coordination among parties as soon as possible, but no later than FY 04, by means such as file transfer protocol (ftp) sites, Web sites, and e-mail forwarding lists As data from core and partnership research projects are produced, around FY 04, archiving of data will be essential to serve research needs A partnership system of data distribution will be designed to make information products readily available to partners and other user groups The ultimate goal for all broad habitat types will be an end-to-end system, in which a monitoring network provides data to models and other applications that provide services to a variety of end users, including the ongoing GEM synthesis, research, and modeling itself

5.3 Watersheds

5.3.1 Key Question

What are the relative roles of natural forces, such as climate, and human activities, such as habitat degradation and fishing, as distant and local factors, in causing short-term and long-lasting changes in marine-related biological production in watersheds?

5 3 2 Schedule

Development of watershed monitoring activity will be led by a core synthesis effort in FY 03, building on preparatory core research in FY 02 to establish an approach to measuring levels of marine influence in animals and plants of the watersheds Core synthesis will assist in developing hypotheses by about FY 04 that can be tested and refined by core research in FY 05 and FY 06 At least one core monitoring station will be initiated by FY 06, but may not be fully operational until FY 07

Table 5 1 presents the proposed schedule and strategy for implementation

5 3 3 Prospective Partner Activities

Partner activities in FY 03 are expected to be the supporting monitoring programs already in place, such as enumeration of animals and plants, water quality monitoring, existing hydrology models, including annual and seasonal runoff, and permitting of human impacts such as resource harvests and land development Starting in FY 04, partners will be encouraged to assist in funding research to further site selection This activity will extend through FY 06, terminating after the monitoring station is fully operational Because an analogous research program is under way at Washington Department of Fish and Wildlife (WDFW), that agency may be willing to share information and the costs of process studies of mutual interest

Table 5 1 Proposed Implementation Strategy for Watershed Habitat

Fiscal Year	Monitoring Activity		Model	Data Management
	Core	Partners		
2003	Synthesis Research	Monitor	Verbal(c)	Prototype
2004	Synthesis Research	Monitor Research	Statistical(c)	Coordination (c) Archiving(c)
2005	Research	Monitor Research	Statistical(c) Numerical prototype (p)	Coordination (c) Archiving (c) Distribution (p)
2006	Research Monitor	Monitor Research	Statistical(c) Numerical (p)	Coordination (c) Archiving (c) Distribution (p)
2007	Monitor Research	Monitor	Numerical (p)	Archiving (c) Distribution (p)

Notes

c = core (GEM program supported) activity

p = partnership (jointly supported) activity

Prospective partners ADF&G USFWS (Kenai Natural Wildlife Refuge [KNWR]) USGS EPA ADEC USFS Cook Inlet Keeper (CIK) Alaska Department of Natural Resources (ADNR) and Washington Department of Fish and Wildlife (WDFW)

Candidate core monitoring activities Kenai River watershed Karluk River watershed

Candidate core variables isotopes of nitrogen in aquatic and riparian plants and animals precursors of reduced iron in water and anadromous fish

5 3 4 Models

Models of the relationship between marine productivity and watershed productivity (Finney et al 2000) are supposed to be verbal as of FY 03 Statistical modeling to describe the strength of relations among variables and power analysis to guide sampling should start in FY 04, continuing through the evaluation of the initial monitoring station in FY 06 The end point of modeling will be a numerical model of the geochemistry of the core variable(s) in the watershed to the boundary of the intertidal-subtidal areas This model will be initiated in about FY 05 and operational (in some sense) by FY 07 It is recognized that a number of partner monitoring activities in addition to the core activity will be needed to create parameters for a numerical model If numerical modeling proves intractable, statistical modeling would be extended in the interim

5 3 5 Candidate Core Monitoring Activities

Candidate core monitoring activities will be chosen to build on existing long time series of data collected by prospective partners The Kenai and Karluk rivers are two likely candidates For the Kenai River watershed, three decades of data on adult salmon returns to the spawning grounds of the watershed can be used as estimates of marine influence In addition, salmon catch data span more than five decades The proximity to Anchorage places the Kenai River watershed under heavy pressure from human activities and impacts, many of which are documented by government regulators Multiple prospective partners have extensive programs in place to monitor vegetation, terrestrial animals, limnology, and other variables of potential relevance to the key question The Karluk River watershed is unique in having a published record of more than 300 years of changes in marine influence in general, and marine nitrogen in particular (Finney et al 2000) In addition, the prospective partners have collected more than eight decades of counts of salmon returns for the watershed

5 3 6 Candidate Core Variables

Isotopes of nitrogen in plants and animals and sources of reduced iron are candidates for core variables, based on work described in the scientific background under marine-terrestrial connections (Section 5 3) and chemical oceanography (Section 5 5) In watersheds of the GEM region, where nitrogen limits productivity, marine nitrogen in anadromous fish species, principally salmon, could be an important driver of watershed productivity Phosphorus and iron from salmon may also be important to watershed productivity, but direct measures of the origin of these elements are not available (Indirect measures might be, for example, phosphorus or iron concentration per gram of fish times average fish weight times return number) A decade of work on the role of iron in primary productivity in marine areas suggests that geophysical and biological processes in watersheds may contribute to marine productivity Processes in the watersheds may limit marine productivity by controlling the availability of precursors of reduced iron

5.4 Intertidal and Subtidal

5 4 1 Key Question

> ***What are the relative roles of natural forces, such as currents and predation, and human activities, such as sediment and pollutant discharge, as distant and local factors, in causing short-term and long lasting changes in community structure and dynamics of the intertidal and subtidal habitats?***

5.4.2 Schedule

Development of the intertidal and subtidal monitoring activities is expected to begin with a planning workshop in FY 02 and an intense core synthesis effort in FY 03 that involves extensive preparatory core research The inherently high variability of the community structure of the intertidal and subtidal habitat–and its vulnerability to the effects of predation and human degradation–may make it difficult to develop a design that can separate human activities from natural forces, forestalling implementation of initial monitoring until FY 06 Core synthesis is planned to provide hypotheses by about FY 05 that can be tested and refined by core research in FY 06 and FY 07 Plans call for at least one core monitoring station to be initiated by FY 06, but it may not be fully operational until FY 07

Table 5 2 presents the proposed schedule and strategy for implementation

Table 5 2 Proposed Implementation Strategy for Intertidal and Subtidal Habitat

Fiscal Year	Monitoring Activity		Model	Data Management
	Core	Partners		
2003	Synthesis Research	Monitor	Verbal(c) Statistical(c)	Prototype Coordination (c)
2004	Synthesis Research	Monitor Research	Verbal(c) Statistical(c)	Coordination (c) Archiving(c)
2005	Research	Monitor Research	Verbal(c) Statistical(c)	Coordination (c) Archiving (c) Distribution (p)
2006	Research Monitor	Monitor Research	Statistical(c)	Coordination (c) Archiving (c) Distribution (p)
2007	Monitor Research	Monitor	Statistical(c) Numerical prototype (p)	Archiving (c) Distribution (p)

Notes

c = core (GEM program supported) activity

p = partnership (jointly supported) activity

Prospective partners ADF&G (Kachemak Bay National Estuarine Research Reserve [KBNERR]) NOAA (National Ocean Service and UAF) Cook Inlet Regional Citizens Advisory Council (CIRCAC) Prince William Sound Regional Citizens Advisory Council (PWSRCAC) USFS EPA-ADEC EMAP) Alyeska Pipeline Service Company

Candidate core monitoring activities Kachemak Bay (Lower Cook Inlet) Green Island (PWS)

Candidate core variables substrate type and distribution species composition and distribution recruitment

5 4 3 Prospective Partner Activities

Partner activities in FY 03 will be the supporting monitoring programs already in place, such as monitoring of individual species for basic biology and contaminant loads, surveys of species composition and distribution, surveys of substrates, and measurements of physical oceanography (see Table 5 2) Starting in FY 04, partners will be encouraged to assist in funding research to further site selection These activities will extend through FY 06, terminating after the monitoring station is fully operational in FY 07

5 4 4 Models

Models of changes in community structure of the intertidal-subtidal areas in response to human activities and natural forcing are expected to be primarily verbal from FY 03 to FY 05 Statistical modeling, particularly power analysis to guide sampling, is expected to be operable as soon as FY 03, because of experience gained in the EVOS coastal habitat program and related damage assessment and restoration work Statistical modeling will continue through the evaluation of the initial monitoring station in FY 06 The end point of a numerical model to combine physical forcing and human activities for describing community structure is a very ambitious undertaking for a core activity within a 5-year time frame and may not be feasible at all without substantial partner support.

5.4.5 Candidate Core Monitoring Activities

Candidates for core monitoring activities will be selected based on substantial partnering opportunities, chances for human activities and impacts, and logistics Likely candidates are Kachemak Bay in Lower Cook Inlet and Green Island in PWS Kachemak Bay is close to the city of Homer and is becoming a developed recreational destination In addition, the bay has the presence of coastal habitat assessment programs already in place within the Kachemak Bay National Estuarine Research Reserve (KBNERR), as well as nearby moorings taking oceanographic measurements The USFS has a long-term ecological monitoring site at Green Island, which is still seeing effects from the 1989 oil spill A new weather station is being installed nearby at Applegate Rocks, and additional oceanographic moorings in nearby Montague Strait are likely

5 4 6 Candidate Core Variables

Community structure in the intertidal and subtidal areas is determined by substrate type and amount, as well as by physical oceanographic features, such as wave action Species composition and distribution are fundamental to determining community structure, as is the recruitment rate of key species such as barnacles, mussels, and clams, depending on substrate

5.5 Alaska Coastal Current

5 5.1 Key Question

What are the relative roles of natural forces, such as the variability in the strength, structure, and dynamics of the ACC, and human activities, such as fishing and pollution, in causing local and distant changes in production of phytoplankton, zooplankton, birds, fish, and mammals?

5 5 2 Schedule

Development of ACC monitoring will require a period of synthesis and research that involves collaboration between physical and biological scientists to decide on how to best detect changes in annual and seasonal production and transfer of energy to higher trophic levels The determination of what physical-chemical processes are most important to measure for primary and secondary production will require a synthesis that combines existing physical and biological information and hypotheses Specific seasonal questions such as what controls the timing, duration, and magnitude of the spring bloom on the inner continental shelf need to be carefully cast as testable hypotheses before committing to long-term monitoring Having the SEA, APEX, GLOBEC Northeast Pacific National Estuary Program (NEP), FOCI, OCC, and NPAFC programs precede and parallel the GEM program is extremely fortuitous for development of this component The experience and lessons from these programs will be extremely beneficial in helping GEM build its core monitoring components For these reasons, development of ACC monitoring activity will begin with a core synthesis effort that is closely coordinated with the ongoing research and monitoring efforts mentioned above

Understanding how best to measure biological productivity and trophic transfer in the ACC will take longer to develop than the approach to physical measurements, which could be developed in a relatively short period of time The long-term observation program being carried out in PWS and across the shelf in the northern GOA under GLOBEC started in 1997 and will extend through 2004 Intense process studies are scheduled for 2001 and 2003 It will take some time to distill the large amount of information available from such studies and other programs to the point of recommending a full suite of core biological measurements for core GEM program monitoring in the ACC

Table 5 3 presents the proposed schedule and strategy for implementation

5 5 3 Prospective Partner Activities

NOAA's interest in the ACC continues to be high, as demonstrated through its participation in the GLOBEC and OCC programs and some continuing work in the FOCI program in Shelikof Strait It is almost certain that the GAK1 station and line, maintained and monitored by the University of Alaska and in place now for decades, will play a central role in future monitoring of the physical structure of the ACC based on temperature and salinity measures Recently added biological measures, including chlorophyll a, will likely be maintained and supplemented Other opportunities for partnerships include GLOBEC's more recently established stations from PWS across the continental shelf and one of the lines used in the FOCI program in the Shelikof Strait The USGS, which has an established set of seabird monitoring colonies spaced at about 500-km intervals around the GOA and into the Bering Sea, is another strong candidate for a partner Close coordination with methods of the colonial seabird program of the USFWS Alaska Maritime Refuge is envisioned to make seabird data consistent around the coast of Alaska For measuring forage species variability, population abundance data from the ADF&G on Pacific herring in PWS and also for populations at Kodiak Island and in Kamishak Bay, although not complete, may be useful Starting in FY 04 and extending through FY 06, partners will be encouraged to assist in funding research to further site selection for monitoring the ACC

Table 5 3 Proposed Implementation Strategy for Alaska Coastal Current Habitat

	Monitoring Activity			
Fiscal Year	**Core**	**Partners**	**Model**	**Data Management**
2003	Synthesis Research	Monitor	Statistical(c) Numerical (p)	Coordination (c)
2004	Synthesis Research	Monitor Research	Statistical(c) Numerical (p)	Coordination (c) Archiving(c)
2005	Research	Monitor Research	Statistical(c) Numerical prototype (p)	Coordination (c) Archiving (c) Distribution (p)
2006	Research Monitor	Monitor Research	Statistical(c) Numerical (p)	Coordination (c) Archiving (c) Distribution (p)
2007	Monitor Research	Monitor	Numerical (p)	Archiving (c) Distribution (p)

Notes

c = core (GEM program supported) activity

p = partnership (jointly supported) activity

Prospective partners UAF (IMS School of Fisheries and Ocean Sciences [SFOS]) U S Department of Interior (DOI) (National Park Service [NPS] USFWS USGS) North Pacific Research Board (NPRB) NOAA (NMFS/National Ocean Service [NOS]) EPA-ADEC EMAP

Candidate core monitoring activities GAK1 Hinchinbrook Entrance, Montague Strait

Candidate core variables temperature, salinity fluorescence plankton forage species

Plankton measurements (settled volume) are now being taken by potential partners at six hatcheries in PWS On the basis of past correlations of plankton-settled volume with annual pink salmon returns and decadal-scale herring abundance, these data could provide information about productivity of the ACC system of relevance to multiple species under certain conditions Extension of the "plankton watch" to hatcheries in other areas and local communities throughout the northern GOA may be a worthwhile and potentially economical way to maintain long-term data sets and archives of plankton Other opportunities to collect samples and analyze plankton communities may include cruises with net and hydroacoustic sampling, as well as satellite images Also of possible merit are the use of ships that offer opportunities, for example, the continuous plankton recorder is recommended to be deployed on oil tankers traveling from Valdez to Long Beach under EVOS sponsorship in FY 02 Certainly any satellite images of the sea surface that measure chlorophyll a concentrations provide very useful synoptic pictures, even taking into account the limitations that cloud cover and lack of subsurface data present Decisions will be made with the guiding philosophy of collecting data of relatively low frequency in space and time so that decadal scale change can be resolved

Perhaps the largest challenge for the ACC habitat will be developing monitoring activities to measure variability in forage fish populations and associated predator populations Some options for exploration of partnerships for assessing forage fish abundance and associated phenomena include the following

- Larval surveys building on the databases and archived specimens from the FOCI program
- Use of forage fish occurrence in the stomachs of large fish collected in the sport fishery–or in some of the large fishery assessment programs conducted by NOAA and ADF&G–as an index of relative abundance (The Trustee Council sponsored a successful study of these occurrences of forage fish in the sport fishery for halibut out of Homer)
- Small mesh trawl surveys conducted by ADF&G around Kodiak Island and Lower Cook Inlet to assess shrimp abundance (A large database from this program extends for some locations back to the 1960s for a large variety of species on the inner shelf)
- Aerial surveys with the use of conventional photography or other sorts of imaging (such as LIDAR) of shallow water aggregations of juveniles or adults
- Hydroacoustic sensors mounted on various ships of opportunity and fixed moorings
- Analysis of food items brought back to the nests of colonial seabirds (such as puffins) as an indication of the relative abundance of various forage fish species in particular areas
- Other net sampling programs that may be under way or contemplated

5 5 4 Models

Several hydrographic and circulation models have been or are being developed for the ACC (see also Chapter 5, Volume II, and Appendix B) A circulation model workshop is planned in FY 02 to consider approaches most likely to be useful to the GEM program Models of the relationship of marine planktonic production to water column structure have been developed in the EVOS SEA program (Eslinger et al 2001) and are expected to eventually be further developed under the GEM program

The GLOBEC nutrient-phytoplankton-zooplankton (NPZ) 1-D and 3-D models are a suite of coupled biological-physical models concerned with the coastal region of the GOA They are addressing effects of concern to the GEM program in the ACC and offshore cross-shelf transport, upstream effects, local production, and conditions conducive to suitable juvenile salmon rearing habitat

Models of particular interest from the FOCI program are the 1-D and 3-D versions of the Shelikof NPZ models, and the GOA Walleye Pollock Stochastic Switch Model (SSM) (see Chapter 5, Volume II, and Appendix B) The Shelikof NPZ models are a set of coupled (biological and physical) models designed to examine hypotheses about pollock recruitment in the Shelikof Strait region The Pollock SSM is a numerical simulation of the process of pollock recruitment Of particular interest to the GEM program is the identification by the SSM of three specific agents of mortality wind mixing, ocean eddies, and random effects Ecopath models developed by Okey, Pauly, and others at the University of British Columbia are also of interest, especially for PWS, but also for the GOA continental shelf and slope (excluding fjord, estuarine, and intertidal areas) (see Appendix B)

5 5 5 Candidate Core Monitoring Activities

It appears that the physical oceanographers have developed a level of understanding about inner-shelf dynamics that will allow the GEM program to identify a core set of measurements, locations, and frequencies that address questions relevant to the GEM program A core monitoring activity based on the partnership at the GAK1 station is likely Others may be added in FY 04 to FY 07 as identified by synthesis and the results of other programs (GLOBEC and FOCI stations and moorings) and as funding allows Full core monitoring in the ACC may not be fully operational until FY 07

5.5 6 Candidate Core Variables

The key variables in measuring the productivity of the ACC are temperature, insolation, salinity, fluorescence, and abundance of key forage species, including fish and zooplankton

5.6 Offshore: Outer Continental Shelf and Oceanic Waters

5.6.1 Key Question

What are the relative roles of natural forces, such as changes in the strength of the Alaska Current and Alaskan Stream, mixed layer depth of the gyre, wind stress, and downwelling, and human activities, such as pollution, in determining production of carbon and its shoreward transport?

5 6 2 Schedule

As with the ACC portion of the program, results of GLOBEC research need to be carefully considered before implementation of long-term monitoring in this broad habitat type This deliberate approach is reflected in the emphasis on synthesis for this habitat type in the early years of the proposed schedule and strategy for implementation (Table 5 4)

Table 5 4 Proposed Implementation Strategy for Offshore Habitat

Fiscal Year	Monitoring Activity		Model	Data Management
	Core	Partners		
2003	Synthesis	Monitor Research	Statistical(c)	Coordination (p)
2004	Synthesis	Monitor Research	Statistical(c)	Coordination (p) Archiving(p)
2005	Synthesis	Monitor Research	Statistical(c) Numerical prototype (p)	Coordination (p) Archiving (p) Distribution (p)
2006	Synthesis	Monitor?	Statistical(c) Numerical (p)	Coordination (p) Archiving (p) Distribution (p)
2007	Synthesis	Monitor?	 Numerical (p)	Archiving (p) Distribution (p)

Notes

c = core (GEM program supported) activity

p = partnership (jointly supported) activity

Prospective partners NPRB NOAA (NMFS/NOS) Canadian Department of Fisheries and Oceans (CDFO) Japan Fishery Agency

Candidate core monitoring activities GLOBEC stations Valdez-Long Beach Line

Candidate core variables nutrients, detritus and plankton temperature and salinity

5 6 3 Prospective Partner Activities

Support of partners in existing monitoring projects may be necessary to obtain sufficient information for design of a monitoring program Because of the expense of initiating most offshore sampling programs, careful selection of partners and the use of long-term, low-frequency data gathering will be key strategies for understanding decadal-scale changes in this environment Current efforts to apply the continuous plankton recorder (CPR) technology on ships of opportunity in the GOA offer partnership opportunities Extension of existing ships of opportunity programs to include measurement of variables of interest to the GEM program is also a possibility

5.6.4 Models

The GLOBEC NPZ 1-D and 3-D models are discussed above in Section 5 5 4 A broader model addressing NPZ for the entire North Pacific is the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO), in which fluxes of nitrogen, silicon, and carbon will be tracked (see Appendix B)

5.6.5 Candidate Core Monitoring Activities

A reasonable oceanographic program in the ACC can probably be extended across the shelf break with the use of existing GLOBEC, FOCI, and OCC sampling stations, moorings, and transects The use of the Valdez-Long Beach line with oil tanker-mounted fluorescence and zooplankton sampling gear appears to be an attractive strategy for long-term, low frequency sampling over large spatial scales

5 6 6 Candidate Core Variables

Particularly crucial aspects of the offshore environment are physical processes and attendant biological responses at the shelf break and front (for example, extent of deep-water intrusion onto the shelf in the late summer and fall), the mixed layer depth in the Alaska Gyre in the spring-summer, and Ekman transport of offshore production onshore Measurements of basic variables are essential to understanding the role of these offshore aspects in affecting productivity of other habitats These variables include temperature, salinity, nutrients, detritus, and plankton

5.7 Research Agenda in Support of Monitoring

The "research agenda" is a list of past and potential Trustee Council activities that future committees and work groups within each habitat type (Chapter 6, Volume I) can build upon Table 5 5 summarizes the planned and potential activities of FY 02 that are of interest in establishing the research agenda for GEM implementation Tables 5 6 and 5 7 summarize activities funded by the Council in FY 01 and FY 00 that are of potential interest to GEM implementation

Editorial note We definitely want to include Tables for FY 00 and FY 01 for studies that were done for "GEM transition and synthesis"

Table 5 5 Fiscal Year 2002 Funded and Deferred Activities for the GEM Program
Listed with project number if assigned and titles of activities

Habitat Type	Synthesis and Workshops	Research	Modeling
Watersheds	02612–Kenai River Marine-Terrestrial Links	02649–Reconstructing sockeye 02667–Commission for the Conservation of Antarctic Marine Living Resources Ecosystem Monitoring Program (CEMP) 02668–Water Quality Database	
Intertidal-Subtidal	02395–Workshop on intertidal monitoring	02556–Mapping intertidal 02538–Herring stock identification 02210–Youth Area Watch	
ACC	Workshop on modeling circulation	02340–GAK1 02552 Exchange between PWS and GOA[a] 02614–Physical data from tankers 02671–Ships opportunity in Lower Cook Inlet 02584–Airborne remote sensing 02561–Community based forage fish sampling 02404–Archival tag testing 02538–Herring stock identification 02210–Youth Area Watch	02603–Ocean Circulation Modeling[a]
Offshore	Workshop on modeling circulation	02614–Physical data from tankers 02624–Ships opportunity CPR (Continuous Plankton Recorder)	02603–Ocean Circulation Modeling[a]

[a]Funding decision deferred to 12/01

Table 5 6 Fiscal Year 2001 Funded Activities for the GEM Program
Listed with project number if assigned and titles of activities

Habitat Type	Synthesis and Workshops	Research	Modeling
Watershed			01391–Cook Inlet Information System 0145–Data System for GEM
Intertidal-Subtidal		01385–Kachemak Bay Monitoring 01210–Youth Area Watch	01391–Cook Inlet Information System 01455–Data System for GEM
ACC		01340–GAK1 01552–Exchange between PWS and GOA 01404–Archival tag testing 01210–Youth Area Watch	01389–3-D Ocean State Simulation Modeling 01391–Cook Inlet Information System 01455–Data System for GEM
Offshore			01389–3-D Ocean State Simulation Modeling 01391–Cook Inlet Information System 01455–Data System for GEM

Table 5 7 Fiscal Year 2000 Funded Activities for the GEM Program
Listed with project number if assigned and titles of activities

Habitat Type	Synthesis and Workshops	Research	Modeling
Watersheds		00567 Contaminants monitoring	01391 Cook Inlet Information System 00455 Data System for GEM
Intertidal-Subtidal	00374 Herring recommendations	00210–Youth Area Watch 00501 Seabird monitoring protocols 00509 Harbor seal experimental design 00510 Intertidal monitoring recommendations 00567 Contaminants monitoring	01391 Cook Inlet Information System 00455 Data System for GEM
ACC	00374 Herring recommendations	01340–GAK1 00552 Exchange between PWS and GOA 00210–Youth Area Watch 00493 Sampling strategies for GOA trawl survey 00501 Seabird monitoring protocols 00567 Contaminants monitoring	01391 Cook Inlet Information System 00455 Data System for GEM
Offshore		00567 Contaminants monitoring	01391 Cook Inlet Information System 00455 Data System for GEM

5.8 References

Eslinger, D , Cooney, R T , McRoy, C P , Ward, A , Kline, T , Simpson, E P , Wang, J , and Allen, J R 2001 Plankton dynamics observed and modeled responses to physical factors in Prince William Sound, Alaska Fisheries Oceanography in press

Finney, B P , Gregory-Eaves, I , Sweetman, J , Douglas, M S V , and Smol, J P 2000 Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years Science 290 795-799

6. PROGRAM MANAGEMENT: PUBLIC ADVICE, SCIENTIFIC GUIDANCE, AND DATA POLICIES

In This Chapter

➢ Discussion of a reconstituted Program Advisory Committee to provide public advice

➢ A draft process for inviting, reviewing, approving and adopting projects

➢ Preliminary descriptions of the processes for getting advice from experts and the public

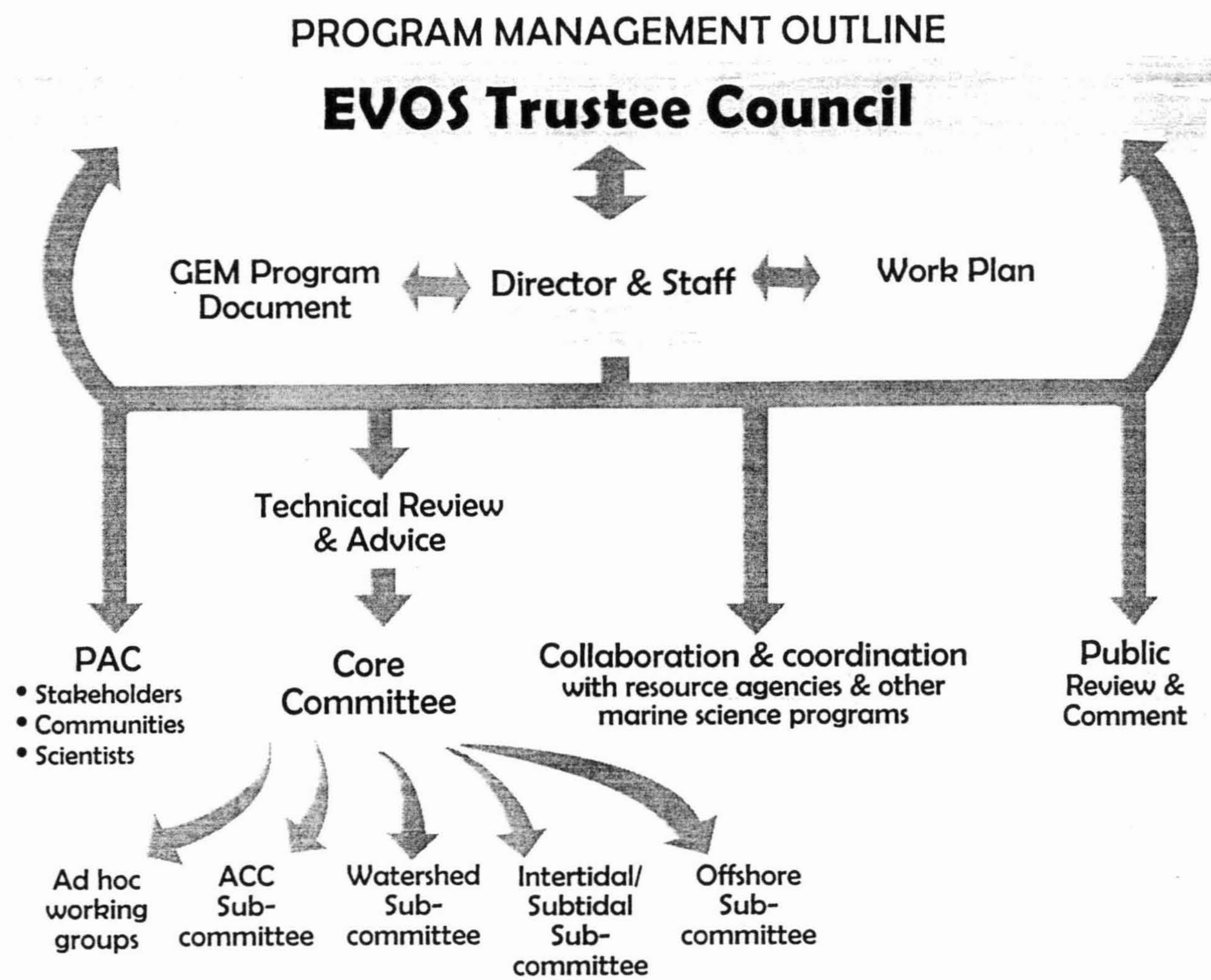
➢ Preliminary data management and information transfer policies

6.1 Public Advice

The importance of public participation in the Trustee Council process, as well as establishment of a public advisory group to advise the trustees, was specifically recognized in the *Exxon Valdez* settlement and is an integral part of the agreement between the state and federal governments Figure 6 1 illustrates the role of public participation in the GEM program

The existing Public Advisory Group (PAG) has 17 members representing 12 interest groups and the public at large, as well as two ex-officio members from the Alaska Legislature The charter for this group must be renewed in January 2003 At that time, it would be appropriate to change the makeup of the PAG to include the participation of additional interests Preliminary input from the current PAG and from some of the community facilitators representing tribal interests calls for a reconstituted Program Advisory Committee (PAC), representing a broad range of stakeholder interests and communities and including a number of scientists with broad vision and stature

One possible scenario is a group of 20, with five scientists and 15 community and stakeholder representatives A decision would need to be made on whether specific seats would be formally designated This group would meet at least twice a year and provide broad program and policy guidance to the Trustee Council and staff on the overall development and progress of the GEM program The group would take an active role in setting priorities and ensuring that the overall program is responsive to public interests and needs



6.2 Program Management and Administration

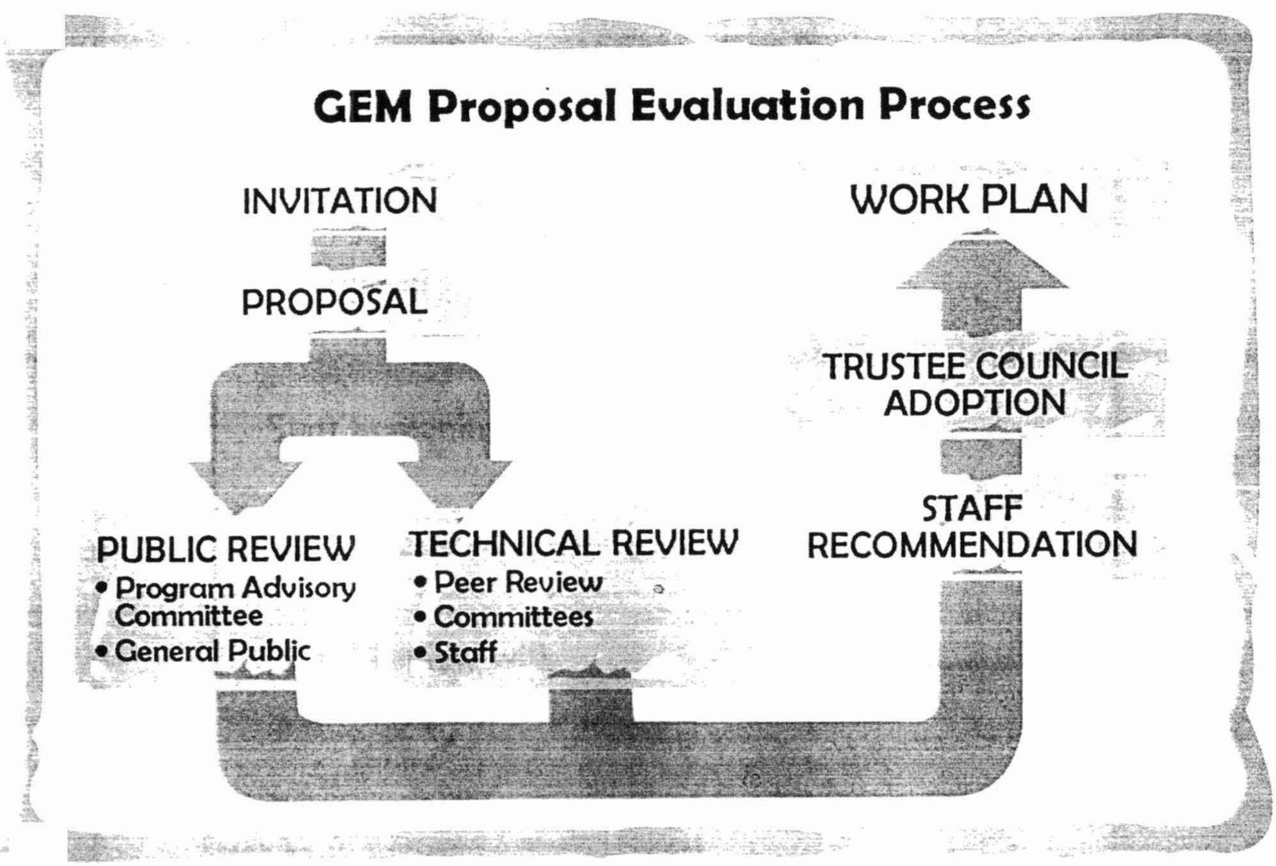
The administration and management of the GEM program must be cost-efficient, have a high degree of scientific credibility, and provide for public access and accountability.

The GEM program will be administered by a core professional staff that is not directly affiliated with any particular agency, institution, or program, as is currently the case with the management of the *Exxon Valdez* Oil Spill Restoration Office. An executive director will oversee the financial, program management and administration, scientific, and public involvement aspects of the program. The executive director and staff, while housed for administrative purposes in a single government agency, will work under a cooperative agreement for all six trustees. The Trustee Council and the staff will receive advice on science and policy matters, including review of monitoring and research activities, from experts and from the public, including the PAC.

6.2.1 Proposal Evaluation Process

The basic work plan process will likely have the following elements or steps, which are also shown in Figure 6.2. As implementation of GEM begins, however, these steps may be modified as efficiencies and improvements are found.

- A "State of the Gulf" workshop will be held periodically, at which the current status of the health of the GOA ecosystem will be assessed. Project investigators, peer reviewers, resource managers, stakeholders, and the public will be invited to this meeting, at which research and monitoring results will be presented and discussed. In some years, this workshop will be replaced by or augmented with a process of consultations and workshops with various committees and work groups of science advisors to evaluate and affirm or revise priorities.
- An *Invitation to Submit Proposals*, which will specify the types of proposals that are priorities for consideration to implement the mission and goals of the GEM program, will be issued periodically. Research proposals are envisioned to be of finite duration and have short-term goals (for example, 2 to 5 years). Monitoring projects will be evaluated and renewed on longer time scales (such as once every 5 years). The *Invitation(s)* will be the vehicle for notifying the scientific community and others that proposals will be considered during a certain period of time. Scientific and public advisors will help provide precision to the specific questions posed in the monitoring plan.
- Proposals received in response to the *Invitation* will be circulated for peer review (see below). Peer review comments and recommendations will be



summarized by staff and provide a basis for preliminary recommendation by the executive director Proposals will be reviewed for their ability to contribute to the information-gathering needs of the central hypothesis and questions, and also for how they contribute to meeting the programmatic goals and policies of the Trustee Council (see Chapter 1, Volume I), such as promoting community involvement, developing resource management applications, and leveraging funds from other sources Past performance of principal investigators will be assessed Staff will also review all budgets In addition, the comments from the PAC and the general public will be solicited

- The executive director will develop a recommendation on each proposal based on the peer review, staff review, and public and scientific advice
- A reasonable period of time for public comment will be built into the proposal review process, including review by the PAC
- The Trustee Council, after receiving advice from its public and scientific advisors and staff, will vote on which proposals to fund

6 2 2 The Work Plan

A Work Plan will document the current activities that implement the program As projects for monitoring and research are approved by the Trustee Council, they will become part of the Work Plan The Trustee Council may be asked to adopt a new Work Plan each year or they may be asked to adopt new groups of projects into the Work Plan on a periodic basis

6 2 3 Reports and Publications

Annual and final reports will be required for all monitoring and research projects and will be reviewed to evaluate whether the investigators are making satisfactory progress toward project objectives Selected annual reports may be sent for peer review All final reports will be subject to independent peer review, and comments from the independent peer reviewers must be addressed in the final versions of final reports All annual and final reports will be archived at the Alaska Resources Library and Information Service (ARLIS)

Publications in the peer-reviewed literature will be expected of program participants

6.2.4 Peer Review

Each project, as well as some annual and all final reports, will be peer-reviewed by appropriate experts identified by staff The peer review may be either paid or volunteer, whichever is most expeditious and appropriate These reviews will be conducted by qualified scientists or other experts who are not also conducting projects funded by the Trustee Council The external technical review process will provide a rigorous critique of the scientific merits of all monitoring and research proposals and selected reports Review functions may be carried out in writing, by telephone and occasionally on site or in person

Special review panels may be convened from time to time to evaluate and make recommendations about aspects of the GEM program At other times, special panels may meet with project investigators and others to fully explore particular topics, problems, or projects Periodic review by an outside entity, such as the National Research Council, may be appropriate

6 3 Guidance on GEM Program Development and Implementation

In addition to peer review and public review and advice, a committee and work group approach will be used guide GEM program development and implementation This approach may include a core committee, subcommittees, and work groups

6 3 1 Core Committee

The core committee would have four purposes

1 Provide leadership in identifying and developing testable hypotheses relevant to the central questions of the GEM plan, consistent with the mission, goals and policies of the Trustee Council

2 Support habitat subcommittees and ad hoc work groups (see below) in identifying and helping implement core variables and core monitoring stations

3 Help identify and recommend syntheses, models, process studies, and other research activities for the *Invitation to Submit Proposals*

4 Assist staff in identifying peer reviewers and possibly participate in the peer review

The core committee would be composed of emeritus and senior scientists and others selected primarily for expertise and leadership in a field of study The scientists serving on the PAC would also serve on the core committee, as would the chairs of each of the habitat subcommittees (see below) In general, the core committee members would not be principal investigators for GEM projects Institutional and professional affiliations would also be of interest in selecting members, because connections to other marine science programs entities will be valuable for ensuring collaboration and coordination on GEM program implementation

6 3 2 Subcommittees

Subcommittees would be organized around the four broad habitat types watershed, intertidal and subtidal, ACC Current, and offshore (Outer continental shelf and Alaska gyre) The chairs of each subcommittee would serve on the core committee

The purposes of the subcommittees would be as follows

- Recommend to the core committee testable hypotheses, items for invitation and peer reviewers in their broad habitat type
- Identify and help guide implementation of core monitoring stations and variables that are relevant to the key questions and testable hypotheses
- Possibly conduct peer review on proposals and reports in their broad habitat type

The subcommittee would be composed of scientists, resource managers, and other experts selected primarily for disciplinary expertise and familiarity with the broad habitat type (watersheds, intertidal and subtidal, ACC, and offshore) Institutional and professional affiliations would also be of interest in selecting members to promote collaboration and cooperation

6 3.3 Work Groups

Ad hoc work groups may be periodically formed to develop specific products as requested by the core committee and subcommittees _ Work groups could also be charged with solving a particular problem in a finite amount of time

6 4 Data Management and Information Transfer Policies

Data management and information transfer policies are an integral part of GEM program management. Clear and effective approaches to gathering information and making it widely available in understandable formats are essential to the successful operation of the GEM program Because the program is a regional program with goals of cooperation, coordination, and integration with existing marine science programs, data policies are to be compatible with, and similar to, existing norms for state, federal, and nongovernmental marine science programs Whenever possible, existing norms will be adapted or adopted for use by the Trustee Council Standards adopted by the Federal Geospatial Data Committee (FGDC), GLOBEC, and the EPA's Environmental Monitoring and Assessment Program will be used as starting points for developing GEM data policies (Options and procedures for data management and information transfer are considered in more detail in Chapter 6, Volume II)

From the fundamental premises stated here, data policies will evolve to support GEM projects as they are implemented (see Chapter 5, Volume I) In the GEM program working definitions, "data" are basic observations on the state of the system, and "information" is data processed to be both understandable and of immediate use to specialists and the public

The GEM data policies incorporate 10 broad elements

1 A commitment to the maintenance and long-term availability of data

2. Full and open sharing of data at low cost, after verification and validation
3. Timely availability of data, depending on the type of data Data will be available almost immediately to 24 months
4. Availability of data on the GEM public Web site
5. Identification of the origin of all data with a citation
6. Adherence to data collection and storage standards
7. Provision of citations to the GEM Bibliography
8. Encouragement of active participation in the GEM Web site for all participants
9. Long-term archiving of all data in a designated storage facility
10. Acceptance of and adherence to the data policies as a condition for participation in the GEM program and receipt of funding

Gulf of Alaska **E**cosystem **M**onitoring and Research Program (GEM)

Volume II
The Historical Legacy: Building Blocks for the Future

Volumes I and II together should be referred to as the GEM Program Document.

Review Draft – July 30, 2001

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OVERVIEW OF THE GEM DOCUMENT

The Gulf Ecosystem Monitoring (GEM) Program Document has been prepared in two volumes to more easily describe the basic monitoring and research program (Volume I) while providing access to the factual basis for the program (Volume II) Volume I explains the basic motivations for the program, information needs, and the strategies for meeting these information needs (see Table O 1 below) Volume II presents the factual basis for the program, including the detailed descriptions of two important components of the program (1) modeling and (2) data management and information transfer Table O 1 identifies the question addressed by each chapter and the products provided The Overview Figure, following the table, illustrates the structure of the GEM Program Document

Table O 1 Contents of the GEM Program Document

Chapter	Title & Question Addressed	Products
Volume I—Strategic Plan for Monitoring and Research		
1	Vision *Why do this and what do we hope to achieve?*	Mission and goals Program context
2	Human Uses and Activities *What are the human activities in the region and their potential impacts?*	Issues of concern to the Trustee Council and public
3	GEM Information Needs *What information do we need?*	Specific questions and information needs
4	Program Components and Strategies *How can we get the information we need?*	Key components and implementation strategies
5	Monitoring Plan & Research Agenda *What are we going to do to get the information when will we do it and with whom?*	Starting point for implementation process
6	Program Management *What are the processes and policies for monitoring and research?*	The Gulf Ecosystem Monitoring and Research Program
Volume II—The Historical Legacy Building Blocks for the Future		
1	Building on Lessons of the Past *What do other regional marine science programs have to teach us?*	Past experience Hypotheses and strategies
2	Lingering Effects of the Oil Spill *What does experience from the oil spill teach us?*	Past experience
3	Scientific Background *What is published that can help us?*	Current knowledge of the Gulf of Alaska General research questions

Table O 1 Contents of the GEM Program Document

Chapter	Title & Question Addressed	Products
4	Conceptual Foundation *How do we think the ecosystem works?*	Central hypothesis and questions
5	Modeling *What is the role of modeling in GEM implementation?*	Modeling definitions and options for program implementation
6	Data Management and Information Transfer *What are the roles of data management and information transfer in GEM implementation?*	Data management and information transfer options for program implementation
A	Appendix A Fish and Invertebrate Species from 1996 Trawl Survey of the Gulf of Alaska	
B	Appendix B North Pacific Models of the Alaska Fisheries Science Center and Selected Other Organizations	
C	Appendix C Gulf Ecosystem Monitoring and Research (GEM) Database	
D	Appendix D Glossary of Existing Agency Programs and Projects	
E	Appendix E Acronyms and Web Links	

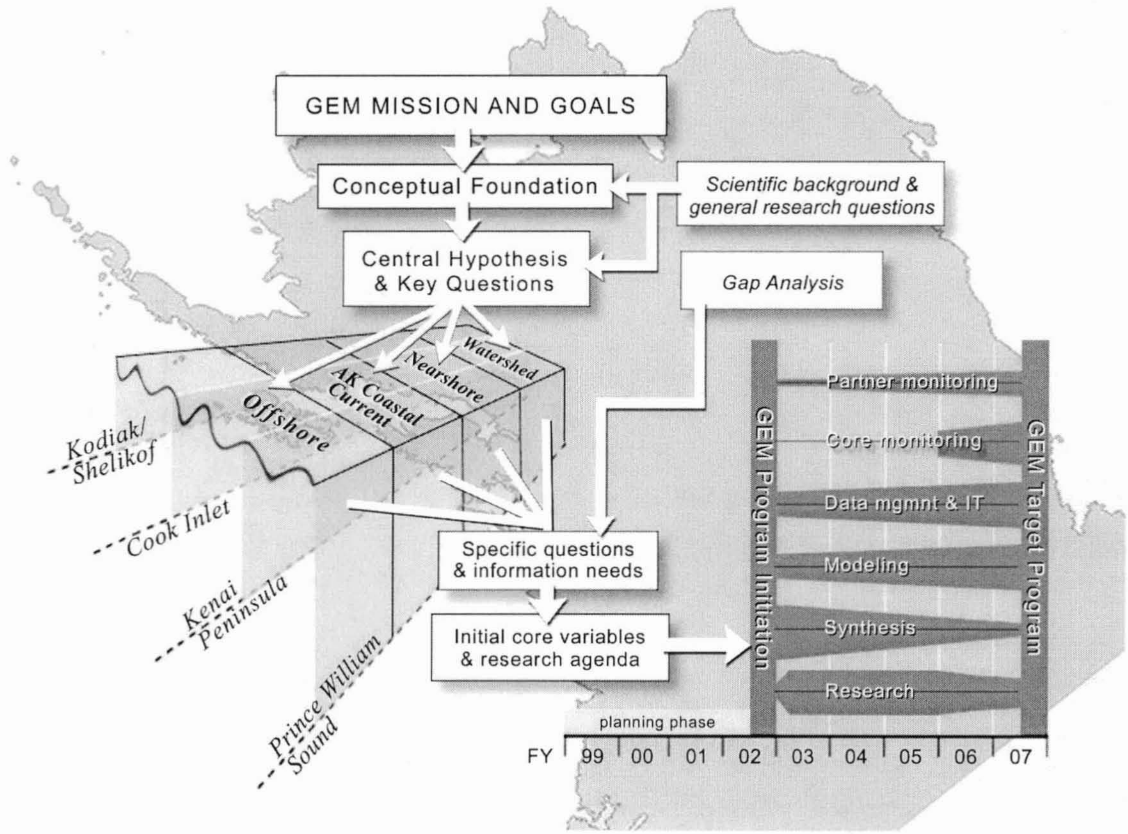

Figure O.1. An overview of the structure of the GEM program document showing the relation of key concepts to the habitat types and the schedule of implementation

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VOLUME II

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Appendices

1. BUILDING ON THE LESSONS OF THE PAST

In This Chapter

- Background on other relevant programs
- Studies supported by Trustee Council funding

The GEM program is not the first attempt to look at large areas of Alaska's marine ecosystems from a broader perspective The *Exxon Valdez* Oil Spill Restoration Program, as well as a number of other programs, provides valuable guidance

As explained in Volume I, long-term environmental monitoring and ecosystem studies will be designed to increase our understanding of the biological processes of the spill area ecosystem in the context of natural forces and human activities

1.1 Alaska Regional Marine Research Plan (1993)

The *Alaska Regional Marine Research Plan* (ARMRP) (1993) is a marine science planning document with a broad geographic scope that was prepared under the U S Regional Marine Research Act of 1991 For all marine areas of Alaska, including the GOA, the plan provided five elements of interest to the GEM program

1 An overview of the status of marine resources,

2 An inventory and description of current and anticipated marine research,

3 A statement of short- and long-term marine research needs and priorities,

4 An assessment of how the research and monitoring activities under the program take advantage of existing projects, and

5 Descriptions, time tables, and budgets for research and monitoring to be conducted under the program

Goals of other major programs are relevant to the GEM effort

ARMRP goals express the scientific needs of the Alaska region as of 1992 and are still relevant to the GEM effort because they will accomplish the following

- Distinguish between natural and human-induced changes in marine ecosystems of the Alaska region,

- Distinguish between natural and human-induced changes in water quality of the Alaska region,
- Stimulate the development of a data gathering and sharing system that will serve scientists in the region from government, academia, and the private sector in dealing with water quality and ecosystem health issues, and
- Provide a forum for enhancing and maintaining broad discussion among the marine scientific community on the most direct and effective way to understand and address issues related to maintaining the health of the water quality and ecosystem health in the region

1.2 Bering Sea Ecosystem Research Plan (1998)

The Bering Sea has received a good deal of attention because of concern about long-term declines in populations of high-profile species such as king and tanner crab, Steller sea lions, spectacled eider, Steller's eider, common murres, thick-billed murres, and red-legged and black-legged kittiwakes (DOI et al 1998b) The GEM mission statement is consistent with the vision of the federal-state regulatory agencies for the *Bering Sea Ecosystem Research Plan* (DOI et al 1998a), which follows "We envision a productive, ecologically diverse Bering Sea ecosystem that will provide long-term, sustained benefits to local communities and the nation" The basic concepts of the GEM program are also consistent with the overarching hypotheses of the Bering Sea plan

- Natural variability in the physical environment causes shifts in trophic (food web) structure and changes in the overall productivity of the Bering Sea
- Human impact leads to environmental degradation, including increased levels of contaminants, loss of habitats, and increased mortality on certain species in the ecosystem that may trigger changes in species composition and abundance

In addition, four of the research themes of the Bering Sea plan–variability and mechanisms in the physical environment, individual species responses, food web dynamics, and contaminants and other introductions—are closely aligned with the conceptual foundation of the GEM program (see Chapter 4, Volume II) Current research programs for the Bering Sea (DOI et al 1997) often overlap with the programs identified in the database of ongoing and historical GOA projects (discussed in Chapter 4, Section 4, Volume I)

1.3 GLOBEC (1991 to Present)

The Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) established the Global Ocean Ecosystem Dynamics (GLOBEC) program in late 1991 GLOBEC is the core project of the International Geosphere-Biosphere Programme responsible for understanding how global change will affect abundance, dιversιty, and productιvιty of marιne populatιons The program focuses on the regulatory control of zooplankton dynamιcs on the bιomass of many fιsh and shellfιsh

The GLOBEC Scιence Plan (U S GLOBEC 1997) descrιbes an approach that uses a combιnatιon of fιeld observatιons and modelιng to concentrate on the mιddle and upper trophιc levels of the ecosystem The GLOBEC goal ιs as follows "To advance our understandιng of the structure and functιonιng of the global ocean ecosystem, ιts major subsystems, and ιts response to physιcal forcιng so that a capabιlιty can be developed to forecast the responses of the marιne ecosystem to global change"

The overarchιng concept ιs that marιne and terrestrιal ecosystems have close connectιons among energy flow, chemιcal cyclιng, and food web structure GEM monιtorιng actιvιtιes wιll be consιstent wιth these addιtιonal GLOBEC concepts

- Changes ιn abundances of bιrds, fιsh, shellfιsh, and mammals (hιgher trophιc levels) usually reflect changes ιn physιcal and chemιcal processes,
- The actual effects on abundances of hιgher trophιc level anιmals may depend on how these physιcal and chemιcal changes act on food productιon through effects on lower trophιc level specιes,
- Changes ιn the domιnant specιes at each trophιc level are consιstent wιth changes ιn the physιcal and chemιcal systems, and
- Understandιng how the domιnant specιes at each trophιc level change through tιme requιres knowledge of the energy and nutrιent budgets of the ecosystem

1 4 Scιentιfιc Legacy of the *Exxon Valdez* Oιl Spιll (1989 to 2002)

Ecologιcal knowledge gaιned ιn the years followιng the 1989 EVOS forms a substantιal portιon of the foundatιon of the GEM program The recovery status of each affected resource ιs based to the extent possιble on knowledge of the resource's role ιn the ecosystem The Trustee Councιl's scιentιfιc legacy creates the need to understand the causes of populatιon trends ιn ιndιvιdual specιes of plants and anιmals through tιme and the need to dιstιnquιsh human ιmpacts from those of clιmate and ιnteractιons wιth related specιes

The studιes supported by the Trustee Councιl sιnce 1989 ιnclude more than 1,60 damage assessment studιes costιng more than $100 mιllιon, as well as hundreds of restoratιon studιes costιng approxιmately $170 mιllιon These studιes have resulted ιn more than 400 peer-revιewed scιentιfιc publιcatιons, ιncludιng numerous dιssertatιons and theses In addιtιon, hundreds of peer-revιewed project reports are avaιlable through the Alaska Resources Lιbrary and Informatιon Servιces (ARLIS) and state and unιversιty lιbrary systems Many fιnal reports are avaιlable ιn electronιc format through the Trustee Councιl offιces or ARLIS A current electronic bibliography of scientific publications sponsored by the Trustee Council is available on its Web site (www oilspill state ak us) or on request to the Trustee Council (EVROTCB 2001) A list of Trustee Council projects, as well as a complete list of final and annual project reports, also is available on the Web site or on request (EVROFAB 2001)

In addition to much specific information on the effects of oil on the plant and animal life in the spill area, the studies also provide a wealth of ecological information Most prominent among the Trustee Council's studies are three ecosystem-scale projects, known by their acronyms SEA, NVP, and APEX

The Sound Ecosystem Assessment (SEA) is the largest of the three studies Funded at $22 million for a seven-year period, SEA brought together a team of scientists from many different disciplines to understand the biological and physical factors responsible for producing herring and salmon in PWS When completed, the data collected during SEA are expected to form the basis of numerical models capable of simulating the oceanographic processes that influence the survival and productivity of juvenile pink salmon and herring in PWS SEA has already provided new insights into the critical factors that influence fisheries production, including ocean currents, nutrient levels, mixing of water masses, salinity, and temperatures These observations have made it possible to model how physical factors influence production of plant and animal plankton, prey, and predators in the food web

The Nearshore Vertebrate Predator (NVP) project is a six-year, $6 5 million study of factors limiting recovery of two fish-eating species, river otters and pigeon guillemots, and two invertebrate-eating species that inhabit nearshore areas, harlequin ducks and sea otters The project looked at oil exposure, as well as natural factors such as food availability, as potential factors in the recovery of these indicator species, and has contributed to increased understanding of the linkages between terrestrial and marine ecosystems (see Chapter 3, Section 2, Volume II)

The Alaska Predator Ecosystem Experiment (APEX) is an eight-year, $10 8 million study of ecological relations among seabirds and their prey species The APEX project explored the critical connection between productivities of marine bird populations and forage fish species, in an attempt to understand how wide-ranging ecological changes might be related to fluctuating seabird populations In addition, analyzing the food of marine birds shows promise in providing abundance estimates for key fish species, such as sand lance and herring

The following topics also have been covered by other Trustee Council-funded studies and the results are available in published scientific literature

- Physical and biological oceanography,
- Marine food web structure and dynamics,
- Predator-prey relationships among birds, fish, and mammals,

- The source and fate of carbon among species,
- Developmental changes in trophic level within species,
- Marine growth and survival of salmon,
- Intertidal community ecology, and
- Early life history and stock structure in herring

Many studies have focused on key individual species injured by the oil spill, including pink and sockeye salmon, cutthroat trout, Pacific herring, black oystercatchers, river otters, harbor seals, mussels, and kelp

One of the most extensive series of single-species investigations is the $14 million suite of pink salmon studies These include monitoring the toxic effect of oil, conducting genetic studies related to survival, and supplementing select populations Another extensive series of studies was done on Pacific herring Roughly $6 million has been spent on the restoration of Pacific herring in addition to the funding for the herring component of SEA Since the crash of 1993, the population has yet to recruit a highly successful post-spill year-class Current investigative strategies are focused on the full range of causes of the crash, such as disease and ecological factors, including the effects of oceanographic processes on year-class strength and adult distribution

More than $5 million has been spent on the restoration of marine mammals, primarily harbor seals, a major source of subsistence food in the diet of Native Alaskans in the northern GOA Harbor seal populations were declining before the spill, took a big hit at the time of the spill event, and have continued to decline ever since, although the rate of decline seems to have slowed Food availability is the major focus of current research, because disease and other factors have been ruled out as causes

1.5 References

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2. LINGERING EFFECTS OF THE *EXXON VALDEZ* OIL SPILL

In This Chapter

- Description of the *Exxon Valdez* oil spill
- Background of restoration funding
- Concerns and how they are being addressed

On March 24, 1989, the *T/V Exxon Valdez* ran aground on Bligh Reef in PWS, spilling almost 11 million gallons of North Slope crude oil The event was the largest tanker spill in U S history, contaminating about 1,500 miles of Alaska's coastline, killing birds, mammals and fish, and disrupting the ecosystem in the path of the spreading oil

In 1991 Exxon Corporation agreed to pay the United States and the State of Alaska $900 million over 10 years to restore, replace, enhance, or acquire the equivalent of natural resources injured by the spill, and the reduced or lost human services they provide (United States of America and State of Alaska 1991) Under the court-approved terms of the settlement, the Trustee Council was formed to administer the restoration funds Twelve years after the spill, total recovery has still not been achieved Table 2 1 lists resources and the status of their recoveries

There are two main concerns about the lingering effects of oiling from the 1989 EVOS The first is the potential effect of pockets of residual oil in the environment Laboratory studies have shown that contact with petroleum hydrocarbons from weathered oil, even in very small amounts, can kill or harm early life stages of pink salmon and Pacific herring It is not yet known, however, whether such effects are actually occurring to any significant degree in PWS or at other localities with residual oil Tissue samples from higher vertebrates, such as sea otters and harlequin ducks, also indicate possible ongoing exposure to petroleum hydrocarbons in PWS The effects of this exposure are not well established at the level of individual animals or at the population level

The second concern is the ability of populations to fully recover by overcoming the changes in the population dynamics resulting from the initial oil-related mortalities and the interaction of these effects with those of other kinds of changes and disturbances in the marine ecosystem Changes in population dynamics are indicated by changes in the age distribution in the population or abundance, among other metrics Sea otters around northern Knight Island are an example of a species that have experienced prolonged changes in population dynamics in

Table 2 1 Status of Resources Injured by the *Exxon Valdez* Oil Spill as of March 1999

Not Recovering	Recovering	Recovered	Recovery Unknown
Common loon	Archaeological resources	Bald eagle	Cutthroat trout
Cormorants (3 species)	Black oystercatcher	River otter	Designated Wilderness Areas
Harbor seal	Clams		Dolly Varden
Harlequin duck	Common Murre		Kittlitz s murrelet
Killer whale (AB pod)	Intertidal communities		Rockfish
Pigeon guillemot	Marbled murrelet		
	Mussels		
	Pacific herring		
	Pink salmon		
	Sea otter		
	Sediments		
	Sockeye salmon		
	Subtidal communities		

The following injured human services are considered to be recovering commercial fishing passive use recreation and tourism and subsistence

the heavily oiled western portion of PWS The combined effects of the oil spill and the 1998 El Niño event on abundance of common murres in the Barren Islands is an example of possible interactive, or cumulative, impacts Another example is how the negative impacts of changes in the availability of forage fishes may have combined with oil-related mortalities to interfere with the rate of recovery of seabirds, such as the pigeon guillemot

During the next several years, studies of lingering oil spill injury and recovery will increasingly be incorporated in long-term environmental monitoring and ecosystem studies These long-term studies are expected to increase our understanding of the biological processes of the spill area ecosystem in the context of natural forces and human activities, including the oil spill Some oil-spill-monitoring activities, (such as residual oil in the environment) may be repeated periodically as may be indicated by information developed in the long-term studies

Long-term environmental monitoring and ecosystem studies will be designed to increase our understanding of the biological processes of the spill area ecosystem in the context of natural forces and human activities

When evaluating lingering effects of the oil spill, it is important to bear in mind that not all scientific results from the NRDA and Trustee Council investigations are available yet Although the oil spill occurred more than a decade ago, results of studies are still being published on a regular basis The Trustee Council database of peer-reviewed publications and theses resulting from its oil spill investigations currently contains more than 400 citations

(EVROTCB 2001) New publications from oil spill investigations are expected for at least the next three years In addition, much additional detailed data that cannot be published in peer-reviewed literature because of space limitations is being added in the form of final reports from oil spill investigations (EVROFAB 2001) It will be a number of years after the completion of the oil spill restoration investigations before this information is fully available

2 1 References

EVROFAB 2001 *Exxon Valdez* Oil Spill Restoration Office bibliography of final and annual reports Anchorage, Alaska, *Exxon Valdez* Oil Spill Trustee Council

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3. SCIENTIFIC BACKGROUND

In This Chapter

- Description of the scientific understanding of the Gulf of Alaska
- Identification of physical, chemical, and biological characteristics
- Discussion of changes in populations, predators, and prey

NOTE An executive summary will be added at the beginning of this chapter

3 1 The Gulf of Alaska

The GOA encompasses watersheds and waters south and east of the Alaska Peninsula from Great Sitkin Island (176° W), north of 52° N to the Canadian mainland on Queen Charlotte Sound (127° 30′ W) Twelve and a half percent of the continental shelf of the United States lies within GOA waters (Hood 1986)

The area of the GOA directly affected by the EVOS (Figure 3 1) encompasses broadly diverse terrestrial and aquatic environments Within the four broad habitat types of the watersheds, intertidal-subtidal, Alaska Coastal Current (ACC), and offshore (continental shelf break and Alaska Gyre), the geological, climatic, oceanographic, and biological processes interact to produce the highly valued natural beauty and bounty of this region

Human uses of the GOA are extensive The GOA is a major source of food and recreation for the entire nation, a source of traditional foods and culture for indigenous peoples, and a source of food and enjoyment for all Alaskans Serving as a "lung" of the planet, GOA resources are part of the process that provides oxygen to the atmosphere In addition, the GOA provides habitat for diverse populations of plants, fish, and wildlife and is a source of beauty and inspiration to those who love natural things

The eastern boundary of the GOA is a geologically young, tectonically active area that contains the world's third largest permanent icefield, after Greenland and Antarctica Consequently, the watersheds of the eastern boundary of the GOA lie in a series of steep, high mountain ranges Glaciers head many watersheds in this area, and the eastern boundary mountains trap weather systems from the west, making orographic, or mountain-directed, forcing important in shaping the region's climate From the southeastern GOA limit (52° N at landfall) moving north, the eastern GOA headwater mountain ranges and height of the highest peaks are the Pacific Coast (10,290 feet [ft]), St Elias (18,000 ft), and Wrangell

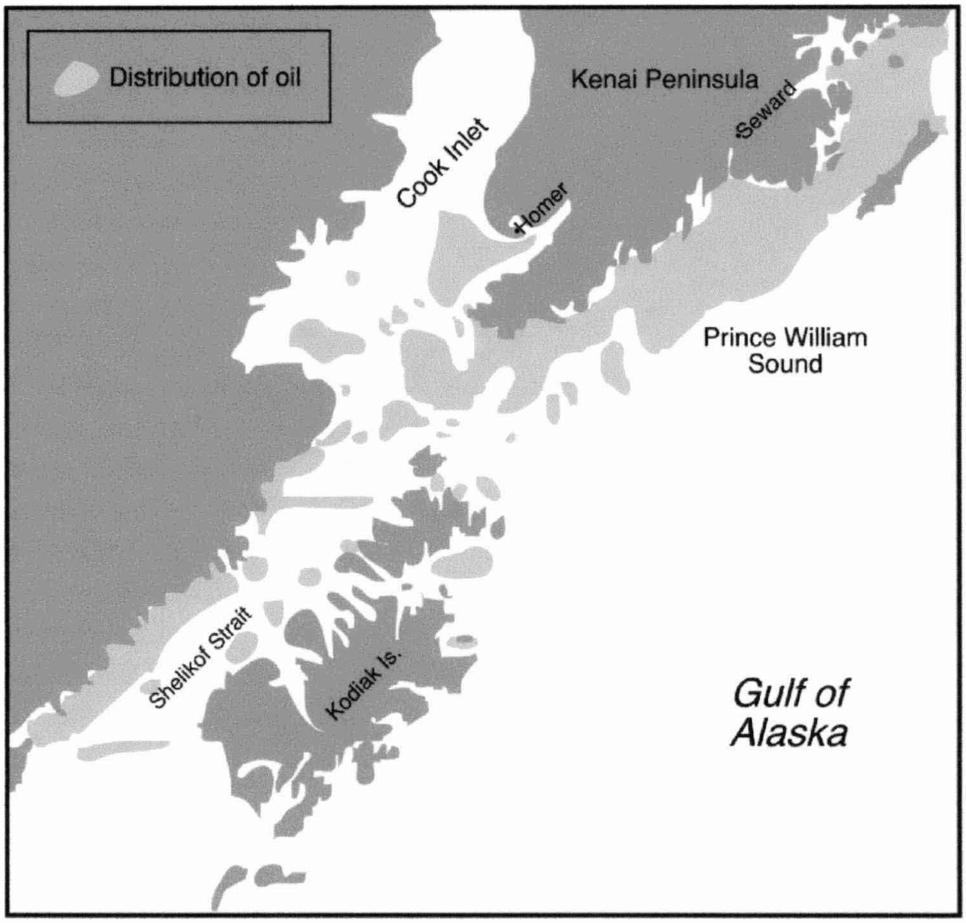


Figure 3.1 Distribution of oil from the *Exxon Valdez* oil spill.

(16,390 ft) Northern boundary mountain ranges from east to west are the Chugach (13,176 ft), Talkeetna (8,800 ft), and Alaska (20,320 ft) The western boundary of the GOA headwaters is formed in the north by the Alaska Range and to the south-southwest by the Aleutian Mountains (7,585 ft)

Relatively few major river systems manage to pierce the eastern boundary mountains, although thousands of small independent drainages dot the eastern coastline and islands of the Inside Passage Major eastern rivers from the south moving north to the perimeter of PWS are the Skeena and Nass (Canada), the Stikine, Taku, Chilkat, Chilkoot, Alsek, Situk, and Copper All major and nearly all smaller watersheds in the GOA region support anadromous fish species For example, although PWS proper has no major river systems, it does have more than 800 independent drainages that are known to support anadromous fish species

To the west of PWS lie the major rivers of Cook Inlet Two major tributaries of Cook Inlet, the Kenai and the Kasilof, originate on the Kenai Peninsula The Kenai Peninsula lies between PWS, the northern GOA and Cook Inlet Cook Inlet's largest northern tributary, the Susitna River, has headwaters in the Alaska Range on the slopes of North America's highest peak, Mt McKinley Moving southwest down the Alaska Peninsula, only two major river systems are found on the western coastal boundary of the GOA, the Crescent and Chignik, although many small coastal watersheds connected to the GOA abound Kodiak Island, off the coast of the Alaska Peninsula, has a number of relatively large river systems, including the Karluk, Red, and Frazer

The nature of the terrestrial boundaries of the GOA is important in defining the processes that drive biological production in all environments As described in more detail below, the ice cap and the eastern boundary mountains create substantial freshwater runoff that controls salinity in the nearshore GOA and helps drive the eastern boundary current. The eastern mountains slow the pace of and deflect weather systems that influence productivity in freshwater and marine environments

The GOA shoreline is bordered by a continental shelf ranging to 200 meters (m) in depth (Figure 3 2) Extensive and spectacular shoreline has been and is being shaped by plate tectonics and massive glacial activity (Hampton et al 1986) In the eastern GOA, the shelf is variable in width from Cape Spencer to Middleton Island It broadens considerably in the north between Middleton Island and the Shumagin Islands and narrows again through the Aleutian Islands The continental slope, down to 2,000 m, is very broad in the eastern GOA, but it narrows steadily southwestward of Kodiak, becoming only a narrow shoulder above the wall of the deep Aleutian Trench just west of Unimak Pass The continental shelf is incised by extensive valleys or canyons that may be important in cross-shelf water movement (Carlson et al 1982), and by very large areas of drowned glacial moraines and slumped sediments (Molnia 1981)

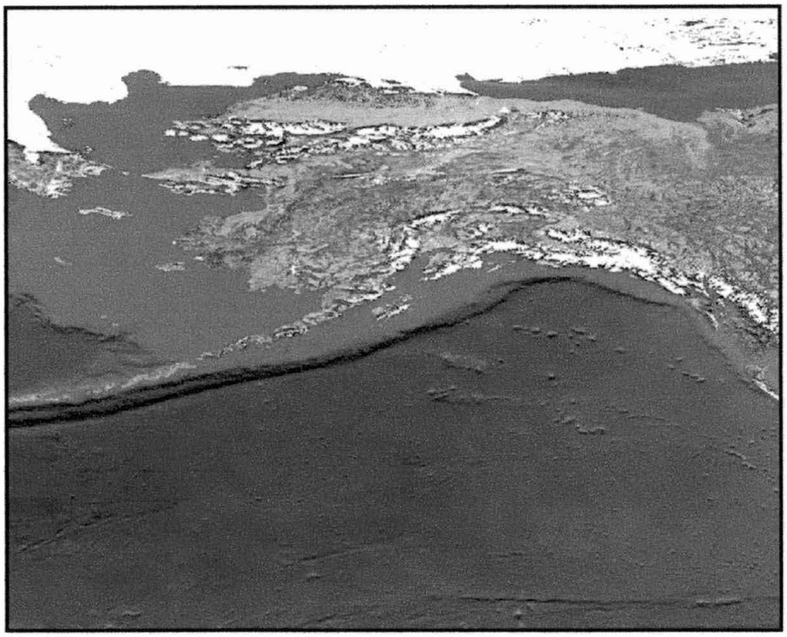


Figure 3.2 Satellite radar image of the northern Gulf of Alaska. Continental shelf, seamounts, and abyssal plain can be seen in relief. (Composite image from Sea-viewing Wide Field-of-view Sensor [SeaWiFS], a National Aeronautics and Space Agency remote-sensing satellite.)

3.2 Climate

3.2.1 Introduction

The weather in the northern GOA, and by extension that of adjacent regions such as PWS, is dominated for much of the year by extratropical cyclones These storms typically form well to the south and east of the region over the warm waters of the central North Pacific Ocean and propagate northwestward into the cooler waters of the GOA (Luick et al 1987, Wilson and Overland 1986) Eventually these storms make landfall in Southcentral or South east Alaska where their further progress is impeded by the extreme terrain of the Saint Elias Mountains and other coastal ranges In fact, weather forecasters call the coastal region between Cordova and Yakutat "Coffin Corner," in reference to the frequency of decaying extratropical storms found there

The high probability of cyclonic disturbances in the northern GOA is significant to the local weather and climate of PWS Associated with these storms are large offshore-directed, low-level pressure gradients (tightly packed isobars roughly parallel to the coast) Depending on other factors (such as static stability, upper-level wind profile) these gradients can produce strong gradient-balance winds parallel to the coastline or downslope (offshore-directed) wind events (Macklin et al 1988) Further, because of the complex glacially sculptured nature of the terrain in PWS, several regions experience significant upslope winds in certain favorable storm situations This wind configuration, in concert with steep terrain and nearly saturated, low-level air masses, produces the local extreme in precipitation responsible for tidewater glaciers of PWS

The combination of general storminess, significant windiness (and concomitant wave generation), and orographically enhanced precipitation are essential features of the northern GOA and PWS, and have a strong impact on the variety and composition of the biota this region supports In addition, the annual melting of seasonal snowfall accumulations, in combination with glacial ablation, is responsible for the bulk freshwater input into PWS In this context, any changes in climate–naturally induced or anthropogenic–that substantively alter the frequency and duration of these common yet transient weather features should also affect related parts of the region ecosystem In the following discussion, the factors responsible for climate change are identified and explained on a general level in preparation for specific relationships among climate, physical, and chemical oceanography, species, and groups of species that follow Climate is recognized to be a major natural force influencing change in biological resources

The GEM mission is to promote, " greater understanding of how its productivity is influenced by natural changes and human activities" (EVOSTC 2000) Climatic forcing is an important natural agent of change in the region's populations of birds, fish, mammals, and other plant and animal species (Hare et al 1999, Mantua et al 1997, Anderson and Piatt 1999, Francis et al 1998) Human activities, or anthropogenic forcing, may have profound effects on climate There is growing evidence that human activities producing "greenhouse gases" such as carbon dioxide may contribute to global climate change by altering the global carbon cycle (Sigman and Boyle 2000, Allen et al 2000) Understanding how natural and human forcing influences biological productivity requires knowledge of the major determinants of climate change described in this section

Climate in the GOA results from the complex interactions of geophysical and astrophysical forces, and also in part by biogeochemical forcing Physical processes acting on the global carbon cycle and its living component, the biological pump, drive oscillations in climate (Sigman and Boyle 2000) The most prominent geophysical feature associated with climate change in the GOA is the Aleutian Low Pressure system (Wilson and Overland 1986) The location and intensity of this system affects storm tracks, air temperatures, wind velocities, ocean currents and other key physical factors in the GOA and adjacent land areas Sharp variations, or oscillations, in the location and intensity of the Aleutian Low are the result of physical factors operating both proximally and at great distances from the GOA (Mantua et al 1997) Periodic changes in the location and intensity of the Aleutian Low are related to movements of adjacent continental air masses and the jet stream to oceanography and weather in the eastern tropical Pacific

Astrophysical forces contribute to long-term trends and periodic changes in the climate of the GOA by controlling the amount of solar radiation that reaches earth, or insolation (Rutherford and D'Hondt 2000) Climate also depends on the amount of global insolation and the proportion of the insolation stored by the atmosphere, oceans, and biological systems (Sigman and Boyle 2000) Changes in climate and biological systems occur through physical forcing of controlling factors, such as solar radiation, strength of lunar mixing of water masses, and patterns of ocean circulation Periodic variations in the earth's solar orbit, the speed of rotation and orientation of the earth, and the degree of inclination of the earth's axis in relation to the sun result in periodic changes in climate and associated biological activity

Understanding climatic change requires sorting out the effects of physical forcing factors that operate simultaneously at different periods Periodicities of physical forcing on factors potentially controlling climate and biological systems include are 100,000 years, 41,000 years, 23,000 years, 10,000 years, 20 years, 18 6 years, and 10 years, among many others For example, Minobe (1999) identified periods of 50 and 20 years in an analysis of the North Pacific Index (NPI) (Figure 3 3) (Minobe 1999)) The NPI is a time series of geographically averaged sea-level pressures representing a univariate (depending on only one random variable) measure of location for the Aleutian Low (Trenberth and Hurrel 1994)

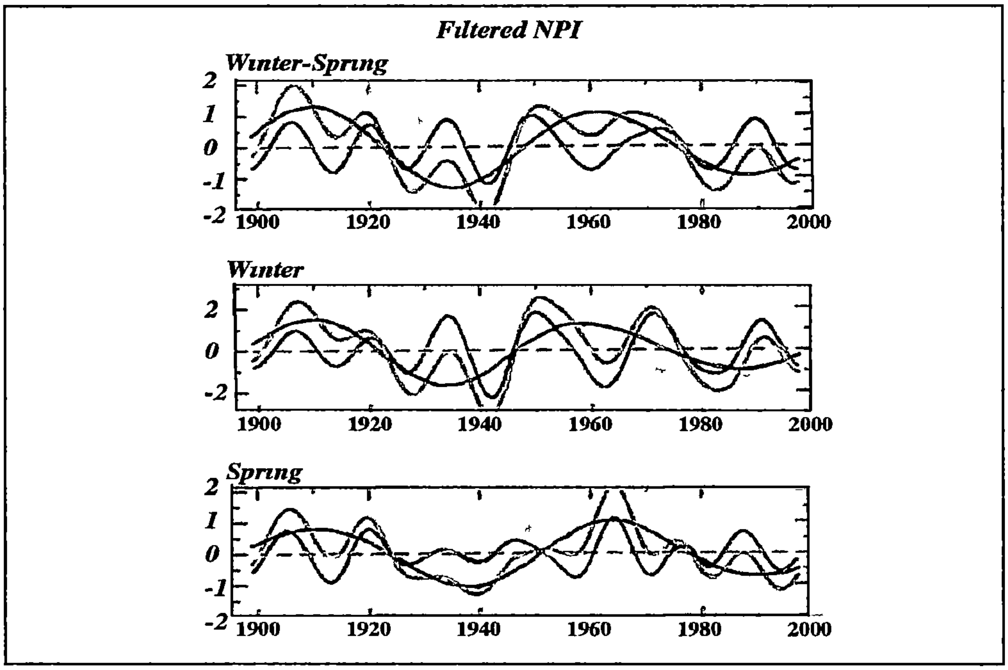


Figure 3 3 Filtered NPI (top) in the winter-spring winter and spring seasons NPI is shown in hectoPascals a measure of barometric pressure at sea level The green curves indicate the 10- to 80-year band-pass filtered NPI data the red curves indicate the 10- to 30-year band-pass filtered (bidecadal filtered) NPI data and the blue curves indicate the 30- to 80-year, band-pass filtered NPI data Source Minobe 1999

Advances and retreats of icefields and glaciers mark major changes in weather and biology Changes in the seasonal and geographic distribution of solar radiation are thought to be primarily responsible for the periodic advance and recession of glaciers during the past 2 million years (Hays et al 1976) The amount of solar radiation reaching earth changes periodically, or oscillates, in response to variations in the path of the earth's orbit about the sun Geographic and seasonal changes in solar radiation caused by periodic variations in the earth's orbit around and orientation toward the sun have been labelled "Milankovich cycles," which are known to have characteristic frequencies of 100,000, 41,000, and 23,000 years (Berger et al 1984) Shifts in the periodicity of long-term weather patterns correspond to shifts from one Milankovich cycle to another How and why shifts from one Milankovich cycle to another occur are among the most important questions in paleoeclimate research (Hays et al 1976, Rutherford and D'Hondt 2000)

3.2 2 Long Time Scales

3.2.2.1 Orbital Eccentricity and Obliquity

Shifts in the periodicity of glaciation from 41,000 to 100,000 years between 1 5 and 0 6 million years before present (Myr bp) emphasize the importance of the atmosphere and oceans in translating the effects of physical forcing into weather cycles Glacial cycles may have initially shifted from the 41,000-year period of the "obliquity cycle" to the 100,000-year period of the "orbital eccentricity" perhaps caused initially by changes in the heat flux, from the equator to the higher latitudes (Rutherford and D'Hondt 2000) (Obliquity is the angle between the plane of the earth's orbit and the equatorial plane) According to the theory advanced by Rutherford and D'Hondt (2000), interactions between long-period physical forcing (Milankovich cycles) and shorter-period forcing (precession) may have been a key factor in lengthening the time period between glaciations in the transition period of 1 5 and 0 6 Myr bp Transitions from glacial to interglacial periods may be triggered by factors such as the micronutrient iron (Martin 1990) that control the activity of the biological pump in the Southern Ocean, described below

Theories about regulation of heat flux from the equator to northern latitudes are central to understanding climate change For example, the heat flux that occurs when the Gulf Stream moves equatorial warmth north to surround the United Kingdom, Iceland, and Northern Europe defines comfortable human life styles in these countries Anything that disrupts this heat flux process would drastically alter climate in Northern Europe

3.2.2.2 Day Length

Day length is increasing by one to two seconds each 100,000 years primarily because of lunar tidal action (U S Naval Observatory [USNO]) Understanding the role of day length in climate variation is problematic because the rotational speed of the earth cannot be predicted exactly due to the effects of a large number of poorly understood sources of variation (USNO) Short-term effects are probably inconsequential biologically, because variations in daily rotational speed are very small, but cumulative effects could be more substantial in the long term

3.2.2.3 Carbon Cycling and the Biological Pump

Changes in the amount of solar radiation available to drive physical and biological systems on earth are not the only causes of climate oscillations in the GOA, or elsewhere in earth Of critical importance to life on earth, changes in insolation result in changes in the amount of a "greenhouse gas," carbon dioxide in the atmosphere resulting from changes in physical properties, such as ocean temperature, and due to biological processes collectively known as the biological pump (Chisholm 2000) The importance of the biological pump in determining levels of atmospheric carbon dioxide is thought to be substantial, since the direct physical and chemical effects of changes in insolation on the carbon cycle alone (Sigman and Boyle 2000) (Figure 3 4) are not sufficient to account for the magnitude of the changes in atmospheric carbon dioxide between major climate changes, such as glaciations

The Biological Pump Photosynthesis and respiration by marine plants and animals play key roles in the global carbon cycle by "pumping" carbon dioxide from the atmosphere to the surface ocean and incorporating it into organic carbon during photosynthesis Organic carbon not liberated as carbon dioxide during respiration is "pumped" (exported) to deep ocean water where bacteria convert it to carbon dioxide Over a period of about 1,000 years, ocean currents return the deep water's carbon dioxide to the surface (through upwelling) where it again drives photosynthesis and ventilates to the atmosphere The degree to which this deep-water's carbon dioxide is "pumped" back into the atmosphere or "pumped" back into deep water depends on the intensity of the photosynthetic activity, which depends on availability of the macronutrients phosphate, nitrate, and silicate, and on micronutrients such as reduced iron (Chisholm 2000)

Areas where nitrates and phosphates do not limit phytoplankton production, such as the Southern Ocean (60° S), can have very large effects on the global carbon cycle through the action of the biological pump When stimulated by the micronutrient iron, the biological pump of the Southern Ocean becomes very strong because of the presence of ample nitrate and phosphate to fuel photosynthesis, as demonstrated by the Southern Ocean iron release experiment (SOIREE) at 61° S 140° E in February 1999 (Boyd et al 2000) SOIREE stimulated phytoplankton production in surface waters for about two weeks fixing up to 3,000 metric ton (mt) of organic carbon Although it has not been demonstrated that "iron fertilization" increases export of carbon to deep waters (Chisholm 2000), it clearly does enhance surface production The Southern Ocean and much of the GOA share the quality of being "high nitrate, low chlorophyll" (HNLC) waters, so it is tempting to speculate that iron would play an important role in controlling production, if not export production, in the GOA

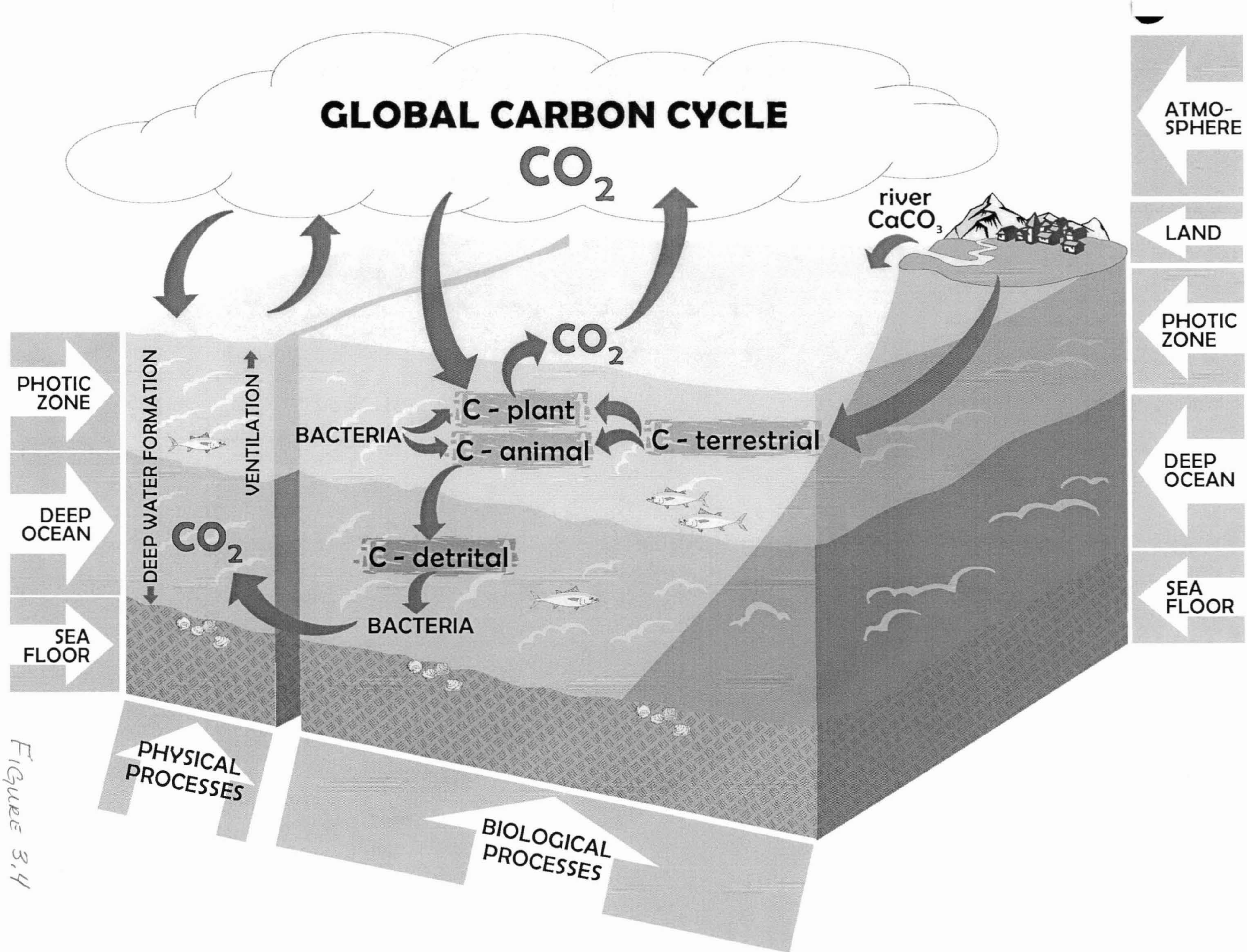

GLOBAL CARBON CYCLE
CO2
river CaCO3
ATMO-SPHERE
LAND
PHOTIC ZONE
DEEP OCEAN
SEA FLOOR
CO2
C - plant
BACTERIA
C - animal
C - terrestrial
PHOTIC ZONE
DEEP OCEAN
SEA FLOOR
DEEP WATER FORMATION
VENTILATION
CO2
C - detrital
BACTERIA
PHYSICAL PROCESSES
BIOLOGICAL PROCESSES

Figure 3.4

The Carbon Cycle An accounting of changes in the amount of carbon in each component of the earth's terrestrial and ocean carbon cycles (Sigmon and Boyd, Figure 3 4), as influenced and represented by the physical and chemical factors of ocean temperature, dissolved inorganic carbon, ocean alkalinity, and the deep reservoir of the nutrients phosphate and nitrate, has to incorporate changes in the strength of the ocean's biological pump to be complete (Sigman and Boyle 2000) The amount of atmospheric carbon dioxide decreases during glacial periods Because physical-chemical effects do not fully account for these changes, the ruling hypothesis is that the biological pump is stronger during glaciations But why would the biological pump be stronger during glaciations?

Two leading theories explain decreases in atmospheric carbon dioxide by means of increased activity in the ocean's biological pump during glaciations (Sigman and Boyle 2000) Both theories explain how increased export production of carbon from surface waters to long-term storage in deep ocean waters can lower atmospheric carbon dioxide during glacial periods The Broecker theory develops mechanisms based on increasing export from low- to mid-latitude surface waters (Broecker 1982, McElroy 1983), and the second theory relies on high-latitude export production of direct relevance to the GOA Patterns and trends in nutrient use in high-latitude oceans, such as the GOA, where nutrients usually do not limit phytoplankton production, could hold the key to understanding climate oscillations

3.2.2.4 Ocean Circulation

Because of the heat energy stored in seawater, oceans are vast integrators of past climatic events, as well as agents and buffers of climate change Wind, precipitation, and other features of climate shape surface ocean currents (Wilson and Overland 1986), and ocean currents in turn strongly feed back into climate Deep ocean waters driven by thermohaline circulation in the Atlantic and southern oceans influence air temperatures over these portions of the globe by transporting and exchanging large quantities of heat energy with the atmosphere (Peixoto and Oort 1992) Patterns of thermohaline (affected by salt and temperature) ocean circulation probably change during periods of glaciation (Lynch-Stieglitz et al 1999) The nature of changes in patterns of thermohaline circulation appear to determine the duration and intensity of climate change (Ganopolski and Rahmstorf 2001) Although the climate of the GOA is not directly affected by thermohaline circulation, climate in the GOA is influenced by thermohaline circulation through climatic linkages to other parts of the globe

Teleconnection between North Pacific and the Tropical Pacific can periodically strongly influence levels of coastal and interior precipitation Because changing patterns in precipitation alter the expression of the ACC (Figure 3 5), which is largely driven by runoff (Royer 1981a), periodically changing weather patterns such as the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) can profoundly alter the circulation and biology of the GOA (See Section 3 2 2 3)

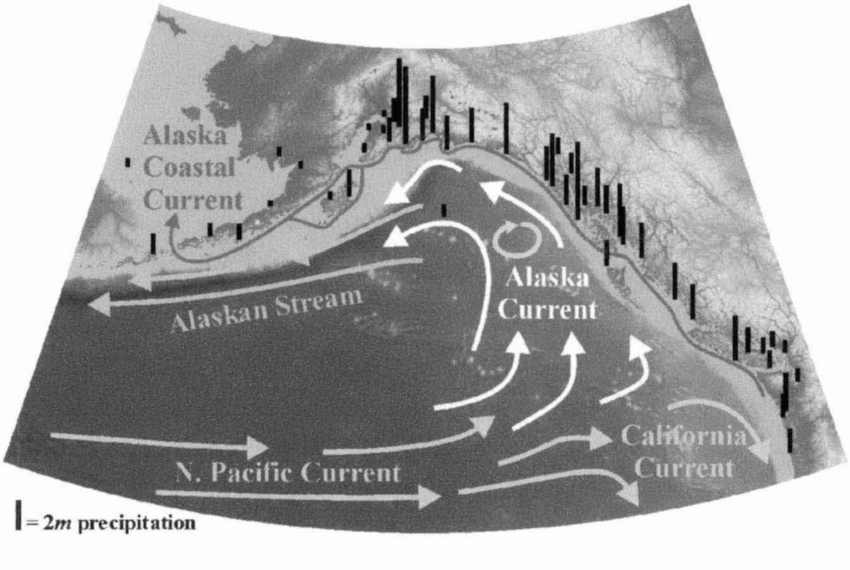


Figure 3.5 Schematic surface circulation fields in the GOA and mean annual precipitation totals from coastal stations (black vertical bars) and for the central GOA (Baumgartner and Reichel 1975).

The effects of the cool ACC and the warmer Alaska Stream moderate air temperatures GOA ocean temperatures are important in determining climate in the fall and early winter in the northern GOA and may be influential at other times of the year Because the cool glacially influenced waters of the ACC moderate air temperatures along the coast, the strength and stability of the ACC are important in determining climate

3.2.3 Multi-decadal and Multi-annual Time Scales

3.2.3.1 Precession and Nutation

Short period changes in the seasonal and geographic distribution of solar radiation are also due to changes in the earth's orientation and rotational speed (day length) (Lambeck 1980) Wobbling (precession) and nodding (nutation) of the earth as it spins on its axis are primarily due to the fluid nature of the atmosphere and oceans, the gravitational attraction of sun and moon, and the irregular shape of the planet.

Small periodic variations in the length of the day occur with periods of 18 6 years, 1 year, and 60 other periodic components The periodic components are due to both lunar and solar tidal forcing In addition to its effect on day length, lunar tidal forcing with a period of 18 6 years has been associated with high-latitude climate forcing, periodic changes in intensity of transport of nutrients by tidal mixing, and periodic changes in fish recruitment (Royer 1993, Parker et al 1995) Biological and physical effects of the lunar tidal cycle may extend beyond effects associated with tidal mixing About one-third of the energy input to the sea by lunar forcing serves to mix deep-water masses with adjacent waters (Egbert and Ray 2000) Oscillations in the lunar energy input could contribute to oscillations in biological productivity through effects on the rate of transport of nutrients to surface waters The lunar tidal cycle appears to be approximately synchronous with the PDO

Contemporary climate in the GOA is defined by large-scale atmospheric and oceanic circulation on a global scale Two periodic changes in ocean and atmospheric conditions are particularly useful for understanding change in the climate of the GOA, the PDO and the ENSO Although weather patterns in the Arctic and north Atlantic are also correlated with weather in the North Pacific, these relations are far from clear The PDO, ENSO, and other patterns of climate variability combine to give the GOA a variable and sometimes severe climate that serves as the incubator for the winter storms that sweep across the North American continent through the Aleutian storm track (Wilson and Overland 1986)

Increased understanding of the PDO has been made possible by simple yet highly descriptive indices of weather, such as the NPI These indices are discussed below Changes in the annual values of these indices led to the realization that weather conditions in the GOA sometimes change sharply from one set of average conditions to a different set during a period of only a few years These rapid climatic and oceanographic regime shifts are associated with similarly rapid changes in the animals and plants of the region that are of vital interest to government, industry, and the general public

3.2.3.2 Pacific Decadal Oscillation

The PDO and associated phenomena appear to be major sources of oceanographic and biological variability (Mantua et al 1997) Associated with the PDO are three semi-permanent atmospheric pressure regions dominating climate in the northern GOA–the Siberian and East Pacific high-pressure systems and the Aleutian Low pressure system These regions have variable, but characteristic, seasonal locations A prominent feature of the PDO and the climate of the GOA is the Aleutian Low, for which average geographic location changes periodically during the winter Wintertime location of the Aleutian Low affects ocean circulation patterns and sea-level pressure patterns It is characteristic of two climatic regimes a southwestern locus called a negative PDO regime (as in 1972) and a northeastern locus called a positive PDO (1977) (Figures 3 6 and 3 7) The location of the Aleutian Low in the winter appears to be synchronized with annual abundances and strength of recruitment of some fish species (Hollowed and Wooster 1992, Francis and Hare 1994) The Aleutian Low pressure system averages about 1,002 millibars (Favorite et al 1976), is most intense in winter, and appears to cycle in its average position and intensity with about a 20- to 25-year period (Rogers 1981, Trenberth and Hurrel 1994)

The PDO is studied with multiple indices, including the anomalies of sea level pressure (as in the NPI, which is discussed below), anomalies of sea surface temperature, and wind stress (Mantua et al 1997, Hare et al 1999) The PDO changes, or oscillates, between positive (warm) and negative (cool) states (Figures 3 8 and 3 9) In decades of positive PDOs, below-normal sea surface temperatures occur in the central and western North Pacific and above normal temperatures occur in the GOA An intense low pressure is centered over the Alaska Peninsula, resulting in the GOA being warm and windy with lots of precipitation In decades of negative PDOs, the opposite sea surface temperature and pressure patterns occur

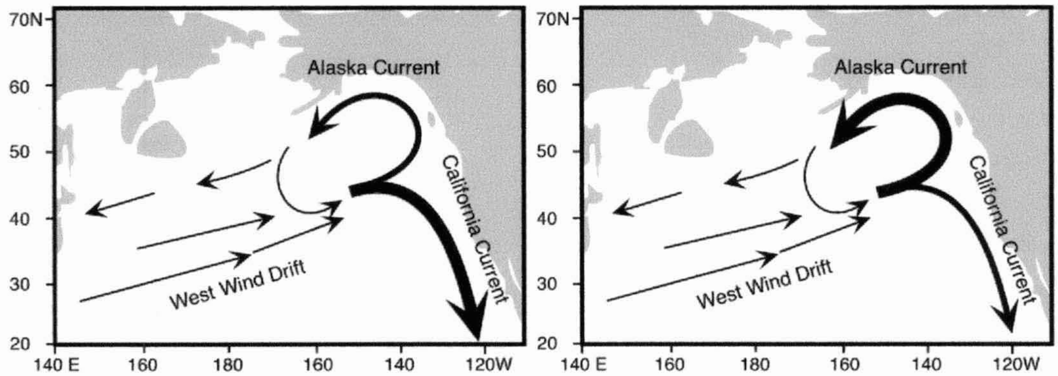


Figure 3.6 Oceanic circulation patterns in the far eastern Pacific Ocean proposed for negative PDO (left) and positive PDO (right). (Hollowed and Wooster 1992).

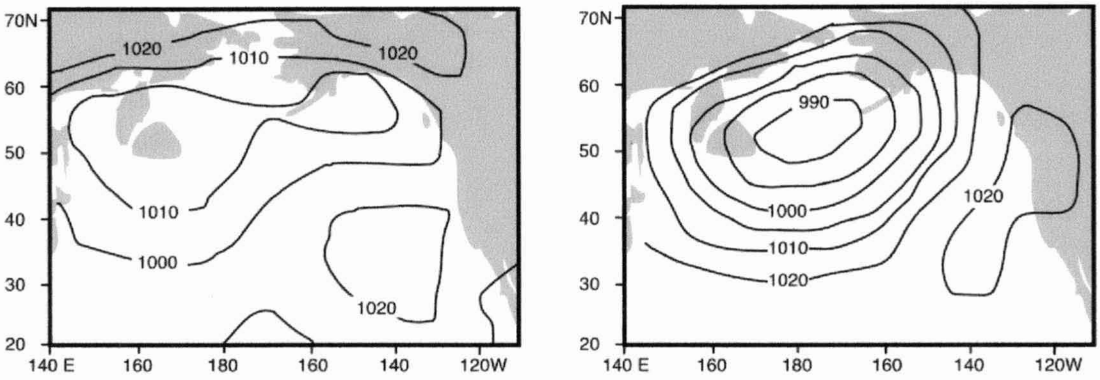
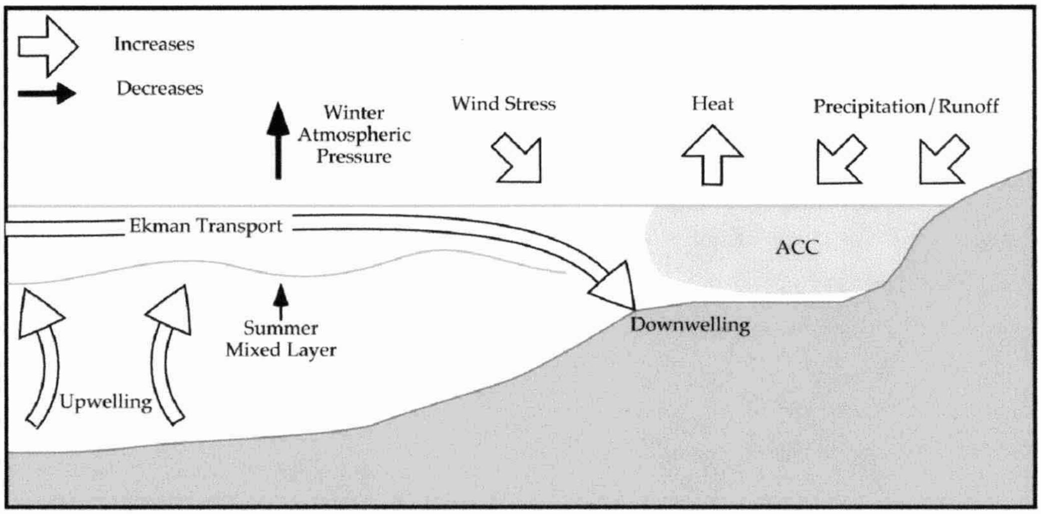


Figure 3.7 Mean sea-level pressure patterns from the winters of 1972 (left) and 1977 (right). (From Emery and Hamilton 1985).

Positive PDO Index

Physics



Positive PDO Index

Biological Production/ Transport

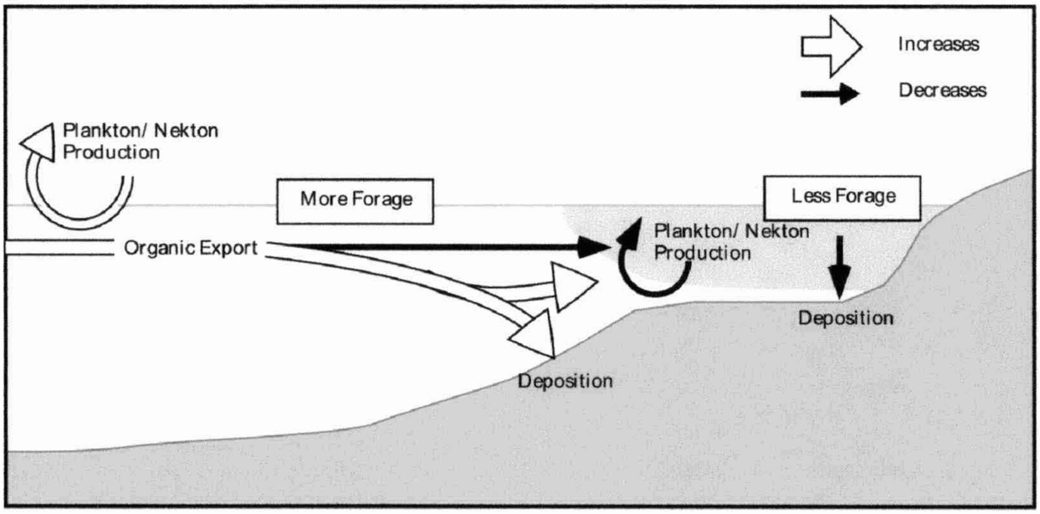
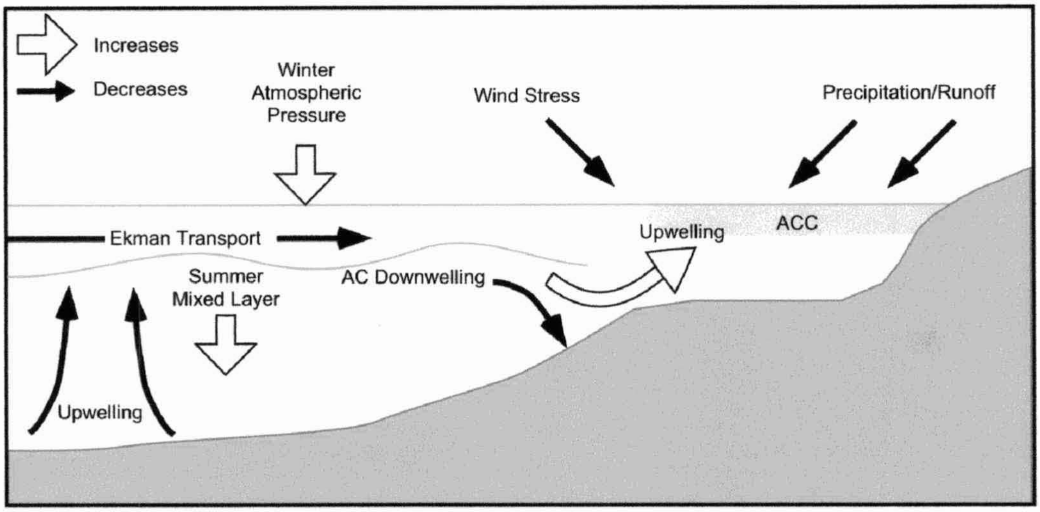


Figure 3.8 Schematic of physical processes during the winter in a positive PDO climatic regime in the Gulf of Alaska from offshore to nearshore areas showing the Alaska Current and the Alaska Coastal Current.

Negative PDO Index

Physics



Negative PDO Index

Biological Production/Transport

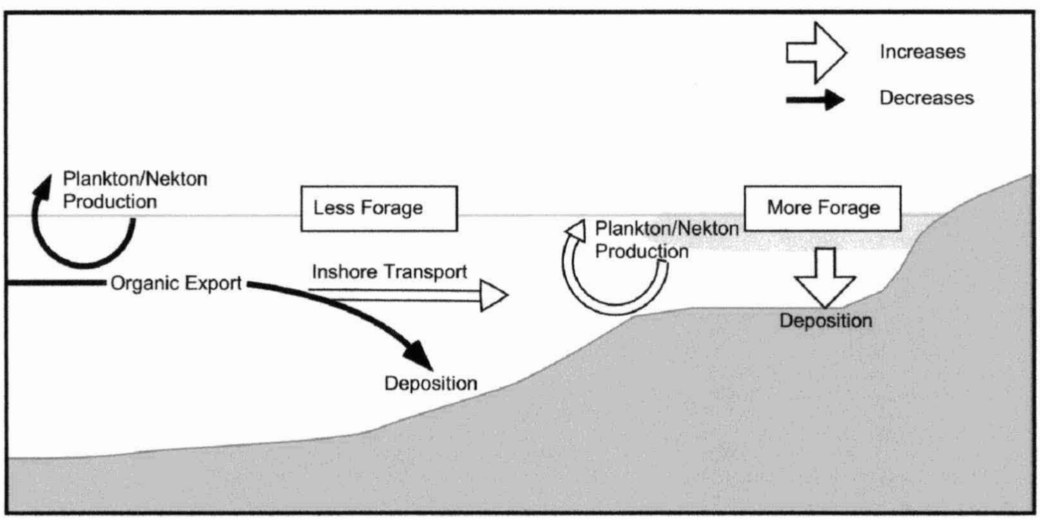


Figure 3.9 Schematic of physical processes during the winter in a negative PDO climatic regime in the Gulf of Alaska from offshore to nearshore areas showing the Alaska Current and the Alaska Coastal Current.

The NPI, a univariate time series representing the strength of the Aleutian Low, shows the same twentieth-century regimes defined by the PDO The NPI is the anomaly, or deviation from the long-term average, of geographically averaged sea-level pressure in the region from 160 E to 140 W, 30 to 65 N, for the years 1899 to 1997 (Trenberth and Hurrel 1994, Trenberth and Paolino 1980) The NPI was used to identify climatic regimes in the twentieth century, for the years 1899 to 1924, 1925 to 1947, 1948 to 1976, and 1977 to 1997, and to explore the interactions of short (20-year) and long (50-year) period effects on the timing of regime shifts (Anderson and Munson 1972) Negative (cool) PDOs occurred during 1890 to 1924 and 1947 to 1976, and positive (warm) PDOs dominated from 1925 to 1946 and from 1977 to about 1995 (Mantua et al 1997, Minobe 1997) Minobe's analysis of the NPI identified a characteristic S-shaped waveform with a 50-year period (sinusoidal pentadecadal) (Figure 4) (Anderson and Munson 1972) His analysis pointed out that rapid transitions from one regime to another could not be fully explained by a single sinusoidal-wavelike effect The speed with which regime shifts occurred in the twentieth century led Minobe to suggest that the pentadecadal cycle is synchronized or phase locked with another climate variation on a shorter bidecadal time scale (Anderson and Munson 1972)

In addition to periodic and seasonal changes, there is evidence that the Aleutian storm track has shifted to an overall more southerly position during the twentieth century (Richardson 1936, Klein 1957, Whittaker and Horn 1982, Wilson and Overland 1986)

3.2.3.3 El Niño Southern OscillationThe ENSO is a weather pattern (Is ENSO really a weather pattern or an ocean/pressure pattern?) originating in the equatorial Pacific with strong influences as far north as the GOA (Emery and Hamilton 1985) ENSO is marked by three states warm, normal, and cool (Enfield 1997) See Figure 3 10 Under normal conditions, the water temperatures at the continental boundary of the eastern Pacific are around 20° C, as cold bottom waters (8 C) mix with warmer surface water to form a large pool of relatively cool water of the coast of Peru When an El Niño (warm) event starts, the pool of cool coastal water at the continental boundary becomes smaller and smaller as warm water masses (20 C to 30° C) from the west move on top of them, and the sea level starts to rise At full El Niño, increases in the surface water temperatures of as much as 5 4 C have been observed very close to the coast of Peru El Niño also brings a sea level rise along the Equator in the eastern Pacific Ocean of as much as 34 centimeters, as warm buoyant waters moving in from the west override cooler, denser water masses at the continental boundary In a cool La Niña event, the sea levels are the opposite from an El Niño, and relatively cool (less than 20° C) waters extend well offshore along the equator Note that the sea surface temperature changes associated with ENSO events extend well into the GOA (Figure 3 10)

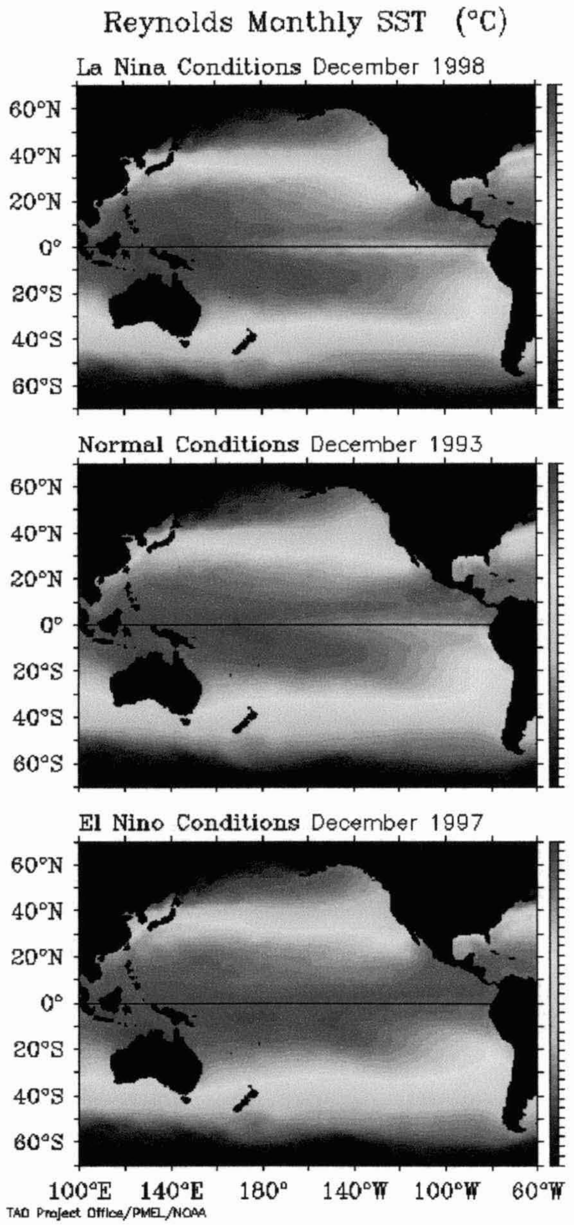


Figure 3.10 Pacific Ocean Reynolds monthly sea surface temperature (SST) in degrees Celsius during La Niña (top), El Niño bottom), and normal (middle) ENSO events. Source: Tropical Atmosphere Ocean Project Office, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, available at <http://www.pmel.noaa.gov/toga-tao/el-nino/la-nina-pacific.html>. also use Martin reference? (Martin 1997) http://www.pmel.noaa.gov/toga-tao/el-nino/la-nina-pacific.html

The ENSO has effects in some of the same geographic areas as PDO, but there are two major differences between these patterns First, an ENSO event does not last as long as a PDO event, and second an ENSO event starts, and is easiest to detect, in the eastern equatorial Pacific, whereas PDO dominates the eastern North Pacific, including the GOA The simultaneous occurrence of two major weather patterns in one location illustrates Minobe's point that multiple forcing factors with different characteristic frequencies must be operating simultaneously to create regime shifts (Figure 3 3)

3.3 Marine-Terrestrial Connections

The role of marine inputs to the watershed phase of regional biogeochemical cycles has been recognized for some time (Mathisen 1972) The following species have been found to transport marine nutrients within watersheds

- Anadromous species, such as salmon (Kline et al 1993, Ben-David et al 1998a),
- Marine-feeding land animals, such as river otters (Ben-David et al 1998b) and coastal mink (Ben-David et al 1997a), and
- Opportunistic scavengers as riverine mink (Ben-David et al 1997a), wolf (Szepanski et al 1999), and martens (Ben-David et al 1997b)

In theory, any terrestrial bird or mammal species that feeds in the marine environment, such as harlequin duck or black-tailed deer, is a pathway to the watersheds for marine nutrients Species that transport marine nutrients play important roles in supporting a wide diversity of other fauna and flora, as determined from levels of marine nitrogen in juvenile fish, invertebrates, and aquatic and riparian plants (Bilby et al 1996, Piorkowski 1995, Ben-David et al 1998a, 1998b) In studies of a small Alaska stream containing chinook salmon, Piorkowski (1995) supported the hypothesis that salmon carcasses can be important in structuring aquatic food webs In particular, microbial composition and diversity determine the ability of the stream ecosystem to use nutrients from salmon carcasses, a principal source of marine nitrogen

The role of marine nutrients in watersheds is key to understanding the relative importance of climate and human-induced changes in population levels of birds, fish, and mammals Indeed, losses of basic habitat productivity because of low numbers of salmon entering a watershed (Kline et al 1993, Mathisen 1972, Piorkowski 1995, Finney et al 2000) may be confused with the effects of fisheries interceptions or marine climate trends Comparison of anadromous fish-bearing streams to non-anadromous streams has demonstrated differences in productivities related to marine nutrient cycling Import of marine nutrients and food energy to the lotic (flowing water) ecosystem may be retarded in systems that have been denuded of salmon for any length of time (Piorkowski 1995)

Paleoecological studies (which focus on ancient events) in watersheds bearing anadromous species can shed light on long-term trends in marine productivity Use of marine nitrogen in sediment cores from freshwater spawning and rearing areas to reconstruct prehistoric abundance of salmon offers some insights into long-term trends in climate, and into how to separate the effects of climate from human impacts such as fishing and habitat degradation (Finney 1998)

As agencies grapple with implementation of ecosystem-based management, conservation actions are likely to focus more on ecosystem processes and less on single species

Watershed studies linking the freshwater and marine portions of the regional ecosystem could pay important benefits to natural resource management agencies As agencies grapple with implementation of ecosystem-based management, conservation actions are likely to focus more on ecosystem processes and less on single species (Mangel et al 1996) In the long-term, protection of Alaska's natural resources will require extending the protection now afforded to single species, such as targeted commercially important salmon stocks, to ecosystem functions (Mangel et al 1996) In process-oriented conservation (Mangel et al 1996), production of ecologically central vertebrate species is combined with measures of the production of other species and measures of energy and nutrient flow among trophic levels to identify and protect ecological processes such as nutrient transport Applications of ecological process measures in Alaska ecosystems have shown the feasibility and potential importance of such measures (Kline et al 1990, Kline et al 1993, Mathisen 1972, Piorkowski 1995, Ben-David et al 1997a, 1997b, 1998a, 1998b, Szepanski et al 1999), as have applications outside of Alaska (Bilby et al 1996, Larkin and Slaney 1997)

3.4 Physical and Geological Oceanography. Coastal Boundaries and Coastal and Ocean Circulation

3.4.1 Physical Setting, Geology, and Geography

The GOA includes the continental shelf, slope, and abyssal plain of the northern part (north of 50° N) of the northeastern Pacific Ocean It extends 3,600 kilometers (km) westward from 127° 30′ W near the northern end of Vancouver Island, British Columbia, to 176° W along the southern edge of the central Aleutian Islands It includes a continental shelf area of about 3 7 x 10^5 km^2 (110,000 square nautical miles [Lynde 1986]) The area of the shelf amounts to about 17% of the entire Alaskan continental shelf area (2 86 x 10^6 km^2 total) and approximately 12 5% of the total continental shelf of the United States (McRoy and Goering 1974) This vast oceanic domain sustains a rich and diverse marine life that supports the economic and subsistence livelihood for both Alaskans and people living in Asia and North America The GOA is also an important transportation corridor for vessels carrying cargo to and from Alaska and vessels traveling the Great Circle Route between North America and Asia

The high-latitude location and geological history of the GOA and adjacent landmass strongly influence present-day regional meteorology, oceanography, and sedimentary environment. The northern extension of the Cascade Range, with mountains ranging in altitude from 3 to 6 km, rings the coast from British Columbia to Southcentral Alaska (Royer 1982) The Aleutian Range spans the Alaska Peninsula in the western GOA and contains peaks exceeding 1000 m in elevation All of the mountains are young and therefore provide plentiful sources of sediment to the ocean The region is seismically active because it lies within the converging boundaries of the Pacific and North American plates The motions of these plates control the seismicity, tectonics, volcanism, and much of the morphology of the GOA and make this region one of the most tectonically active regions on earth (Jacob 1986) Indeed, tectonic motion continuously reshapes the seafloor through faulting, subsidence, landslides, tsunamis, and soil liquefaction For example, as much as 15 m of uplift occurred over portions of the shelf during the Great Alaska Earthquake of 1964 (Malloy and Merrill 1972, Plafker 1972, von Huene et al 1972) These geological processes influence ocean circulation patterns, delivery of terrestrial sediments to the ocean, and reworking of seabed sediments

Approximately 20% of the GOA watershed is covered by glaciers today (Royer 1982) making the region the third greatest glacial field on earth (Meier 1984) The glaciers reflect both the subpolar, maritime climate and the regional distribution of mountains, or orography, of the GOA (see Section 3 3) of the GOA The climate setting includes high rates of precipitation and cool temperatures, especially at high altitudes, that enhance the formation of the icefields and glaciers The icefields are both a source and sink for the fresh water delivered to the ocean In some years the glaciers gain and store the precipitation as ice and snow, in other years, the stored precipitation is released into the numerous streams and rivers draining into the GOA Glacial scouring of the underlying bedrock provides an abundance of fine-grained sediments to the GOA shelf and basin (Hampton et al 1986) The major inputs of glacial sediment are the Bering and Malaspina glaciers and the Alsek and Copper rivers in the northern GOA and the Knik, Matanuska, and Susitna rivers that feed Cook Inlet in the northwest GOA (Hampton et al 1986)

The bathymetry, or bottom depth variations, of the GOA reflects the diverse and complex geomorphological processes that have worked the region during millions of years The GOA abyssal plain gradually shoals from a 5,000-m depth in the southwestern GOA to less than 3000 m in the northeastern GOA Maximal depths exceed 7,000 m near the central Aleutian Trench along the continental slope south of the Aleutian Islands Numerous seamounts, remnants of subsea volcanoes associated with spreading centers in the Pacific lithospheric plate (at the earth's crust), are scattered across the central basin Several of the seamounts or guyots (flat-topped seamounts) rise to within a few hundred meters of the sea surface and provide important mesopelagic (middle depth of the open sea) habitat for pelagic (open sea) and benthic (bottom) marine organisms

The continental shelf varies in width from about 5 km off the Queen Charlotte Islands in the eastern GOA to about 200 km north and south of Kodiak Island Along the Aleutian Islands, the shelf break is extremely narrow or even absent, as depths plunge rapidly north and south of the island chain The numerous passes between these islands control the flow between the GOA and the Bering Sea, with depths (and inflow) generally increasing in the westerly direction (Favorite 1974) In the eastern Aleutians, most of the passes are shallow and narrow, the largest being Amukta Pass with a maximal depth of 430 m and an area of about 20 km^2 (Favorite 1974) Unimak Pass is the easternmost pass (of oceanographic significance) and connects the southeast Bering Sea shelf directly to the GOA shelf near the Shumagin Islands This pass is about 75 m deep and has a cross-sectional area of about 1 km^2 (Schumacher et al 1982)

The shelf topography in the northern GOA is enormously complex because of both tectonic and glacial processes (Figure 3 11) Numerous troughs and canyons, many oriented across the shelf, punctuate the sea floor Subsea embankments and ridges abound as a result of subsidence, uplift, and glacial moraines These geological processes have also shaped the immensely complicated coastline that includes numerous silled and unsilled fjords, embayments, capes, and island groups

The northwestern GOA includes several prominent geological features that influence the regional oceanography Kayak Island, which extends about 50 km across the shelf east of the mouth of the Copper River, can deflect inner shelf waters offshore Interaction of shelf currents with this island can also spawn eddies that transport nearshore waters, which have a high suspended sediment load, onto the outer shelf (Ahlnaes et al 1987)

PWS, which lies west of Kayak Island, is a large complex, fjord-type estuarine system with characteristics of an inland sea (Muench and Heggie 1978) The sound communicates with the GOA shelf through Hinchinbrook Entrance in the eastern sound and Montague Strait and several smaller passes in the western sound The shelf is relatively shallow (about 125 m deep) south of Hinchinbrook Entrance and along the eastern shore of Montague Strait Hinchinbrook Canyon, however, has depths of about 200 m and extends southward from Hinchinbrook Entrance and opens onto the continental slope This canyon is a potentially important conduit by which slope waters can communicate directly with sound Central PWS is about 60 km by 90 km with depths typically in excess of 200 m and a maximal depth of about 750 m in the northern sound The entrances to PWS are guarded by the shelf, sills, or both of about 180-m depth Numerous islands are scattered throughout the sound and bays, fjords, and numerous glaciers are interspersed along its rugged coastline

FIGURE 3 11

(Figure 1, from (Hampton et al 1986) p 97)

Several silled fjords indent the northern GOA coast, between PWS and Cook Inlet. Inner fjord depths can exceed 250 m, which are greater than the depths over the adjacent shelf. To the west of the Kenai Peninsula is Cook Inlet, which extends about 275 km from its mouth to Anchorage at its head. The inlet is about 90 km wide at its mouth, narrows to about 20 km at the Forelands some 200 km from the mouth, and then widens to about 30 km near Anchorage. Upper Cook Inlet branches into two narrow arms (Turnagain and Knik) that extend inland another 70 km. Depths range from 100 m to 150 m at the mouth of Cook Inlet to less than 40 m in the upper end, with the upper arms being so shallow that extensive mudflats are exposed during low tides. The bottom topography throughout the inlet reflects extensive faulting and glacial erosion (Hampton et al. 1986).

At its mouth, Cook Inlet communicates with the northern shelf through Kennedy Entrance, to the east, and with Shelikof Strait, to the west. The latter is a 200-km by 50-km rectangular channel between Kodiak Island and the Alaska Peninsula with numerous fjords indenting the coast along both sides of the strait. The main channel, with depths between 150 and 300 m, veers southeastward at the lower end of Kodiak Island and intersects the continental slope west of Chirikof Island. Southwest of Shelikof Strait bottom depths shoal to 100 to 150 m, and the shelf is complicated by the passes and channels associated with the Shumagin and Semidi islands.

3.4.2 Atmospheric Forcing of GOA Waters

The climate over the GOA is largely shaped by three semi-permanent atmospheric pressure patterns: the Aleutian Low, the Siberian High, and the East Pacific High (Wilson and Overland 1986). These systems represent statistical composites of many individual pressure cells moving across the northern North Pacific. The climatological position of these pressure systems varies seasonally, as shown in Figure 3.12. From October through April, the cold air masses of the Siberian High deepen over northeastern Siberia, and the East Pacific High is centered off the southwest coast of California. From May through September, the Siberian High weakens and the East Pacific High migrates northward to about 40° N and attains its greatest intensity (highest pressure) in June. The seasonal changes in intensity and position of these high-pressure systems influence the strength and propagation paths of low-pressure systems (cyclones) over the North Pacific. In winter, the Siberian High forces storms into the GOA, and lows are strong; in summer, these systems are weaker and propagate along a more northerly track across the Bering Sea and into the Arctic Ocean.

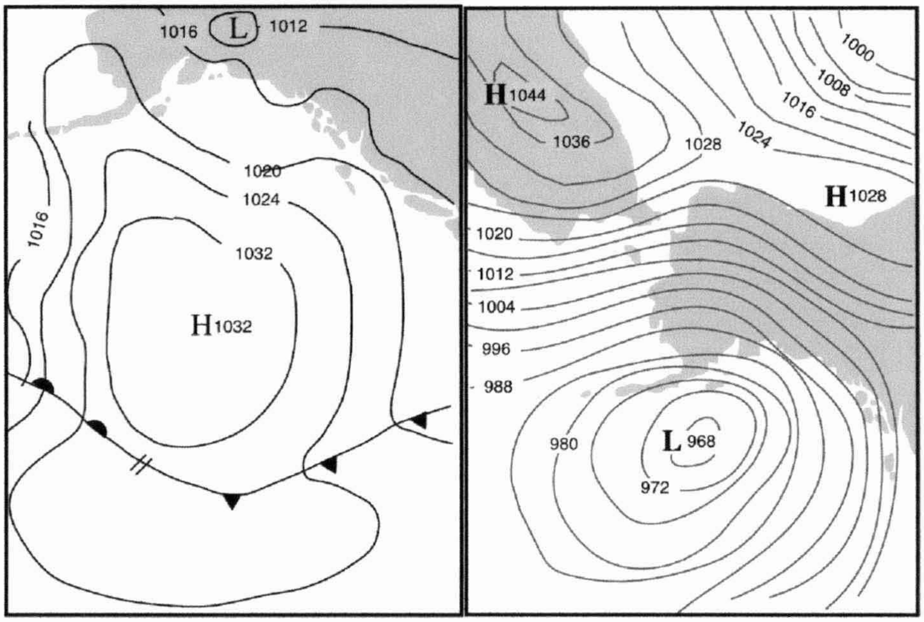


Figure 3.12 Typical summer (left) and winter (right) examples of the Aleutian Low and Siberian High pressure systems. Contours are sea-level pressure in millibars. (From Carter). need reference

The low-pressure storm systems that compose the Aleutian Low form in three ways Many are generated in the western Pacific when cold, dry air flows off Asia and encounters northward-flowing, warm ocean waters along the Asian continent Additional formation regions occur in the central Pacific along the Subarctic Front (near 35° N) where strong latitudinal gradients of ocean temperature interact with unstable, winter air masses (Roden 1970) Finally, the GOA can also be a region of active cyclogenesis (low-pressure formation), particularly in winter when frigid air spills southward over the frozen Bering Sea, the Alaska mainland, or both (Winston 1955) Such conditions can be hazardous to mariners because the accompanying high wind speeds and subfreezing air temperatures can lead to rapid vessel icing (Overland 1990)

Regardless of origin, these lows generally strengthen as they track eastward across the North Pacific This intensification results from the flux of heat and moisture from the ocean to the atmosphere The lows attain maximal strength (lowest pressure) in the western and central GOA Once in the GOA, the coastal mountains inhibit inland propagation, so that the storms often stall and dissipate here Indeed, Russian mariners refer to the northeastern GOA as the "graveyard of lows" (Plakhotnik 1964)

The mountains also force air masses upward, resulting in cooling, condensation, and enhanced precipitation The precipitation feeds numerous mountain drainages that feed the GOA or, in winter, is stored in snowfields and glaciers where it can remain for periods ranging from months to years

Seasonal variations in the intensity and paths of these low-pressure systems markedly influence meteorological conditions in the GOA Of particular importance to the marine ecosystem are the seasonal changes in radiation, wind velocity, precipitation, and coastal runoff

Seasonal variations in the intensity and paths of low-pressure systems influence meteorological conditions in the GOA

The incoming short-wave radiation that warms the sea surface and provides the energy for marine photosynthesis is strongly affected by cloud cover Throughout the year, cloud cover of more than 75% occurs over the northern GOA more than 60% of the time (Brower et al 1988), and cloud cover of less than 25% occurs less than 15% of the time Interannual variability in cloud cover, especially in summer, can affect sea-surface temperatures and possibly the mixed-layer structure (which also depends heavily on salinity distribution) The anomalously warm surface waters observed in the summer and fall of 1997 were probably due to unusually low cloud cover and mild winds (Hunt et al 1999) The characteristic cloud cover is so heavy that it hinders the effective use of passive microwave sensors, such as Advanced Very High Resolution Radar (AVHRR) and Sea-viewing Wide Field of view Sensor (SeaWifs), in ecosystem monitoring

The cyclonic (counterclockwise) winds associated with the low-pressure systems force an onshore surface transport (Ekman transport) over the shelf and downwelling along the coast. Figure 3 13 shows the mean monthly Upwelling Index on the northern GOA shelf This index is negative (implying downwelling) in most months, indicating the prevalence of onshore Ekman transport and coastal convergence Downwelling favorable winds are strongest from November through March, and feeble or even weakly anticyclonic (upwelling favorable) in summer when the Aleutian Low is displaced by the East Pacific High (Royer 1975, Wilson and Overland 1986) Over the central basin, these winds exert a cyclonic torque (or wind-stress curl) that forces the large-scale ocean circulation

The high rates of precipitation are evident in long-term average measurements Figure 3 5 is a composite of long-term average annual precipitation measurements from stations around the GOA Precipitation rates of 2 to 4 meters per year ($m\text{-}yr^{-1}$) are typical throughout the region, but rates in southeast Alaska and PWS exceed 4 $m\text{-}yr^{-1}$ Except over the Alaska Peninsula in the western GOA, the coastal precipitation rates are much greater than the estimated net precipitation rate of 1 $m\text{-}yr^{-1}$ over the central basin (Baumgartner and Reichel 1975) The coastal estimates are undoubtedly biased because most of the measurements are made at sea level and therefore do not fully capture the influence of altitude on the precipitative flux

Figure 3 13 also includes the mean monthly coastal discharge from Southeast and Southcentral Alaska as estimated by Royer (1982) On an annual average this freshwater influx is enormous and amounts to about 23,000 $m^3 s^{-1}$, or about 20% greater than the mean annual Mississippi River discharge, and accounts for nearly 40% of the freshwater flux into the GOA This runoff enters the shelf mainly through many small (and ungauged) drainage systems, rather than from a few major rivers Consequently, the discharge can be thought of as a diffuse, coastal "line" source" around the GOA perimeter, rather than arising from a few, large "point" sources The discharge is greatest in early fall and decreases rapidly through winter, when precipitation is stored as snow There is a secondary runoff peak in spring and summer, because of snowmelt (Royer 1982) The phasing and magnitude of this freshwater flux is important, because salinity primarily affects water densities (and therefore ocean dynamics) in the northern GOA

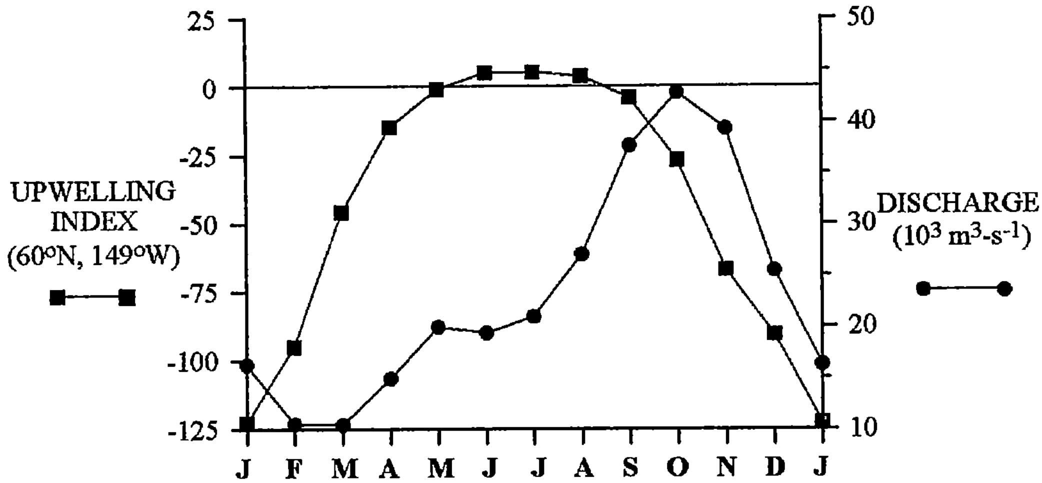


Figure 3 13 Mean monthly Upwelling Index 1946 to 1999 (red) and mean monthly coastal discharge 1930 to 1999 (blue) (Royer 1982, 2000) in the northern GOA Negative values of the Index imply onshore Ekman transport and coastal downwelling Discharge is shown in cubic meters per second, a measure of flow

Figure 3 13 shows that the seasonal variation in wind stress and freshwater discharge is large, but also that these variables are not in-phase with one another, downwelling is maximal in winter and minimal in summer, whereas discharge is maximal in fall and minimal in late winter Both winds and buoyant discharge affect the vertical density stratification and contribute to the formation of horizontal pressure (and density) gradients over the shelf and slope The wind field over the shelf is spatially coherent (Livingstone and Royer 1980) because the scale of the storm systems that enter the GOA are comparable to the size of the basin The alongshore coherence of the wind field and the distributed nature of the coastal discharge suggest that forcing by winds and buoyancy is approximately uniform along the length of the shelf Both the winds and buoyant flux force the mean cyclonic alongshore flow over the GOA shelf and slope (Reed and Schumacher 1986, Royer 1998), as shown schematically in Figure 3 3 On the inner shelf, the flow consists of the ACC, and over the slope, it consists of the Alaska Current (eastern and northeastern GOA) and the Alaskan Stream (northwestern GOA) These current systems are extensive, swift, and continuous over a vast alongshore extent. Thus, the shelf and slope are strongly affected by advection (transport of momentum, energy, and dissolve and suspended materials by ocean currents), implying that climate perturbations, even those occurring far from the GEM study area, can be efficiently communicated into the northwestern GOA by the ocean circulation The strong advection also implies that processes occurring far upstream might substantially influence biological production within the GEM area

3 4.3 Physical Oceanography of the Gulf of Alaska Shelf and Shelf Slope

The GOA shelf can be divided on the basis of water-mass structure and circulation characteristics into three domains

- The inner shelf (or ACC domain) consisting of the ACC,
- The outer shelf, including the shelf-break front, and
- The mid-shelf region between the inner and outer shelves

Because the boundaries separating these regions are dynamic, their locations vary in space and time Although dynamic connections among these domains undoubtedly exist, the nature of these links is poorly understood

The ACC is the most prominent aspect of the shelf circulation It is a persistent circulation feature that flows cyclonically (westward in the northern GOA) throughout the year This current originates on the British Columbian shelf (although in some months or years, it might originate as far south as the Columbia River [Royer 1998, Thomson et al 1989]), about 2,500 km from its entrance into the Bering Sea through Unimak Pass, in the western GOA (Schumacher et al 1982)

The ACC is a swift (20 to 180 centimeters per second [cm s^{-1}] [0 4 to 3 6 knots]), coastally trapped flow typically found within 35 km of the shore (Royer 1981b, Johnson et al 1988, Stabeno et al 1995) Much or all of the ACC loops through southern PWS, entering through Hinchinbrook Entrance and exiting through Montague Strait (Niebauer et al 1994) Therefore, the ACC potentially is important to the circulation dynamics of PWS, clearly, it is a critical advective and migratory path for material and organisms between the GOA and sound West of PWS, the ACC branches northeast of Kodiak Island The bulk of the current curves around the mouth of Cook Inlet and continues southward through Shelikof Strait (Muench et al 1978), the remainder flows southward along the shelf east of Kodiak Island (Stabeno et al 1995) Although there are no long-term (multiyear) estimates of transport in the ACC, direct measurements (Schumacher et al 1990, Stabeno et al 1995) along the Kenai Peninsula and upstream of Kodiak suggest an average transport of about 0 8 Sverdrup (Sv, a unit of flow equal to 1 million cubic meters per second [1 Sv equals 10^6 m^3 s^{1}]), with a maximum in winter and a minimum in summer

The large annual cycle in wind and freshwater discharge is reflected in the mean monthly temperatures and salinities at hydrographic station GAK 1, near Seward, on the inner shelf (Figure 3 14) Mean monthly sea-surface temperatures range from about 3 5° C in March to about 14° C in August The amplitude of the annual temperature cycle, however, diminishes with depth, with the annual range being only about 1° C at depths greater than 150 m Surface temperatures are colder than subsurface temperatures from November through May, and the water column has little thermal stratification from December through May

Surface salinities range from a maximum of about 31 practical salinity units (psu) in late winter to a minimum of 25 psu in August Vertical salinity (density) gradients are minimal in March and April and maximal in the summer months Surface stratification commences in April or May (somewhat earlier in PWS), as cyclonic wind stress decreases and runoff increases, and is greatest in mid- to late summer The inner shelf and PWS stratify first, because runoff initially is confined to nearshore regions and only gradually spreads offshore through ocean processes Solar heating provides additional surface buoyancy by warming the upper layers uniformly across the shelf However, the thermal stratification remains weak until late May or June As winds intensify in fall, the stratification erodes, resulting from stronger vertical mixing and increased downwelling, which causes surface waters to sink along the coast

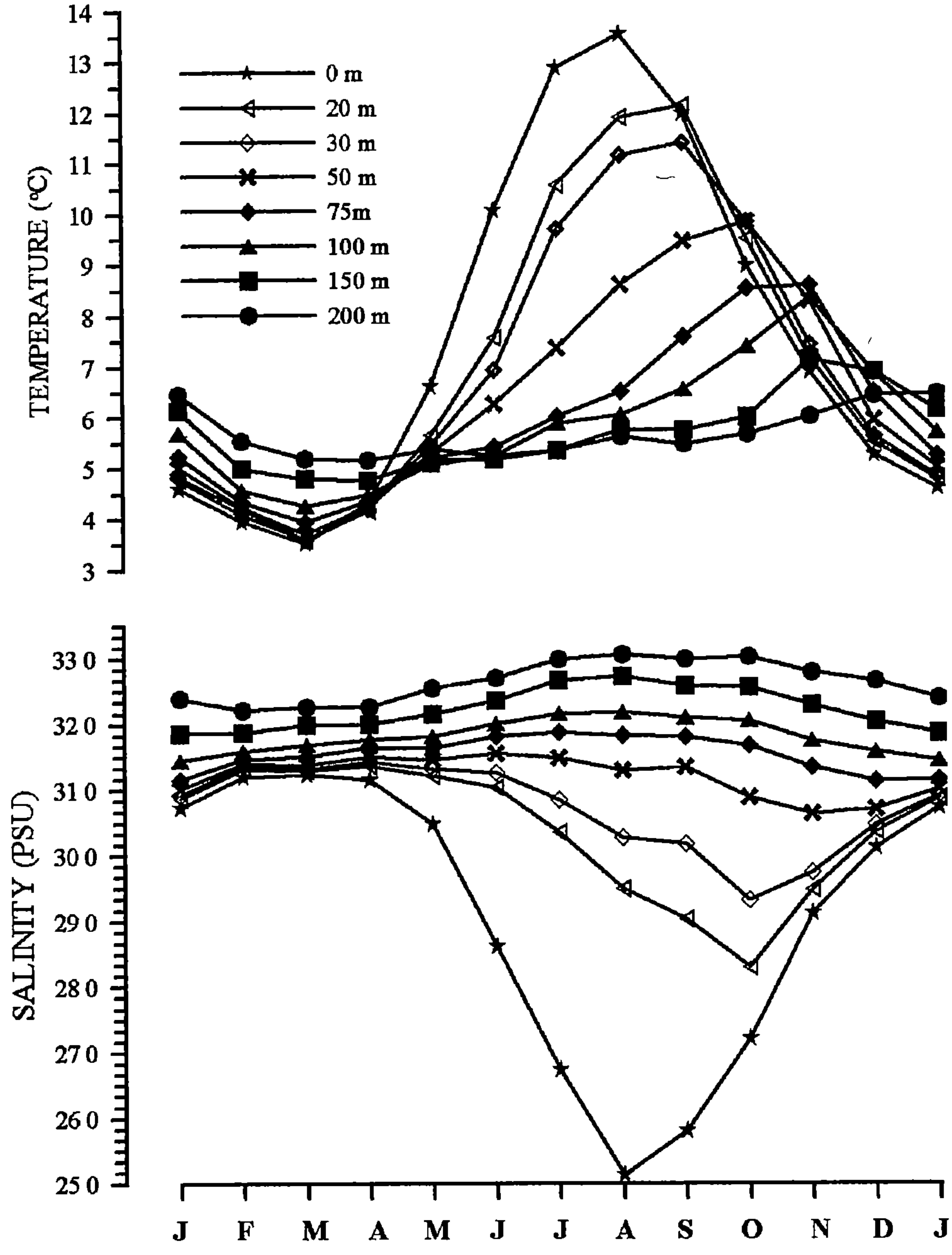


Figure 3 14 The mean annual cycle of temperature (upper) and salinity (lower) at various depths at station GAK 1 on the inner shelf of the northern GOA The monthly estimates are based on data collected from 1970 through 1999 (The figure includes updated information [Xiong and Royer 1984])

Within the ACC, the annual amplitude in salinity diminishes with depth and has a minimum of about 0 5 psu at about the 100-m depth At greater depths, the annual amplitude increases but the annual salinity cycle is out of phase with near-surface salinity changes For example, at and below the 1,50 m depth, the salinity is minimal in March and maximal in late summer-early fall The phase difference between the near-surface and near-bottom layers reflects the combined influence of winds and coastal discharge In summer, when downwelling relaxes, salty, nutrient-rich water from offshore invades the inner shelf (Royer 1975) The upper portion of the water column is freshest in summer, when the winds are weak (little mixing) and coastal discharge is increasing Vertical mixing is strong through the winter and redistributes fresh water, salt, and possibly nutrients throughout the water column

The effects of the seasonal cycle of wind- and buoyancy forcing are also reflected in both the hydrographic properties and the along-shore velocity structure of the shelf The seasonal transitions in temperature and salinity properties are shown in Figure 3 15, which is constructed from cross-shore sections along the Seward Line in the northern GOA for April (representative of late winter), August (summer), and October (fall)

The ACC domain, or inner shelf, is within 50 km of the coast From February through April, the vertical and cross-shelf gradients of salinity and temperature are weak, and the ACC front lies within about 10 km of the coast and extends from the surface to the bottom Vertical shears (gradients) of the along-shelf velocity are weak and the current dynamics are primarily wind-driven and barotropic (controlled by sea-surface slopes setup by the winds) at this time (Johnson et al 1988, Stabeno et al 1995) In summer (late May to early September), the vertical stratification is large, but cross-shelf salinity (and density) gradients are weak The ACC front extends from 30 to 50 km offshore and usually no deeper than 40 m The along-shelf flow is weak, although highly variable, in summer Vertical stratification weakens in fall, but the cross-shelf salinity gradients and the ACC front are stronger than at other times of the year As coastal downwelling increases, the front moves shoreward to within 30 km of the coast and steepens so that the base of the front intersects the bottom between the 50 and 100 m isobaths

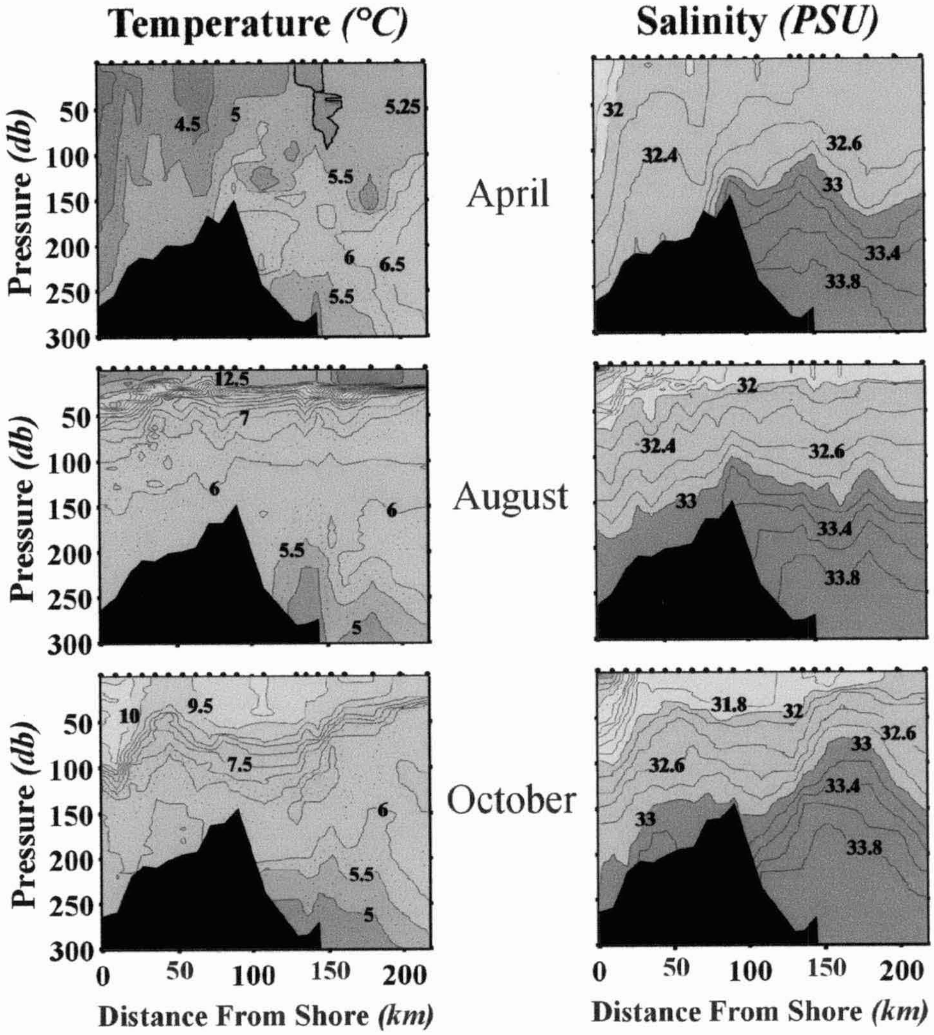


Figure 3.15 Seasonal cross-shore distributions of temperature (left) and salinity (right) along the Seward Line in the northern GOA. The graphs are based on data collected in 1999 as part of the GOA GLOBEC program (Weingartner 2001). The vertical axis is in pressure units (decibars [db]), with 1 db the equivalent of about 1 m.

Theory (Garrett and Loder 1981, Yankovsky and Chapman 1997, Chapman and Lentz 1994, Chapman 2000) suggests that seasonal variations in the ACC frontal structure should strongly influence the vertical and horizontal transport and mixing of dissolved and suspended material, both across and along the inner shelf Royer et al (1979) showed that surface drifters released seaward of the ACC front first drifted onshore (in accordance with Ekman dynamics) and then drifted alongshore upon encountering the ACC front. Conversely, Johnson et al (1988) showed that, inshore of the front, the surface layer spreads offshore, with this offshore flow increasing as discharge increases in fall Taken together, these results suggest cross-frontal convergence arising from differing dynamics on either side of the ACC front Buoyancy effects dominate at the surface inshore of the front (at least for part of the year), wind forcing dominates offshore of the front Convergence across the front would tend to accumulate plankton along the frontal boundary, possibly attracting foraging fish, seabirds, and marine mammals (Haldorson 2001) The front might also be a region of significant vertical motions Downwelling velocities of about 30 meters per day (m-d^{-1}) in the upper 30 m of the water column are possible in fall (This estimate is based on the assumption that the cross-frontal convergence occurs over a frontal width of 15 km with an onshore Ekman flow of 3 cm-s^{-1} seaward of the front and an offshore flow of ~15 cm-s^{-1} [Johnson et al 1988] inshore of the front)

The mid-shelf domain covers the region between 50 and 125 km from the coast. Here cross-shelf temperature and salinity gradients are weak in all seasons In general, the strongest horizontal density gradients occur within the bottom 50 m of the water column, probably associated with the inshore location of the shelf-break front (which does not always have a surface expression) The bottom of the shelf-break front is generally found farther inshore in summer than in fall or winter Over the upper portion of the mid-shelf water column, the vertical stratification is largely controlled by salinity in most months, although vertical salinity gradients are weaker here in summer and fall than on the inner shelf Consequently, in summer, thermal stratification plays an important role in stratifying the mid-shelf water column Here, the along-shelf flow is weakly westward on average because of the feeble horizontal density gradients Both the flow and horizontal density gradients are highly variable, however, because of energetic mesoscale (10- to 50-km) flow features Potential sources for the mesoscale variability are as follows

1 Separation of the ACC from capes (Ahlnaes et al 1987),
2 Instabilities of the ACC (Mysak et al 1981, Bograd et al 1994),
3 Interactions of the shelf flow with topography (Lagerloef 1983), and
4 Meandering of the Alaska Current along the continental slope (Niebauer et al 1981)

This mesoscale variability is very difficult to quantify, because it depends on spatial variations in the coastline and the bottom topography and on seasonal variations in the winds and shelf density structure Nevertheless, these mesoscale features appear to be biologically significant For example, Incze et al (1989), Vastano et al (1992), Schumacher and Kendall (1991), Schumacher et al (1993), and Bograd et al (1994) show the coincidence between larval pollock numbers and the presence of eddies in Shelikof Strait Moreover, the nutritional condition of first-feeding larvae is significantly better inside than outside of eddies (Canino et al 1991)

The inner and mid-shelf domains share two other noteworthy characteristics First, during much of the year, the cross-shelf sea surface temperature contrasts are generally small (about 2°C) The small thermal gradients and heavy cloud cover reduce the utility of thermal infrared radiometry in assessing circulation features and frontal boundaries in the northern GOA

Second, the bottom-water properties of the shelf change markedly throughout the year The above figures show that the high-salinity bottom waters carried inshore are drawn from over the continental slope in summer This inflow occurs annually and probably exerts an important dynamical influence on the shelf circulation by modifying the bottom boundary layer (Gawarkiewicz and Chapman 1992, Chapman 2000, Pickart 2000) It might also serve as an important seasonal onshore pathway for oceanic zooplankton These animals migrate diurnally over the full depth of the water column, during the long summer day length, the zooplankton will spend more time at the bottom than at the surface The bottom flow that transports the high-salinity water shoreward might then result in a net shoreward flux of zooplankton in summer The summertime inflow of saline water onto the inner shelf is one means by which the slope and basin interior communicates directly with the nearshore, because (as discussed below) this water is drawn from within the permanent halocline (depth horizon over which salinity changes rapidly) of the GOA The deep summer inflow is a potentially important conduit for nutrients from offshore to onshore Inflow, however, is not the only means by which nutrient-rich offshore water can supply the shelf Other mechanisms include flow-up canyons intersecting the shelf break (Klinck 1996, Allen 1996, Allen 2000, Hickey 1997), topographically-induced upwelling (Freeland and Denman 1982), and shelf-break eddies and flow meanders (Bower 1991)

The third domain, consisting of the shelf break and continental slope is influenced by the Alaska Current, which flows along the northeastern and northern GOA, and its transformation west of 150° W, into the southwestward-flowing Alaskan Stream These currents comprise the poleward limb of the North Pacific Subarctic Gyre and provide the oceanic connection between the GOA shelf and the Pacific Ocean The Alaska Current is a broad (300 km), sluggish (5 to 15 cm s^{-1}) flow with weak horizontal and vertical velocity shears The Alaskan Stream is a narrow (100 km), swift (100 cm s^{-1}) flow with large velocity shear over the upper 500 m (Reed and Schumacher 1986) The stream continues westward along the southern flank of the Alaska Peninsula and Aleutian Islands and gradually weakens west of 180° W (Thomson 1972) The convergence of the Alaska Current into the Alaskan Stream probably entails concomitant changes in the velocity and thermohaline gradients along the shelf break. Insofar as these gradients influence fluxes between the shelf and slope (Gawarkiewicz 1991), the transformation of the Alaska Current into the Alaskan Stream implies that shelf-break exchange mechanisms are not uniform around the GOA. Moreover, the effects of these exchanges on the shelf will also be influenced by the shelf width, which varies from 50 km or less in the eastern and northeastern GOA to about 200 km in the northern and northwestern GOA.

The Alaskan Stream has a mean annual volume transport (flow of water) of between 15 and 20 Sv (Reed and Schumacher 1986, Musgrave et al. 1992), and although seasonal transport variations appear small, interannual transport variations may be as great as 30% (Royer 1981a). Thomson et al. (1990) found that the Alaska Current is swifter and narrower in winter than in summer. Surface salinities within the Alaska Current vary by only about 0.5 psu throughout the year, whereas the seasonal change in sea surface temperature (SST) is comparable to that of the shelf (about 10° C). Nevertheless, horizontal and vertical density gradients are controlled by the salinity distribution. Maximal stratification occurs between depths of 100 and 300 m and is associated with the permanent halocline of the GOA. Halocline salinities range between 33 and 34 psu, and temperatures are between 5° C and 6° C (Tully and Barber 1960, Dodimead et al. 1963, Reid Jr. 1965, Favorite et al. 1976, Musgrave et al. 1992). These water-mass characteristics are identical to the properties of the deep water that floods the shelf bottom each summer (Figure 3.15.)

Although eddy energies of the Alaskan Stream appear small (Royer 1981a, Reed and Schumacher 1986), significant alteration of the slope and shelf-break circulation is likely during occasional passage of large (200-km-diameter) eddies that populate the interior basin (Crawford et al. 1999). Musgrave et al. (1992) show considerable alteration in the structure of the shelf-break front off Kodiak Island during the passage of one such eddy. These eddies are long-lived (2 to 3 years) and energetic, having typical swirl speeds of 20 to 50 cm s^{-1} (Tabata 1982, Musgrave et al. 1992, Okkonen 1992, Crawford et al. 1999). They form in the eastern GOA, primarily in years of anomalously strong cyclonic wind forcing along the eastern boundary (Willmott and Mysak 1980, Melsom A. et al. 1999, Meyers and Basu 1999) and then propagate westward at about 2 to 3 cm s^{-1}. Most of the eddies remain over the deep basin and far from the continental slope, however, some propagate along the slope, requiring several months to transit from Yakutat to Kodiak Island (Crawford et al. 1999, Okkonen 2001).

Eddies that impinge upon the continental slope could significantly influence the shelf circulation and exchanges between the shelf and slope of salt, heat, nutrients, and plankton. Their influence on shelf-slope exchange in the northern GOA has not been ascertained, but because they propagate slowly, are long-lived, and form episodically, they could be a source of interannual variability for this shelf. These eddies have many features in common with the Gulf Stream rings that significantly modify shelf properties along the East Coast of the United States (Houghton et al 1986, Ramp 1986, Joyce et al 1992, Wang 1992, Schlitz submitted) In the eastern GOA, Whitney et al (1998) showed that these eddies cause a net offshelf nutrient flux In the northern GOA, they might have the opposite effect, because nutrient concentrations are generally higher over the slope than on the shelf (Whitledge 2000, Childers 2000)

3 4 4 Biophysical Implications

The magnitude of the spring phytoplankton bloom depends on surface nutrient concentrations and water-column stability The annual resupply of nutrients to the euphotic zone is not understood for the inner shelf, however Cross-shelf, surface Ekman transport in winter cannot account for the high nutrient concentrations observed on the inner shelf in spring (Childers 2000) and (Whitledge 2000) Turbulent mixing during late fall and winter could mix the nutrient-rich deep water (brought onto the shelf in summer) up into the surface layer in time for the spring bloom If so, vernal nutrient levels might result from a two-stage preconditioning process occurring during the several months preceding the spring bloom The first stage occurs in summer and is related to the onshelf movement of saline, nutrient-rich, bottom water as described above The quantity of nutrients carried onshore then depends upon the summer wind field and the properties of the slope source water that contributes to this inflow The second step occurs in fall and winter and depends on turbulence Current instabilities, downwelling-induced convection, and diffusion accomplish the vertical mixing The extent of this mixing depends upon the seasonally varying stratification and the vertical and horizontal velocity structure of the ACC Each of these mechanisms probably varies from year to year, suggesting that spring nutrient concentrations will also vary

Another potentially important nutrient source for the inner shelf in spring is PWS Winter mixing in the sound could bring nutrient-rich water to the surface, where it is exported to the shelf by that portion of the ACC that loops through PWS

The timing of the spring bloom depends on development of stratification within the euphotic zone The euphotic zone extends from the surface to a depth where sufficient light still exists to support photosynthesis Stratification within the euphotic zone is influenced by freshwater discharge and solar heating Preliminary GLOBEC data (Whitledge 2000) (Stockwell 2000) suggest that the spring bloom begins in protected regions of PWS in late March as day length increases and stratification builds as a result of snowmelt, rainfall, and the sheltering effect of the PWS from winds The bloom on the shelf lags that of PWS by from 2 to 6 weeks and may not proceed simultaneously across the shelf This delay results from the time required to stratify the shelf Because density is strongly affected by salinity and, therefore, by the spreading of fresh water on the shelf, stratification does not evolve by vertical (one-dimensional) processes phase-locked to the annual solar cycle. Rather, stratification depends primarily on the rate at which fresh water spreads offshore, which is a consequence of three-dimensional circulation and mixing processes intimately associated with ocean dynamics.

Several implications follow from this hypothesis. First, spring bloom dynamics on the shelf are not as tightly coupled to the solar cycle as on mid-latitude shelves where temperature controls density. Second, mixed-layer development depends on processes operating spanning a range of time scales and involves a plethora of variables that affect vertical mixing and the offshore flux of fresh water from the nearshore. These variables include the fractions of winter precipitation delivered to the coast as snow and rain, the timing and rate of spring snowmelt (a function of air temperature and cloudiness), and the wind velocity. The relevant time scales range from a few days (storm events) to seasonal or longer. The long time scales follow from the fact that the shelf circulation, particularly the ACC, can advect the freshwater that contributes to stratification from very distant regions. Third, interannual variability in the onset and strength of stratification on the GOA continental shelf is probably greater than for mid-latitude shelves. This expectation follows from the fact that several potentially interacting parameters affect stratification, and each or all can vary considerably from year to year. Therefore, application of Gargett's (1997) hypothesis of the optimal stability window to the GOA shelf involves more degrees of freedom than its use on either mid-latitude shelves or the central GOA (where temperature exerts primary control on stratification in the euphotic zone).

All of these considerations suggest that stratification probably does not develop uniformly in space or time on the GOA shelf. The implications are potentially enormous with respect to feeding opportunities for zooplankton in spring. These animals must encounter abundant prey shortly after migrating to the surface from their overwintering depths. Emergence from diapause (a period of reduced metabolism and inactivity) is tightly coupled to the solar cycle, rather than the onset of stratification. Conceivably then, zooplankton recruitment success might depend on shelf physical processes occurring over a period of several months prior to the onset of the bloom. In particular, the magnitude and phasing of the spring bloom might be preconditioned by shelf processes that occurred throughout the preceding summer and winter. Perturbations in the magnitude and phasing of the spring bloom might propagate through the food chain and affect summer and fall feeding success of juvenile fishes (Denman et al. 1989).

3.4.5 Tides

The tides in the GOA are of the mixed type with the principal lunar semi-diurnal (M_2) tide being dominant and the luni-solar diurnal (K_1) tide being, in general, of secondary importance. AUTHOR (WEINGARTNER): PLEASE HELP DEVELOP SOME DEFINITIONS FOR THE ABBREVIATIONS. OR CAN WE DELETE THEM BECAUSE THEY ARE NOT USED AGAIN? Tidal characteristics (amplitudes and velocities) are strongly influenced by the complex shelf and slope bathymetry and coastal geometry, however Consequently, spatial variations in the tidal characteristics of these two species are large For example, Anchorage has the largest tidal amplitudes in the northern GOA, with the M_2 tide being about 3 6 m and the K_1 tide being about 0 7 m In contrast, the amplitudes of both of these constituents in Kodiak and Seward are less than half those of Anchorage Foreman et al (Foreman et al 2000) found that the cross-shelf flux of tidal energy onto the northwest GOA shelf is enormous and is accompanied by high (bottom) frictional dissipation rates Their model estimates indicate that the tidal dissipation rate in Kennedy Entrance accounts for nearly 50% of the total dissipation of the M_2 constituent in the GOA Further, about one-third of the energy of the K_1 tide in the GOA is dissipated in Cook Inlet Some of the energy lost from tides is available for mixing, which would reduce vertical stratification and enhance the transfer of nutrients into the euphotic zone

The interaction of the tidal wave with varying bottom topography can also generate shelf waves at the diurnal frequency and generate residual flows The waves are a prominent feature of the low-frequency circulation along the British Columbian shelf (Crawford 1984, Crawford and Thomson 1984, Flather 1988, Foreman and Thomson 1997, Cummins and Oey 2000) and could affect pycnocline displacements (The pycnocline is a vertical layer across which water density changes are large and stable) The model of Foreman et al (Foreman et al 2000) predicts diurnal-period shelf waves in the northwest GOA and especially along the Kodiak shelf break Although no observations are available to confirm the presence of such waves along the Kodiak shelf, their presence could influence biological production here as well as the dispersal of planktonic organisms Residual flows resulting from non-linear tidal dynamics could (locally) influence the transport of suspended and dissolved materials on the shelf

Seasonal changes in water-column stratification can also affect the vertical distribution of tidal energy over the shelf through the generation of internal (baroclinic) waves of tidal period Such motions are likely to occur in summer and fall in the northwestern GOA where the flux of barotropic tidal energy (which is nearly uniformly distributed over the water column) across the shelf break (Foreman et al 2000) interacts with the highly stratified water column on the shelf The internal waves generated can have small spatial scales (10s of km) in contrast to the large scale (1,000s of km) of the generating barotropic tidal waves Moreover, the phases and amplitudes of the baroclinic tides will vary with seasonal changes in stratification Although no systematic investigation of internal tides on the GOA shelf has been conducted, Danielson (2000) found that the tidal velocities in the ACC near Seward in winter are about 5 cm s^{-1} and are barotropic However, in late summer, tidal velocities in the upper 50 m are about 20 cm s^{-1} whereas below 100-m depth they are about 5 cm s^{-1} Internal tides will also displace the pycnocline sufficiently to have biological consequences, including the pumping of nutrients into the surface layer, the dispersal of plankton and small fishes, and the formation of transitory and small-scale zones of horizontal divergence and convergence that affect feeding behaviors (Mann and Lazier 1996) Stratified tidal flows might also be significant for some silled fjords The interaction of the tide with the sill can enhance mixing and exchange (Farmer and Smith 1980, Freeland and Farmer 1980) and can resupply the inner fjord with nutrient-rich, high-salinity water and plankton through Bernoulli suction effects (Thompson and Golding 1981, Thomson and Wolanski 1984)

3.4.6 Gulf of Alaska Basin

The circulation in the central GOA consists of the cyclonically (counterclockwise) flowing Alaska Gyre, which is part of the more extensive subarctic gyre of the North Pacific Ocean The center of the gyre is at about 53° N, and 145° to 150° W The gyre includes the Alaska Current and Stream and the eastward-flowing North Pacific Current along the southern boundary of the GOA The latter is a trans-Pacific flow that originates at the confluence of the northward-flowing Kuroshio Current and the southward-flowing Oyashio Current in the western Pacific Some water from the Alaska Stream apparently recirculates into the North Pacific Current, but the strength and location of this recirculation is poorly understood and appears to be extremely variable (Favorite et al 1976) The North Pacific Current bifurcates off of the western coast of North America, with the northward flow feeding the Alaska Gyre and the southward branch entering the California Current The bifurcation zone is located roughly along the zero line in the climatological mean for the wind stress curl The gyral flow reflects the large-scale cyclonic wind-stress distribution over the GOA Mean speeds of drifters deployed in the upper 150 m of this gyre (far from the continental slope) are 2 to 10 cm s^{-1}, but the variability is large (Thomson et al 1990) These cyclonic winds also force a long-term average upwelling rate of about 10 to 30 m yr^{-1} in the gyre center (Xie and Hsieh 1995)

The vertical thermohaline structure of the Alaska Gyre is described by Tully and Barber (1960) and Dodimead et al (1963) and consists of the following components

1 A seasonally varying upper layer that extends from the surface to about the 100-m depth,

2 A halocline that extends from 100 m to about the 200-m depth over which salinity increases from 33 to 34 psu and temperatures decrease from 6 to 4° C, and

3 A deep layer, extending from the bottom of the halocline to about the 1,000-m depth, over which salinity increases more slowly to about 34 4 psu and temperatures decrease from 4° to 3° C

Below the deep layer salinity increases more slowly to its maximal value of about 34 7 psu at the bottom

The seasonal variations of the upper layer reflect the effects of wind-mixing and heat exchange with the atmosphere–essentially one-dimensional mixing processes. The ocean loses heat to the atmosphere from October through March and gains heat from April through September. The upper layer is isohaline and isothermal in winter down to the top of the halocline. At this time, upper-layer salinities range from 32.5 to 32.8 psu, and temperatures range from 4° to 6° C. The upper layer is fresher and colder in the northern GOA and saltier and warmer in the southern GOA. The upper layer gradually freshens and warms in spring, as wind speeds decrease and solar heating increases. A summer mixed layer forms that includes a weak secondary halocline and a strong seasonal thermocline, with both centered at about the 30-m depth. The seasonal pycnocline erodes and upper layer properties revert to winter conditions as cooling and wind-mixing increase in fall.

The halocline is a permanent feature of the Subarctic North Pacific Ocean and represents the deepest limit over which winter mixing occurs within the upper layer. The halocline results from the high (compared with other ocean basins) rates of precipitation and runoff in conjunction with large-scale, three-dimensional circulation and interior mixing processes occurring over the North Pacific (Reid Jr. 1965, Warren 1983, Van Scoy et al. 1991, Musgrave et al. 1992). The strong density gradient of the halocline effectively limits vertical exchange between saline and nutrient-rich deep water and the upper layer. The deep waters of the GOA consist of the North Pacific Intermediate Water (formed in the northwestern Pacific Ocean) and, at greater depths, contributions from the North Atlantic. Mean flows in the deep interior are feeble ($1\ cm\ s^{-1}$), and the flow dynamics are governed by both the climatological wind stress distribution (Koblinsky et al. 1989) and the global thermohaline circulation (Warren and Owens 1985) modified by the bottom topography. The thermohaline circulation carries nutrient-rich waters into the North Pacific and forces a weak and deep upwelling throughout the region (Stommel and Arons 1960a, 1960b, Reid 1981).

3.4.7 General Research Questions

What physical-chemical processes control primary and secondary production, and in particular, what processes control the timing, duration, and magnitude of the spring bloom on the inner continental shelf, including the inlets, sounds, and fjords?

Does stratification of the water column in the euphotic zone of the ACC depend primarily on the rate at which fresh water spreads offshore as a consequence of three-dimensional circulation and mixing processes associated with ocean dynamics? (Section 3.5.4.4)

Do physical oceanographic shelf processes in the ACC in the months leading up to the spring bloom precondition the magnitude and sequence of biological events during the spring bloom? (Section 3.4.4)

Does zooplankton recruitment in the ACC depend on shelf physical processes during a "preconditioning period" leading up to the onset of the spring bloom? (Section 3 4 4)

What are the sources of the nutrients in the euphotic zone on the inner shelf in the spring? (Section 3 4 4)

How are exchanges of carbon and nutrients, detritus and plankton, at the shelf break influenced by the interactions of physical processes with the Alaska Stream and the Alaska Current with the complex bathymetry of the northern and western GOA?

What is the effect of eddy structure on nutrient flux across the continental shelf slope? (Section 3 4 4)

How and where does the interaction of the tidal wave with varying bottom topography generate residual flows that transport nutrients and carbon across water mass boundaries on the inner shelf?

Do diurnal-period shelf waves along the Kodiak shelf influence biological production and the dispersal of planktonic organisms? (Section 3 4 5)

3.5 Chemical Oceanography: Marine Nutrients and Fertility

The overall fertility of the GOA depends primarily on nutrient resupply from deep-water sources to the surface layer were plants grow Rates of carbon fixation by phytoplankton in the euphotic zone are limited seasonally and annually by changing light levels and the kinds and supply rates of several dissolved inorganic chemical species Three elements–nitrogen, phosphorus, and silicon–are essential to the photosynthetic process (Parsons et al 1984) Other dissolved inorganic constituents such as iron are also believed to control rates of photosynthesis at some locations and times (Freeland et al 1997, Martin and Gordon 1988, Pahlow and Riebsell 2000)

Organic matter synthesized by plants in the lighted surface layer is consumed there or sinks down into the deeper water column where some may eventually reach the seabed The unconsumed portion is oxidized to inorganic dissolved forms by bacteria at all depths In the euphotic zone, inorganic nutrients excreted by zooplankton and by micronekton and macronekton (fish), liberated by bacterial oxidation (a process referred to as remineralization), or both excreted and liberated are immediately recycled by phytoplankton (Nekton is swimming marine life) In contrast, living cells, organic detritus (remains of dead organisms), and fecal pellets that escape the euphotic zone by sinking are remineralized below the lighted upper layer, and the resulting inorganic forms are lost to surface plant stocks The result of these combined processes leads to vertical distributions of dissolved inorganic nitrogen, phosphorus, and silicon in which the surface concentrations are much lower than those found deeper in the water column Such is the case for the GOA (Reeburgh and Kipphut 1986) Geostrophic (shaped by the earth's rotation) and wind-forced upwelling and deep seasonal overturn provide local mechanisms that bring nutrient enriched deep water back into the surface layer each year (Schumacher and Royer 1993) Additionally, at depths shallower than about 100 m, tidal mixing resulting from friction across the bottom can interact with the wind-mixed surface layer to provide an intermittent avenue for surface nutrient replenishment during all seasons

Concentrations of the dissolved inorganic forms of nitrogen (nitrate, nitrite, and ammonia), phosphorus (phosphate), and silicon (silicate) occur at some of the highest levels measured anywhere in the deep waters of the GOA (Mantyla and Reid 1983) A permanent pycnocline, resulting from the relatively low salinity of the upper 120 to 150 m, limits access to this valuable pool, however, deep winter mixing rarely reaches below about 110 m in waters over the deep ocean (Dodimead et al 1963, Favorite et al 1976) Although upwelling occurs in the center of the Alaska Gyre, it is believed to be only on the order of a meter (or considerably less) per day (Sugimoto 1993, Xie and Hsieh 1995), a relatively modest rate compared to some regions of high productivity like the Peru or Oregon coastal upwellings Away from the Alaska Gyre upwelling along the northern continental margin of the GOA, the prevailing winds drive a predominately downwelling environment over the shelf for 7 to 8 months each year Although this condition usually moderates during the summer, there is little evidence that wind-forced coastal upwelling is ever well developed Instead, during the period of relaxed downwelling or sporadic and weak upwelling, a rebound of isopycnal (density boundaries, waters having the same densities) surfaces along the shelf edge permits the run-up of dense slope water onto and across the shelf This subsurface water, containing elevated concentrations of dissolved nutrients, flows into the deeper coastal basins and fjords (Muench and Heggie 1978, Heggie and Burrell 1981) Presumably the timing and duration of this coastal bottom renewal is related to the nature of the Pacific High pressure dominance in the GOA each summer

The coastal and inshore waters in the northern GOA are also influenced by runoff from a large number of streams, rivers, and glaciers in the rugged coastal margin In these areas that are largely untouched by agriculture, this input probably contributes little to the coastal nutrient cycle, except possibly as a source for silicon and iron (Burrell 1986) Therefore, the major pool of plant nutrients for water column production in ocean, shelf, and coastal regions is derived from marine sources and resides in the deep waters below the surface production zone

The major pool of plant nutrients for water column production in ocean, shelf, and coastal regions is in deep waters

Because light limits carbon fixation during the winter months, there is a strong seasonal signal in nutrient concentrations of the euphotic zone in upper-layer shelf, coastal, and inside waters During the winter, dissolved inorganic plant nutrients build their concentrations in the deepening wind-mixed layer as deeper, nutrient rich water becomes involved in the seasonal overturn at a time when uptake by phytoplankton is minimal Under seasonal light limitation, surface nutrient concentrations probably peak in early March, just before the onset of the annual plankton production cycle. By mid- to late-May and early June, euphotic zone nutrients are drawn down dramatically to seasonal lows as the stratification that initiates the spring "bloom" of plant plankton severely restricts the vertical flux of new nutrients (Goering et al. 1973). Nitrate can become undetectable or nearly so during the summer months in many shelf and coastal areas, and ammonia (excreted by grazers) becomes important in sustaining the much-reduced primary productivity. Later in fall, with the onset of the Aleutian Low pressure system and the storms that it produces, a cooling and deepening wind-mixed layer can reinject sufficient new nutrients into a shrinking euphotic zone to initiate a fall plant bloom in some years (Eslinger et al. 2001).

The strong seasonal signal of nutrients and plant stocks evident on the continental shelf is diminished in surface waters seaward of the shelf break in the GOA. The region beyond the continental shelf break is described as "high nutrient, low chlorophyll." It was believed historically that grazing by a collective of large calanoid copepods (species of zooplankton endemic to the subarctic Pacific) consumed enough plant biomass each year to control the overall productivity below levels needed to completely exhaust the surface nitrogen (Heinrich 1962, Parsons and Lalli 1988).

More recently, iron limitation has been posed as a mechanism controlling primary production in the GOA and in several other offshore regions of the world's oceans (Martin and Gordon 1988). Contemporary research in the GOA has revealed that control of the amount of food produced by phytoplankton through grazing of zooplankters is probably important, although the species of zooplankton involved are not the large calanoid copepods (Dagg and Walser 1987, Frost 1991, Dagg 1993). Production of phytoplankton is thought to be controlled by an assemblage of microzooplankters, microconsumers, represented by abundant ciliate protozoans and small flagellates, rather than by large calanoid copepods (Booth et al. 1993). Because the growth rates of these grazers are higher than those of the plants, it is hypothesized that these microconsumers are capable of efficiently tracking and limiting the overall oceanic productivity by eating the primary producers, the phytoplankton (Banse 1982). The control mechanism is made possible because the plant communities are dominated by very small cells, 10 micrometers or less, that can serve as food for the microconsumers.

A counter-hypothesis asserts that the small size of the plants is actually in response to low levels of iron. It is known that faced with nutrient limitation, phytoplankton communities generally shift to small-sized species whose surface-area-to-volume ratios are high. Resolution of these related ideas is sought in continuing studies of the oceanic production cycle.

Surprising recent observations demonstrate a trend in increasing temperatures in the upper layers that may be causing a shift in the seasonal nutrient balance offshore (Freeland et al. 1997, Polovina et al. 1995). For the first time, there are reports that nitrogen has been drawn down to undetectable levels along line P in the southern GOA out to a distance of 600 km from the coast (Welch 2001) Line P is a an oceanographic transect run by the Canadian government that is the oldest source of data from the southern GOA In addition, the evidence provided by Welch indicates that the winter mixed layer is shoaling under long-term warming conditions

An essential issue for the GEM program will be to understand how, at a variety of spatial and temporal scales, the supply rates of inorganic nitrogen, phosphorus, silicon, and other essential nutrients for plant growth in the euphotic zone are mediated by climate-driven physical mechanisms in the GOA Inorganic nutrient supplies might be influenced by climate changes in the following ways

- Upwelling in the Alaska Gyre,
- Deep winter mixing,
- Shelf and coastal upwelling and downwelling,
- Vertical transport in frontal zones and eddies, and
- Deep and shallow cross-shelf transports

In addition to these mechanisms, the ACC may play a role that has yet to be determined in the supply rates of dissolved inorganic nutrients to nearshore habitats (Schumacher and Royer 1993) Finally, the import of marine-derived nitrogen associated with the spawning migrations of salmon and other anadromous fishes has been described as a novel means by which the oceanic GOA enriches the terrestrial margin each year This allochthonous input (food from an outside source) to the drainages bordering the GOA is clearly important in many freshwater nursery areas hosting the early life stages of Pacific salmon (Finney 1998) and must vary with interannual and longer-term changes in salmon abundance

3 5 1 General Research Questions

How are the supplies of inorganic nitrogen, phosphorous, silicon, and other nutrients essential for plant growth in the euphotic zone influenced by climate-driven physical mechanisms in the GOA?

What is the role of the Pacific High pressure system in determining the timing and duration of the movement of dense slope water onto and across the shelf to renew nutrients in the coastal bottom waters? (Section 3 5)

Is freshwater runoff a source of iron and silicon that is important to marine productivity in the ACC and other marine waters? (Section 3 5)

Does iron limitation control the species and size distribution of the plankton communities in the offshore areas?

Does zooplankton, especially microzooplankton, control the amount of food produced by phytoplankton in the offshore?

3.6 Biological Oceanography: Plankton and Productivity

3 6 1 Plankton Investigations in the Gulf of Alaska

Much of what is presently understood about the plankton communities and their productivity in the GOA has arisen from several programs examining the open ocean and shelf environments These programs have included the following

- U S -Canada NORPAC surveys (LeBrasseur 1965),
- Subarctic Pacific Ecosystem Research (SUPER) project of the National Science Foundation (NSF) (Miller 1993),
- The multi-decadal plankton observations from Canadian Ocean Station P (OSP) and Line P (McAllister 1969, Fulton 1983, Frost 1983, Parsons and Lalli 1988),
- Annual summer Japanese vessel surveys by Hokkaido University (Kawamura 1988),
- The Outer Continental Shelf Energy Assessment Program (OCSEAP) by Minerals Management Service (MMS) and National Oceanic and Atmospheric Administration (NOAA) (Hood and Zimmerman 1986), and
- The Shelikof Strait Fisheries Oceanography Cooperative Investigation (FOCI) study by NOAA and NMFS (Kendall et al 1996)

It is not understood how the quite different ecosystems of lower trophic levels in the northeastern subarctic Pacific Ocean are phased through time and interact at their boundaries over the shelf

Additional and more recent programs include the North Pacific GLOBEC of the NSF and those supported by the EVOS Trustee Council The above-mentioned programs and a few other studies provide a reasonably coherent first-order picture of the structure and function of lower trophic levels in the northeastern subarctic Pacific Ocean A serious gap in the detailed understanding of relationships between the observed inshore and offshore production cycles remains, however–namely how these quite different ecosystems are phased through time and interact at their boundaries over the shelf As a result, information is lacking about how the effects of future climate change may manifest in food webs supporting higher level consumers

3 6 2 Seasonal and Annual Plankton Dynamics

The composition, distribution, abundance, and productivity of plant and animal plankton communities in the GOA have been reviewed by Sambrotto and Lorenzen (1986), Cooney (1986), Miller (1993), and Mackas and Frost (1993) In general, dramatic differences are observed between pelagic communities over the deep ocean, and those found in shelf, coastal, and protected inside waters (sounds, fjords, and estuaries) Specifically, the euphotic zone seaward of the shelf edge is dominated year round by very small phytoplankters–tiny diatoms, naked flagellates, and cyanobacteria (Booth 1988) Most are smaller than 10 microns in size, and their combined standing stocks (measured as chlorophyll concentration) occur at very low and seasonally stable levels It was originally hypothesized that a small group of large oceanic copepods (*Neocalanus* spp and *Eucalanus bungii*) limited plant numbers and open ocean production by efficiently controlling the plant stocks through grazing (Heinrich 1962) More recent evidence, however, indicates the predominant grazers on the oceanic flora are not the large calanoids (Dagg 1993), but instead abundant populations of ciliate protozoans and heterotrophic microflagellates (Miller et al 1991a, 1991b, Frost 1993) It has been further suggested that in these high nutrient, low chlorophyll oceanic waters, very low levels of dissolved inorganic iron (coming mainly from atmospheric sources) are ultimately responsible for structuring the composition of the primary producers and consumers (Martin and Gordon 1988, Martin 1991) Close reproductive and trophic coupling between the nanophytoplankton and microconsumers appears to restrict levels of primary productivity below that needed to exhaust all of the seasonally available nitrogen each year (Banse 1982) Moreover, the excreta of the microconsumers is diffuse, with low sinking rates, and is easily oxidized by bacteria Ammonia (derived from grazer-released urea) is a preferred plant nutrient, and the first oxidation product recycled in this way Wheeler and Kokkinakis (1990) demonstrated that as long as ammonia is available for the plants, nitrate uptake in the euphotic zone is much reduced Together, these findings are painting a considerably revised picture of lower trophic level relationships and nutrient balances at the base of the offshore pelagic ecosystem in the GOA

In contrast, shelf, coastal, and inside waters host a more traditional plankton community in which large and small diatoms and dinoflagellates support a copepod-dominated grazing assemblage (Sambrotto and Lorenzen 1986, Cooney 1986) Here, the annual production cycle is characterized by well-defined spring (and sometimes fall) blooms of large diatom species (most larger than 50 microns) whose productivities are limited annually by the rapid utilization of dissolved inorganic nitrogen, phosphorus, and silicon in the euphotic zone (Eslinger et al 2001, Ward 1997) These blooms typically begin in late March and early April in response to a seasonal stabilization of the winter-conditioned deep mixed layer High rates of photosynthesis typically last only 4 to 6 weeks (Goering et al 1973) Strong periods of wind, tidal mixing, or both during the bloom can prolong these events by interrupting the conditions of light and stability needed to support plant growth When the phytoplankton bloom is prolonged in this way, its intensity is lessened, but considerably more organic matter is apparently directed into pelagic food webs, rather than sinking to feed seabed consumers (Eslinger et al 2001) Accelerated seasonal warming and freshening of the upper layers in May and June provide increasing stratification that eventually restricts the vertical flux of new nutrients and limits summer primary productivity to very low levels In some years, a fall bloom of diatoms occurs in September and October in response to a deepening wind-mixed layer and enhanced nutrient levels The ecological significance of the fall portion of the pelagic production cycle remains largely undescribed

In both the ocean and shelf domains, strong seasonal signals occur in standing stocks and estimates of daily and annual rates of production for the phytoplankton and zooplankton Some of the earliest measurements of photosynthesis at OSP placed the annual primary production in the southern part of the Alaska Gyre at about 50 grams of carbon per square meter per year (g C m^{-2} y^{-1}) (McAllister 1969), or somewhat lower than the overall world ocean average of 70 g C m^{-2} y^{-1} More recent studies using other techniques, however, have suggested higher annual rates, somewhere between 100 to 170 g C m^{-2} y^{-1} (Welschmeyer et al 1993) Unlike the production cycle over the shelf, the oceanic primary productivity does not produce an identifiable spring/summer plant bloom Instead, the oceanic phytoplankton stock remains at low levels (about 0 3 milligrams [mg] of chlorophyll a m^{-3}) year-round for reasons discussed above In stark contrast, oceanic stocks of zooplankton (upper 150 m) do exhibit marked seasonality Late winter values of 5 to 20 mg m^{-3} (wet weight) rise to 100 to 500 mg m^{-3} in mid-summer, when upper-layer populations of large calanoids dominate the standing stock Assuming the zooplankton production is roughly 15% of the oceanic primary productivity (Parsons 1986), annual estimates of zooplankton carbon production estimated from primary productivity range between 8 and 26 g C m^{-2} Given that the carbon content of an average zooplankter is approximately 45% of the dry weight, and that dry weight is about 15 % of the wet weight (Omori 1969), the carbon production can be converted to estimates of biomass Results from this calculation suggest that between 119 and 385 g of biomass m^{-2} may be produced each year in the upper layers of the oceanic regime from sources thought to be largely zooplankton

The shelf, coastal, and inside waters present a mosaic of many different pelagic habitats The open shelf (depths less than 200 m) is narrow in the east between Yakutat and Kayak Island (20 to 25 km in some places), but broadens in the north and west beyond the Copper River (about 100 to 200 km) The shelf is punctuated by submarine canyons and deep straits, but also rises to extensive shallow shoals at some locations The rugged northern coastal margin is characterized by numerous islands, coastal and protected fjords, and estuaries Only PWS is deeper than 400 m

Although the measurements are sparse, the open shelf and coastal areas of the northern GOA are believed to be quite productive, particularly the region between PWS and Shelikof Strait (Sambrotto and Lorenzen 1986) Coastal transport and turbulence along the Kenai Peninsula, in lower Cook Inlet, and around Kodiak and Afognak islands appears to enhance nutrient supplies during the spring and summer Annual rates of primary production approaching 200 to 300 g C m^{-2} y^{-1} have been described In other coastal fjords, sounds, and bays, the estimates of annual primary production range from 140 to more than 200 g C m^{-2} y^{-1} (Goering et al 1973, Sambrotto and Lorenzen 1986) Assuming again that the annual zooplankton production is roughly 15% of the primary productivity, yearly zooplankton growth in shelf and coastal areas probably ranges between about 21 and 45 g C m^{-2} y^{-1}, or 311 to 667 g m^{-2} y^{-1} wet weight. In PWS, the wet-weight biomass of zooplankton caught in nets (net-zooplankton) in the upper 50 m varies from a low in February of about 10 mg m^{-3} to a high of more than 600 mg m^{-3} in June and July (Cooney et al. 2001a). For selected other coastal areas outside PWS, the seasonal range of zooplankton biomass includes winter lows of about 40 mg m^{-3} to spring/summer highs approaching 5,000 mg m^{-3} (in outer Kachemak Bay, for which a conversion of settled volumes may have been contaminated by large phytoplankton in the samples, see (Cooney 1986).

In addition to strong seasonality in standing stocks and rates of production, plankton communities also exhibit predictable seasonal species succession each year in the oceanic and shelf environments. Over the shelf, the large diatom-dominated spring bloom gives way to dinoflagellates and other smaller forms as nutrient supplies diminish in late May and early June. Ward (1997) described the phytoplankton species succession in PWS. She found that early season dominance in the phytoplankton bloom was shared by the large chain-forming diatoms *Skeletonema, Thalassiosira*, and *Chaetoceros*. Later in June, under post-bloom nutrient restriction, diatoms were dominated by smaller *Rhizosolenia* and tiny flagellates. This seasonal shift in dominance from larger to smaller plant species in response to declining nutrient concentrations and supply rates is commonly observed in other high-latitude systems and is believed to be responsible for driving the succession in the grazing community. Because of the iron limitation in the oceanic regime, the primary producer community is more stable there, with tiny diatoms, microflagellates, and cyanobacteria dominating year-round.

The zooplankton succession is somewhat more complex and involves interchanges between the ocean and shelf ecosystems. In the late winter and spring, the early copepodite stages of *Neocalanus* spp. begin arriving in the upper layers from deepwater spawning populations (Miller 1988, Miller and Nielsen 1988, Miller and Clemons 1988). This arrival occurs in some coastal areas (at depths of more than 400m) in late February and early March, but is delayed about 30 days in the open ocean. Both *Neocalanus* spp. and *Eucalanus bungii* are interzonal seasonal migrators, living a portion of their life cycle in the upper layers as developing copepodites, and later resting in diapause in the deep water preparing for reproduction at depth. While maturing in the oceanic surface water, *Neocalanus plumchrus* and *N. flemingeri* inhabit the wind-mixed layer above the seasonal thermocline (upper 25 to 30 m), while *N. cristatus* (the largest of the subarctic copepods) and *Eucalanus bungii* are found below the seasonal stratification (Mackas et al. 1993). This unusual partitioning of the surface ocean environment by these species has not yet been verified for shelf and coastal waters, although it has been suggested that the partitioning may occur in the deep-water fjords and sounds (Cooney unpublished).

Along with the early copepodites of the interzonal migrators, the late winter and spring shelf zooplankton community also hosts small numbers of *Pseudocalanus* spp , *Metridia pacifica*, *M okhotensis*, and adult *Calanus marshallae* Because these copepods must first feed before reproducing, their seasonal numbers and biomass are set by the timing, intensity and duration of the diatom bloom By May and early June, the abundances of small copepods like *Pseudocalanus* and *Acartia* are increasing, but the community biomass is often dominated by relatively small numbers of very large developmental stages (C4 and C5) of *Neocalanus* (Cooney et al 2001a) After *Neocalanus* leaves the surface waters in late May and early June for diapause deep below the surface (at locations where depths permit), *Pseudocalanus, Acartia*, and *Centropages* (small copepods), the pteropod *Limacina pacifica*, and larvaceans (*Oikopleura* and *Fritillaria*) occur in increasing abundance Later, from summer to fall and extending into early winter, carnivorous jellyplankters represented by ctenophores, small hydromedusae, and chaetognaths (*Sagitta elegans*) become common These shifting seasonal dominants are joined by several different euphausiids (*Euphausia* and *Thysanoessa*) and amphipods (*Cyphocaris* and *Parathemisto*) throughout the year Despite the fact that the subarctic net-zooplankton community consists of a large number of different types of animal (taxa), most of the biomass and much of the abundance in the upper 100 m is accounted for by fewer than two dozen species (Cooney 1986)

3 6.3 Interannual and Decadal-Scale Variation in Plankton Stocks

Few measurements and estimates are available for year-to-year and decadal-scale variability in primary and secondary productivity in all marine environments in the northern GOA (Sambrotto and Lorenzen 1986) Fortunately, some information is available about variable levels of zooplankton stocks Frost (1993) described interannual changes in net-zooplankton sampled from 1956 to 1980 at Canadian OSP Year-to-year variations in stocks of about a factor of five were characteristic of that data set, and a slight positive correlation with salinity was observed Cooney et al (2001b) examined an 18-year time series of zooplankton settled volumes from eastern PWS collected near salmon hatcheries by the personnel of the Prince William Sound Aquaculture Corporation, Cordova Once again, annual springtime differences of about a factor of five were apparent in that data In addition, from 1981 to 1991, settled zooplankton volumes in PWS were also strongly and positively correlated with the strength of the Bakun upwelling index calculated for a location near Hinchinbrook Entrance This correlation completely disappeared after 1991, however (Eslinger et al 2001) Also of some interest, the years of highest settled volumes in eastern PWS (1985 and 1989) were only moderate years for zooplankton reported by Incze et al (1997) for Shelikof Strait, suggesting the Kodiak shelf and PWS regions were phased differently for at least those years Sugimoto and Tadokoro (1997) report a regime shift in the subarctic Pacific and Bering Sea in the early 1990s that generally resulted in lower

Few measurements are available for variability of marine environment productivity in the northern GOA zooplankton stocks in both regions Perhaps in response to this phenomenon, springtime settled zooplankton volumes in PWS also declined by about 50% after 1991 (Cooney et al 2001b)

The most provocative picture of decadal-scale change in zooplankton abundance in the GOA is provided by Brodeur and Ware (1992) With the use of spatially distributed oceanic data sets reporting zooplankton biomass from 1956 to 1962, and again from 1980 to 1989, these authors were apparently able to capture large-scale properties of the pelagic production cycle during both positive and negative aspects of the PDO (Mantua et al 1997) A doubling of net-zooplankton biomass was observed under conditions of increased winter winds responding to an intensified Aleutian Low pressure system (the decade of the 1980s) This sustained doubling of biomass was also reflected at higher trophic levels in the offshore food web (Brodeur and Ware 1995) It is generally believed the observed production stimulation during the decade of the 1980s was created by increased nutrient levels associated with greater upwelling in the Alaska Gyre The observed horizontal pattern of upper layer zooplankton stocks (Figure 3 16) was an impressive areal expansion (positive PDO) or contraction (negative PDO) Under periods of intensified winter winds, some of the highest oceanic zooplankton concentrations were developed in a band along the shelf edge in the northern regions in the GOA Unfortunately, data from the shelf itself during this same time period are not sufficient to ascertain how this elevated biomass may have intruded the continental margin or reached the coastal areas

3.6.4 Factors Effecting Trophic Exchanges Between the Plankton and Larger Consumers

Most would concede that the general theory of trophodynamics articulated by Lindeman (1942) nearly 50 years ago to represent ways in which matter and energy are transferred through aquatic communities (by different levels of producers and consumers) is an overly simplistic picture of complex interactions and non-linear relationships Useful in the lecture hall as a teaching tool, and successfully applied to certain problems where first-order estimates of production at hypothetical levels are sought based on estimates of plankton productivity, these formulations usually lack any dynamic connection with the physical environment or nutrient levels They also generally fail to delineate seasonality or other important temporal variability Nonetheless, because of the ease of their application and the acceptance of certain simplifying assumptions (generalized ecological transfer efficiencies and lumping taxa within trophic levels), the linear food-web or carbon budget approach continues to be used for selected purposes

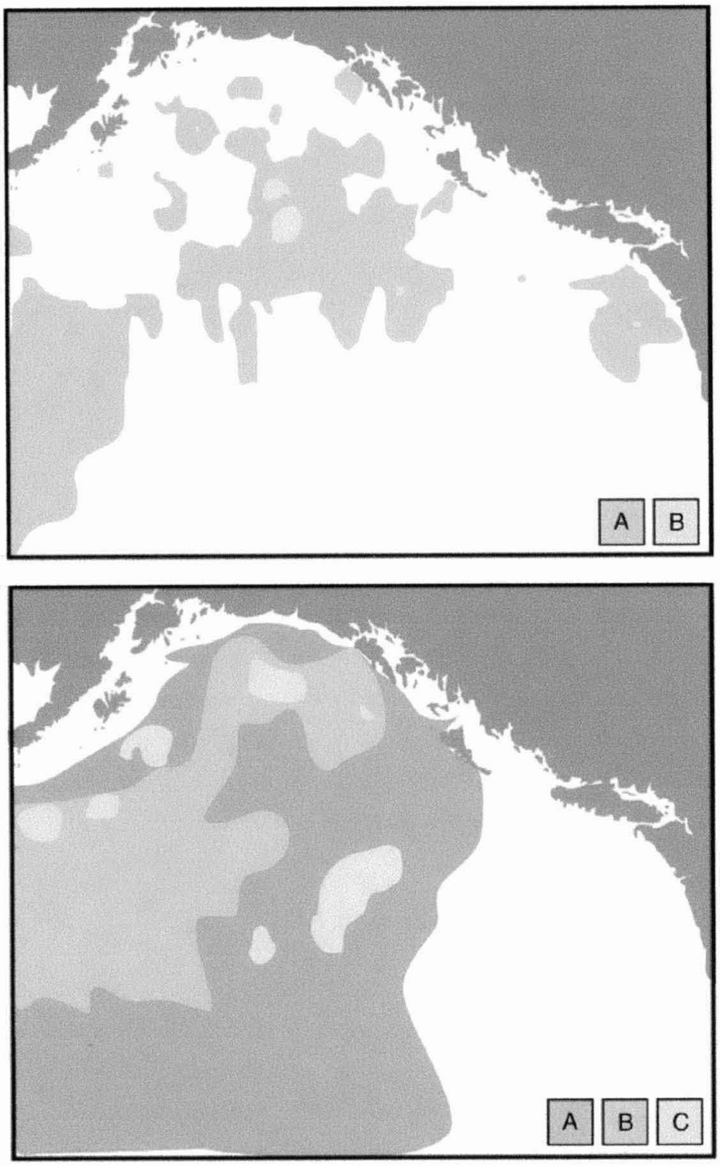


Figure 3.16 Biomass of plankton for the spring and summer period contrasted for a negative PDO period (top) and a positive PDO period (bottom). The shaded boxes present zooplankton biomass as follows: A represents 100 to 200 g/1,000 m^3; B represents 201 to 300 g/m^3, and C represents more than 300 g/m^3.

Bottom-up trophic models of food-web structure supporting the production of fishes, birds, and mammals in open ocean, slope, estuarine, and fjord environments in the GOA were formulated by Parsons (1986) in a synthesis of information compiled primarily as the result of the MMS-funded OCS studies. More recently Okey and Pauly (1998) developed a mass balance formulation with the Ecopath model of trophic mass balance for a PWS food web as the result of the EVOS Restoration Program. These models are certainly instructive at some level of generality, but their usefulness for describing specific climate-related mechanisms that might modify food-web transfers is probably limited by their detachment from the physical environment and their reliance on annually or seasonally averaged stock sizes and productivities.

Instead, it may be more instructive to examine how evolved behavioral traits and other aspects of the life histories of the dominant plankters (and other forage taxa) lend themselves to food-web transfers that could be affected by climate change. To do this, it will be important to study how the biology at lower trophic levels interacts (on a variety of time and space scales) with the physical environment to create enhanced (or diminished) trophic opportunities in the consumer matrix of different habitats and seasonal characterizations that pervade the marine ecosystem in the northern GOA. The compressed nature of the annual plankton production cycle in oceanic, shelf, and coastal waters seemingly places a premium on "timing" as a strategy to maximize the chances for successfully linking consumers to each year's burst of organic matter synthesis. Paul and Smith (1993) found that yellowfin sole replenished their seasonally depleted energy reserves each year in a short period of about 1 month following the peak in primary productivity. This rapid replenishment of energy reserves is presumably possible because of the structural properties of forage populations that occur abundantly during the short and intense production cycle. Patch-dependent feeding is a term used to describe how many consumers respond to the grainy time and space distributions of food in their feeding environments (Valiela 1995). In the case of plankters, which by definition move with the water, temporal and spatial patchiness can be created or dissipated through interactions with (1) physical processes such as vertical and horizontal transport and diffusion, and (2) biological attributes such as rapid growth and swarming or layering in association with feeding, reproductive behaviors, or both.

For example, the more than 2 month maturation process for the large oceanic copepods (*Neocalanus* spp.) growing in the near-surface of the open ocean, shelf, and some coastal environments concludes with a short period (15 to 30 days) in which the biomass peaks each year, is concentrated in the largest (C4 and C5) copepodites, and is compressed into relatively thin layers and swarms contiguous for tens, possibly hundreds of km (Mackas et al. 1993, Cooney 1989, Coyle 1997, Kirsch et al. 2000). In its most concentrated form, this seasonally ephemeral biomass is an important source of food for diving sea birds (Coyle 1997), whales, and planktivorous fishes such as adult Alaska pollock and Pacific herring (Willette et al. 1999). Acoustic observations suggest the degree of plankton swarming or layering depends, in part, on the strength of water column mixing and stability Numerical models of the production cycle in PWS demonstrated that interannual variations in the timing of the annual peak in zooplankton probably reflects differences in the timing of the earlier phytoplankton bloom each year Eslinger et al (2001) reported that the spring diatom bloom varied by as much as 3 weeks from year to year in PWS, but that the annual peak in zooplankton always lagged the plants by about 25 to 30 days Year-to-year shifts of a week or more in the peak of zooplankton biomass may profoundly influence the effectiveness of food-web transfers to fishes, birds, and other consumers with severe consequences Pacific herring have apparently evolved a reproductive strategy to place age-0 juveniles in the water column precisely at the time of the mid-summer peak in plankton forage Failure to successfully provision themselves by missing the most optimal summer feeding conditions may contribute to high rates of winter starvation for age-0 herring in PWS (Cooney et al 2001b)

In another example, Cooney (1983) reported a possible interaction between the movements occurring over the life cycle of large oceanic calanoid zooplankton, ontogentic migrations and an enrichment of feeding habitats for fishes, birds, and mammals over the shelf forced by localized convergences in the late winter and spring months As previously mentioned, *Neocalanus* spp arrive in the surface waters of the deep ocean in March and April each year Early copepodite stages are presumably carried across the shelf in the wind-forced Ekman flow (upper 60 to 90 m) where they eventually encounter zones of surface convergence (Cooney 1986) *Neocalanus* spp in the shelf environment depends on the spring diatom bloom for growth and maturation Because the developing copepodites have an affinity for the upper layers where the phytoplankton production occurs (Mackas et al 1993), they may be able to counteract regions of downwelling and convergence by continuing to migrate upward in these zones (a few tens of m per day at most) Where they successfully detach themselves from the downwelling water, populations advected shoreward into convergences (possibly in the frontal region of the ACC) will accumulate These zones of high copepod (and perhaps other taxa) biomass should represent regions of potentially high trophic efficiency for planktivores built and maintained for a few weeks by wind-forced horizontal and vertical transport.

In a related exercise, Cooney (1988) calculated that nearly 10 million metric tons of zooplankton could be introduced to the shelf annually over 1,000 km of coastline in the northern GOA by the wind-forced shoreward Ekman transport each year If only a portion of this biomass is retained in shelf and coastal food webs, the "lateral input" of ocean-derived zooplankton (much of it represented by the large interzonal calanoids) may partially explain how the seasonally persistent downwelling shelf sustains the observed high annual production at higher trophic levels Kline (1999a), in studies of carbon and nitrogen isotopes of zooplankton sampled in PWS, found that 50% or more of the diapausing *Neocalanus cristatus* overwintering in the deep water originated from populations outside PWS each year Similar isotopic signals in herring and other coastal fishes seem to confirm a partial role for the bordering ocean in "feeding" at least some coastal habitats

Coyle (1997) described the dynamics of *Neocalanus cristatus* in frontal areas along the northern and southern approaches to the Aleutian Islands In regions near water column instabilities that fostered nutrient exchange for nearby stratified phytoplankton populations, these large oceanic copepods occurred along pycnoclines in subsurface swarms and layers that were in turn attractive feeding sites for diving least auklets These trophic associations (observed acoustically) formed and dissipated in response to weather and tidal modified forcing of the waters over the shelf north and south of the Aleutian Islands

Kirsch et al (2000) described dense layers (10 to 20 m in vertical extent) of C4 and C5 *Neocalanus plumchrus, N flemingeri,* and *Calanus marshalle* in the upper 50 m of PWS that serve as seasonally important feeding zones for adult Alaska pollock and Pacific herring Swarming behavior in the upper layers by these copepods, responding to the distribution of their food in the euphotic zone, compresses *Neocalanus* into layers stretching for tens of km that are readily located and utilized by planktivores Other observations at the time found the layers of copepods were absent or only weakly developed in areas with high mixing energy like outer Montague Strait

Diel migrations of many taxa bring deep populations into the surface waters each night. The large bodied copepod *Metridia* spp and many Pacific euphausiids (*Euphausia* and *Thysanoessa*) represent zooplankters that undergo substantial daily migrations from deep to shallow waters at night. A variety of reasons have been proposed for this behavior (Longhurst 1976) Regardless of the "why," vertically migrating populations that build local concentrations near the sea surface during darkness represent another way that behavioral traits are responsible for creating patchiness that may enhance trophic exchange Cooney (1989) and Stockmar (1994) studied diel and spatial changes in the biomass of net-zooplankton and micronekton in the upper 10 m of the open ocean and shelf habitats in the northern GOA They found a consistent enrichment of biomass in the surface waters at night caused by *Metridia pacifica* and several different euphausiids that often exceeded daylight levels by a factor of five or six

Springer, et al (1996) make a strong case for the enhancement of primary and secondary productivity along the shelf edge of the southeastern Bering Sea Citing tidal mixing, transverse circulation, and eddies as mechanisms to increase nutrient supplies, this so-called "greenbelt" is described as 60% more productive than the outer-shelf environment and 270% more productive than the bordering deep ocean Earlier, Cooney and Coyle (1982) documented the presence of a high-density band of upper-layer zooplankton along the shelf edge of the eastern Bering Sea Comprised primarily of *Metridia* spp , *Neocalanus* spp , and *Eucalanus bungi,* this narrow zone of elevated biomass is apparently also a part of the greenbelt Although these features have yet to be described for the northern GOA, the present North Pacific GLOBEC study (Weingartner 2000) is monitoring primary productivity and zooplankton stocks along cross-shelf transects that should intercept a shelf-edge greenbelt if one is present in the northern GOA

Finally, meso and large-scale eddy formation over the shelf and slope regimes may also influence the patchiness of plankton in ways that could be susceptible to changing climate forcing A permanent feature (eddy) in the coastal water west of Kayak Island is often visible because of entrained sediment from the Copper River Formed by a branch of the ACC, this eddy may help concentrate plankton populations of the upper layer in ways that could later influence PWS (Reed and Schumacher 1986) Vaughan et al (2001) and Wang (2001) describe surface eddies in the central region of PWS with implications for the transport and retention of icthyoplankton These eddies (cyclonic and anticyclonic) are believed to form in response to seasonal changes in freshwater outflow and wind forcing Large-scale coastal and shelf eddies apparently form near Sitka and propagate north and west around the periphery of the GOA (Musgrave et al 1992) Similar features on the east coast of the United States have been shown to be long-lived (many months) and capable of sustaining unique biological assemblages as they move through time and space These same characteristics are also expected for the northern GOA

3 6 5 Climate Forcing of Plankton Production in the Gulf of Alaska

A major challenge for the GEM program will be to eventually produce a detailed understanding of lower trophic level processes that arise through biological interactions with the spatially distributed geological and physical properties of the northern GOA This evolving understanding must take into account the flow-through nature of the northern and eastern regions–downstream from southern Southeast Alaska and Northern Canada (through the ACC) and also downstream from portions of the southern oceanic Subarctic and Transition Zone domains (through the North Pacific and Alaska currents) The "open" condition places increasing importance on understanding levels of plankton imports (from the south) and exports (to the west) in the periphery of the GOA affected by the ACC (Napp et al 1996) and shelf-break flows (Alaska Current and Alaska Stream) It will also be necessary to understand the effects that the open ocean gyre may exert on shelf and coastal plankton stocks and their seasonal and annual production within the northern GOA Here too the import (or export) of nutrients, organic detritus, and living plankton stocks to (or from) the shelf must be evaluated under different conditions of climate and weather

The picture that emerges from the aggregate of previous and ongoing plankton studies portrays a large oceanic ecosystem forced strongly by physical processes that are meteorologically driven Physical processes such as deep and shallow currents, large-scale and localized upwelling and downwelling, seasonally phased precipitation, and runoff may bring about changes in the ecosystem The reproduction, growth and death processes of the plants and animals of the oceanic ecosystem appear to be responding primarily to marked seasonality and interannual and longer-period shifts in the intensity and location of the winter

Aleutian Low pressure system. Increased upwelling in the offshore Alaska Gyre may promote higher rates of nutrient renewal in the oceanic surface waters with attendant increases in primary and secondary productivity. Elevated wind-forcing probably accelerates the transport of upper-layer oceanic zooplankton shoreward to the shelf edge and beyond. The frequency and degree to which this ocean-derived biomass "feeds" the food webs of the continental shelf and coastal areas will depend, in part, on biological interactions with a large array of physical processes and phenomena. Processes and phenomena active in regions of horizontal and vertical currents associated with oceanographic fronts, eddies, coastal jets, shelf-break flows, and turbulence are expected to have a strong influence on the movement of ocean biomass onto the shelf and coastal areas. The actual effect of such processes and phenomena on distribution of oceanic biomass also depends on responses of plankton production to changes in levels of freshwater runoff in these regions, and on the seasonal and longer cycles in temperature and salinity. Specific mechanisms by which surface zone nutrient levels are cycled and maintained in the variety of different habitats that compose the open shelf and rugged coastal margins must be understood in much greater detail to be useful to the overall GEM mission.

It seems likely that the sophisticated understanding sought by the GEM program of climate influences on the coupled nutrient and plankton production regimes that support selected consumer stocks may have to come from studies that abandon the practice of lumping taxa within broad ecologically functional units, and instead focus on "key species." Fortunately, the subarctic pelagic ecosystem (oceanic, shelf, and coastal) is dominated by a relatively small number of plankton species that serve as major conduits for matter and energy exchange to higher-level consumers each year. In the case of the zooplankton, fewer than 50 species within a handful of major taxa comprise 95% or more of the abundance and biomass throughout the year. Because of this pattern of dominance, and further because of the different life history strategies employed by these species, a more comprehensive understanding of their ecological roles is both necessary and feasible. A decision to conduct dominant species ecology must be understood at all levels of the study so that, for instance, technicians conducting future stomach analyses of fishes, birds, or mammals will report not just "large copepods and amphipods," but rather *Neocalanus cristatus* and *Parathemisto libellula*. This nuance holds particular importance for future modelers working on numerical formulations that include "plankton." Without this degree of specificity, it is unlikely that further (field and numerical) studies will forge the understanding of lower trophic level function sought by the GEM program in the northern GOA.

3.6.6 General Research Questions

What are the relationships between the inshore (watersheds, intertidal-subtidal, and ACC) and offshore production cycles, how are the inshore and offshore phased through time, and how do they interact at their boundaries over the shelf?

- How are the relationships between offshore and inshore production manifested in food webs supporting birds, fish and mammals?
- How are the effects of future climate change manifested in inshore and offshore food webs supporting birds, fish and mammals?

What are the changes in abundance of the individual species of large copepods, amphipods and euphausiids that make up the bulk of the secondary production in the inshore and offshore GOA?

3 7 Nearshore Benthic Communities

Because the GOA covers a vast and diverse area, its benthic communities exhibit tremendous variation (Feder and Jewett 1986) As in any marine benthic system, however, the composition, functioning, and dynamics of the GOA benthic communities change predictably with certain universally important variables The most important two environmental variables are water depth and substratum type (Rafaelli and Hawkins 1996) The following depth zones are typically distinguished

- The intertidal zone,
- The shallow subtidal zone (bounded by depth of light penetration sufficient for photosythesis of benthic algae),
- The continental shelf (to about 200 m), and
- The continental slope (from 200 to 4,000 m)

The most fundamental substratum distinctions are hard bottom (rocks, boulders, cobbles) and soft bottom (mobile sedimentary habitats like sands and muds) Within these two types, geomorphology varies substantially, with biological implications that often induce further habitat partitioning (Page et al 1995, Sundberg et al 1996)

Understanding of community composition and seasonal dynamics of GOA benthos has grown dramatically over the past 30 years, with two distinct pulses of research First, in contemplation of exploration and development of the oil and gas resources of the region, the MMS, NOAA NMFS, and Alyeska Consortium funded geographically focused benthic survey and monitoring work in the 1970s This work provided the first windows into the quantitative benthic ecology of the region Focus was most intense on lower Cook Inlet, the Aleutian Islands, the Alaska Peninsula, Kodiak Island, and northeast GOA, including the Valdez Arm in PWS (Rosenberg 1972, Hood and Zimmerman 1986) The second phase of growth in knowledge of the benthos of the GOA region was triggered by the EVOS in 1989 This work had broad geographic coverage of the rocky intertidal zone The area receiving the most intense study was PWS, where the spill originated Geographic coverage also included two other regions, the Kenai Peninsula-lower Cook Inlet and the Kodiak archipelago-Alaska Peninsula (Page et al 1995, Gilfillan et al 1995a, Gilfillan et al 1996b, Highsmith et al 1994b, Highsmith et al 1996, Houghton et al 1996a, Houghton et al 1996b, Sundberg et al 1996) Some of this benthic study following the oil spill was conducted in other habitats (soft substrata [Driskell et al 1996]) and at other depths (shallow and deep subtidal habitats (Houghton et al 1993, Armstrong et al 1995, Dean et al 1996a, Dean et al 1996b, Dean et al 1998, Dean et al 2000, Feder and Blanchard 1998, Jewett et al 1999) Herring Bay on Knight Island in PWS was a site of especially intense monitoring and experimentation on rocky intertidal communities following the oil spill (van Tamelen et al 1997)

3 7 1 Intertidal Communities

The intertidal habitat is the portion of the shoreline in between the high and low (0 0-m datum) tide marks This intertidal zone occupies the unique triple interface among the land, sea, and air The land provides substrate for occupation by intertidal organisms, the seawater the vehicle to supply necessary nutrients, and the air a medium for passage of solar energy, yet a source of physical stresses (Connell 1972, Underwood and Denley 1984, Peterson 1991) Interfaces between separate systems are locations of typically high biological activity As a triple interface, the intertidal zone is exceptionally rich and biologically productive (Ricketts and Calvin 1968, Leigh et al 1987) Wind and tidal energy combine to subsidize the intertidal zone with planktonic foods produced in the photic (sun-lit) zone of the coastal ocean Runoff from the adjacent land mass injects new supplies of inorganic nutrients to help fuel coastal production of benthic algae, although such runoff in Alaska is typically nutrient-poor and can be very turbid (Hood and Zimmerman 1986) The consequent abundance and diversity of life and life forms in the intertidal zone serves many important consumers, coming from land, sea, and air, and including humans The aesthetic, economic, cultural, and recreational values of the intertidal zone and its resources augment its significance, especially in the GOA region (Peterson 2001)

The biota of intertidal habitats varies with changes in physical substrate type, wave energy regime, and atmospheric climate (Lubchenco and Gaines 1981) Substrata in the GOA intertidal zone differ as a function of size, ranging from immobile rock walls and platforms, to boulders and cobbles, to gravel, to sands, and finally to muds at the finest end of this particle-size spectrum Rock surfaces in the intertidal zone are populated by epibiota, which are most commonly attached macro- and microalgae, sessile, or immobile, suspension-feeding invertebrates, and mobile grazing invertebrates, as well as predatory seastars and gastropods (Connell 1972, Rafaelli and Hawkins 1996) Unconsolidated (soft) substrata–the sands and muds–are occupied by large plants in low-energy environments, such as marshes, and microalgae and infaunal (buried) invertebrates in all energy regimes (Peterson 1991) Mobile scavenging and predatory invertebrates occur on both types of substratum Intertidal communities vary with wave energy because of biomechanical constraints (especially on potentially significant predators), changing levels of food subsidy, and interdependencies between wave energy and substratum type (Leigh et al 1987, Denny 1988) Intertidal communities tend to be most luxurious in temperate climates, ice scour and turbid fresh water limit intertidal biota at high latitudes such as those in the eastern GOA The rocky intertidal communities of the Pacific Northwest, including the rocky shores of islands in the GOA region, are highly diverse, although less so than those in Washington These communities are also productive, although limited by disturbance of winter storms and reduced solar insulation (Bakus 1978)

The rocky intertidal ecosystem may represent the best understood natural community of plants and animals on earth Ecologists realized more than 40 years ago that this system was uniquely well suited to experimentation because the habitat was accessible and basically two-dimensional and the organisms were manipulable and observable Consequently, ecological science has used sophisticated experimental manipulations to produce a detailed understanding of the complex processes involved in determining patterns of distribution and abundance of rocky intertidal organisms (Paine et al 1996, Dayton 1971, Connell 1972, Underwood and Denley 1984) Plants and animals of temperate rocky shores exhibit strong patterns of vertical zonation in the intertidal zone Physical stresses tend to limit the upper distributions of species populations and to be more important higher onshore, competition for space and predation tend to limit distributions lower on the shore Surface space for attachment is potentially limiting to both plants and animals in the rocky intertidal zone In the absence of disturbance, space becomes limiting, and competition for that limited space results in competitive exclusion of inferior competitors and monopolization of space by a competitive dominant Physical disturbance, biological disturbance, and recruitment limitation are all processes that can serve to maintain densities below the level at which competitive exclusion occurs (Menge and Sutherland 1987) Because of the importance of such strong biological interactions in determining the community structure and dynamics in this system, changes in abundance of certain keystone species can produce intense direct and indirect effects on other species that cascade through the ecosystem (Menge et al 1994, Wootton 1994, Menge 1995), (Paine et al 1996)

Intertidal communities occupying unconsolidated sediments (sands and muds) are quite different from those found on rocky shores (Peterson 1991) These soft-bottom communities are composed of infaunal (buried) invertebrates, mobile microalgae, and abundant transient consumers, such as shorebirds, fishes, and crustaceans (Rafaelli and Hawkins 1996) Macroalgae are sparse, and are found attached to large shell fragments or other stable hard substrata In very low energy environments, large plants, such as salt marsh grasses and forbs high on shore and seagrasses low on shore, occur in intertidal soft sediments (Peterson 1991) The large stretch of intertidal soft-sediment shore in between those vegetated zones has an empty appearance, which is misleading The plants are microscopic and productive, the invertebrate animals are buried out of sight. The soft-bottom intertidal habitat represents a critically important feeding ground, especially for shorebirds, because the flat topography allows easier access than is provided by steep rocky coasts and because invertebrates without heavy protective calcium carbonate shells are common, particularly polychaetes and amphipods (Peterson 1991)

The intertidal shorelines of the GOA exhibit a wide range of habitat types True soft-sediment shores are not common, except in Cook Inlet Marshes, fine-grained and coarse-grained sand beaches, and exposed and sheltered tidal flats represent a small fraction of the coastline in the GOA Sheltered and exposed rocky shores, wave-cut platforms, and beaches with varying mixtures of sand, gravel, cobble, and boulders are the dominant habitats in this region (Page et al 1995, Sundberg et al 1996) Abundance, biomass, productivity, and diversity of intertidal communities on the shores of the eastern GOA with nearby glaciers are depressed by proximity to sources of runoff from glacier ice melt The islands in PWS and the Aleutian Islands, for example, have richer intertidal communities than the mainland of the northeast GOA, and the intertidal communities of Kodiak and Afognak tend to be richer than those of the Shelikof Strait mainland on the Alaska Peninsula (Bakus 1978, Highsmith et al 1994b) Glacier ice melt depresses intertidal biotic communities by introducing turbidity and freshwater stresses

Winter ice scour seasonally denudes epibiota along the Cook Inlet shores (Bakus 1978) Intense wave exposure can cause substratum instability on intertidal cobble and boulder shores, thereby removing intertidal epibiota directly through abrasion (Sousa 1979) Shores with well rounded cobbles and boulders have accordingly poorer intertidal biotas than those with reduced levels of physical disturbance Bashing from logs also represents an agent of disturbance to those rocky shores exposed to intense wave action in this region (Dayton 1971) Consequently, exposed rocky coastlines may experience more seasonal fluctuations in epibiotic coverage than communities on similar substrata in protected fjords and embayments (Bakus 1978)

The rocky intertidal shores of the spill area exhibit a typical pattern of vertical zonation, although the particular species that dominate vary in importance as a function of changing habitat conditions (Highsmith et al 1996, Houghton et al 1996a, Houghton et al 1996b) Vertical zonation on intertidal rocky shores is a universal feature, caused by a combination of direct and indirect effects of height-specific duration of exposure to air (Paine 1966, Connell 1972)

The uppermost intertidal zone on rocky shores of the GOA is characterized by a dark band of the alga *Verruccaria* The rockweed (*Fucus gardneri*) dominates the upper intertidal zone, which also includes two common barnacles (*Balanus glandula* and *Chthamalus dalli*), two abundant limpets (*Tectura persona* and *Lottia pelta*), and the periwinkle (*Littorina sitkana*) (SAI 1980, Hood and Zimmerman 1986, Highsmith et al 1994b)

The middle intertidal zone commonly has even higher cover of *Fucus*, along with beds of blue mussels (*Mytilus trossulus*), the periwinkle (*Littorina scutulata*), barnacles, and the predatory drilling snail (*Nucella lamellosa and N. lima*) (Carroll and Highsmith 1996). In the low intertidal zone, a red alga (*Rhodymenia palmata*) often is dominant, although mussel beds often occupy large areas and the grazing chitons (*Katharina tunicata, Mopalia mucosa,* and *Tonicella lineata*) and predatory seastars (*Leptasterias hexactis* and others) occur here (SAI 1980, Highsmith et al. 1994b). The blue mussel is a very significant member of this community because it is a potential competitive dominant (VanBlaricom 1987) and because its byssus and between-shell interstices provide a protected habitat for a diverse suite of smaller mobile invertebrates, including isopods, amphipods, polychaetes, gastropods, and crabs (Suchanek 1985).

Abundances of rocky intertidal plants and animals in the GOA are controlled by the same suite of factors that affect rocky shore abundances and dynamics elsewhere, especially in the Pacific Northwest. Physical factors, such as wave action from winter storms, exposure to air high on shore, ice scour, and low salinity and turbidity from glacial and land runoff, have important effects on wave-exposed areas (Dayton 1971, Dayton 1975, Bakus 1978).

Biological controls also exert significant influences. Probably the most significant of these likely controlling factors for intertidal biota are predation and recruitment limitation. Predation by seastars is an important control of invertebrate prey population abundances and, therefore, of community composition low on intertidal rocky shores (Paine 1966, Dethier and Duggins 1988). Because blue mussels are typically the preferred prey and represent the dominant competitor for potentially limited attachment space, this predation by seastars has important cascading effects of enhancing abundances of poorer competitors on the rock surfaces (Paine 1966). Predation by gastropods occasionally helps control mussel abundances (Carroll and Highsmith 1996) and barnacle populations higher on shore in the GOA (Ebert and Lees 1996). Shorebird predation, especially by black oystercatchers, is also known to limit abundances of limpets on horizontal rock surfaces of the Pacific Northwest intertidal zones, and this process can be readily disrupted by human inference with the shy shorebirds (Lindberg et al. 1998). The presence of numerous strong biotic interactions in this rocky intertidal community of the GOA led to many indirect effects of the EVOS in this system (Peterson 2001). Because of the influence of current flows and mortality factors such as predation in the water column, larval recruitment can also limit population abundances of marine invertebrates on intertidal rocky coasts (Gaines and Roughgarden 1987, Menge and Sutherland 1987). With a short warm season of high production in the GOA, the potential for such recruitment limitation seems high, but process studies to characterize and quantify this factor have not been conducted in the GOA. Changes in primary production, water temperature (and thus breeding season), and physical transport dynamics associated with regional climate shifts could reasonably be expected to regulate the intensity of recruitment limitation on some rocky shores in the GOA.

The consequences of change caused by various natural and human-driven factors on the structure and dynamics of the rocky intertidal communities are not well developed in the scientific literature. For example, human harvest by fisheries or subsistence users of important apex predators that exert top-down control on intertidal communities could cause substantial cascading effects through the system. But the seastars and gastropods that are the strong predatory interactors in this community in the GOA region are not targets for harvest. The mussels that are taken in subsistence harvest provide important ecosystem services as structural habitat for small invertebrates (Suchanek 1985), as a dominant space competitor (Paine 1966), and as a widely used prey resource (Peterson 2001), but mussels do not appear limited in abundance in the GOA region.

Oceanographic processes related to climate change, either natural or human-driven through global warming, have the potential to either enhance or reduce recruitment of component invertebrate species of the rocky intertidal communities, but studies of the connections between coastal physical dynamics and shoreline communities are in their infancy (Caley et al. 1996). Perhaps the best documented driver of change in composition and dynamics of rocky intertidal communities is the impact of oil spills. The cleanup treatments after the spill, either dispersants (Southward and Southward 1978) or pressurized washes (Mearns 1996), have far more serious impacts than the oil itself. Because of the important strong interactions among species in rocky shore communities, the multiple indirect effects of oil spills on this system take about a decade to work their way out of the system (Southward and Southward 1978, Peterson 2001). Intensive sampling and experimental work on rocky intertidal communities on sheltered shores in PWS following the EVOS make this region data-rich relative to most other Alaskan shores.

Intertidal soft sediments in the spill region of the GOA typically possess lower biomass of macroalgae and invertebrates than corresponding rocky shores at the same elevations (SAI 1980, Highsmith et al. 1994b). The taxonomic groups that dominate intertidal soft bottoms are polychaete worms, mollusks (especially bivalves), and amphipods (Driskell et al. 1996). Sandy sediments have higher representation by suspension-feeding invertebrates, whereas finer, muddy sediments are dominated by deposit-feeding species (Bakus 1978, Feder and Jewett 1986). Intertidal sandy beaches are habitat for several large suspension-feeding clams in the GOA that represent important prey resources for many valued consumers and that support commercial, recreational, and subsistence harvest (Feder and Kaiser 1980). Most important are the littleneck clam (*Protothaca staminea*), the butter clam (*Saxidomus giganteus*), the razor clam (*Siliqua patula*), the cockle (*Clinocardium nuttallii*), the pink-neck clam (*Spisula polynyma*), the gapers (*Tresus nuttallii* and *T. capax*), and others (Feder and Paul 1974). In mudflats, such as those along the shores of Cook Inlet, dense beds of a deposit-feeding clam, *Macoma balthica*, and the soft-shell clam (*Mya arenaria*) frequently occur (Feder et al. 1990). These two relatively soft-shelled clams are significant food resources for many seaducks, and the hard-shelled clams are important prey for sea otters.

(Kvitek and Oliver 1992, Kvitek et al 1992), black and brown bears (Bakus 1978), and several invertebrate consumers Intertidal soft-bottom habitats are also important feeding grounds for shorebirds and for demersal (deep-water) fishes and crustaceans (Peterson 2001) In addition to macrofaunal invertebrates, smaller meiofaunal invertebrates are abundant on intertidal sedimentary shores Macrofauna describes animals that are retained on a 0 5-mm mesh, meiofauna refers to animals passing through a 0 5-mm mesh but retained on 0 06-mm mesh, and microfauna are animals smaller than 0 06 mm Nematode worms and harpacticoid_copepods are the most common meofaunal taxa in the GOA region (Feder and Paul 1980b) Harpacticoids serve an important role in the coastal food chain as prey for juvenile fishes, including salmonids (Sturdevant et al 1996)

Little information exists on the dynamics of long-term change in structure and composition of intertidal communities in soft sediments anywhere Some of the best understanding of important processes actually comes from the northern GOA region The Alaska earthquake of 1964 had a tremendous influence on soft-sediment intertidal communities because of the geomorphological modifications of habitat (NRC 1971) Uplift of the shoreline around Cordova, for example, was great enough to elevate the sedimentary shelf habitat out of the depth range that could be occupied by many species of clams Clam populations in Cordova, a town once called the clam capital of the world, have never recovered from the earthquake The re-invasion of sea otters has similarly caused tremendous changes in clam populations in shallow soft-sediment communities of the northern GOA, mostly in subtidal areas, but also in intertidal sedimentary environments (Kvitek et al 1992)

Human impacts can cause change in soft-sediment intertidal communities as well Probably the most common means by which human activities modify soft-sediment communities in intertidal habitats is through alteration of sediments themselves The application of pressurized wash after the EVOS, for example, eroded fine sediments from intertidal areas (Driskell et al 1996) and may be responsible for long delay in recovery of clams and other invertebrates because of a slow return of sediments (Coats et al 1999, Shigenaka et al 1999) Addition of organic enrichment can stimulate growth, abundance, and production of opportunistic infaunal invertebrates such as several polychaetes and oligochaetes in intertidal sediments Such responses were documented following the EVOS (Gilfillan et al 1995a, Jewett et al 1999), presumably because the oil itself represented organic enrichment that entered the food chain through enhanced bacterial production (Peterson 2001) Other types of organic enrichment, such as biochemical oxygen demand in treated wastewater from municipal treatment facilities or industrial discharges, can create these same responses Deposits of toxic heavy metals from mining or other industrial activities and of toxic synthetic organic or natural organic contaminants, like PAHs in oil, can cause change in intertidal benthic communities by selectively removing sensitive taxa such as echinoderms and some crustaceans (Jewett et al 1999)

Intertidal communities are open to use by consumers from other systems The great extent and importance of this habitat as a feeding grounds for major marine, terrestrial, and aerial predators render the intertidal system a key to integrating understanding of the function in the entire coastal ecosystem (Peterson 2001) The intertidal habitats of the GOA are critically important feeding grounds for many important consumers

> *The intertidal habitats of the GOA are critically important feeding grounds for marine, terrestrial, and avian consumers*

- Marine–sea otters, juvenile Dungeness and other crabs, juvenile shrimps, rockfishes, cod, cutthroat trout, and Dolly Varden char in summer, and juvenile fishes of other stocks exploited commercially, recreationally, and for subsistence, including pink and chum salmon,
- Terrestrial–brown bears, black bears, river otters, Sitka black-tailed deer, and humans, and
- Avian–black oystercatchers and other shorebirds, harlequin ducks, surf scoters, goldeneyes, and other seaducks, and bald eagles

Intertidal gravels in anadromous streams are important spawning grounds for pink salmon, especially in PWS Therefore, the intertidal habitat provides vital ecosystem services in the form of prey resources, spawning habitat, and nursery, as well as human services in the form of commercial, recreational, and subsistence harvest of shellfishes and aesthetic, cultural, and recreational opportunities In short, a habitat that represents only a small fraction of the total area of the seafloor may be the most valuable for the services it provides to the coastal ecosystem and to humans

3.7 2 Subtidal Communities

The subtidal habitat is the portion of the seafloor found at depths below the low tide (0 0 m datum) mark on shore This habitat includes a relatively narrow band of shallow subtidal bottom at depths in the photic zone (the zone penetrated by light), where plants can live, and a large area of unlit seafloor, the deep subtidal bottom extending across the continental shelf and slope to depths of 4,000 m in the GOA (Feder and Jewett 1986) The depth to which sufficient light penetrates to support photosynthesis and the slope of the subtidal seafloor determine the width of the shallow subtidal zone Along a tectonic coastline like the GOA, depth gradients are typically steep In addition, injection of turbidity from glacier ice melt along the coast reduces light penetration through the seawater These factors combine to produce a shallow subtidal zone supporting benthic plant production in the region of the spill that is very narrow Consequently, the vast majority of the subtidal ecosystem, the deep subtidal area on the continental shelf and slope, depends on an energy subsidy in the form of inputs of organic matter from other marine and, to some small extent, even terrestrial habitats These organic inputs include most importantly detritus from production of intertidal seaweeds and from shallow subtidal seagrasses, seaweeds, and kelps, as well as particulate inputs from phytoplankton, zooplankton, and zooplankton fecal pellets sinking down from the photic zone above to settle on the seafloor In addition, the carcasses of large animals such as whales, other marine mammals, and fishes occasionally sink to the bottom and provide large discrete packages of detritus to fuel subsequent microbial and animal production in the deep subtidal ecosystem

Although narrow, the shallow subtidal zone in which primary production does occur is of substantial ecological significance Many of these vegetated habitats, especially seagrass beds, macrophyte beds, and kelps, provide the following

1 Nursery grounds for marine animals from other habitats,

2 Unique habitat for a resident community of plant-associated animals,

3 Feeding grounds for important consumers, including marine mammals, seaducks, and many fishes and shellfishes, and

4 A source of primary production for export as detritus to the deeper unlit seafloor ecosystem (Schiel and Foster 1986, Duggins et al 1989)

In the spill area, eelgrass (*Zostera marina*) beds are common in shallow sedimentary bottoms at the margins of protected embayments (McRoy 1970), whereas on shallow rocky subtidal habitats, the kelps *Agarum, Laminaria,* and *Nereocystis* form dense beds along a large fraction of the coast (Calvin and Ellis 1978, SAI 1980, Dean et al 1996a) Productivity estimates in wet weight for larger kelps *Nereocystis* and *Laminaria* in the northeastern GOA range up to 37 to 72 $kg/m^2/yr$ (O'Clair and Zimmerman 1986) In this shallow subtidal zone, primary production also occurs in the form of single-celled algae These microbial plants include both the phytoplankton in the water column and benthic microalgae on and in the sediments and rocks of the shallow seafloor Both the planktonic and the benthic microalgae represent ecologically important food sources for herbivorous marine consumers The typically high turnover rates and high food value of these microalgal foods in the shallow subtidal zone helps explain the high production of invertebrate and vertebrate consumers in this environment

The sessile or slow-moving benthic invertebrates on the seafloor represent the bulk of the herbivore trophic level in the subtidal ecosystem This benthic invertebrate fauna in the shallow subtidal zone differs markedly as a function of bottom type (Peterson 1991) Rocky bottoms are inhabited by epifaunal benthic invertebrates, such as sponges, bryozoans, barnacles, anthozoans, tunicates, and mussels Sand and mud bottoms are occupied largely by infaunal (buried) invertebrates, such as polychaete worms, clams, nematodes, and amphipods The feeding or trophic types of benthic invertebrates vary with environment, especially with current flow regime (Rhoads and Young 1970) Under more rapid flows, the benthos is dominated by suspension feeders, animals extracting particulate foods out of suspension in the water column Under slower flows, deposit feeders dominate the benthos, feeding on organic materials deposited on or in the seafloor

The benthos also includes some predatory invertebrates, such as seastars (for example, leather star, *Dermasterias imbricata,* and sunflower star, *Pycnopodia helianthoides*), crabs (for example, helmet crab, *Telmessus cheiragonus*), some gastropods, and some scavenging invertebrates (Dean et al 1996b) Benthic invertebrates of soft sediments are distinguished by size, with entirely different taxa and even phyla occurring in the separate size classes Macrofauna include the most widely recognized groups such as polychaete worms, clams, gastropods, amphipods, holothurians, and seastars (Hatch 2001, Driskell et al 1996) Meiofauna include most prominently in the GOA nematodes, harpacticoid copepods, and turbellarians (Feder and Paul 1980b) Finally, microfauna include most prominently foraminifera, ciliates, and other protozoans Because the actual species composition of the benthos changes with water depth, the shallow and deep subtidal benthic faunas in the spill zone hold few species in common Soft-sediment communities of Alaska are best described and understood in various locations within PWS, as a consequence of the intense study after the oil spill

The shallow subtidal rocky shores that are vegetated also include suites of benthic invertebrates unique to those systems These benthic invertebrates either directly consume the large plants, such as sea urchins, or else are associated with the plant as habitat. Those species that depend upon the plant as habitat, such as several species of amphipods, crabs and other crustaceans, gastropods, and polychaetes, often are grazers as well, taking some mixture of macrophytic and epiphytic algae in their diets Grazing by sea urchins on kelps is sufficiently intense in the absence of predation on the urchins, especially by sea otters in the spill area, to create what are known as "urchin barrens" in which the macrophytic vegetation is virtually removed from the seafloor (Estes and Palmisano 1974, Simenstad et al 1978) In fact, this shallow subtidal community on rocky shores of the GOA represents the best example in all of marine ecology of a system controlled by top-down predation Sea otters control abundance of the green sea urchin, *Strongylocentrotus droebachiensis* When released from that otter predation, sea urchin abundance increases to create fronts of urchins that overgraze and denude the kelps and other macroalgae, leaving only crustose forms behind (Simenstad et al 1978) This loss of macroalgal habitat then reduces the algal associated invertebrate populations and the fishes that use the vegetated habitat as nursery These reductions in turn can influence productivity and abundance of piscivorous seabirds (Estes and Palmisano 1974) Recently, reduction of traditional marine mammal prey of killer whales has induced those apex consumers to switch to eating sea otters in the Aleutians, thereby extending this trophic cascade of strong interactions to yet another level (Estes et al 1998, Estes 1999)

Predation and biogenic habitat influence the shallow subtidal community on rocky shores of the GOA

Consequently, the shallow subtidal community on rocky shores of the GOA is strongly influenced by predation and provision of biogenic habitat (Estes and Duggins 1995) Human disruption of the apex predators by hunting them (as historically occurred on sea otters [Simenstad et al 1978]) or by reducing their prey (as may conceivably be occurring in the case of the Steller sea lions and harbor seals through overfishing their own prey fishes [NRC 1996]) has great potential to create tremendous cascading effects through the shallow subtidal benthic ecosystem Furthermore, if concentration and biomagnification of organic contaminants such as PCBs, DDT, DDE, and dioxins in the tissues of apex predators, in particular in transient killer whales (Matkin unpublished data), causes impaired reproductive success, then human industrial pollution has great potential to modify these coastal subtidal communities on rocky shores

The shallow subtidal benthic communities in soft sediments of the GOA region function somewhat differently from their counterparts on rocky substrata These communities are important for nutrient regeneration by microbial decomposition and for production of benthic invertebrates that serve as prey for demersal shrimps, crabs, and fishes In some protected areas within bays, however, the shallow subtidal benthos is structured by emergent plants, specifically eelgrass in the GOA These eelgrass beds perform ecological functions similar to those of macrophyte-dominated rocky shores, namely nursery functions, phytal habitat roles, feeding grounds, and sources of primary production (Jewett et al 1999) In the vegetated habitats of the shallow subtidal zone, the demersal fish assemblage is typically more diverse than and quite different from the demersal fishes of the deeper subtidal zone (Hood and Zimmerman 1986) In eelgrass (*Zostera*) beds as well as in the beds of small kelps and other macrophytes (*Agarum, Nereocystis* and *Laminaria*) in the GOA, juveniles of many species that live in deeper waters as adults use this environment as a nursery for their young because of high production of food materials and protection from predators afforded by the shielding vegetation (Dean et al 2000) Furthermore, several fishes are associated with the plant habitat itself, including especially pickers that consume crustaceans and other invertebrates from plant surfaces, a niche that is unavailable in the absence of the vegetation Both types of vegetated habitats in the shallow subtidal zone of the GOA contain larger predatory invertebrates, specifically seastars and crabs I some cases, the same species occupy both eelgrass and kelp habitats (Dean et al 1996b)

Microbial decomposers play an extremely significant role in both shallow and deep subtidal sedimentary habitats of the sea (Braddock et al 1996) Fungi and especially bacteria become associated with particulate organic matter and degrade the organic compounds This decomposition process releases the nutrients such as phosphorus and nitrogen in a form that can be reused by plants when the water mass is ultimately recycled into the photic zone In short, benthic decomposers of the subtidal seafloor play a necessary role in the nutrient cycling upon which sustained production of the sea depends In addition, these decomposers themselves represent the foods for many deposit-feeding invertebrates of the subtidal seafloor Much of the detritus that reaches the seafloor is composed of relatively refractive organic compounds that are not readily assimilated in the guts of animal consumers The growth of microbial decomposers on this detritus acts to convert these materials into more utilizable nitrogen-rich biomass, namely fungi and especially bacteria Bacteria also scavenge dissolved organic materials and repackage them into particulate bacterial biomass, which is then available for use in consumer food chains

In the subtidal habitats, the benthic invertebrates serve as the prey for mobile epibenthic invertebrates and for demersal fishes (Hood and Zimmerman 1986, Jewett and Feder 1982) Mobile epibenthic invertebrates are distinguished from the benthos itself by their greater mobility and their only partial association with the seafloor The vast majority of this group is composed of crustaceans, namely crabs, shrimps, tanaids, and some larger amphipods (Armstrong et al 1995, Orensanz et al 1998) In the GOA, this group includes Dungeness crabs, king crabs, snow crabs, Tanner crabs, both *Crangon* and *Pandalus* shrimps, such as spot shrimp, coon-striped shrimp, pink shrimp, and gray shrimp, and other shellfish resources that had great commercial importance before the climatic phase shift of the mid 1970s (Anderson and Piatt 1999, Mueter and Norcross 1999, Mueter and Norcross 2000) Climate and physical oceanography have the potential to exert important influences on recruitment and year-class strength of subtidal fishery stocks in the GOA (Zheng and Kruse 2000b), but the mechanisms and processes are poorly understood Demersal fishes are those fishes closely associated with the seafloor, including flounders, halibut, sole, rockfishes, Pacific Ocean perch, and gadids like cod and walleye pollock They feed predominantly on the epibenthic invertebrates–the shrimps, crabs, and amphipods–but in addition prey directly on some sessile benthic invertebrates as well Juvenile flatfish feed heavily by cropping (partial predation) on exposed siphons of clams and exposed palps of polychaetes This role of provision of benthic invertebrate prey for demersal crustaceans and fishes is an important ecosystem service of the shallow subtidal seafloor

The shift in the late 1970s from crabs and shrimps to dominance by demersal fishes associated with the shift in climatic regime implies a strong role for environmental forcing of community composition in this shallow subtidal system, although mechanisms of change dynamics are not understood (NRC 1996) Because of the effects of trawling on biogenic habitat, such as sponges and erect bryozoans, in subtidal soft sediments and the potential for fisheries exploitation to modify abundances of both targeted stocks and species caught as by-catch (Dayton et al 1995), fishery impacts to the soft-bottom benthic community are a possible driver of community change Because the demersal fishes that are taken by trawl and other fisheries represent the prey of threatened and endangered marine mammals such as Steller sea lions, the possible implications of fishing impacts to this community are important (NRC 1996)

The benthic invertebrate community of shallow unvegetated subtidal sediments has served worldwide as an indicator system for the biological influence of marine pollution The infaunal invertebrates that compose this bottom community are sessile or slow-moving They are diverse, composed of many phyla and taxa with diverse responses to the suite of potential pollutants that deposit upon the sedimentary seafloor Consequently, this system is an ideal choice to monitor and test effects of marine pollution (Warwick 1993) The subtidal benthic community on the sedimentary seafloor is limited by food supply Consequently, community abundance and biomass reflect the effects of organic enrichment. This is evident from variation in biomass among subtidal benthic communities geographically within the GOA (Feder and Jewett 1986) Therefore, changes in primary productivity in the water column above, allocation of that production between zooplanktonic herbivores and benthic invertebrates, and physical transport regimes combine to cause spatially explicit modification of soft-sediment benthic communities in unvegetated subtidal sediments that can serve to monitor ecosystem status Furthermore, the taxonomic composition of soft-sediment benthic communities responds differentially to organic loading and toxic pollution (Warwick and Clarke 1993, Peterson et al 1996), thereby rendering this system an excellent choice for monitoring to test among alternative drivers of ecosystem change Among common invertebrate taxa of subtidal sedimentary habitats, the echinoderms and crustaceans (especially amphipods) are highly sensitive to toxic accumulation of heavy metals, PAHs, and synthetic organic compounds Other taxa such as polychaetes include many opportunistic species that bloom with loading with organic pollutants, thereby allowing inferences about causation of anthropogenic responses (Peterson et al 1996) This capability of subtidal benthic communities in soft sediments may prove useful in testing among alternative explanations for ecosystem change in the GOA

The deeper subtidal habitats on the outer continental shelf and the continental slope are not well studied in the GOA system (Bakus 1978, SAI 1980a, SAI 1980b) There has been some description of the mobile epibenthic communities and the demersal fish communities of these deeper benthic habitats (Feder and Jewett 1986) Most sampling of these deeper benthic habitats involves trawling and focuses on the stocks of crabs, shrimps, and demersal fishes that are commercially exploited (Rosenberg 1972, Bakus 1978) The continental shelf as a whole (shallow to deep) represents a key fishing grounds in the GOA and has correspondingly high value to humans Because community structure of benthic systems can be modified dramatically by the physical damage done by trawls to biogenic habitat such as sponges and soft corals (Dayton et al 1995), this human activity is the object of concern The continental slope, on the other hand, does not experience great fishing pressure

3 7 3 General Research Questions

How do the substrates, bathymetry, physical factors, biological forces such as predation and competition, and human activities act together to define community structure?

What controls the rates of recruitment of key plant and animal species to the nearshore benthic communities?

- To what degree do recruitment processes control community structure and population abundances in intertidal-subtidal benthic systems?
- How does predation limit the abundance, diversity, and size composition of benthic marine invertebrates

What is the relationship between biological production processes and physical transport phenomena in the coastal ocean and settlement patterns and intensities of various species in intertidal-subtidal benthic communities?

How do biological interactions, both direct (such as predation and interference competition), and indirect (such as trophic cascades), influence the dynamics of community change and successional recovery from disturbance in intertidal-subtidal systems?

How does intertidal and subtidal habitat change influence species of fish, seabirds, and marine mammals from this and the other systems?

- How do offshore, ACC, and watershed processes influence the abundance, production, and dynamics of inter-tidal and subtidal species such as fishes, seabirds, and marine mammals?
- How do intertidal and subtidal habitats influence the abundance, production, and dynamics of species such as fishes, seabirds, and marine mammals in the offshore, ACC and watershed habitats?
- What are the relative contributions of carbon fixed by microalgae and macroalgae in the intertidal and subtidal?

What are the approaches to measuring community structure that allow the effects of human activities to be distinguished from the effects of natural forces in the intertidal and subtidal?

To what degree do human activities, such as watershed modifications, POP (POP stands for?) releases, organic loading, and direct and indirect effects of exploitation of marine resources, have important impacts on intertidal-subtidal benthic communities on rocky shores and in sedimentary habitats?

What is the degree to which toxins ingested by benthic invertebrates are transferred up the food chain in a form that can affect reproduction, growth, or survival of vertebrate consumers of those benthic prey?

What is the functional significance of biodiversity and apparent functional redundancy of the diverse suite of component species of intertidal/subtidal communities?

3.8 Forage Species

3 8 1 Definition

Forage species include a broad suite of species that are commonly consumed by higher trophic level species (fish, seabirds, and marine mammals) Specifies included in the forage species complex varies among authors and management agencies The North Pacific Fisheries Management Council (NPFMC) groundfish fisheries management plan defines the forage species complex as a group of species that includes the following (NMFS 2001)

- Smelts (capelin, rainbow smelt, eulachon, and family Osmeridae),
- Pacific sand lance (*Ammodytes hexapterus*),
- Lantern fishes (family Myctophidae),
- Deep-sea smelts (family Bathylagidae),
- Pacific sandfish (*Trichòdon trichodon*),
- Euphausiids (*Thysanopoda, Euphausia, Thysanoesssa, and Stylocheiron*),
- Gunnels (family Pholidae),
- Pricklebacks (family Stichaeidae),
- Bristlemouths, lightfishes, and anglemouths

Springer and Speckman (1997) extend this definition to include juvenile stages of commercially exploited species such as Pacific herring (*Clupea pallasi*), walleye pollock (*Theragra chalcogramma*), and Pacific salmon (*Oncorhynchus* sp) For the purposes of this background review, the GEM program focuses on a subset of species that are commonly found in coastal or oceanic regions of the GEM study region In the shelf environment, this subset includes euphausiids, capelin, eulachon, sand lance, juvenile pollock, juvenile herring and juvenile pink salmon (*Oncorhynchus gorbuscha)* In the offshore environment, this subset includes common myctophids, such as small-finned lantern fishes (*Stenobrachius leucopsarus* and *Diaphus theta*), and bathylagids, such as the northern smoothtounge (*Leuroglossus schmidti*) This partitioning allows GEM to highlight several key research questions that could be the focus of future GEM programs

A more complete description of the life history characteristics of the forage species identified by the GEM program can be found in Hart (1973, NMFS 2001) Table 3 1 summarizes key features of the life history characteristics

3 8 2 Resource Exploitation in the GEM Region

Small amounts of non-commercial forage species are taken as bycatch in federal and state fisheries in the GOA (NPFMC 2000, NMFS 2001) In an attempt to discourage the development of target fisheries for forage species, the NPFMC restricts the catch of forage species to no more than 2% of the total landed catch of commercial fisheries in federal waters (NMFS 2001) Although the bycatch of non-commercial forage species tends to be low relative to target fisheries for commercially exploited species, the percentage of the bycatch relative to regional abundances of individual forage species is often not known because of the difficulty involved in assessing these species

Pacific salmon fisheries off the coast of Alaska are managed by a complex system of treaties, regulations, and international agreements State and federal agencies cooperate in managing salmon resources The State of Alaska regulates commercial fisheries for salmon within state waters where the majority of the catch occurs Federal agencies control the bycatch of juvenile salmon in groundfish fisheries through prohibited-species bycatch restrictions (NMFS 2001) In the GEM study region, pink salmon are primarily harvested by purse seines Most of the pink salmon taken in PWS are of hatchery origin

State and federal agencies also cooperate in managing Pacific herring fisheries Most of the directed herring removals occur within state waters and are regulated by ADF&G In federal waters, the removals of Pacific herring in groundfish fisheries are regulated through prohibited-species bycatch restrictions (NMFS 2001)

State and federal agencies regulate commercial removals of walleye Pollock The majority of the catch occurs in federal waters, however, small state fisheries have started in PWS In federal waters, the catch is regulated by federal agencies based on recommended harvest regulations provided by the NPFMC The catch of juvenile pollock is assessed within the stock assessment and fisheries evaluation (SAFE) reports Juvenile pollock catch is included in considerations regarding annual quotas for this species The lack of a market for juvenile pollock less than 30 centimeters (cm) in length serves as an incentive to industry to minimize the bycatch of juvenile pollock Efforts to minimize bycatch of juvenile pollock in pollock target fisheries include the voluntary adoption of alternative mesh configurations designed to reduce the retention of small pollock (Erickson et al 1999)

3 8 3 Assessment Methods and Challenges

There are several impediments to the development of forage species assessments The diversity of life history characteristics confound efforts to develop a multipurpose survey to assess forage species as a single complex In addition, several forage species are small and pelagic, making them less vulnerable to the standard trawl gear used in broad-scale surveys to assess stocks conducted by ADF&G or NMFS A high priority should be placed on research designed to overcome these impediments

Several authors have reported on possible trends in forage species abundance in the shelf and offshore environment (Hay et al 1997, Anderson and Piatt 1999, Blackburn and Anderson 1997, Beamish et al 1999a) These papers rely on anecdotal information from surveys that were designed to assess the abundance of another species (such as shrimp, salmon, crab, or groundfish) Indices of abundance based on these data may be subject to error because of problems with the selectivity of the gear or the limited spatial or temporal scope of the surveys

An assessment designed for forage species is needed to develop an accurate evaluation of the distribution and abundance of this important group of species It is unlikely that a single survey would be adequate for all forage species, therefore, a variety of survey methods should be considered Potential survey methods for forage species are identified in Table 3 2

Table 3 1 Summary of Key Life History Characteristics of Selected Forage Species

Characteristics	Euphausiids 11 species	Capelin *Mallotus villasus*	Eulachon *Thaleichthyes pacificus*	Pacific sand lance *Ammodytes hexapterus*	Walleye Pollock *Theragra chalcogramma*	Pacific herring *Clupea pallasii*	Pink salmon *Oncorhynchus gorbuscha*	Northern lanternfish *Stenobrachius leucopsarus*
Maximum age (years)	2	4	5	3	21	18	2	6
Maximum length (centimeters)	4	25	25	15	80	45	65	9
Prey	planktivorous	planktivorous	planktivorous	planktivorous	plankton and fish	planktivorous	plankton and fish	planktivorous
Peak spawning	spring	spring	spring	winter	winter-spring	winter-spring	summer	unknown–winter?
Spawn location	unknown	intertidal	rivers	late fall early winter	pelagic on shelf	nearshore	rivers	unknown
Abundance trend	unknown (uncertain)	low stable (uncertain)	low stable (uncertain)	unknown	low stable	low	high stable	unknown
Foraging habitat	pelagic–mid water over shelf	pelagic–mid-water over shelf	pelagic–mid-water over shelf	demersal–0-100 m	mesopelagic–demersal and over shelf	pelagic shelf	pelagic shelf and open ocean	mesopelagic–outer shelf and open ocean

Table 3 2 Potential Surveys for Assessment of Selected Forage Species

Type	Candidate Species
Small mesh mid-water surveys	Euphausiids capelin eulachon juvenile pollock (age 0 and age 1) juvenile herring small finned lanternfishes northern smoothtongue
High-speed near-surface trawls	Juvenile salmon
Acoustic mid-water trawl surveys	Capelin eulachon juvenile pollock juvenile herring euphausiids
Small-mesh beach seines	Sand lance
Aerial spawning surveys	Pacific herring and capelin
Light detection and ranging (LIDAR)	Useful for species within the upper 50 m
Monitoring diets of key bird predators	Juvenile pollock capelin and sand lance

3.8.4 Hypotheses About Factors Influencing Food Production for Forage Fish Production

Several hypotheses (summarized below) have been advanced to explain trends in forage fish distribution and abundance For the most part, these hypotheses are based on research in the shelf and coastal waters of the western central GOA ecosystem, including PWS Detailed process-oriented research has been conducted to confirm hypotheses for a small number of forage species, and these studies were often conducted in a limited geographic area representing only a fraction of the range of the species

1 Feeding opportunities for early feeding larvae Shifts in large-scale atmospheric forcing controls the structure of marine fish communities in the western central GOA ecosystem through its role in determining the timing of peak production Species that spawn in the winter and early spring will be favored by periods of early peak production, while species that spawn in the late spring and summer will be favored by periods of delayed production (Mackas et al 1998, Anderson and Piatt 1999)

2 Concentration of prey for early feeding larvae Ocean conditions that favor concentration of forage fish and their prey will enhance production of forage species The FOCI program identified a potential mechanism linking increased precipitation to enhanced eddy formation and reduced larval mortality Eddies are believed to provide a favorable environment for pollock larvae by increasing the probability of encounters between larvae and their prey (Megrey et al 1996) Research is needed to determine whether this mechanism may be important for other forage fishes within the western and central GOA

3 Prey dispersal for early feeding larvae An inverse or dome-shaped relationship exists between the amount of wind mixing and forage fish production Bailey and Macklin (1995b) compared hatch date distributions

of larval pollock with daily wind mixing This analysis showed that first-feeding larvae exhibited higher survival during periods of low wind mixing Megrey et al (1996) speculated that extremes in wind mixing would result in reduced pollock survival because low-wind mixing would reduce the availability of nutrients in the mixed layer and high-wind mixing would lead to reduced encounters between pollock and their prey

4 Competition for prey At finer spatial scales, prey resources for forage fish may be limited, leading to resource partitioning to minimize competition between forage fish species that occupy similar habitats Willette et al (1997) examined the diets of juvenile walleye pollock, Pacific herring, pink salmon, and chum salmon in PWS Their study revealed that two species pairs (walleye pollock and Pacific herring, and pink and chum salmon) exhibited a high degree of dietary overlap This finding suggests that in PWS, competition for food resources may occur within these pairs when food abundance is limited Purcell and Sturdevant (2001) found evidence of potential competition between zooplantivorous jellyfish and juvenile fishes in PWS Their study showed high diet overlaps in the diets of pelagic coelenterates and forage species and that these species co-occur spatially and temporally in PWS

5 Prey utilization Overwintering mortality of forage species is dependent on the amount of energy accumulated during the summer Field and laboratory experiments suggest that the overwintering success of both age-0 Pacific herring and age-0 walleye pollock may be dependent on the amount of energy accumulated during summer (Foy and Paul 1999, Sogard and Olla in press) However, the early life history strategy of walleye pollock may make them less susceptible to starvation during the winter period Paul and Paul (1999) compared the growh strategies of larval and age-0 walleye pollock and Pacific herring This comparison revealed that walleye pollock metamorphose early, allowing for an extended growth period, while Pacific herring metamorphose later and accumulate energy for overwintering Rapid growth provides increased swimming speed leading to more successful prey capture and predator avoidance The benefits of the pollock strategy may allow them to continue to grow through the winter (Paul et al 1998)

3.8.4.1 Food Quality

Efforts to improve understanding of the mechanisms underlying the production of forage species would benefit from an improved understanding of the principal prey utilized by forage species Although detailed information exists for commercial species such as juvenile pollock, salmon, and herring (Cianelli and Brodeur 1997, Willette et al 1997), only limited information is available to describe the prey preferences of many members of the forage fish complex In particular, information is lacking in the case of offshore species

3 8 5 Hypotheses About Predation on Forage Fish

By definition, forage species represent an important prey resource for many higher-trophic-level consumers (fish, seabirds, and marine mammals) Top-down predation pressure on forage fish depends on several factors, including predator abundance, the abundance of alternative prey, the density of prey, and the patchiness of prey Changes in these factors will influence the relative importance of top trophic-level forcing on forage fish production

Evidence suggests that in some years, fish predation may exhibit a measurable effect on forage species production in the GEM region Anderson and Piatt (1999) noted that the post regime shift increase in gadoid and pleuronectid fishes coincided with marked declines in capelin and shrimp populations They proposed that this inverse relationship could be caused by increased predation mortality due to an increase in picivorous (fish-eating) species Consistent with this hypothesis, Bailey (2000) performed a retrospective analysis of factors influencing juvenile pollock survival He provided evidence that during the 1980s, pollock populations were largely influenced by environmental conditions, and after the mid-1980s, juvenile mortality was higher, resulting from the buildup of large fish predator populations In PWS, Cooney (1993) speculated that pollock predation could explain some of the observed trends in juvenile salmon survival He suggested that years of high copepod abundance were associated with high juvenile salmon survival, because pollock relied on an alternative prey resource In the open ocean, Beamish et al (1999a) proposed that mesopelagic fishes transfer and redistribute energy through two primary trophic pathways (1) abundant zooplankton to *S leucopsarsus* and then squid, and (2) *S leucopsarsus, D theta,* and *L schmidti* to walleye pollock, salmon, dolphin, and whales The division of energy through these pathways is thought to influence the amount of energy reaching the sea floor

The importance of forage fish in seabird and marine mammal diets has been demonstrated by a number of authors (Hatch and Sanger 1992, Springer et al 1996, Kuletz et al 1997, Ostrand et al 1998) There is little evidence that seabird predation is sufficient to regulate the production of forage fishes in the GEM region, however Note to author Recent anecdotal evidence published in Nature (Thomas and Thorne) circumstantially links predation by sea lions and seabirds to control of herring populations in PWS Growth in humpback whale populations may not be inconsequential with respect to control of small herring populations This does not change the conclusion of this paragraph, but perhaps should be mentioned Therefore, key research elements for predation of forage species by marine mammals and seabirds should focus on the role of oceanographic features in concentrating forage species within the foraging range of seabirds and marine mammals

While only a few studies have examined the importance of gradients (fronts) or water mass characteristics in aggregating forage species for top predators in the GEM region, the importance of these features is well known in other regions In the Atlantic, aggregations of capelin appear to be associated with strong thermal fronts (Marchland et al 1999) Likewise, climate impacts on the distribution and productivity of Antarctic krill (*Euphausia seperba*) have been shown to produce important impacts on higher trophic level consumers (Reid and Croxall 2001, Loeb 1997) Hay et al (1997) found that, in warm years, eulachon off the coast of British Columbia were more abundant in the offshore environment, while in cool years, eulachon were more common in the nearshore environment. Consistent with the hypothesis of Hay et al, Carscadden and Nakashima (1997) noted a marked decline in offshore capelin abundance during a cool period in 1990s in the Atlantic

3 8.6 Hypotheses Concerning Contamination

Because of the broad distribution and abundance of contaminants, there is little evidence to suggest that contaminants regulate the production of forage species in Alaska waters If forage species exhibit subpopulation genetic structure, contaminants could be influential in the local mortality rate of forage fish subpopulations The small size, short life span, and importance as a prey item for higher trophic level foragers make forage species ideal indicators of regional contaminant levels (Yeardley 2000) For example, Roger et al (1990) noted that the high lipid content of eulachons suggests that they may be potential integrators of low-level contaminants If forage species are to be used as a regional indicator of ecosystem conditions, research is needed to determine whether forage species bioaccumulate toxic chemicals Studies are needed to determine whether observed accumulations of toxic chemicals are sufficient to change mortality rage of forage species If forage species accumulate lethal levels of toxic chemicals at the regional level, genetic studies are needed to determine whether these populations represent genetically unique subpopulation segments

3.8 7 General Research Questions

How can trends in abundance of forage species be explained?

- What is the role of large-scale atmospheric forcing in controlling the structure of marine fish communities in the western central GOA ecosystem?
- Are species that spawn in the winter favored by periods of early peak primary production, and species that spawn in the spring and summer favored by periods of delayed production?

Do ocean conditions that favor concentration of forage fish and their prey enhance production of forage species?

- Do eddies favor enhanced production and recruitment of forage species?

Is the amount of wind mixing inversely or directly (for example, Rothschild-Osborn) proportional to forage fish production?

Does interspecific competition at small spatial scales limit production of forage fish species that occupy similar habitats?

Does predation limit the abundance of forage species populations?

Does the aggregation of forage species by gradients (fronts) or water mass characteristics allow top predators to control forage species abundance in the ACC and offshore?

What is the role of food quality as shown by prey preference selection in controlling forage species abundance?

What is the role of accumulations of toxic chemicals in forage species in influencing reproduction, growth, and death of forage species?

3.9 Seabirds

3 9 1 Overview

The GOA supports huge numbers of resident seabirds 26 species nest around the periphery of the GOA, with an estimated total on the order of 8 million birds (Table 3 3) Note to author Are sea ducks not considered seabirds? Seaducks should be included somewhere, since they are important members of shallow marine communities Most species are colonial and aggregate during summer at about 800 colonies A variety of habitats are used for nesting, such as cliff faces, boulder and talus fields, crevices, and burrows in soft soil Two species, Kittlitz's and marbled murrelets, are not colonial and nest in very atypical habitats Kittlitz's murrelets nest on scree fields in high alpine regions often many kilometers from the coast, and marbled murrelets nest mainly in mature trees in old-growth conifer forests, also often distant from the coast.

Table 3 3 Nestıng Seabırds ın the Gulf of Alaska

English Name	Scientific Name	Abundance[1] (thousands)	Biomass[2] (tonnes)	Nesting Habitat[3]	Foraging Mode[4]
Northern fulmar	*Fulmarus glacıalıs*	440	268	Clıff	SF
Fork-taıled storm-petrel	*Oceanodroma furcata*	640	32	Burrow	SF
Leach's storm-petrel	*Oceanodroma leucorhoa*	1 067	53	Burrow	SF
Double-crested cormorant	*Phalacrocorax aurıtus*	3 3	6	Clıff	CD
Brandt's cormorant	*Phalacrocorax penıcıllatus*	0 086	0 2	Clıff	CD
Pelagıc cormorant	*Phalacrocorax pelagıcus*	21	40	Clıff	CD
Red-faced cormorant	*Phalacrocorax urıle*	20	38	Clıff	CD
Unıdentıfied cormorant	*Phalacrocorax* spp	15	29	Clıff	CD
Mew gull	*Larus canus*	15	11	Ground	SF
Herrıng gull	*Larus argentatus*	1	1	Ground	SF S
Glaucous-wınged gull	*Larus glauscescens*	185	241	Ground	SF S
Black-legged kıttıwake	*Rıssa trıdactyla*	675	270	Clıff	SF
Arctıc tern	*Sterna paradısaea*	8 9	1 2	Ground	SF
Aleutıan tern	*Sterna aleutıca*	9 4	1 2	Ground	SF
Unıdentıfied tern	*Sterna spp*	1 7	0 22	Ground	SF
Common murre	*Urıa aalge*	589	589	Clıff	DD
Thıck-bılled murre	*Urıa lomvıa*	55	55	Clıff	DD
Unıdentıfied murre[5]	*Urıa spp*	1 197	1 197	Clıff	DD
Pıgeon guıllemot	*Cepphus columba*	24	13	Crevıce	CD
Marbled murrelet	*Brachyramphus marmoratus*	200	48	Tree	CD
Kıttlıtz's murrelet	*Brachyramphus brevırostrıs*	+	+	Scree	CD
Ancıent murrelet	*Synthlıboramphus antıquum*	164	38	Burrow	CD
Cassın's auklet	*Ptychoramphus aleutıcus*	355	71	Burrow	DD
Parakeet auklet	*Cerorhınca monocerata*	58	17	Crevıce	DD
Least auklet	*Aethıa pusılla*	0 02	0 0018	Talus	DD
Crested auklet	*Aethıa crıstatella*	46	14	Talus	DD
Rhınoceros auklet	*Cyclorrhynchus psıttacula*	170	90	Burrow	DD
Tufted puffin	*Lunda cırrhata*	1 093	874	Burrow	DD
Horned puffin	*Fratercula cornıculata*	773	425	Crevıce	DD
Total		**7,826**	**4,423**		

[1]From U S Fısh and Wıldlıfe Servıce (USFWS), seabırd colony database marbled murrelet ın Gulf of Alaska from Pıatt and Ford (1993)

[2]Based on weıghts of seabırds presented by DeGange and Sanger (1986)

[3]Prıncıpal type

[4]SF = surface-feeder CD = coastal dıver DD = deep dıver S = scavenger From DeGange and Sanger (1986)

[5]Essentıally all common murres

Predation by terrestrial mammals and rapacious birds undoubtedly is responsible for the nesting habitats and habits adopted by seabirds Cliff-nesting species are free to nest on mainland sites, because mammals cannot reach them and they are large enough to defend themselves and their nests against most avian predators Ground-nesting species do not have this option and must nest only on islands free from predatory mammals Additionally, some ground-nesting species come and go to and from colonies only at night, apparently to further thwart avian predators

Foxes, rats, voles, and ground squirrels were variously introduced to most islands in the Aleutians and GOA between the late 1700s and early 1900s and severely reduced the abundances of many species of ground-nesting seabirds, such as storm-petrels, auklets, murrelets, and puffins (Bailey and Kaiser 1993, Boersma and Groom 1993, Springer et al 1993) Today, even though foxes no longer exist on most islands, numbers of these species of ground-nesting seabirds still likely reflect the effects of introduced mammals Moreover, predators that occur naturally occasionally have large, local effects on nesting seabirds in the GOA (Oakley and Kuletz 1996, Seiser 2000)

The distribution and abundance of nesting seabirds in the GOA is therefore governed primarily by the availability of suitable, safe nesting habitats, as well as by the availability of prey For example, cliff-nesting species, such as murres and kittiwakes, require cliffs facing the sea Therefore, regardless of the biomass of potential forage species in the eastern GOA, there are no murres or kittiwakes in much of the region because of the lack of sea cliffs Where suitable nesting habitat does exist, seabirds nearly always occupy it, and fluctuations in their productivity and abundance through time are thought to be determined for the most part by fluctuations in prey populations

Species that nest on cliff faces, such as murres and kittiwakes, are the most well-studied because of their visibility Completing censuses of cliff-nesting seabirds is comparatively easy, as is measuring several components of their breeding biology, including the study of recurring natural phenomena such as migration (phenology) and reproductive success Consequently, precise estimates of abundance and productivity, and trends in these variables through time, are available for murres and kittiwakes at many colonies in the GOA In addition to their visibility, murres and kittiwakes are extremely numerous and widely-distributed, and more is known about them than about any other species

In contrast, seabirds that nest underground are difficult to study A further complication is that some of these are nocturnal as well Despite huge numbers and broad distributions of some diurnal species, such as puffins, and nocturnal species, such as storm-petrels, much less is known about population sizes and productivity or trends in these parameters through time and space They do have scientific value, however, because other characteristics of their biology offer valuable opportunities for obtaining information on the distribution and dynamics of prey populations important to a variety of seabirds and marine mammals

Most seabirds in the GOA are primarily piscivorous (fish eating) during the nesting season The principal exceptions include northern fulmars, storm-petrels, and thick-billed murres, which consume large amounts of squid, auklets, which specialize on zooplankton, and gulls, terns, and guillemots, which consume considerable amounts of crustaceans in addition to fish Many species of fishes are taken, although a comparatively small number contribute the bulk of the biomass to diets of most seabirds Overall, the three most important species of fishes are sand lance, capelin, and pollock At certain colonies, at certain times, in certain years, or any combination of these conditions, the myctophids, Pacific cod, saffron cod, herring, sablefish, pricklebacks, prowfish, and salmon are also important to some species (Hatch 1984, Baird and Gould 1986, DeGange and Sanger 1986, Sanger 1987, Hatch and Sanger 1992, Irons 1992, Piatt and Anderson 1996, Suryan et al 2000, Gill and Hatch unpublished data)

Resident GOA seabirds can be divided into three groups based on their foraging behavior (Table 3 3) Surface-feeders, as their name implies, obtain all of their food from about the upper 1 m of the water column and often forage over broad areas Coastal divers can generally reach bottom and typically forage in shallow water near shore Pelagic mid-water and deep divers are capable of exploiting prey at depths of up to nearly 200 m and of foraging over large areas (Schneider and Hunt 1982, Piatt and Nettleship 1985) Most individuals of most species forage over the continental shelf during summer This is due primarily to the location of nesting areas, which are along the mainland coast and on nearshore islands, and the distribution of forage species, which in aggregate are more diverse and abundant on the shelf than off the shelf Exceptions to this generalization are the fulmars and storm-petrels, which have anatomical, behavioral, and physiological adaptations that allow them to forage at great distances from their nesting areas, giving them access to resources off the shelf (Boersma and Groom 1993, Hatch 1993), and species such as kittiwakes that typically feed over the shelf, but which can efficiently exploit prey off the shelf when those prey are within foraging range from their nesting locations (Hunt et al 1981, Springer et al 1996, Hatch unpublished data)

Characteristics such as broad sampling of forage populations and sensitivity to prey availability make seabirds valuable tools in the study of marine ecosystems

Therefore, as a group, seabirds sample forage populations broadly in three dimensions These characteristics, plus variations in diet between species and the sensitivity of various components of their breeding biology and population abundance to fluctuations in prey availability, make seabirds in the GOA, as elsewhere, valuable tools in the study of marine ecosystems (Cairns 1987, Aebischer et al 1990, Furness and Nettleship 1991, Springer 1991, Hatch and Sanger 1992, Montevecchi and Myers 1996, Piatt and Anderson 1996, Springer et al 1996)

Seabird populations in the North Pacific from California to Arctic Alaska are very dynamic, waxing and waning in response to changes in prey abundance, predators, entanglement in fishing gear, and oil spills (Anderson et al 1980, Ainley and Broekelheid 1990, Paine et al 1990, Murphy et al 1991, Hatch 1993, Hatch et al 1993, Ainley et al 1994, Byrd et al 1998, Divoky 1998) Oil spilled from the *Exxon Valdez* killed an estimated 250,000 seabirds in the GOA, 185,000 of which were murres (Piatt and Ford 1996) Most murre mortality occurred downstream from PWS near the Barren Islands and Alaska Peninsula and had an unknown effect on the abundance of murres at regional colonies There is evidence that the immediate mortality and lingering effects of the spill in PWS have depressed the abundance of several other species of seabirds there throughout the 1990s (Irons et al 2000)

A strong case also has been made for a broad-scale decline in seabird abundance in the GOA during the past 2 to 3 decades beginning before the EVOS Marine birds counted at sea in summer in PWS apparently declined by some 25% in aggregate between 1972 and the early 1990s (Kuletz et al 1997) Many species contributed to the decline, including loons, cormorants (-95%), mergansers, Bonaparte's gulls, glaucous-winged gulls (-69%), black-legged kittiwakes (-57%), arctic terns, pigeon guillemots (-75%), marbled and Kittlitz's murrelets (-68%), parakeet auklets, tufted puffins, and horned puffins (-65%) (Klosiewski and Laing 1994) Other census data further indicated that for the marbled murrelet, at-sea winter abundance declined by more than 50% throughout the GOA during this time (Piatt and Naslund 1994) Results from studies at several murre colonies in the GOA in summer tend to support this pattern Piatt and Anderson (1996) reviewed the abundance histories of 16 colonies and concluded that many were in decline before the EVOS Therefore, it proved difficult to estimate the effect oil had on murre populations

It is generally thought that alterations in forage fish abundance and community structure brought on by environmental change not associated with the oil spill, such as climate change, have been primarily responsible for falling seabird populations (Oakley and Kuletz 1996, Piatt and Anderson 1996, Hayes and Kuletz 1997, Kuletz et al 1997, Anderson and Piatt 1999) For example, pigeon guillemot numbers in PWS in 1978 to 1980 averaged about 40% higher than in the early 1990s, and they declined further through 1996 (Oakley and Kuletz 1996) The decline in abundance was accompanied by a decline in the occurrence of sand lance in their diets, and it has been suggested that cause and effect relate the two Because sand lance has a much higher fat content than the forage species guillemots switched to, such as pollock and blennies, it is nutritionally superior (Anthony and Roby 1997, Van Pelt et al 1997) In Kachemak Bay, sand lance was particularly abundant in diets of guillemots nesting in high-density colonies in the late-1990s, and chicks fed predominantly sand lance grew faster than chicks fed lower-quality prey (Prichard 1997) Likewise, reductions in energy-dense capelin in the GOA and in diets of several species of seabird in the 1980s compared to the 1970s also have been linked to population declines (Piatt and Anderson 1996, Anderson and Piatt 1999)

Additional evidence of possible climate-mediated population decline is the frequency and magnitude of large seabird die-offs in the past 2 decades Some of these involved huge numbers of surface-feeding species in summer, particularly kittiwakes and shearwaters in the GOA and especially the Bering Sea, during years of strong El Niño events, notably 1983 and 1997 (Nysewander and Trapp 1984, Mendenhall 1997) Others involved principally murres in the GOA in winter In 1993, on the order of 100,000 common murres starved to death, and in 1997, at least tens of thousands suffered a similar fate (Piatt and van Pelt 1993, Piatt unpublished data) Such acute mortality, when added to the normal, or perhaps elevated, attrition suffered by juvenile birds in recent years, could have significant repercussions on population size As Piatt and Anderson (Piatt and Anderson 1996) note, there was only 1 reported die-off of seabirds in the general region before 1983, and that was in the Bering Sea in 1970 (Bailey and Davenport 1972)

There is no evidence that seabirds in the GOA have been directly affected by commercial fisheries Most of the prey of seabirds are not targeted, for example, sand lance and capelin Adults of some prey species are fished, such as pollock, Pacific cod, and herring, but most seabirds can feed only on the small age-0 and age-1 fish of these large types and therefore do not compete with commercial fisheries for biomass Indirect effects of commercial fishing are possible if stock sizes are affected by fishing and if stock size influences the abundance of young age classes of those species or the abundance of other forage species

3 9 2 Case Studies

A lot of information has been collected on seabirds in the GOA in the past 3 decades, although much of the data obtained in the last 10 years has not yet been published or even presented Therefore, the integration of all results into a composite picture of seabird ecology is not currently possible Nevertheless, good information is available for some aspects of the biology of certain species at certain sites, and these examples can be used to give a general idea of the status of seabirds and their sensitivity to change in the environment Prominent species are the black-legged kittiwake and common murre They are among the most abundant and widely distributed seabirds, nesting at hundreds of colonies from Southeastern Alaska to Unimak Pass These attributes and their ease of study have made them the best known of all species in the GOA Information on trends in abundance, productivity, and diets of kittiwakes and murres at several locations spans periods of 1 to more than 4 decades Information on other species, notably fulmars and puffins, at some colonies provides additional context

> *The black-legged kittiwake and common murre are the most abundant, most widely distributed, and best known bird species in the GOA*

3.9.2.1 Middleton Island

The longest time series of reliable abundance estimates for seabirds in the GOA comes from Middleton Island, where the first count was made in 1956 (Rausch 1958) Between 1956 and 1974, the number of kittiwakes increased by an order of magnitude, from about 14,000 to 144,000 birds (Baird and Gould 1986) That increase is thought to have been made possible by the 1964 earthquake, which uplifted large sections of Middleton Island and created extensive new nesting habitat Numbers of kittiwakes remained high there throughout the 1970s, but began to decline steadily in the early 1980s from a peak of about 166,000 birds to about 16,000 today (Hatch et al 1993, Hatch unpublished data)

The decline in abundance has been accompanied by generally low productivity since the early 1980s, averaging just 0 06 chicks per pair between 1983 and 1999 (Table 3 4) Supplemental feeding of kittiwakes in recent years altered a variety of adult breeding parameters sensitive to food supply and increased survival of chicks, strongly supporting the notion that food limitation has been the cause of poor productivity and population decline (Gill 1999, Gill and Hatch unpublished data)

The longest time series of abundance data for murres also comes from Middleton Island As with kittiwakes, the murre population increased by about an order of magnitude following the 1964 earthquake, numbering 6,000 to 7,000 individuals by the mid-1970s Also like kittiwakes, murre abundance at Middleton Island was in decline by the end of the decade, falling to about 4,000 individuals by 1985 The population abruptly increased the following year to nearly 8,000 birds, where it remained through 1988, rapidly declined again to about 2000 by 1992, and has been more or less stable since (Hatch unpublished data) The cause of the decline is thought to have been driven in part by the growth of vegetation that hampers access of chicks to the sea once they leave the nest (Hatch unpublished data), but the sharp increases and decreases during the course of the overall decline argues for other controlling factors

Glaucous-winged gulls also probably nested in comparatively small numbers on Middleton Island before 1964, although no counts were made in the early years By 1973 there were fewer than 1,000 individuals and fewer than 2,000 a decade later However, in contrast to findings for murres and kittiwakes, the population ballooned to more than 12,000 birds between 1984 and 1993, and now totals about 11,000 (Hatch unpublished data) Predation by gulls on kittiwake and murre eggs and chicks may have contributed to the declines of those species (2001)

The abundance of rhinoceros auklets on Middleton Island more than doubled from about 1,800 to 4,100 burrows between 1978 and 1998 (Hatch unpublished data) Although there are no hard data, it seems likely that few or no rhinoceros auklets nested there before the earthquake because of a lack of habitat (Hatch unpublished data) Therefore, the increase in rhinoceros auklet abundance might be just the result of an increase in the extent of nesting habitat as vegetation covered uplifted soils At St. Lazaria Island in Southeast Alaska, however, rhinoceros auklet numbers nearly doubled during the 1990s (Byrd et al 1999), indicating that other factors are possibly involved

Table 3.4 Trends in Kittiwake Abundance and Productivity at Colonies in the Gulf of Alaska

Colony(s)	Population Trajectory	Average Production, 1983-2000	Number of Colonies	Colony years
Gull Island[1]	Up	0.39	1	15
Prince William Sound[2]	Up	0.30	4	67
Barren Island[3]	Level	0.40	1	7
Prince William Sound–Overall[2]	Level	0.13	22	372
Prince William Sound[2]	Up-Down	0.14	5	94
Prince William Sound[2]	Level	0.15	2	34
Chiniak Bay[2]	Level	0.19	1	16
Semidi Islands[3, 4]	Down	0.05	1	11
Chisik Island[1]	Down	0.06	1	9
Prince William Sound[2]	Down	0.04	11	177
Middleton Island[4]	Down	0.06	1	?

[1]From J. Piatt (unpublished data)

[2]From D. Irons (unpublished data)

[3]From USFWS (unpublished data)

[4]From S. Hatch (unpublished data)

Table 3.4 needs to be explained fully by the author the first time it is cited in Section 3.9.2.1. Also the three groups in the table should be labeled using the blank lines above each group, and a distinction needs to be drawn among the four different PWS colonies and this distinction needs to be explained in Section 3.9.2.1 the first time the Table is cited. Alternatively, the table and its contents could be fully explained in the caption and table notes.

A lack of adequate data precludes firm conclusions about trends in abundance of tufted puffins, but it is thought that they are increasing in abundance on Middleton Island as well (Hatch unpublished data).

Pelagic cormorants are known to move between nesting areas within colonies between years; therefore, census data are not necessarily as accurate for them as for other cliff-nesting species of seabirds. The data show that numbers of nesting pairs were comparatively stable at about 2,000 to 2,800 between the mid-1970s and mid-1980s. The number of pairs was extremely volatile from 1985 to 1993, however, rising and falling by as much as 700% between consecutive years. In 1993, pelagic cormorants numbered about 800 pairs, and have increased steadily since then to about 1,600 pairs (Hatch unpublished data).

Seabirds at Middleton Island feed on a variety of forage species common throughout the GOA (Hatch 1984, Hatch and Gill unpublished data). Early in the nesting season kittiwakes typically prey on extremely energy-dense myctophids, which are generally restricted in their distribution to deep-water regions off continental shelves (Willis et al 1988, Sobolevsky et al 1996) Later they switch to other, likely more accessible, prey and feed chicks primarily on sand lance, although capelin and sablefish are also important in some years (Hatch and Gill unpublished data)

Rhinoceros auklets feed on numerous species of fishes, but seem to be sand lance specialists (Hatch 1984, Vermeer and Westrheim 1984, Vermeer et al 1987) At Middleton Island, sand lance contributed on average 62% of the biomass fed to chicks in 11 years between 1978 and 2000 (Hatch unpublished data) In years of apparent low abundance during the first half of the 1990s, pink salmon, capelin, greenlings, and sablefish replaced sand lance

Tufted puffins at Middleton Island feed their chicks predominantly sand lance in years when sand lance are most abundant· sand lance make up as much as 90% of biomass in peak years Tufted puffins apparently switch to other prey sooner than rhinoceros auklets when sand lance is scarce Alternative prey of tufted puffins consists mainly of pollock and prowfish, with somewhat lesser amounts of sablefish (Hatch unpublished data)

3.9.2.2 Prince William Sound

Twenty-three kittiwake colonies in PWS were first counted in 1972, but were not counted again until 1984 These and an additional six colonies have been visited nearly each year since (Irons 1996, Irons unpublished data) During this time, long-term increases and decreases have been noted at various colonies, but no obvious geographic pattern to the changes was found Instead, four colonies have grown to large size, and numerous smaller colonies have declined, with some disappearing completely Note to author Are any of these colonies represented by the four colonies in Table 3 4? Several other colonies first increased, then decreased, and two have not changed appreciably At least some of these changes likely resulted from movements of adults between sites (Irons unpublished data) For example, as the Icy Bay colony declined from about 2,400 birds in 1972 to fewer than 100 by 2000, the nearby North Icy Bay colony grew from about 500 birds in 1972 to about 2,000 by the late 1990s Overall, the total abundance of kittiwakes in PWS has remained stable, or perhaps increased slightly, despite substantial interannual variability, for example, decreasing by 45% between 1991 and 1993 and increasing by 35% between 1999 and 2000

Overall productivity likewise has been highly variable between years, but generally has been much greater than at Middleton Island, averaging 0 13 chicks per pair since 1984 (Table 3 4) Note to author There are four values in Table 3 4 and they do not average 0 13 Average productivity differed considerably between colonies with different population trajectories, however (Table 3 4) The average productivity of four colonies with increasing populations was twice that of two stable colonies and five colonies that experienced matching increases and decreases, while productivity at those was nearly four times as great as that at 11 declining colonies

3.9.2.3 Lower Cook Inlet

Kittiwakes at Chisik Island in Lower Cook Inlet were first counted in 1971 (Snarski 1971), and the population appears to have fallen steadily since then By 1978, the number of birds was down by about 40% and today it is just 25% of the 1971 total (Piatt unpublished data) The trend in murre abundance at Chisik Island has paralleled that of kittiwakes, but the decline has been even steeper The population fell by more than half between 1971 and 1978, and today stands at just about 10% of its former abundance Kittiwake productivity has been poor in most years, averaging just 0 06 chicks per pair (Table 3 4) Less is known about productivity of murres, which has been estimated only since 1996 In that time, it has been variable and averaged 0 56 chicks per pair (Table 3 5)

Table 3 5 Trends in Murre Abundance and Productivity at Colonies in the Gulf of Alaska

Colony	Population Trajectory	Average Production, 1989-2000	Range	Colony years
Gull Island[1]	Up	0 52	0 28-0 65	4
Chisik Island [1]	Down	0 56	0 18-0 74	4
Barren Island [2]	Up	0 73	0 58-0 75	5
Semidi Islands [2 3]	Up	0 48	0 21-0 58	6

[1]From J Piatt (unpublished data)

[2]From USFWS (unpublished data)

[3]From S Hatch (unpublished data)

In contrast, just across Cook Inlet at Gull Island in lower Kachemak Bay, numbers of kittiwakes and murres have increased substantially since counts were first made in 1976 The abundance of kittiwakes more than doubled between the mid-1970s and mid-1980s, peaked in 1988, and has averaged about 10% to 15% lower through the 1990s (Piatt unpublished data) The growth in numbers of murres was somewhat less abrupt, but more enduring, with steady, exponential growth of about 300% through 1999 Productivity of kittiwakes at Gull Island has been much higher than at Chisik Island, and has been among the highest anywhere in the GOA with comparable data (Table 3 4) Productivity of murres at Gull Island has been less variable than at Chisik Island, but has averaged essentially the same, 0 52 chick per adult (Table 3 5)

Kittiwakes were first counted on the Barren Islands, at the mouth of Cook Inlet, in 1977 The next counts in 1989 to 1991 were apparently comparable Systematic counts began in 1993 and have continued since It is not known if the earlier (1977 to 1991) and later (1993 to 1999) groups are comparable Within-group data indicate that there was no apparent change in kittiwake abundance during either time period Likewise, there are two groups of counts for murres—7 counts between 1975 and 1991 and 10 systematic counts between 1991 and 1999 Counts in the early part of the first interval are not comparable to later counts in that interval, therefore, it is not known whether murre numbers changed from the 1970s to the late 1980s Since 1989, however, the population has steadily grown by about 40% (Roseneau unpublished data) Kittiwake productivity at the Barren Islands in the 1990s was as high as at Gull Island (Table 3 4) Murre productivity since 1995 has averaged 0 73 chick per pair, which is higher than at either of the other colonies in Lower Cook Inlet.

Kittiwakes and murres at all three locations prey on a similar suite of forage fishes, but the proportion of each species in diets varies depending on their relative abundance Sand lance, capelin, and cods are the three most important taxa of prey (Piatt unpublished data, Roseneau unpublished data) Among the cods, the proportions of pollock, Pacific cod, and saffron cod vary by location A variety of evidence from the Lower Cook Inlet region indicates that population trends of kittiwakes and murres at the three colonies are directly related to the abundance of prey available to the birds (Kitaysky et al 1999, Robards et al 1999, Piatt unpublished data, Roseneau unpublished data)

3.9.2.4 Kodiak Island

Of numerous seabird colonies on Kodiak Island, only the one at Chiniak Bay has received much attention Kittiwakes were first counted there in 1975 to 1977 and numbers were stable They were next counted in 1984, by which time the population had more than doubled Numbers have since been variable, but showed no significant changes until 1999, when they were about twice as great as in 1997 to 1998 Kittiwake productivity at Chiniak Bay was very high for at least 2 years in the mid-1970s (about 1 chick per nest), but was poor in the 1980s, averaging just 0 11 chick per nest between 1983 and 1989 Productivity improved in the 1990s, averaging 0 24 chick per nest, and has averaged 0 19 chick per nest overall since 1983 (Table 3 4) This pattern of productivity contrasts with patterns seen in PWS and at Gull Island Note to the author There are four different PWS colonies in Table 3 4

Kittiwakes at Chiniak Bay preyed primarily on sand lance and capelin in the 1970s Variations in diet between years were correlated with variations in productivity (Baird 1990)

3.9.2.5 Semidi Islands

Approximately 2,500,000 seabirds, or about a third of all the seabirds nesting in the GOA, are found on the Semidi Islands, including about 10% of the kittiwakes, half of the murres and horned puffins, and nearly all of the northern fulmars (Hatch and Hatch 1983) Seabird studies on the Semidi Islands began in 1976 and have continued in most years since Most work has occurred at Chowiet Island, which hosts on the order of 400,000 birds of at least 15 species, with the cliff-nesting species–kittiwakes, murres, and fulmars–receiving the greatest attention

The number of kittiwakes at Chowiet Island varied little through 1981, although the number of nests grew by 60% No counts were made in 1982 to 1988 Kittiwake abundance in 1989 and 1990 had not changed, but it declined abruptly in 1991, and has averaged about 30% lower since The number of kittiwake nests in

1989 had fallen back to the late 1970s level, where it has tended to remain (USFWS unpublished data) Productivity of kittiwakes at Chowiet Island was generally high between 1976 and 1981, averaging 0 43 chick per nest, with the highest level (about 1 chick per nest) in 1981 Kittiwakes began failing to produce chicks at least by 1983 (no data were obtained in 1982), however, and in 11 years between then and 1998, the average productivity has been just 0 05 chick per nest (Table 3 4) Accompanying the decline in abundance and collapse of productivity was a delay of 9 days in the mean laying date in the 1990s compared to the 1970s and early 1980s Poor productivity and delayed laying are both symptomatic of food stress

Murre abundance on Chowiet Island was stable between 1977 and 1981 Abundance was the same in 1989 when counts were next made, but in contrast to findings for kittiwakes, the population has grown steadily since, standing 30% higher by 1998 As for kittiwakes, the mean laying date of murres was about 10 days later in the 1990s than in the 1970s Productivity has not varied appreciably between years, except in 1998 when it was very low The average productivity since 1989 was 0 48 chick per pair, or about the same as at Chisik and Gull islands (Table 3 5)

Trends in fulmar abundance, productivity, and phenology through time exhibited patterns similar to those of kittiwakes and murres As with murres, abundance has increased numbers of fulmars grew steadily between 1976 and 1981, and generally continued that trajectory at least through the mid-1990s An exceptionally low number recorded in 1998, the last year they were counted and the only year since 1995, may be an artifact and not representative of the long-term trend, or it may represent a real decline As with kittiwakes, productivity of fulmars was lower in the 1980s and 1990s, averaging just 0 24 chick per nest from 1983 through 1998, compared to an average of 0 52 chick per nest from 1976 through 1981 In addition, as found for both kittiwakes and murres, the nesting phenology of fulmars was conspicuously later in the 1990s than in the 1970s

Little is directly known about diets of kittiwakes and murres at the Semidi Islands, but based on diets of rhinoceros auklets and tufted and horned puffins there (Hatch 1984, Hatch and Sanger 1992), it can be assumed that the usual food sources–sand lance, capelin, and pollock–are most important These prey also are significant for fulmars In general, the diets of fulmars overlap extensively with those of kittiwakes and murres, although overall fulmar diets are much more varied (Sanger 1987, Hatch 1993) For example, fulmars are noted for eating large amounts of jellyfish and offal and for feeding jellyfish to chicks

3 9.3 Conclusions

Seabird populations at colonies in the GOA are very dynamic, with numerous examples of growth and decline during the past 3 decades

In spite of considerable uncertainty about the magnitude, a widespread decline in the abundance of murres in the GOA may have occurred since the 1970s

Numbers are clearly down in such diverse habitats as Middleton Island, which lies near the edge of the continental shelf and is the most oceanic of all colonies in the GOA, at Chisik Island, which is arguably the most neritic (nearshore) colony, and apparently at several colonies along the south side of the Alaska Peninsula. Murre numbers are not uniformly down, however, they have increased dramatically at Gull Island during the past 15 years and at the Barren Islands and the Semidi Islands during the past 10 years. Although comparatively little is known about murre productivity, it has been essentially the same in recent years at the declining colony on Chisik Island as at the growing colonies on Gull Island and the Semidi Islands. At Chisik Island, the rate of decline of the population equals the estimated adult mortality-productivity seems to be sufficient to maintain numbers if those birds were recruiting to the population. Therefore, recruitment appears to have been lacking, which could be explained by poor survival of birds raised there or by emigration to other colonies (Piatt personal communication). At Gull Island, productivity and recruitment can account for only about half the rate of population growth, with immigration required to explain the other half.

In most cases, local trends in the abundance of murres and kittiwakes, likely reflect mesoscale or regional processes affecting prey availability. For example, differences in population trends of both species at Chisik Island and Gull Island, and differences in productivity of kittiwakes between the islands, are related to regional variations in the abundance of forage fishes (Piatt unpublished data). The similarity in murre productivity between colonies is likely explained by flexible time budgets, which buffers them against fluctuations in prey (Burger and Piatt 1990, Zador and Piatt 1999).

There is not enough information to determine whether total kittiwake abundance in the GOA has changed one way or another. Many examples of growth, decline, and stasis in individual colonies are available, but there is no apparent broad geographic pattern to the trends. At the few colonies where both kittiwakes and murres have been monitored, abundances of the two species tend to track each other through time. Kittiwakes, along with murres, have declined at Middleton Island and Chisik Island, and apparently increased, with murres, at Gull Island. The one exception is at Chowiet Island in the Semidi Islands, where kittiwakes decreased and murres increased. Elsewhere, kittiwakes have increased at Chiniak Bay on Kodiak Island and remained stable overall in PWS.

There is a strong correlation between population trajectory and long-term average productivity of kittiwakes at many colonies. Those colonies that are increasing in size have the highest productivity, those that are declining have the lowest. Colonies that show no change have intermediate levels. There are various interpretations of such a relationship. One is that productivity and subsequent recruitment of young determines abundance. Another is that kittiwake abundance and productivity simply track changes in prey, that is, in years of high prey abundance, more adults attend colonies and produce greater numbers of chicks than in years of low prey abundance There would not necessarily have to be any other relationship between the two

There are conspicuous temporal patterns of kittiwake productivity at many colonies during the past 17 years Productivity at colonies in PWS and at Gull Island has varied in tandem, with peaks and valleys at about 5-year intervals' high productivity in the mid- to late 1980s, low in the early 1990s, and higher again after 1995 For most of the record, from the early 1980s through the mid-1990s, this pattern was opposite that at Chiniak Bay on Kodiak Island, where productivity peaked in the early 1990s while it bottomed-out in PWS and at Gull Island Productivity at the three locations tended to track together during the latter half of the 1990s

Kittiwake productivity and population trends in PWS are well-correlated before 1991 and since 1991, but the sign (positive or negative) of the relationship differs Before 1991, high productivity was associated with low numbers of birds at the colonies, but since 1991, the relationship has been opposite A similar switch occurred at about the same time in the relationship between kittiwake productivity in PWS and the abundance of age-1 herring Such differences in sign and behavior of relationships before and after the 1989-to-1990 regime shift have been pointed out for kittiwakes in the Bering Sea and for various other ecosystem components of the North Pacific It has been suggested that the differences reflect fundamental changes in ecosystem processes (Springer 1998, Welch et al 1998, Hare and Mantua 2000)

The peaks and valleys in kittiwake productivity in PWS have punctuated a general declining trend during the longer term If productivity depends more on prey abundance than on predation, then it seems as though prey have tended to decline throughout PWS in the past 17 years, notwithstanding apparent oscillations

3 9 4 Future Directions

Seabirds in the GOA are sensitive indicators of variability in the abundance of forage fishes through time and space How well information from particular species at particular colonies reflects broad patterns of ecosystem behavior in the GOA remains to be seen The problem is that nearly all of the colonies are situated in habitats with distinct mesoscale or regional properties PWS is a prime example, where colonies are located at the heads of fjords with and without glaciers, in bays and on islands around the perimeter of the main body of the sound, and on islands in the center of the sound The Barren Islands and Gull Island are strongly influenced by intense upwelling in Kennedy Entrance that greatly modifies local physical conditions and production processes waters in the relatively small region are cold, nutrient-rich, and productive Chisik Island lies in the path of the outflow of warm, nutrient-poor water from Cook Inlet The Semidi Islands lie at the downstream end of Shelikof Strait and the center of distribution of spawning pollock in the GOA

Thus, there are various trends in abundance of kittiwakes at the numerous colonies in PWS Trends in abundance of kittiwakes and murres at the Barren Islands and Gull Island are opposite those at neighboring Chisik Island, and patterns of kittiwake productivity at Gull Island and Chiniak Bay are opposite of each other Only Middleton Island, which sits isolated near the edge of the continental shelf and the Alaska Stream, and sites on or near the coast of the Alaska Peninsula west of Kodiak Island, which lie in the flow of the Alaska Coastal Current, seem to have the potential to represent gulf-wide variability unencumbered by possibly confusing smaller-scale features

On the other hand, there is reason for optimism that broad-scale variability is indeed expressed in seabird biology In spite of a wide variety of local habitat characteristics and population trends of kittiwakes at the many colonies in PWS, and large differences in average long-term productivity among colonies with differing abundance trends, a common temporal pattern of productivity has been shared by almost all colonies Concordant, clearly defined peaks and valleys have been observed at about 5-year intervals A sound-wide environmental signal has propagated through the kittiwakes regardless of their location or status

Moreover, the signal captured by kittiwakes in PWS and expressed in patterns of productivity was also captured by kittiwakes at Gull Island, implying that they may not be as ecologically separated as one might assume considering their geographic distance and characteristics of their environments And further expanding the spatial dimension, the temporal pattern of sand lance abundance in the vicinity of Middleton Island during the past 15 years, as revealed by its occurrence in diets of rhinoceros auklets and tufted puffins there, matches closely the patterns of kittiwake productivity in PWS and at Gull Island Although a long geographical stretch, it might not be such a long ecological stretch when viewed broadly, at the GOA scale, rather than in a regional geographic and ecological context And finally, the kittiwakes at Chiniak Bay also seemed to be attuned to this same signal, notwithstanding the fact that it apparently led to opposite behavior in the local system for some of the time One thing that is fairly certain of is that the temporal and spatial patterns in various components of seabird biology exhibited in the GOA do reflect underlying patterns in food-web production and ecosystem processes Because of the range of oceanographic situations surrounding the various colonies, detailed information from them should prove valuable in building a composite view of ecosystem behavior in the GOA

A variety of approaches to developing a long-term monitoring program in the GOA might work, but the framework that has evolved over the past 3 decades already has proved useful In-depth work is occurring or has occurred in many years since the 1970s at well-placed locations throughout the GOA These locations include St Lazaria Island and Forrester Island in Southeast Alaska, Middleton Island, many colonies in PWS, Chisik Island, Gull Island, and the Barren Islands in Lower Cook Inlet; Kodiak Island, the Semidi Islands, and Aiktak Island on the south side of Unimak Pass Colonies at these locations share several well-known, tractable species that provide complementary views of the ecosystem, particularly if they are systematically exploited for their contributions Just as information from each of these colonies will help build a composite broad view of the GOA, information from several species of seabirds at each colony will help build a composite regional view of ecosystem behavior

Therefore, the most popular species should continue to be the main focus These are kittiwakes and murres, the species in the GOA with the highest combined score of abundance, distribution, and ease of study Elements of their biology are sensitive to variability in prey, as seen in the GOA and numerous places elsewhere in the North Pacific and North Atlantic

Kittiwakes and murres do not do some things as well as second-tier species, namely the puffins Comparatively little is known about population trends of puffins, despite the fact that they are among the most abundant and widespread of the seabirds in the GOA This lack of knowledge results because they nest underground However, puffins have been used to monitor trends in forage fish abundance at numerous colonies throughout the GOA, Aleutian Islands, and British Columbia (Hatch 1984, Vermeer and Westrheim 1984, Hatch and Sanger 1992, Hatch unpublished data, Piatt unpublished data) Diets of the three species of puffins overlap extensively, but each samples the environment somewhat differently variability in diets among the puffins, locations, and time reveals geographic patterns of forage fish community structure and fluctuations in the abundances of individual species Puffins return whole, fresh prey to their chicks, a behavior that provides an economical, efficient means of measuring various attributes of forage fish populations, such as individual growth rates within and between years and relative year-class strength

Third-tier species, the cormorants, guillemots, and storm-petrels, also have attributes that can provide additional useful information Cormorant and guillemot diets overlap extensively with those of kittiwakes, murres, and puffins, but the cormorants and guillemots sample prey much nearer to colonies and sample additional species not used by the others Storm-petrels, in contrast, range widely and sample oceanic prey not commonly consumed by any other species In combination, the diets, abundance, and productivity of the various species of seabirds provide information on prey at multiple spatial scales around colonies In situations when this information can be easily obtained, it should not be overlooked

A successful strategy for seabird monitoring will balance breadth (geographic and ecological) with intensity (how much is done at each site) On the one hand, it is important to select a sufficient number of sites to adequately represent a range of environmental conditions in mesoscale and macroscale dimensions On the other hand, studies must be thorough at each colony Simply comparing population trends of one or two species may give uncertain, possibly misleading information on underlying conditions of the environment. Without additional information on such things as survival, emigration, recruitment, diet, and physiological condition of the birds, conclusions about causes of population change, or about what population change is saying about the environment versus what productivity is saying, are elusive

Another need for a long-term monitoring plan is knowledge about when reliable time series begin For example, several estimates of murre abundance at colonies in the GOA from the 1970s are likely not comparable to more recent systematic counts (Erikson 1995, Roseneau unpublished data) Inappropriate comparisons could result in erroneous conclusions about population changes that might further lead to unsupported speculation concerning broader trends in ecosystem change This (this what? please clarify) is nicely illustrated by census data from the western Alaska Peninsula If taken at face value, the information indicates that declines in the abundance of murres have been particularly severe at colonies from the Shumagin Islands westward to Unimak Pass However, the trend data for two of the colonies, Bird Island and Unga Island, consist of single counts made in each of 2 years at both colonies The first counts in 1973 were made in mid-June, which is early in the nesting season when murre numbers are unstable at colonies and often much higher than later during the census period (Hatch and Hatch 1989) At another of the colonies, Aiktak Island, the evidence of decline is based on a single count of nearly 13,000 birds in 1980, the first year a census of the colony was performed (Byrd et al 1999) Single counts in 1982, 1989, and 1990 ranged between 175 and about 8,000 birds And, the lower boundary of the 90% confidence interval about the mean of multiple counts in 1998 was less than zero, and the upper boundary was nearly as great as the first count in 1980 One must therefore ask if the murre population has indeed changed at all over the long term at Aiktak Island, or at the other colonies in the region where similar uncertainty exists, and if so how much

In spite of such caveats, information gained from seabirds in the past 3 decades reveals a great deal about the nature of variability in the GOA We can be certain that the perpetuation and refinement of seabird studies will continue to provide insights and hypotheses useful to the broader goal of understanding the GOA ecosystem

Critical Information Needs

- Continuing information on productivity, population trends, and diets of seabirds in the GOA,
- Information on the annual survival of seabirds at nesting colonies,
- Information on rates of immigration and emigration between colonies,
- Information on functional relationships between seabird abundance, behavior, and productivity and prey availability, and
- Information on functional relationships between elements of food web production at all trophic levels and environmental variability

3 9 5 General Research Questions

What is the relation between abundance of seabird populations and the availability of forage species, including fish?

- Are alterations in forage fish abundance and community structure brought on by environmental change capable of controlling seabird populations?
- Do local trends in the abundance of murres and kittiwakes reflect mesoscale or regional climatic and oceanographic processes affecting prey availability?
- How can influences of prey availability on seabird abundance be separated from the influences of mesoscale or regional properties unique to the location of the colony, such the presence of glaciers?

What is the relation between commercial fishing and the abundance of seabird populations?

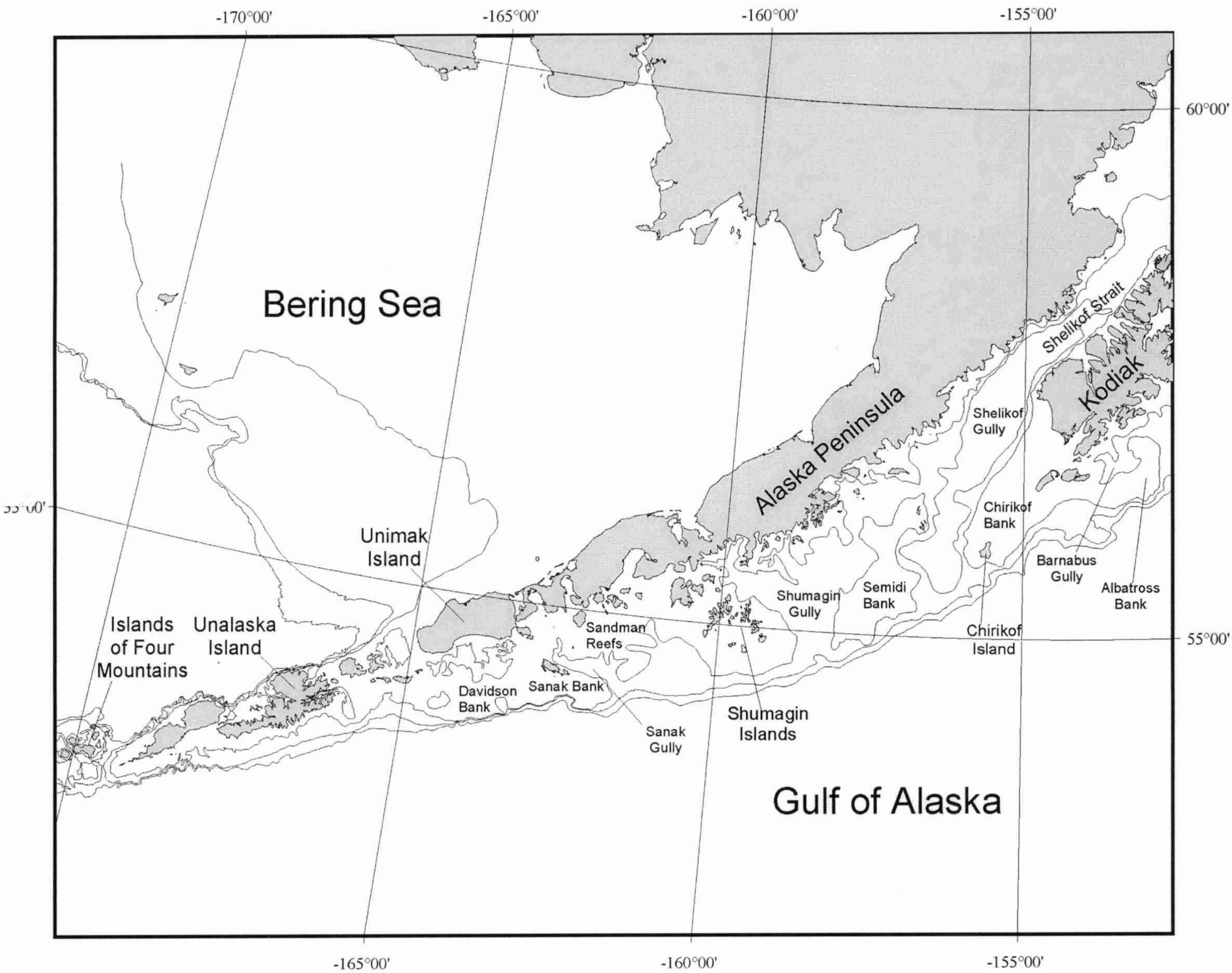
3.10 Fish and Shellfish

3 10 1 Introduction

The GOA is well known for its fish and shellfish because of its long-standing and highly valuable commercial and recreational fisheries (Table 2 1) Less well known are the non-commercial fish and invertebrate species that compose the bulk of the animal biomass in the GOA As a rule, the economically important species are fairly well known from trawl, trap, and hook catches made by research and commercial vessels (Cooney 1986, Martin 1997a, Witherell 1999a, Kruse et al 2000a) By the same rule, the majority of fish and shellfish species are less well known, having been sampled during research investigations of limited duration (Feder and Jewett 1986, Rogers et al 1986, Highsmith et al 1994a, Purcell et al 2000, Rooper and Haldorson) Species not commercially harvested are less well studied than commercially harvested species, such as Tanner crab For example, because no commercial fisheries are allowed for such forage fishes as eulachon, sand lance, capelin, and lantern fish, the fluctuations of their populations are not well documented More detailed consideration of some of the less economically important, but more ecologically prominent forage species is found in Section 3 8, Forage Species, and some of the less common shellfish species are considered in Section 3 7, Nearshore Benthic Communities

The marine fish and shellfish of the GOA fall into two major groups (Feder and Jewett 1986, Rogers et al 1986, Cooney 1986, Cooney 1986, Martin 1997b)

1 Fish–bony fish, sharks, skates, and rays,
2 Shellfish–the mollusks (bivalves including scallops, squid and octopus), and Crustaceans–crabs and shrimp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Bering Sea
Alaska Peninsula
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Unimak
Island
Semidi
Bank
Shumagin
Gully
Chirikof
Island
Islands
of Four
Mountains
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Sandman
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Davidson
Bank
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Shumagin
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Gulf of Alaska
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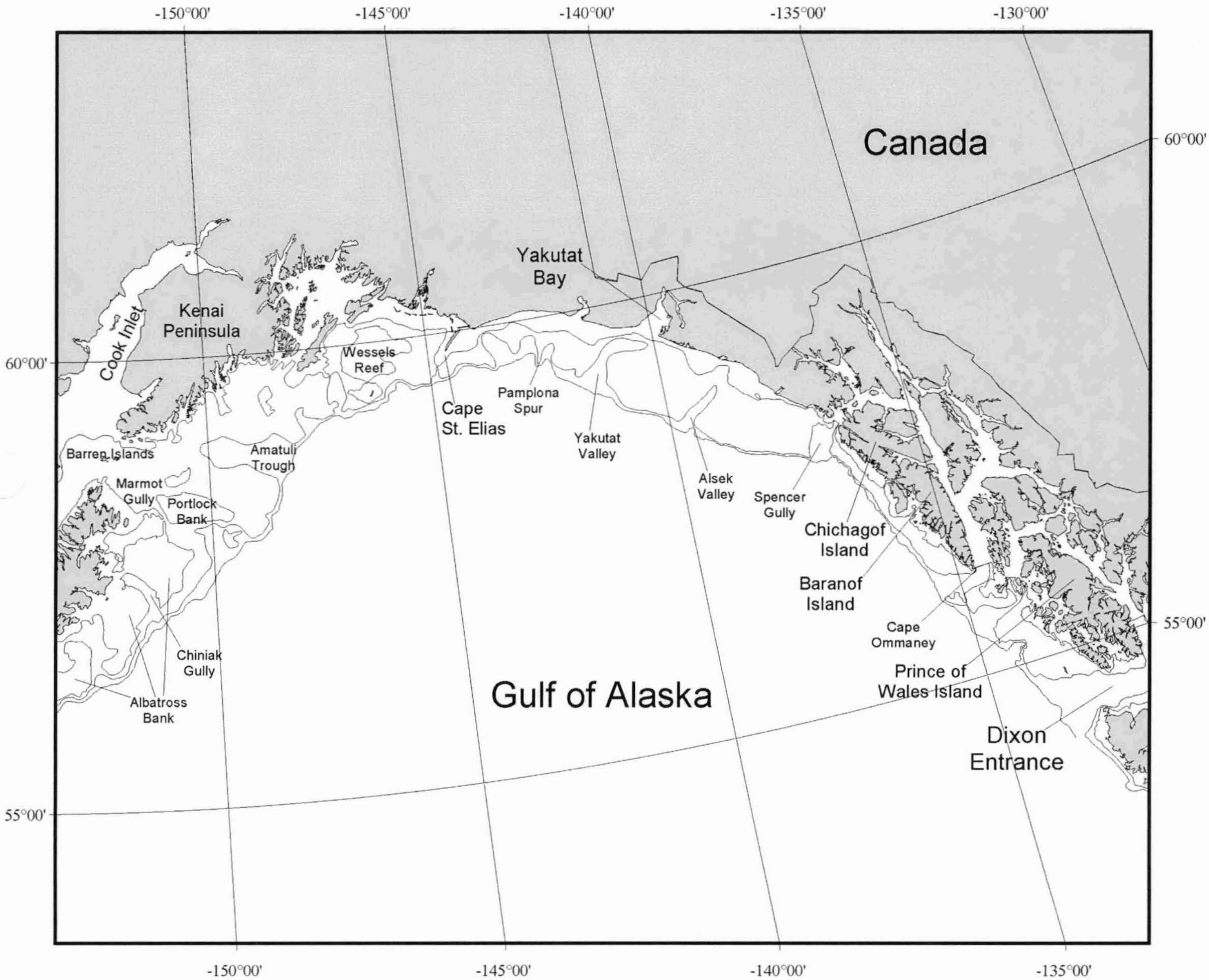
Figure 3.17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Canada
Yakutat Bay
Cook Inlet
Kenai Peninsula
Wessels Reef
Pamplona Spur
Cape St. Elias
Yakutat Valley
Barren Islands
Amatuli Trough
Alsek Valley
Spencer Gully
Marmot Gully
Portlock Bank
Chichagof Island
Baranof Island
Cape Ommaney
Chiniak Gully
Albatross Bank
Prince of Wales Island
Gulf of Alaska
Dixon Entrance
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60°00'
55°00'

Note that three other ecologically important groups, the pelagic jellyfish (Cnidaria), the bottom dwelling starfish and urchins (Echinodermata), and the segmented worms (Annelida) are not included in the category of the fish and shellfish A list of all the scientific names and many common names of the species accessible to trawl gear on the continental shelf and shelf break of the GOA is found in Appendix A

As would be expected with high marine productivity, the fish and shellfish fisheries of the GOA have been among the world's richest in the second half of the 20th century Major fisheries include, or have included, halibut, groundfish (Pacific cod, pollock, sablefish, Pacific ocean perch and other rockfish, flatfish such as soles and flounders), Pacific herring, multiple species of Pandalid shrimp and red king crab, five species of Pacific salmon, scallops, and other invertebrates (Kruse et al 2000a, Witherell and Kimball 2000, Cooney 1986) The status of major fisheries and stocks of interest are addressed in the subsections below

3 10 2 Overview of Fish

Most of the approximately 287 known GOA fish species are bony fish, and the largest number of species is in the sculpin family (Cottidae), followed in order of number of species by the snailfish family (Cyclopteridae), the rockfish family (Scorpaenidae) and the flatfish family (Pleuronectidae) (Tables 3 6 and 3 7) (Cooney 1986) The bony fish dominate the number of species in the GOA, with less than 10% of species being cartilaginous fishes (Petromyzontidae to Acipenseridae, Table 3 6) Species diversity in the fish depends on the type of gear used to sample (Table 3 6) It is important to keep in mid that trawl gear surveys are not designed or intended to estimate species diversity A comparison of the known fish species composition (Table 3 6, left two columns) to the species composition in the predominant types of trawl gear surveys (Table 3 6, right two columns) shows that trawl gear samples underestimate the fish species diversity of the GOA (Cooney 1986) The longest standing trawl gear surveys for the GOA are limited to the continental shelf and the shelf break (to 500 m before 1999 and to 1,000 m thereafter) The NMFS has measured relative abundance and distribution of the principal groundfish and commercially important invertebrate species (Martin 1997b), and before 1980, the International Pacific Halibut Commission (IPHC) collected information on the abundance, distribution and age structure of halibut (Figure 3 17) Hook and line surveys for Pacific halibut, sablefish, rockfish, and Pacific cod on the continental shelf in the GOA have been conducted by the IPHC since 1962 (Clark et al)

FIGURE 3 17

FIGURE NOT YET PREPARED (after Martin D H Pages 4 and 5)

Table 3 6 Fish Families and the Approximate Number of Genera and Species Reported from the Gulf of Alaska

Family	Quast and Hall[1]		Miscellaneous Surveys[2]	
	Number of Genera	Number of Species	Number of Genera	Number of Species
Petromyzontidae	2	3	-	-
Hexanchidae	1	1	-	-
Lamnidae	2	2	1	1
Carcharhinidae	1	1	-	-
Squalidae	2	2	1	1
Rajidae	1	7	1	4
Acipenseridae	1	2	-	-
Clupeidae	2	2	1	1
Salmonidae	6	12	1	3
Osmeridae	5	6	5	6
Bathylagidae	1	4	-	-
Opisthoproctidae	1	1	-	-
Gonostomatidae	2	4	-	-
Melanostomiidae	1	1	-	-
Chauliodontidae	1	1	1	1
Alepocephalidae	1	1	-	-
Anotopteridae	1	1	-	-
Scopelarchidae	1	1	-	-
Myctophidae	7	10	1	1
Oneirodidae	1	3	-	-
Moridae	1	1	-	-
Gadidae	5	5	5	5
Ophidiidae	2	2	-	-
Zoarcidae	6	11	4	7
Macrouridae	1	3	1	1
Scomberesocidae	1	1	1	1
Melamphaidae	3	3	-	-
Zeidae	1	1	-	-
Lampridae	1	1	-	-
Trachipteridae	1	1	-	-
Gasterosteidae	2	2	-	-
Scorpaenidae	2	22	2	30
Hexagrammidae	3	6	3	5
Anoplopomatidae	2	2	1	1
Cottidae	30	54	15	24
Psychrolutidae	1	1	-	-

Table 3 6 Fish Families and the Approximate Number of Genera and Species Reported from the Gulf of Alaska

	Quast and Hall[1]		Miscellaneous Surveys[2]	
Family	**Number of Genera**	**Number of Species**	**Number of Genera**	**Number of Species**
Agonidae	8	12	8	9
Cyclopteridae	12	38	5	7
Bramidae	1	1	-	-
Pentacerotidae	1	1	-	-
Sphyracnidae	1	1	-	-
Trichodontidae	2	2	1	1
Bathymasteridae	2	4	2	2
Anarhichadidae	1	1	1	1
Stichaeidae	10	15	4	6
Ptilichthyidae	1	1	-	-
Pholididae	2	4	-	-
Scytalinidae	1	1	-	-
Zaproridae	1	1	1	1
Ammodytidae	1	1	1	1
Scombridae	2	2	-	-
Centrolophidae	1	1	-	-
Bothidae	1	1	-	-
Pleuronectidae	15	17	15	16
Cryptacanthodidae[3]	2	2	2	2
Totals	**167**	287	84	138

Sources Hood and Zimmerman 1986 (after Ronholt Shippen and Brown 1978)

[1]After Quast and Hall (1972)

[2]Gulf of Alaska exploratory BCF, IPHC and NNIFS trawl survey data

[3]Quast and Hall (1972) include these genera and species in the family Stichaeidae while Hart (1973) recognizes a separate family

Table 3 7 Proportion of the Total Species Composition of Gulf of Alaska Fish Fauna Contributed by the 10 Dominant Fish Families in Two Different Surveys

Family[1]	Percentage of Total Fish Species	Family[2]	Percentage of Total Fish Species
Cottidae	19	Scorpaenidae	10
Cyclopteridae	13	Cottidae	8
Scorpaenidae	8	Pleuronectidae	6
Pleuronectidae	6	Agonidae	3
Stichaeidae	5	Zoarcidae	2
Salmonidae	4	Cyclopteridae	2
Agonidae	4	Stichaeidae	2
Zoarcidae	4	Osmeridae	2
Myctophidae	3	Gadidae	2
Rajidae	2	Hexagrammidae	2
Total	**68**		**39**

Source Hood and Zimmerman 1986
[1]From Quast and Hall (1972)
[2]From GOA exploratory cruises and resource assessment surveys

On the basis of the biomass available to trawl gear on the continental shelf and shelf break, flatfish and rockfish dominate the fish fauna in most areas of the GOA As of 1996, a flatfish species, arrowtooth flounder, dominated the overall trawl survey of the fish biomass in the GOA, followed by Pacific ocean perch (rockfish), walleye pollock (gadid), Pacific halibut (flatfish), and Pacific cod (gadid) (Martin 1997a) Biomass of the arrowtooth flounder is approaching 2 million mt, and its biomass has been steadily increasing since 1977 (Witherell 1999a) Of the next 15 largest biomasses of species in the 1996 NMFS survey, 6 were flatfish and 5 were rockfish

Geographic distributions of GOA fish biomass in the NMFS trawl surveys are different from the overall total In the western GOA, Atka mackeral (Hexagrammid) had the highest biomass in the Shumagin Islands, but this species was not among the 20 largest biomasses of species in the four other INPFC areas of the GOA Arrowtooth flounder dominate the trawl survey biomass throughout the GOA They are the most or second most abundant in all five areas Flatfish and especially soles comprise a large number of high-biomass species in the western and northwestern GOA (Shumagin Islands, Chirikof, and Kodiak), and rockfish have a large number of high-biomass species in the northeastern and eastern GOA (Yakutat and Southeast) Pollock and cod are a dominant part of the biomass in the western GOA, but less so in the east Pacific sleeper sharks are among the 20 largest biomasses of species in the north (Chirikof, Kodiak, and Yakutat), but not in the south (Shumagin Islands and Southeast) The only anadromous species, the eulachon, occurs among the 20 largest biomasses in the north, but not in the south

With the use of a variety of gear types, including trawl net, try net, trammel net, beach seine, and tow net in waters less than 100 m, Rogers et al (1986) provided a detailed image of the distribution of fish species and biomass with depth and by region As was the case for the 1996 NMFS trawl surveys, species composition and relative biomass of fish species in multi-gear surveys change substantially in moving from the nearshore toward offshore areas in the GOA, as well as from one region to the next The findings of the multiple gear surveys were consistent with the trawl survey observations in that shallow (smaller than 100 m) fish assemblages were more diverse in the north and west of the GOA than in the northeast and east (Table 3 8 in comparison to Table 3 6)

Table 3 8 Comparison of the Number of Fish Families and Species Found at less than 100 m in Different Regions of the GOA

Location	Number of Families	Number of Species
Kodiak	22	101
Lower Cook Inlet	25	105
Prince William Sound	18	72
Southeast Alaska	NA	51

Information summarized from Rogers et al (1986)

NA = not available

Other trends in distribution correspond to reproduction and seasonal changes in shallow waters in some species of nearshore fishes. Estuarine bays in the Kodiak archipelago are nursery areas, with larvae and juveniles being found in nearshore and pelagic habitats within bays (Rogers et al. 1986). Blackburn (1979 in [Rogers et al. 1986]) found a trend of larger fish with increasing depth in studies of Ugak Bay and Alitak Bay on Kodiak Island. Most species of nearshore fish apparently move to deeper water in the winter. In Lower Cook Inlet and Southeast Alaska, juveniles and other smaller size classes of the species of local fish assemblages are found close to shore, water temperatures permitting, and larger size classes are found farther offshore at depths greater than 30 m at all times of the year.

Nearshore areas of the GOA provide rearing environments for the juveniles of many fish species. Important nursery grounds for juvenile flatfishes, such as soles and Pacific halibut, are found in waters of Kachemak Bay and other waters of Lower Cook Inlet, as well as in Chiniak Bay on Kodiak Island (Norcross 1998). In Kachemak Bay, summer habitats of some juvenile flatfishes are shallower than winter habitats. Juvenile flatfish distributions in coastal waters are defined by substrate type, typically mud and mud-sand, and by depth, typically 10 to 80 m, and in the case of Chiniak Bay, by temperature. Deep-water and shallow-water assemblages were identified for the groundfish communities in both Kachemak and Chiniak bays, however, the limiting depths were different for the se two localities (Norcross 1998, Mueter and Norcross 1999).

Both salmon and groundfish populations in the northeastern Pacific appear to vary annually in concert with features of climate, but the responses appear to be different (Francis et al. 1998). Annual groundfish recruitments follow a cycle with a roughly 10-year period that may be related to the ENSO (Hollowed and Wooster 1992), whereas salmon abundance changes sharply at intervals of 20 to 25 years in concert with the PDO (Brodeur et al. 1996). The ENSO and the PDO were shown to be independent of one another (Mantua et al. 1997). The opposite responses of groundfish and salmon (positive) and crab (negative) recruitment to intensified Aleutian lows may be because different species-specific mechanisms are invoked by the same weather pattern. Because the groundfish species described by Hollowed and Wooster (1992, 1995) were mostly winter spawners, Zheng and Kruse (2000b) hypothesize that strengthened Aleutian lows increase advection of eggs and larvae of groundfish toward onshore nursery areas, improving survival. Salmon, on the other hand, benefit from increased production of prey items under intense lows. The possible links between Aleutian lows, PDOs, and ENSO and populations of fish and other animals are discussed further below and in a recent review paper (Francis et al. 1998).

3.10.2.1 Salmon

The GOA is the crossroads of the world for Pacific salmon. Salmon from Japan, Russia, all of Alaska, British Columbia, and the Pacific Northwest spend part of each life cycle in the GOA (Myers et al. 2000). Five species of salmon–pink, chum, sockeye, coho and Chinook–are very common in the GOA. These species appear in the GOA as early as the first year of life (all pink, chum, and ocean type chinook and some sockeye), however, others may appear during the second (all coho and stream-type Chinook and most sockeye) and rarely during the third or later years (some sockeye) (see (Groot and Margolis 1991) Ecologically, the salmon species may be divided into two broad groups, marine planktivores (pink, chum, and sockeye) and marine piscivores (coho and chinook) Further ecological differentiation is apparent within planktivores For example, the size groups of plankton consumed by chum and sockeye are inferred to be quite different, because chum use short stubby gill rakers to separate food from water, and sockeye have long feathery gill rakers as filters

Distribution within the GOA changes with time after marine entry (Nagasawa 2000), as salmon disperse among coastal feeding grounds according to species and stock, age, size, feeding behavior, food preferences, and other factors (Myers et al 2000) During the first year of marine life, salmon are located in estuaries, bays, and coastal areas within the ACC and continental shelf (Myers et al 2000) With time and growth, first-year salmon move farther away from their river of origin and father offshore First-year salmon move out of the ACC into colder waters in fall and winter of their first year at sea

Salmon of all ages are thought to exhibit seasonal migrations in spring and fall between onshore and offshore marine areas In the fall, salmon of all ages move offshore to spend the winter in waters between 4° C and 8° C that are relatively poor in food, perhaps as an energy conservation strategy for surviving the winter (Nagasawa 2000) In the spring, salmon move onshore into waters that may reach 15° C where food sources are relatively abundant

Salmon populations overall are at very high levels in Alaska, with the notable exceptions of western Alaska chum and chinook populations originating in drainages between Norton Sound in the north and the Kuskokwim River, west of Bristol Bay (ADF&G 1998) On Norton Sound, the chum salmon populations of the Penny and Cripple rivers have exhibited very low to zero spawning stocks in the past 5 years Another notable exception to the record high levels of Alaska salmon production are the Kvichak River sockeye populations of Bristol Bay, which have faltered Some "off-peak cycle" brood years have recently failed to produce as expected (Kruse et al 2000b)

The situation in Western Alaska notwithstanding, the 1999 commercial harvest of 404,000 mt of salmon in Alaska was the second largest in recorded history behind 1995 (451,000 mt) (Kruse et al 2000b) A large portion of the record harvests in 1999 was pink salmon from areas adjacent to the GOA, PWS, and Southeast Alaska The status of salmon populations and fisheries in the following areas were recently evaluated in terms of levels of harvest and spawning escapements areas coincident with habitats in the north central GOA of the Stellar sea lion, which is listed as an endangered species under the Endangered Species Act of 1973 (ESA), Kodiak, the Alaska Peninsula, and Bristol Bay All major commercial salmon stocks were judged to be healthy, with the exception of the Kvichak River off-cycle brood years (Kruse et al 2000b)

Given that marine migration patterns of each stock are thought to be characteristic and somewhat unique (Myers et al 2000), the contrast in the status of salmon stocks between Western and Southcentral and Southeast Alaska offers some intriguing research questions about the role of marine processes in salmon production (Cooney 1984) Understanding the processes that connect salmon production to climate, marine food production, and fishing requires understanding of the marine pathways of the salmon through time (Beamish et al 1999b) Therefore, research approaches to understanding changes in salmon abundance on annual and decadal scales need to encompass localities that are representative of the full life cycle of the salmon and, in particular, in estuarine and marine environments Scientific information on freshwater localities is far more common than that available for estuarine and marine areas Given the current state of information on both hatchery and wild salmon, it is highly desirable to focus current and future efforts on estuaries and marine areas for understanding migratory pathways and other habitats, physiological indicators of individual health, trophic dynamics, and the forcing effects of weather and oceanographic processes (Brodeur et al 2000)

3.10.2.2 Pacific Herring

Pacific herring (herring) populations (Funk 2000) occur in the northeast GOA, with commercial concentrations in Southeast Alaska (Sitka), PWS, western Lower Cook Inlet, and occasionally around Kodiak Most of the historical information on herring in the GOA comes from coastal marine fisheries that started in Alaska in 1878 (Kruse et al 2000b), however, intensive ecological investigations at the end of the 20th century have added information on early life history (Norcross et al 1999) Herring deposit eggs onto vegetation in the intertidal and near subtidal waters in late spring, undergo a period of larval drift, and spend the first summer and winter nearshore in sheltered embayments Transport of larvae by currents in relation to sites that are suitable summer feeding and overwintering grounds is likely an important factor affecting survival in the first year of life in PWS (Norcross et al 1999), as is the nutritional status of these age-0 herring in the fall of the year (Foy and Paul 1999) Some portion of the mature herring must migrate annually between onshore spawning grounds and offshore feeding grounds, however, the geography of the life cycle between spawning and maturation is less certain

Although the geographic scope of the herring life cycle in the Bering Sea is fairly well understood, inferences from the Bering Sea to the GOA are not direct because of apparent differences in life history strategies between the herring of the two regions (Funk 2000) Adult herring in the GOA are smaller and have shorter life spans than those in the Bering Sea Perhaps GOA herring migrate shorter distances to food sources that are not as rich as those available to Bering Sea herring, which migrate long distances from spawning to feed among the rich food sources of the continental shelf break (Funk 2000). Genetic analyses indicate that Bering Sea and GOA herring populations are reproductively isolated (Funk 2000).

Another ecologically significant characteristic of Pacific herring is the temporal change in size at age over time (Brown 2000). Annual deviations from long-term (1927 to 1998) mean length at age for Sitka Sound herring indicate a decadal-scale oscillation between positive and negative deviations. This finding is consistent with the reported coincidence of size-at-age data for Pacific herring with the PDO (Ware 1991). Herring may be affected by ENSO events. Decreased catches, recruitments, and weight-at-age of herring are at times associated with ENSO events. Seabirds in the GOA that depend on herring and other pelagic forage species showed widespread mortalities and breeding failures during the ENSO events of 1983 and 1993 (Bailey et al. 1995b). The similarities between the annual patterns of abundance and the location of weather systems (annual geographically averaged sea-level atmospheric pressure) are not as clear with herring as for other fish species, such as salmon. The difference may result because herring populations tend to be dominated by the occasional strong year class and show considerable variability in landings through the years.

The current status of herring populations may be closely related to historical fishing patterns. Long-term changes associated with commercial fishing have occurred in the apparent geographic distribution and abundance of GOA herring. Herring-reduction fisheries (oil and meal) from 1878 to 1967 reached a peak harvest of 142,000 mt in 1934. That exploitation rates were high may be inferred from the fact that some locations of major herring-reduction fisheries, such as Seldovia Bay (Kenai Peninsula and Lower Cook Inlet) are now devoid of herring. It is speculated that reduction fisheries at geographic bottlenecks between herring spawning and feeding grounds, such as the entrance to Seldovia Bay and the passes of southwestern PWS, were able to apply very high exploitation rates to the adult population. Harvest management applied by the State of Alaska relies on biomass estimates, and harvests are held to a small fraction of the estimated biomass. Harvest is not allowed until the population estimate rises above a minimum or "threshold" biomass level.

Recent statewide herring harvests have averaged less than a third of the 1934 peak. Direct comparison of past and present catch statistics is problematic, however, because current rates of harvest are thought to be substantially below those applied in 1934 (Kruse et al. 2000b). Also note that recent statewide figures for herring harvests include substantial harvests from outside the GOA, and herring-reduction fisheries were located in the GOA. Populations of herring were targeted for sac roe starting in the 1970s and for sac roe and roe on kelp in the 1980s. Regional herring population status is variable. Population levels of herring in PWS remained at low levels in 2000, and commercial harvests were not allowed in 1994, 1995, and 1996, nor since 1998. In 1999, fishing operations were halted because of low biomass and poor recruitment. Disease is strongly suspected as a factor in keeping the population levels low. The herring fishery of Lower Cook

Inlet in Kamishak Bay closed in 1999 after a very small catch in 1998 and remains closed because of low biomass levels Catches in the Kodiak fishery for herring sac roe are declining The bait fishery in Shelikof Strait was closed in 1999 because of its possible relation to depressed Kamishak Bay herring populations

Significant questions remain about the geographic extent of the stocks to which the biomass estimates and fishing exploitation rates may apply in PWS (Norcross et al 1999) The geomorphology of PWS in relation to currents plays an important role in determining the retention of larvae in nearshore areas conducive to growth and survival The degree to which spawning aggregations of herring may represent individual stocks is a significant question, because the actual exploitation rate of herring in PWS depends on how many stocks are defined Although it is not clear how many stocks of herring occupy PWS, conditions appear to favor more than one spawning stock (Norcross et al 1999)

Water temperatures appear to play important roles in growth and survival of age-0 herring Warm summer water temperatures may be conducive to growth and survival, however, the opposite appears to be true of warm water temperatures in spring and winter Increased metabolic demands imposed by warm water on yolk-sac larvae and overwintering age-0 herring could decrease survival (Norcross et al 1999) Availability of food before winter, and perhaps during winter may be key to survival of age-0 herring Input of food from the GOA may be an important key to survival for age-0 herring at some localities Differential survival among nursery areas because of interannual variation in climate and accessibility of GOA food sources could be a key determinant of year-class strength in PWS The sources of variability mean that geographic locality is no guarantee of any particular level of survival from year to year Sampling whole body energy content of age-0 herring at the end of the first winter among bays could provide an indicator of year class strength (Norcross et al 1999)

Questions relating to the ability of disease outbreaks to control herring populations have recently been explored Work has identified the diseases, Viral Hemorrhagic Septicemia and a fungus as factors potentially limiting the abundance of herring in PWS (Hostettler et al 2000, Crane and Galasso 1999)

3.10.2.3 Pollock

Pollock are an ecologically dominant and economically important cod-like fish in the GOA They appear to spawn at the same locations within the same marine areas each year, with location of spawning and migrations of adults linked to patterns of larval drift and locations of feeding grounds (Bailey et al 1999) Spawning occurs at depths of 100 to 400 m, and as a result, the distributions of eggs and larvae in some areas may have been well below the depths of historical ichthyoplankton surveys Pollock larvae feed on early developmental stages of copepods and, as juveniles, move on to feed on larger zooplankton such as euphausiids and small fishes, including pollock Although cannibalism is regarded as significant in the Bering Sea, it is not thought to be a significant factor in the

GOA Pollock eggs and larvae are important sources of food for other zooplankters, and year class strength in pollock is thought to be related abundances of marine mammals and seabirds, at least in the Bering Sea

Pollock mature at about age 4 and may live as long as 20 years (Bailey et al 1999) Adult walleye pollock are distributed throughout the GOA at depths above 500 m A substantial portion (45%) of the total pollock biomass as well as the highest catches per unit effort (CPUEs) of the 1996 NMFS survey were found at less than 200 m in the area between Kodiak and Chirikof islands (Martin 1997a) In the western GOA, the highest pollock catches and CPUEs of the 1996 NMFS trawl survey were found at less than 200 m, whereas in Yakutat and Southeast Alaska the substantial availability of pollock to trawl gear persists above 300 m Pollock larger than 30 cm were rarely found above 200 m in the eastern GOA in 1996 (Yakutat and Southeast), although pollock of all sizes (about 10 to 70 cm) were found at all depths down to 500 m in the western GOA (Martin 1997a) Although pollock are commonly found in the outer continental shelf and slope, they may also be found in nearshore areas where they may be important predators and prey, for example, in PWS (Willette et al in press)

Populations of pollock in the GOA are considered to be separate from those in the Bering Sea (Bailey et al 1999) Among the most commercially important of the GOA groundfish species, exploitable biomasses of pollock populations in 1999 were estimated at 738,000 mt, down from a peak of about 3 million mt in 1982 (Witherell 1999b) Annual numbers of 2-year-old pollock entering the fishable population (recruitment) from 198 to 1987 were erratic and usually lower than recruitments estimated in 1977 to 1980

Following the climatic regime shift in 1978, pollock and other cod-like fish have dramatically increased, replacing shrimp in nearshore waters as the dominant group of organisms caught in mid-water trawls on the shelf (Piatt and Anderson 1996) Recruitment in pollock is heavily influenced by oceanographic conditions experienced by the eggs and larvae Good conditions for juveniles of the 1976 and 1978 year class contributed to the 1982 peak in pollock biomass in the GOA (Bailey et al 1999) Populations have gradually declined since then (Witherell 1999b) Increasing mortality schedules in 1986 to 1991 may indicate increasing predation and deteriorating physical conditions for both juveniles and adults in the GOA (Bailey et al 1999) The larger-than-average year class for GOA Pollock in 1988 may be related to high rates of juvenile growth coincident with warm water temperatures, lack of winds, low predator abundance, and low larval mortality rates (Bailey et al 1996) As has been shown to be the case with other groundfish species, GOA pollock recruitments are positively correlated with ENSO events (Bailey et al 1995b)

Issues in the management of pollock that currently remain unresolved include the geographic boundaries of stocks, their extent of migration, the effects of fishing in one geographic locale on the populations of pollock and predators in other geographic locales, and what controls the annual recruitment of young pollock to the fishable populations (Bailey et al 1999) In relation to stock structure, spawning aggregations in PWS, the Shumagin Islands (southwest Kodiak), and Shelikof Strait (separating Kodiak from the Alaska Peninsula) may represent separate stocks Conditions of weather and changing ocean currents and eddies in the Shelikof Strait have the capacity to alter survival of pollock larvae from year to year (Bailey et al 1995a) In particular, the effects of shifts in the strength of the ACC on larval transport pose important questions for how year class strength is determined In 1996, anomalous relaxation of winds resulted in a dramatic increase in larval retention in the Shelikof basin Increased larval retention may be favorable to survival of pollock larvae in this area, with some exceptions (Bailey et al 1999)

3.10.2.4 Pacific Cod

Pacific cod is a groundfish with demersal eggs and larvae found throughout the GOA on the continental shelf and shelf break Pacific cod of the GOA are also an economically and ecologically important species Pacific cod had an estimated fishable population of 648,000 mt in 1999, which is on the low end of the range of 600,000 to 950,000 mt estimated for 1978 to 1999 Annual recruitments of GOA Pacific cod have been relatively stable since 1978, with exceptionally large numbers of 3-year-old recruits appearing in 1980 and 1998 Biomass of the dominant flatfish in the GOA, the arrowtooth flounder, is approaching 2 million mt. Arrowtooth flounder is not heavily harvested, and their biomass has been steadily increasing since 1977

Pacific cod are found throughout the GOA at depths less than 500 m They are most abundant in the western GOA (Kodiak, Chirikof and Shumagin Islands) where Pacific cod larger than 30 cm are found at all depths above 300 m, but smaller individuals are rarely found at depths less than 100 m (Martin 1997a)

3.10.2.5 Halibut

Pacific halibut are common throughout the GOA at depths less than 400 m, and halibut are available to trawl gear at depths of 500 m (Martin 1997a) In the 1996 NMFS trawl survey, the largest catches and the highest CPUE were found at depths of less than 100 m east southeast of Kodiak on the Albatross Banks (Figure 3 17) In most areas of the GOA, the average weight and length of halibut caught in trawl gear increases with depth, even though the CPUE declines with depth, particularly in the western GOA (Shumagin Islands, Chirikof, and Kodiak) (Martin 1997a)

The exploitable biomass of another flatfish, the highly prized Pacific halibut, in 1999 was estimated at 258,000 mt, which is above average for 1974 to 1999 (Witherell 1999b) Exploitable biomass of Pacific halibut was also increasing from 1974 to 1988, after which it declined slightly

Pacific halibut appear to undergo decadal-scale changes in recruitment, which have been correlated with both the 18 6-year cycle for lunar nodal tide (Parker et al 1995) and the PDO

3 10 3 Overview of Shellfish and Benthic Invertebrates

Shellfish are commonly found on or near the surface of the sea floor, they are epibenthic, as adults, and in the water column, pelagic, for varying lengths of time as pre-adults Exceptions to this rule abound, particularly among mollusks such as squid, which live free of the bottom as adults Beyond the nearshore environment (at depths greater than 25 m), the shellfish and other invertebrates dominate the number of species and the biomass of the bottom, just as other assemblages of invertebrates dominate the nearshore (see Section 3 7) Among the shellfish, the arthropods and mollusks often have the largest number of species For example, of 287 species of bottom fauna identified in waters deeper than 25 m in Lower Cook Inlet, more than 67% were arthropods and mollusks (Feder and Jewett 1986) Many of the commercially important species of the GOA are dependent for food to a greater or lesser extent on benthic invertebrates discussed here (Commercially important crabs and shrimp are discussed below) Commercial crabs and shrimps, and scallops, join the fish species of Pacific cod, walleye pollock, halibut, and Pacific Ocean perch as members of the subtidal benthic food web for part of each life cycle Detritus, bacteria, and microalgae form the base for the benthic invertebrates of the GOA continental shelf, which are predominantly filter feeders (60%), and detritus eaters (33%) (Semenov 1965 in [Feder and Jewett 1986]) Small mollusks, small crustaceans, polychaete annelids, and other worm-like invertebrates make up the filter-feeding and detrivore component of this food web

Regional differences are pronounced in the benthic food webs of the GOA The eastern GOA has few filter feeders and lower average biomass relative to the northern and western GOA, in large part because of the nature of substrates and currents In particular the benthic species composition and productivity in the GOA is determined in part by the ACC, particularly in the embayments and fjords (Feder and Jewett 1986) The ACC brings freshwater to the environments containing the pelagic shellfish larvae and heavy sediment loads that define the bottom habitats of the later stages of the life cycle Biomass of filter feeders on the continental shelf in the western Gulf (138 grams per square meter [g/m^2]) is far higher than that found in the northeastern or eastern GOA combined (33 2 g/m^2) Biomasses of detritus feeders in the western (31 g/m^2) and eastern (12 g/m^2) GOA are lower than those found in the northeastern GOA (43 g/m^2) Biomasses of all trophic groups on the shelf break are lower than those of the adjacent shelf The distribution of benthic invertebrates in the GOA attests to the validity of the hypothesis that the type of bottom sediment, as influenced by proximity to alluvial inputs and currents, determines the species composition, production, and productivities of benthic communities (Semenov 1965 in (Feder and Jewett 1986) Sediment size is dominant among the factors controlling the distribution of benthic species (Feder and Jewett 1986)

3.10.3.1 Crab

The principal commercial crab species in the GOA are the king crabs (*Paralithodes* spp), the tanner crab (*Chionoecetes bairdi*), and the Dungeness crab

(*Cancer magister*) All species have benthic adults and pelagic larvae, although the life history strategies vary substantially within and among species For example, the pelagic stages of the red king crab are herbivorous, those of the tanner crab are carnivorous, and those of the golden king crab do not feed until they metamorphose into the benthic stages The benthic stages of all crab species feed to a large extent on the less well known invertebrates of the benthic environments (Feder and Paul 1980a, Jewett and Feder 1983, Feder and Jewett 1986) discussed briefly above under the shellfish overview

The status of crab populations is relatively poor in comparison to the groundfish populations (Kruse et al 2000a) Crab catches in the GOA have shown sharp changes with time, perhaps indicative of sensitivity to climatic forcing in some species, to fishing, or a to combination of factors (Zheng and Kruse 2000b) The red king crab stock of the GOA collapsed in the early 1980s and currently shows no signs of recovery The tanner crab populations in PWS, Cook Inlet, Kodiak, and the Alaska Peninsula have declined to low levels in the early 1990s, and harvest levels have been sharply reduced (Kruse et al 2000b)

In a study of time-series data on recruitment for 15 crab stocks in the Bering Sea, Aleutian Islands, and GOA, time trends in 7 of 15 crab stocks are significantly correlated with time series of the strength of Aleutian Low climate regimes (Zheng and Kruse 2000a) Time trends in recruitments among some king crab stocks were correlated over broad geographic regions, suggesting a significant role of environmental forcing in regulation of population numbers for these species The increased ocean productivity associated with the intense Aleutian Low and warmer temperatures was inversely related to recruitment for 7 of the 15 crab stocks The seven significantly negative correlations between ocean productivity and crab recruitment were from Bristol Bay, Cook Inlet ,and the GOA Crab stocks declined as the Aleutian Low intensified A significant inverse relation between the brood strength of red king crab and Aleutian Low intensity was reported earlier for one of the stocks in this study, red king crab from Bristol Bay (Tyler and Kruse 1996)

Tyler and Kruse (1996, 1997) and (Zheng and Kruse 2000a) have articulated an explicit series of hypotheses linking features of physical and geological oceanography to the reproductive and developmental biology of red king and tanner crab The hypotheses explain observed relations between climate and recruitment. Tanner and red king crab in the Bering Sea are thought to respond differently to the physical factors associated with the Aleutian Low because of the distribution of the different types of sea bottom required by the post-planktonic stage of each species Suitable bottom habitat for red king crabs in the Bering Sea is more generally nearshore, whereas suitable bottom habitat for tanner crab is offshore Intense Aleutian Low conditions favor surface currents that carry or hold planktonic crab larvae onshore, whereas weak Aleutian Low conditions favor surface currents that move larvae offshore The process may not be species specific, but stock specific, depending on the location of suitable settling habitat in relation to the prevailing currents In the case of red king crab, Zheng and Kruse (2000b) explain the apparent paradox of lowered recruitment for red king crab during periods of increased primary productivity. Red king crab eat diatoms, but show a preference for diatoms similar to *Thalassiosira* spp., which dominate in years of weak lows and stable water columns. Strong lows contribute to well-mixed water columns and a diverse assemblage of primary producers, which may be unfavorable for red king crab larvae, but favorable for tanner crab larvae. Tanner crab larvae eat copepods, which are favored by the higher temperatures associated with intense lows.

Recently completed modeling studies (Rosenkrantz 1999) support climatic variables as determinants of recruitment success in tanner crab. Predominant wind direction and temperature of bottom water were strongly related to strength of tanner crab year classes in the Bering Sea. Northeast winds are thought to set up ocean transport processes that promote year-class strength by carrying the larvae toward suitable habitat. Elevated bottom-water temperatures were expected to augment the effect of northeast wind by increasing survival of newly hatched larvae (Rosenkrantz 1999).

3.10.3.2 Shrimp

The shrimp were once among the dominant benthic epifauna in Lower Cook Inlet and Kodiak and along the Alaska Peninsula (Anderson and Piatt 1999, Feder and Jewett 1986) and of substantial commercial importance in the GOA. Five species of Pandalid shrimp dominated the commercial catches, which occurred west of 144° W longitude in PWS, Cook Inlet, Kodiak and along the Alaska Peninsula (Kruse et al. 2000b). Shrimp fisheries in the GOA peaked at 67,000 mt in 1973, reached 59,000 mt in 1977, and declined thereafter to the point where shrimp fishing is virtually nonexistent in the GOA today.

Regional fisheries follow the pattern seen for the GOA as a whole. The trawl fishery for northern shrimp (*Pandalus borealis*) in Lower Cook Inlet peaked at 2,800 mt in 1980 to 1981 and was closed in 1987 to 1988. The fishery for northern and sidestriped shrimp (*P. dispar*) along the outer Kenai Peninsula peaked at 888 mt in 1984 to 1985 and closed in 1997 to 1998. The pot fishery for spot (*P. platyceros*) and coonstriped shrimp (*P. hypsinotus*) in PWS increased rapidly after 1978 to its peak harvest of 132 mt in 1986. This pot fishery then declined to its low of 8 mt in 1991 and has been closed since 1992. The trawl shrimp fishery for northern shrimp in PWS peaked at 586 mt in 1984 and switched to sidestriped shrimp in 1987. The PWS trawl fishery for sidestriped shrimp peaked at 89 mt in 1992, and the northern shrimp catch was virtually zero at this time. The PWS catch of sidestriped shrimp in 1999 was 29 mt and falling. The Kodiak trawl fishery for northern shrimp peaked at 37,265 mt in 1971, and catch thereafter declined to 3 mt in 1997 to 1998. In the Aleutian Islands, shrimp catches after the 1978 season declined precipitously, and the fishery has not rebounded since.

3.10.4 General Research Questions

The following general research questions summarize the scientific questions posed or suggested by Section 3 10

How can trends in abundance of fish and shellfish species be explained?

- What is the role of large-scale atmospheric forcing in controlling the structure and abundance of marine fish and shellfish communities in the western central GOA ecosystem?
  - Does large-scale atmospheric forcing control the quality of food available to larval fish and shellfish through its influence on the species composition and size distribution of primary producers?
  - How do the rates of recruitment of benthic animals with planktonic larvae respond to mechanisms of transport that may control the distribution of larvae relative to suitable bottom habitat?
  - How do the rates of recruitment of fish species with planktonic larvae respond to mechanisms of transport that may control the distribution of larvae relative to suitable juvenile rearing habitat?
- Are fish species that spawn in the winter favored by periods of early peak production, and species that spawn in the spring and summer favored by periods of delayed production?
- What life history strategies permit the arrowtooth flounder to be so widespread and abundant?

How well are the species composition, relative abundances and trophic structure of fish and shellfish communities understood, based on current sampling methods?

What are the underlying mechanisms whereby climate induces changes in productivity, and whereby fishing induces variations in the ocean production of salmon?

- How can salmon stocks be identified?
- What are the ecological processes in the ocean that control productivity of salmon?
- What are the interannual variations in ocean growth, distribution, and migratory timing of salmon stocks?
- What are the annual levels of ocean production of salmon in the North Pacific and by region of origin?

3.11 Marine Mammals

3.11 1 General Characteristics of the GOA Marine Mammal Fauna

The GOA has a mostly temperate marine mammal fauna Calkins (1986) provided the only previously published review of GOA marine mammals, and listed 26 species as occurring in the region Five of those (pilot whale, Risso's dolphin, right whale dolphin, white sided dolphin, and California sea lion) are primarily southern species that occur occasionally in Southeast Alaska but rarely, if at all, in the EVOS region He also listed the Pacific walrus, which is a subarctic species that occurs in the GOA only as occasional wanderers

Table 3 9 provides a summary of the general characteristics of 20 marine mammal species that occur regularly in the GEM region, including 7 baleen whales, 8 toothed whales and porpoises, 4 pinnipeds, and the sea otter Useful reviews of information on these species can be found in Lentfer (1988), Calkins (1986), Perry et al (1999), Forney et al (2000), and Ferrero et al (2000) Various aspects of marine mammal biology are described in detail in Reynolds and Rommel (1999)

Most of the marine mammal species shown in Table 3 9 are widely distributed in the North Pacific Ocean, and the animals that inhabit the GEM region represent only part of the total population Application of modern molecular genetics techniques, however, has provided much new information on population structures (Dizon et al 1997) Researchers have found that for species such as killer whales (Hoelzel et al 1998), beluga whales (O'Corry-Crowe and Lowry 1997), (Bickham et al 1996), harbor seals (Westlake and O'Corry-Crowe 1997), and sea otters (Scribner et al 1997), genetic exchange among adjacent and sometimes overlapping groups of animals is so low that they need to be managed as separate stocks

Taxonomically the GOA marine mammal fauna can be broken down into four major groups

- Mysticete cetaceans–baleen whales,
- Odontocete cetaceans–toothed whales,
- Pinnipeds–seals, sea lions, and fur seals, and
- Mustelids-sea otters

The baleen whales are primarily summer seasonal visitors to the GOA that come to the continental shelf and offshore waters to feed on zooplankton and small schooling fishes (Calkins 1986, Perry et al 1999) Breeding and calving occur in more southerly, warmer, regions The GOA is primarily a migration route for the gray whale, which breeds and calves in Baja California, Mexico, and has its primary feeding grounds in the northern Bering and Chukchi seas Jones et al 1984

Table 3.9 Summary of Characteristics of Marine Mammal Species That Occur Regularly in the GOA EVOS Area

Species shown in bold are those that have been selected as focal species for GEM

	Use of Gulf of Alaska by Species			Population Status		Management Classification		
Species	**Residence**	**Habitats[1]**	**Activities[2]**	**Abundance[3]**	**Trend**	**EVOS**	**MMPA**	**ESA**
Mysticetes								
Blue whale	seasonal	S D	F	small?	unknown		depleted	endangered
Fin whale	seasonal	S, D	F	medium?	unknown		depleted	endangered
Sei whale	seasonal	S, D	F	medium?	unknown		depleted	endangered
Humpback whale	seasonal	C, S D	F	medium	increasing		depleted	endangered
Gray whale	seasonal	C S	M F?	large	increasing			
Right whale	seasonal	S	F	small	unknown		depleted	endangered
Minke whale	resident?	C S	F, C, B?	medium?	unknown			
Odontocetes								
Sperm whale	seasonal?	S, O	F	large?	unknown		depleted	endangered
Killer whale	**resident**	**C, S, D**	**F, C, B**	**small**	**unknown**	**damaged**		
Beluga whale	**resident**	**C, S**	**F, C, B**	**small**	**declining?**		**depleted**	
Beaked whale[4]	resident?	S D	F, C, B	unknown	unknown			
Dall's porpoise	resident	S, D	F, C, B	large	unknown			
Harbor porpoise	resident	C S	F C, B	large	unknown			
Pinnipeds								
Steller sea lion	**resident**	**T, C, S, D**	**F, C, B**	**large**	**declining**		**depleted**	**endangered**
Northern fur seal	seasonal	S, D	M F	large	stable		depleted	
Harbor seal	**resident**	**T, C, S**	**F, C, B**	**large**	**declining**	**damaged**		
Elephant seal	seasonal	S, D	F	large	increasing			
Mustelids								
Sea otter	**resident**	**T, C, S**	**F, C, B**	**large**	**unknown**	**damaged**		

[1] T = terrestrial, C = coastal, S = continental shelf, D = deep water
[2] F = feeding M = migrating, C = calving/pupping, B = breeding
[3] small = <1 000, medium = 1,000-10 000, large = >10,000
[4] Probably includes at least 3 species Baird's beaked whale, Cuvier's beaked whale, and Bering Sea beaked whale

The large species of baleen whales were all greatly reduced by commercial over-exploitation (Perry et al 1999) Historical information on stock structure and abundance is very limited, and, partly because of their broad distributions, accurately assessing current abundance and population trend is generally difficult (Ferrero et al 2000) Humpback whales and gray whales are exceptions to that generalization For humpbacks, estimates of population size based on individual identifications from fluke photos (Calambokidis et al 1997) suggest that the central North Pacific stock is increasing (Ferrero et al 2000) For many years, systematic counts have been made of gray whales migrating along the California coast, and results indicate that since the 1960s the population has been increasing by 2 5% per year (Breiwick 1999)

The situation with sperm whales is much like that of the large baleen whales Many features of their basic biology, such as stock structure, distribution, migratory patterns, and feeding ecology, are poorly known They occur throughout the North Pacific, mostly in deep water south of 50° N latitude, but some are seen in the northern GOA at least in summer (Calkins 1986, Perry et al 1999) From what is known of their diet, sperm whales eat mostly deep-water fishes and squids North Pacific sperm whales were intensely harvested, with more than 250,000 killed during 1947 to 1987 (Perry et al 1999) Current abundance and population trend are complete unknowns

In contrast to the baleen whales and sperm whale, the smaller toothed whales are primarily resident in the GOA Very little is known about the biology of beaked whales, but the other species have been relatively well studied Two species, killer whales and beluga whales, have been selected as focal species for GEM and are discussed in detail in later sections Harbor porpoises and Dall's porpoises both have relatively large populations, and with the exception of incidental take in commercial fisheries, they are unlikely to have been significantly impacted by human activities (Ferrero et al 2000) Both species feed on small fishes and squids, with Dall's porpoises using mostly continental shelf and slope areas and harbor porpoises most common in coastal and continental shelf waters (Calkins 1986)

The two resident pinniped species, Steller sea lions and harbor seals, are both focal species for GEM and will be discussed later in this section Northern fur seals pup and breed on islands in the Bering Sea (Pribilof Islands and Bogoslof Island) A portion of the population migrates through the GEM region on its way to and from their rookeries Adult fur seals may feed in the GOA during migration and winter months, and non-breeding animals may feed in the area year-round Small fishes and squids are the primary foods of fur seals (Calkins 1986) Historically, northern fur seals were depleted by commercial harvests, but the population is now large, numbering about 1 million animals, and currently stable (Ferrero et al 2000) Northern elephant seals pup and breed at rookeries in California and Mexico After breeding, adult males go to the GOA to feed on deep-water fishes and cephalopods (Stewart 1997) The northern elephant seal population was greatly depleted by harvesting, but it is currently large and growing (Forney et al 2000)

The sea otter is a focal species for GEM and is discussed later in this section

As a group marine mammals are managed and protected by domestic legislation and international treaties that generally do not apply to other marine species (Baur et al 1999) (see Table 3 9) Early protective efforts were in response to the need to limit commercial harvests and to reduce their impacts on declining and depleted populations The North Pacific Fur Seal Convention, agreed to in 1911, provided protection to both fur seals and sea otters In 1946, the International Convention for the Regulation of Whaling began to manage harvests of large whales, and it provided progressive protection to stocks as they became over-exploited The ESA provides protection to marine mammals (and other species) that may be in danger of extinction because of human activities The SEA also allows protection of "critical habitat" needed by those species All species of marine mammals are covered by the Marine Mammal Protection Act (MMPA), which became federal law in 1972 Primary objectives of the MMPA are to "maintain the health and stability of the marine ecosystem," and for each marine mammal species to "obtain an optimum sustainable population keeping in mind the carrying capacity of the habitat." Provisions of the MMPA put a moratorium on all "taking" of marine mammals, with exceptions allowed for subsistence hunting by Alaska Natives, scientific research, public display, commercial fishing, and certain other human activities, subject to restrictions and permitting Species determined to be below their "optimum sustainable population" level, and those listed as threatened or endangered under provisions of the ESA, are listed as depleted under the MMPA and may be given additional protection Certain species of marine mammals were determined to have been damaged by the EVOS, and therefore have been subjects of EVOS restoration activities

Another unique aspect of marine mammal management is the strong involvement of Alaska Natives in the process Alaska Natives have formed a number of groups that represent their interests in research, management, conservation, and traditional subsistence uses of marine mammals Groups especially relevant to the EVOS GOA region include the Alaska Native Harbor Seal Commission (ANHSC), the Alaska Sea Otter and Steller Sea Lion Commission, and the Cook Inlet Marine Mammal Council The ANHSC has been particularly active in the EVOS region, and has received funds from the Trustee Council to conduct a biosampling program in PWS and the GOA, and to contribute information about the distribution, abundance, and health of seals Congress has recognized the benefits of involving Alaska Natives in marine mammal management, and has included provisions for co-management programs (Alaska Native organizations working as partners with federal management agencies) in the 1994 amendments to the MMPA

As will be discussed in detail in the following sections, some marine mammal populations have declined in the GOA (and elsewhere in Alaska) in recent years

In general, the causes of those declines are unclear, but there has been speculation that they may be in some way related to the climactic regime shift that occurred in the region. The evidence supporting such a connection is the temporal coincidence of the shift to a warmer regime, which happened in the mid-1970s, and the decline of harbor seals and Steller sea lions that has occurred in the 1970s through the 1990s.

The National Research Council (NRC) reviewed evidence for a linkage between climate and marine mammal declines as part of their effort to explain changes that have occurred in recent years in the Bering Sea (NRC 1996). They found data that showed some likely negative effects of cold weather on northern fur seal pups (Trites 1990) and a strong influence of warm El Niño conditions on California sea lions (Trillmich and Ono 1991). Because most GOA marine mammals have broad ranges that include waters much warmer than the GOA, it is unlikely that a warmer regime has had any direct negative effect on their reproduction or survival. The warmer conditions, however, have resulted in changes in fish and invertebrate populations (Anderson et al. 1997) that may in turn have affected the nutrition of harbor seals and Steller sea lions (Alaska Sea Grant College Program 1993). The NRC concluded that food limitation was likely a factor in Bering Sea pinniped population declines, but that this was due to a complex suite of biological and physical interactions and not simply the regime shift (NRC 1996).

3.11.2 Focal marine mammal species for the GEM program

3.11.2.1 Killer Whale

Killer whales are medium- sized, toothed whales. They are a cosmopolitan species generally found throughout the world's oceans, but most common in colder nearshore waters (Heyning and Dahlheim 1988). Sightings in Alaska show a wide distribution, mostly on the continental shelf, but also offshore (Braham and Dahlheim 1982). Because there has been no real effort to track individual killer whales, the understanding of movements is based primarily on sightings of animals that can be identified by marks and pigmentation patterns (Bigg et al. 1987). The general pattern seems to be that some killer whales may stay in areas for several months while feeding on seasonally abundant prey, but long-distance movements are not uncommon (Ferrero et al. 2000).

In the GOA, killer whales are seen frequently in Southeast Alaska and the area between PWS and Kodiak (Matkin and Saulitis 1994). Within the EVOS GOA region, whales are seen most commonly in southwestern PWS, Kenai Fiords, and southern Resurrection Bay (Matkin et al. 2000). Whales move back and forth between these areas as well as to and from Southeast Alaska (Matkin et al. 1997). Sightings from the area around Kodiak suggest that killer whales are common, but there has been little study effort devoted to that region (Matkin and Saulitis 1994).

Killer whales have been studied in detail in easily accessible areas such as Washington state, British Columbia, Southeast Alaska, and PWS. Researchers have found that killer whales have a very complex social system and population structure Studies of association patterns (Matkin et al 1998), vocalizations (Ford 1991, Saulitis 1993), feeding behavior (Ford et al 1998), and molecular genetics (Hoelzel et al 1998, Barrett-Lennard et al in press) have shown that there are two primary types of killer whales The types are termed "transient" and "resident " A primary ecological difference between the two types is that residents eat fish, while transients mostly prey on other marine mammals (Ford et al 1998) Within each of these general types, killer whales are divided into pods that may be composed of one or more matrilineal groups In resident whales, the pods are very stable through time, with virtually no permanent exchange of individuals between pods, but new pods may be formed by splitting off of a maternal group A third killer whale type called "offshore" has been encountered, but little is known about them (Ford et al 1994)

What is known of the life history and biology of killer whales in Alaska was compiled in Matkin and Saulitis (1994) Both females and males are thought to become sexually mature at about 15 years of age Females may produce calves until they are about 40, at intervals of 2 to 12 years Mating occurs mostly during May through October, and most births happen between fall and spring Maximum longevity has been estimated to be 80 to 90 years for females and 50 to 60 years for males Killer whales have no natural enemies, but in some areas, local abundance and pod structure have been affected by human activities, including live captures for public display, interactions with commercial fisheries, and the EVOS (Olesiuk et al 1990, Dahlheim and Matkin 1994, Matkin et al 1994, Ferrero et al 2000, Forney et al 2000) Normal birth and death rates for resident killer whales are about 2% per year (Olesiuk et al 1990)

Surface observations and examination of stomach contents from stranded animals have shown that as a group killer whales can and do eat a wide array of prey, including fishes, birds, and mammals (Matkin and Saulitis 1994) More detailed studies have documented considerable prey specialization in certain pods and individuals Resident killer whales in the PWS feed mostly on coho salmon during the summer (Matkin et al 1997) and on chinook salmon in winter and spring (Matkin 2000) Transient whales in the same area eat mostly harbor seals, Dall's porpoise, and harbor porpoise (Saulitis 1993, Matkin and Saulitis 1994) Some GOA transient killer whales occasionally eat Steller sea lions (Barrett-Lennard et al 1995)

It is difficult to come up with meaningful population estimates for killer whales, partly because they may move over great distances and partly because some groups (such as the offshore type) and areas (such as the GOA west of Resurrection Bay) have been poorly studied Ferrero et al (2000) gave a minimum estimate of 717 whales in the northern resident stock of the eastern North Pacific, and Forney et al (2000) gave a minimum number of 376 for the transient stock of the eastern North Pacific Reliable data on trend in abundance are not available for either stock The most recent census (1999) indicates that there are 135 killer whales in the eight pods that regularly use the Kenai Fiords-PWS region (Matkin 2000)

Studies of killer whales in the PWS area began in the late 1970s (von Ziegesar et al 1986, Leatherwood et al 1990) Because killer whales were determined to have been damaged by the EVOS, killer whale studies were intensified during 1989 to 2000 (Matkin et al 1994, 2000) Those long-term studies allow accurate determination of numbers, because all individuals in each pod are photoidentified nearly every year Births and deaths of individual animals are monitored, which allows the calculation of reproductive and survival rates for each pod (Matkin and Saulitis 1994, Matkin et al 2000)

Matkin et al (1999) used association and genealogical data to organize the resident killer whales in the EVOS GOA area into nine pods Data on the number of whales in each of those pods for the period from 1984 to 2000 are shown in Table 3 10 All resident pods with the exception of AB pod have either increased or stayed the same since 1984 The number of whales in AB pod decreased by 36% from 1988 to 1990 and has stayed about the same since Since 1990, the recruitment rate for AB pod has been similar to other resident pods, but the mortality rate has been more than twice as high (Matkin et al 2000)

Less is known about transient killer whales, and their stock structure within the eastern North Pacific is less clear Stock assessment reports have dealt with all transient whales that occur from Alaska to California as a single stock (Forney et al 2000) Studies have shown, however, that two groups of whales that occur in the EVOS GOA region, called AT1 transients and GOA transients, are genetically and acoustically distinct from one another and from other west coast transients (Saulitis 1993, Barrett-Lennard et al in press) GOA transients range widely, but are seen only occasionally in the PWS-Kenai Fiords area The AT1 pod occurs in the PWS-Kenai Fiords area year-round (Saulitis 1993, Matkin et al 2000) The number of whales in the AT1 pod has declined by more than 50% since 1988, with only 10 individuals remaining in 2000 (Table 3 10)

The declines in the AB and AT1 killer whale pods are issues of major conservation concern Thirteen whales, mostly juveniles and adult females, disappeared from AB pod from March 1989 to June 1990, the highest mortality rate ever seen in a resident killer whale pod Although 12 calves have been born in AB pod since then, there is no clear trend toward recovery because an additional 10 animals have died For the AT1 transients, 12 whales have died since 1988 and no calves have been recruited to the group since 1984 (Matkin 2000)

Table 3 10 Number of whales Photographically Identified in Killer Whale Pods in the GOA EVOS Area, 1984 to 2000

Pod Identifier	1984	1988	1990	2000
Resident Pods				
AB	35	36	23	25
AD05	13	11	12	13
AD16	6	5	5	6
AE	13	12	13	18
AI	6	6	6	6
AJ	25	26	28	36
AK	7	8	9	11
AN10	12	13	13	20
AN20	23	26	29	[1]
Transient Groups				
AT1	22	22	13	10

Source Matkin et al 2000 and (Matkin personal communication)

[1] The entire AN20 pod has not been photographed since 1991

The causes of the declines in these two killer whale pods are not entirely clear Killer whales are only rarely caught incidental to commercial fishing operations (Ferrero et al 2000) In the mid-1980s, however, the AB pod was involved in a different type of interaction with the longline fisheries for sablefish and halibut (Matkin and Saulitis 1994) Whales removed hooked fish from the lines, and fishermen attempted to deter them by shooting at them and detonating explosives A number of whales were seen with gunshot wounds, and some of those later disappeared In spite of eight mortalities during the previous 4 years, the pod numbered 36 animals in 1988, one more than in 1984 (Matkin et al 1994) In March to September 1989, members of the AB pod were several times seen swimming in oil from the EVOS Although a direct cause-effect relationship cannot be shown, there is reason to believe that the population decline is in some way due to the spill (Dahlheim and Matkin 1994, Matkin et al 1994) Members of the AT1 transient group were also seen in oil in summer 1989, and many members of the group were missing the following year and have not been seen since (Matkin et al 1994, 2000) An additional concern related to the potential effects of contact with oil is the consumption of harbor seals, which AT1 transients feed on to a large extent (Saulitis 1993) Because many harbor seals were coated with oil by the spill (Lowry et al 1994), the whales may have ingested contaminated prey In addition, the harbor seal population has decreased Harbor seal numbers were declining in parts of PWS before 1989, an estimated 300 seals were killed by the spill, and the seal population has continued to decline at least through 1997 (Frost et al 1994, Frost et al 1999) Therefore, the lack of recruitment into the AT1 pod may be at least partly caused by the severe reduction of harbor seal numbers in the EVOS GOA region (Matkin et al 2000)

Other than their general status under the MMPA, Alaskan killer whales have not been afforded any special legal protection Although the AB pod is part of a larger resident population, the AT1 group is a distinct population that is demographically and genetically isolated from other killer whales For that reason, protective listing under the ESA may be warranted for the AT1 group

3.11.2.2 Beluga Whale

Belugas, also called white whales or belukhas, are medium-sized, toothed whales They have a disjunct circumpolar distribution and occur principally in arctic and subarctic waters (O'Corry-Crowe and Lowry 1997) Recent studies have shown that belugas are separated into a number of discrete genetic groups (stocks), that generally correspond to groups of animals that summer in different regions (O'Corry-Crowe et al 1997, Brown Gladden et al 1999) There are four relatively large stocks that range throughout western and northern Alaska and a small stock that occurs in Cook Inlet and the GOA (O'Corry-Crowe and Lowry 1997)

In the GOA, belugas are seen most commonly in Cook Inlet, but sightings have been made near Kodiak Island, in PWS, and in Yakutat Bay (Laidre et al in press) The fact that there have been several reports of belugas in Yakutat Bay during 1976 to 1998 suggests the possibility of a small resident group there The other sightings have most likely been of animals from the main Cook Inlet concentration

Because summer surveys of belugas in Cook Inlet have been conducted at irregular intervals since the 1960s and annually since 1993, beluga distribution in that region is fairly well known (Klinkhart 1966, Calkins 1984, Rugh et al in press) Belugas may be found throughout Cook Inlet, and in mid-summer they are always most common near the mouths of large rivers in Upper Cook Inlet, especially the Beluga River, the Susitna River, and Chickaloon Bay Other areas where they have been commonly seen include Turnagain Arm, Knik Arm, Kachemak Bay, Redoubt Bay, and Trading Bay Rugh et al (in press) compared the distribution of June and July sightings made in the 1990s with earlier years They found that the proportion of sightings in Upper Cook Inlet has increased greatly in the last decade, and they conclude that the number of sightings in Lower Cook Inlet and in offshore waters has declined during the years

In February-March 1997, aerial surveys were conducted with the specific goal of gathering information on winter distribution of the Cook Inlet beluga stock (Hansen and Hubbard 1999) The area surveyed included Cook Inlet and parts of the GOA between Kodiak Island and Yakutat Bay Almost all beluga sightings (150 out of 160) were in the middle part of Cook Inlet, and the remaining sightings were in Yakutat Bay

Since 1999, the NMFS National Marine Mammal Laboratory (NMML) has gathered data on Cook Inlet beluga distribution and movements through use of satellite-linked tags In 1999, one whale that was tagged and tracked for 110 days (from May 31 to September 17) stayed in Upper Cook Inlet (Ferrero et al in press) To try to obtain information on winter distribution, two tags were attached to whales on September 13, 2000 The whales were tracked until mid-January During that time, they moved around quite a bit in Upper Cook Inlet, but did not go south of Kalgin Island (NMML unpublished data available at http //nmml afsc noaa gov/CetaceanAssessment/Folder/2000_beluga_whale_tagging htm)

In many parts of Alaska, including Cook Inlet, belugas are most common in nearshore waters during the summer (Calkins 1986, Frost and Lowry 1990) Proposed reasons for the use of nearshore habitats include the possible advantage of warm protected waters for newborn calves (Sergeant and Brodie 1969), facilitation of the epidermal molt by fresh water and rubbing on gravel (St. Aubin et al 1990, Smith et al 1992), and feeding on seasonally abundant coastal and anadromous fishes (Seaman et al 1985, Frost and Lowry 1990) Although there have been no direct studies of the diet of Cook Inlet beluga whales, at least part of the reason for their congregating nearshore and near river mouths must be to feed on abundant fishes such as salmon and eulachon (Calkins 1984, Moore et al in press)

There has been no life history information collected from Cook Inlet belugas Biological characteristics of belugas in other areas were reported by Hazard (1988) Females become sexually mature at 4 to 7 years of age and males at 7 to 9 years Mature females give birth to calves every 2 to 3 years, mostly in late spring or summer The maximum life span has not been well defined, but is likely to be about 40 years In the southern part of their range, belugas are preyed upon by killer whales, and in more northern areas by polar bears

Beluga whales are difficult to enumerate for a number of reasons Principal problems are that whales are easy to miss in muddy water or when whitecaps are present, and in all conditions some fraction of the population will be underwater where they cannot be seen Early survey efforts largely ignored these problems and just reported the number of animals counted, which during the 1960s to 1980s was usually a few hundred In 1994 the NMFS NMML began to produce annual estimates of population size with standardized aerial surveys of the entire Cook Inlet and a sophisticated set of methods to correct for whales that were missed by observers (Hobbs et al in press, Rugh et al in press, Hobbs 2000) For each survey, they reported the number of whales counted and an estimate of the total population size (Table 3 11) Unfortunately because of problems inherent in counting whales from the air, the annual estimates are imprecise and have a relatively large coefficient of variation Nonetheless, regression analysis shows a statistically significant population decline during the 7- year period The 2000 population is most likely at least one-third smaller than it was in 1994 The 95% confidence limits for the 2000 survey were 279 to 679 whales, meaning it is very likely that the true current population size is somewhere in that range

Available data suggest that beluga whales in Cook Inlet rarely become entangled in fishing gear (Ferrero et al 2000) The largest source of mortality in recent years has been hunting by Alaska Natives Although harvest data are imprecise, estimates of the annual number of whales killed during 1993 to 1998 ranged from 21 to 123 animals (Ferrero et al 2000, Mahoney and Shelden in press) This compares to a likely sustainable harvest of about 20 whales from a population of 500

Table 3 11 Counts and Population Estimates for Cook Inlet Beluga Whales, 1993 to 2000

Year	Whale Count	Abundance Estimate	Coefficient of Variation
1994	281	653	0 43
1995	324	491	0 44
1996	307	594	0 28
1997	264	440	0 14
1998	193	347	0 29
1999	217	357	0 20
2000	184	435	0 23

Source (Hobbs Rugh and DeMaster in press)and (Hobbs personal communication) ref

Because of the population decline and the potential for continued overharvest, several environmental groups and one individual submitted a petition to NMFS in March 1999 requesting that the Cook Inlet beluga whale be listed as an endangered species under the ESA Responding to the same problems, Senator Ted Stevens inserted language into federal legislation passed in May 1999 that prohibited any hunting of beluga whales by Alaska Natives, unless they had entered into a co-management agreement with NMFS to regulate the hunt. In May 2000, NMFS finalized a designation of depletion under provisions of the MMPA for the Cook Inlet beluga population, and in June 2000, the agency determined that a listing under the ESA was not warranted There was no legal harvest of Cook Inlet belugas in either 1999 or 2000 NMFS is currently working through provisions of the MMPA to allow a small, regulated take of Cook Inlet belugas to satisfy the cultural needs of Alaska Natives

Although overharvest by Alaska Natives in the 1990s appears to be sufficient to explain the population decline, concerns that this small isolated population may be vulnerable to other threats remain Areas of concern that have been identified include commercial fishing, oil and gas development, municipal discharges, noise from aircraft and ships, shipping traffic, and tourism (Moore et al in press)

3.11.2.3 Steller Sea Lion

Steller sea lions are the largest species of otariid (eared seal) They are distributed around the North Pacific rim from northern Japan, the Kuril Islands and Okhotsk Sea, through the Aleutian Islands and Bering Sea, along the southern coast of Alaska, and south to California (Kenyon and Rice 1961, Loughlin et al 1984, Loughlin et al 1992) Most large rookeries are in the GOA and Aleutian Islands The northernmost rookery, Seal Rocks, is in the EVOS region at the entrance to PWS Currently the largest rookery is on Lowrie Island, in the Forrester Island complex in southern Southeast Alaska

Steller sea lions are listed as two distinct population segments under the ESA an eastern population that includes all animals east of Cape Suckling, Alaska, and a western population that includes all animals at and west of Cape Suckling This distinction is based mostly on results from mitochondrial DNA genetic studies that found a distinct break in the distribution of haplotypes between locations sampled in the western part of the range and eastern locations, indicating restricted gene flow between two populations (Bickham et al 1996, Bickham et al 1998a) Information on distribution, population response, and phenotypic characteristics, also support the concept of two Steller sea lion stocks (Loughlin 1997)

Most adult Steller sea lions occupy rookeries during the pupping and breeding season, which extends from late May to early July (Pitcher and Calkins 1981, Gisiner 1985) Some juveniles and non-breeding adults may summer at or near the rookeries, but most use other locations as haul-outs During fall and winter, sea lions may be at rookery and haul-out sites that are used during the summer, and they are also seen at other locations They do not make regular migrations, but do move considerable distances When they reach adulthood, females generally return to the rookeries of their birth to pup and breed (Kenyon and Rice 1961, Calkins and Pitcher 1982, Loughlin et al 1984)

Steller sea lions use a number of marine and terrestrial habitats Adults congregate for pupping and breeding on rookeries that are usually on sand, gravel, cobble, boulder, or bedrock beaches of relatively remote islands Haul-outs are sites used by adult sea lions during times other than the breeding season, and by non-breeding adults and subadults throughout the year Haul-outs may be at sites also used as rookeries, or on other rocks, reefs, beaches, jetties, breakwaters, navigational aids, floating docks, and sea ice With the exception of sea ice, sites used for rookeries and haul-outs are traditional and the specific locations used vary little from year to year Factors that influence the suitability of a particular area are poorly understood (Gentry 1970, Sandegren 1970, Calkins and Pitcher 1982)

When not on land, Steller sea lions are seen near shore and out to the edge of the continental shelf, in the GOA, they commonly occur near the 200-m depth contour (Kajimura and Loughlin 1988) Studies with using satellite-linked telemetry have provided detailed information on at-sea movements (Merrick and Loughlin 1997) Adult females tagged at rookeries in the central GOA and Aleutian Islands in summer made short trips to sea and generally stayed on the continental shelf In winter, adult females ranged more widely with some moving to seamounts far offshore Pups tracked during the winter made relatively short trips to sea, but one moved 320 km from the eastern Aleutians to the Pribilof Islands

Female Steller sea lions reach sexual maturity at 3 to 6 years of age and most breed annually during June and July (Pitcher and Calkins 1981) Males reach sexual maturity at 3 to 7 years of age and physical maturity by age 10, they establish territories on rookeries during the breeding season, and one male may breed with several females (Thorsteinson and Lensink 1962, Gentry 1970, Sandegren 1970, Gisiner 1985) Territorial males fast for long periods during the pupping and breeding season Pups are born on land, normally in late May to June, and they stay on land for about 2 weeks, then spend an increasing amount of time in intertidal areas and swimming near shore After giving birth, sea lion mothers attend pups constantly for about 10 days, then alternate trips to sea for feeding with returns to the rookery to suckle their pup Unlike most pinnipeds, for which weaning is predictable and abrupt, Steller sea lions may continue to nurse until they are at least three years old (Gentry 1970, Sandegren 1970, Calkins and Pitcher 1982)

Steller sea lions die from a number of causes, including disease, predation, shooting by humans, and entanglement in fishing nets or debris (Merrick et al 1987) In addition, pups may die from drowning, starvation caused by separation from the mother, crushing by larger animals, and biting by females other than the mother (Orr and Poulter 1967, Edie 1977)

Steller sea lions are generalist predators that mostly eat a variety of fishes and invertebrates (Pitcher 1981, NMFS 2000) Seals, sea otters, and birds are also occasionally eaten (Gentry and Johnson 1981, Pitcher and Fay 1982, Daniel and Schneeweis 1992) Much effort has been devoted to describing the diet of sea lions in the GOA In the mid 1970s and mid 1980s, the primary food found in sea lion stomachs was walleye pollock. Octopus, squid, herring, Pacific cod, flatfishes, capelin, and sand lance also were consumed frequently (Pitcher 1981, Calkins and Goodwin 1988) In the 1970s, walleye pollock was the most important prey in all seasons, except summer, when small forage fishes (capelin, herring, and sand lance) were eaten more frequently (Merrick and Calkins 1996) Results from examination of scats collected on rookeries and haul-outs in the GOA in the 1990s confirmed that pollock has been overall the dominant prey, with Pacific cod and salmon also important in some months (Merrick et al 1997, NMFS 2000) The diet of juvenile Steller sea lions has not been studied in detail, but it is known that they eat somewhat smaller pollock than do adults (Frost and Lowry 1986, Calkins 1998) Available data suggest that the average daily food requirement for sea lions is on the order of 5% to 8% of their body weight per day (Kastelein et al 1990, Rosen and Trites 2000)

Satellite-linked tags attached to sea lions have provided information on the amount of time spent diving and diving depths (Merrick and Loughlin 1997) Adult females in winter spent the most time feeding and dove the deepest, and young of the year spent relatively little time diving to shallow depths As young of the year matured, foraging effort increased from November to May

The abundance of Steller sea lions in the western population has decreased greatly since the 1960s, to the extent that the species has been listed as endangered under the ESA From the mid-late 1970s through 2000, index counts of adults and juveniles for the western population as a whole declined by 83% from 109,880 to 18,193 (NMFS 2000) Declines in the eastern GOA (Seal Rocks to Outer Island) and central GOA (Sugarloaf Island to Chowiet Island) have been of a generally similar magnitude (73% and 87%), but it appears that the decline in the eastern GOA began later than in the western GOA and other regions (Table 3 12) Counts of pups on rookeries have shown similar declines Modeling and tagging studies have suggested that the proximate cause of the population decline is probably a reduction in survival of juvenile animals (York 1994, Chumbley et al 1997) Birth rates are also comparatively low (Calkins and Goodwin 1988), which could be a contributing factor Population viability analysis suggests that if the decline continues at its current rate some rookeries will go extinct in the next 40 to 50 years, and the entire western population could be extinct within 100 to 120 years (York et al 1996)

Table 3 12 Index Counts of Steller Sea Lions in the Eastern Gulf of Alaska (Seal Rocks to Outer Island) and Western Gulf of Alaska (Sugarloaf Island to Chowiet Island)

Survey Year	Eastern GOA	Central GOA	Western Stock Total
1976	7 053	24 678	109,880[a]
1985	--	19 002	--
1989	7 241	8 552	--
1990	5 444	7 050	30 525
1991	4 596	6 273	29 418
1992	3 738	5 721	27 286
1994	3 369	4 520	24 119
1996	2 133	3 915	22 223
1997	--	3 352	--
1998	--	3 346	20 201
1999	1 952	--	--
2000	1,894	3,177	18 193

Source author? (1999)and (NMFS 2000)

Dashes indicate no count in that year

[1] Uses counts in the Aleutian Islands made in 1977 and 1979

A number of factors have been suggested that may have affected the western Steller sea lion population in the past 3 to 4 decades (Merrick et al 1987, NMFS 1992, NMFS 2000) There is no evidence that patterns of predation, disease, or environmental contaminants have changed sufficiently to have caused such a major decrease in abundance (Loughlin 1998) In the past, many sea lions were killed in commercial harvests, by incidental entanglement in nets, and by shooting to reduce damage to fishing gear and fish depredation (Alverson 1992) That mortality may have played some part in the early stages of the decline, but such killing has been eliminated or greatly reduced and cannot explain the widespread, continuing decline Subsistence hunting by Alaska Natives occurs at low levels and is not judged to be an important factor overall (Ferrero et al 2000) Currently the most likely explanation is that sea lions, especially juveniles, are experiencing higher than normal mortality because they are nutritionally limited (Loughlin 1998, NMFS 2000) The nutritional limitation could be caused by environmental changes that have affected sea lion prey species, competition for prey with commercial fisheries, or some combination of the two

The decline of the western population of Steller sea lions, and the need to recover the population and protect critical habitat as required by the ESA, have been a major conservation issue in recent years (Lowry et al 1989, Fritz et al 1995) Actions proposed to facilitate recovery may have substantial effects on commercial fisheries and coastal communities in the GOA and elsewhere (NMFS 2000)

3.11.2.4 Pacific Harbor Seal

Harbor seals are medium-sized, "earless" seals that are widespread in temperate waters of both the North Atlantic and the North Pacific In the North Pacific, their distribution is nearly continuous from Baja California, Mexico, to the GOA and Bering Sea, through the Aleutian Islands, and to eastern Russia and northern Japan (Shaughnessy and Fay 1977, Hoover-Miller 1994)

Harbor seals are found primarily in the coastal zone where they feed and haul out to rest, give birth, care for their young, and molt Haul-out sites include intertidal reefs, rocky shores, mud and sand bars, gravel and sand beaches, and floating glacial ice (Hoover-Miller 1994) From the results of satellite tagging studies in PWS, most adult harbor seals are known to use the same few haul-outs for most of the year (Frost et al 1996, Frost et al 1997)

Although it is relatively easy to study harbor seals while they are on haul-outs, their distribution and movements at sea are not as well understood During 1992 to 1997, as part of EVOS restoration studies, satellite-linked depth recorders (SDRs) were attached to seals in PWS to study their at-sea behavior Analysis of the tracking data from 49 subadult and adult harbor seals indicated that most tagged seals stayed in or near PWS, but some subadults moved 300 to 500 km east and west in the GOA (Frost et al 2001, Lowry et al 2001) Virtually all relocations were on the continental shelf in water less than 200 m deep Most feeding trips for adults went 10 km or less from haul-outs, and juveniles fed mostly within 25 km

Patterns of diving (effort and depth) varied geographically and seasonally During 1997 to 1999, SDRs were attached to 27 recently weaned harbor seal pups in PWS Preliminary analysis of those data (Frost et al 1998, Lowry and Frost unpublished) did not show any extraordinary movement patterns

SDRs have also been attached to harbor seals in Southeast Alaska and the Kodiak region Preliminary results from those tagging efforts have been reported in Small et al (1997, 1998) The data are currently being analyzed and prepared for publication (Small R 2001)

Overall, harbor seals are relatively sedentary and they show considerable fidelity to haul-out sites (Pitcher and McAllister 1981, Frost et al 1996, Frost et al 1997) For management purposes, NMFS has delineated three harbor seal stocks in Alaska

1 The southeast Alaska stock, including animals east and south of Cape Suckling,

2 The GOA stock, including animals from Cape Suckling to Unimak Pass and westward through the Aleutian Islands, and

3 The Bering Sea stock including animals in Bristol Bay and the Pribilof Islands (Ferrero et al 2000)

During the past several years, an in-depth study of Alaska harbor seal genetics has been conducted by the NMFS Southwest Fisheries Science Center Preliminary analysis of those data indicate a number of relatively small population units with very limited dispersal among them (O'Corry-Crowe et al in press), in (Small et al 1999) Results suggest that within the EVOS area, there are multiple harbor seal stocks that may require individual management attention NMFS scientists are currently analyzing the molecular genetics data and preparing it for publication NMFS managers are evaluating those results with the intention of refining stock boundaries for Alaska harbor seals

Hoover-Miller (Hoover-Miller 1994) summarized available information on Alaska harbor seal biology and life history Both male and female harbor seals reach sexual maturity at 3 to 7 years old Adult females give birth to single pups once a year, on land or on glacial ice In PWS and the GOA, most pupping occurs from mid-May through June Newborn harbor seals pups are born with their eyes open, with an adult-like coat, and are immediately able to swim Pups are weaned when they are 3 to 6 weeks old Once each year in July to September, harbor seals shed their old hair and grow a new coat. During this time, the seals spend more time hauled out than they do at other times For that reason, the molt period is a good time to count seals to estimate population sizes and trends

Most information about the diet of harbor seals in PWS and the GOA was collected in the mid-1970s by examination of stomach contents (Pitcher 1980) The major prey overall in both PWS and adjacent parts of the GOA was pollock

Octopus, capelin, Pacific cod, and herring also are eaten frequently. Stomachs of young seals contained mostly pollock, capelin, eulachon, and herring. As part of EVOS restoration studies, blubber samples from PWS harbor seals have been analyzed for their fatty acid composition to examine their recent diets (Iverson et al. 1997), and (Lowry and Frost unpublished). Initial results showed that herring, pollock, other fishes, and cephalopods (a class of squid and octopi) had been eaten. Seals sampled at the same haul-out had similar fatty acid compositions, suggesting that they had fed locally on similar prey. In contrast, seals sampled from areas as little as 80 km apart had different fatty acid compositions, indicating substantially different diets. Small et al. (1999) have examined scats from harbor seals collected near Kodiak and found mostly remains of sculpins, greenling, sand lance, and pollock.

Known predators of harbor seals include killer whales, Steller sea lions, and sharks. The impact of these predators on harbor seal populations is unknown, but may be significant. In PWS alone, killer whales may eat as many as 400 harbor seals per year (Matkin 2000). The incidence of sharks caught on halibut longlines in the GOA has increased greatly in the last decade (Lowry and Frost unpublished data). The degree to which these sharks prey on harbor seals is unknown, but seal remains have been observed in their stomachs (Matkin 2000).

Before the MMPA, harbor seals were hunted commercially in Alaska, and they were also killed to reduce their predation on commercially important fishes (Hoover-Miller 1994). Such kills, which exceeded 10,000 animals in many years, were largely stopped in 1972. The MMPA allowed fishermen to shoot seals if they were damaging their gear or catch and could not be deterred by other means. A few hundred animals probably were killed annually for that reason during 1973 to 1993. In 1994, the MMPA was amended to require that fishermen use only non-lethal means to keep marine mammals away from their gear.

Harbor seals have been and continue to be an important food and handicraft resource for Alaska Native subsistence hunters in PWS and the GOA. The ADF&G Division of Subsistence estimated the size of the harbor seal harvest annually during 1992 to 1998. The average annual kill during that period was approximately 380 seals in PWS and 360 for Kodiak, Cook Inlet-Kenai, and the south Alaska Peninsula combined (Wolfe and Hutchinson-Scarbrough 1999). About 88% of the seals shot were retrieved, and 12% were struck and lost. Although harvests at individual villages have varied from year to year, regional harvest levels have shown no clear trend.

Harbor seals are sometimes entangled and killed in the gear set by several commercial fisheries that operate in the EVOS GOA region. Ferrero et al. (2000) estimated an average minimum annual mortality of 36 animals for the GOA stock. This figure was an underestimate, because there have not been observer programs for several of the fisheries that are likely to interact with harbor seals.

Some harbor seals were killed by the EVOS, at least in PWS (Frost et al 1994) In August and September 1989, ADF&G flew aerial surveys of harbor seals in oiled and unoiled areas of central and eastern PWS Results of those surveys were compared to earlier surveys of the same haul-outs conducted in 1983, 1984, and 1988 Before the EVOS, counts in oiled and unoiled areas of PWS were declining at a similar rate, about 12% per year From 1988 to 1989, however, there was a 43% decline in counts of seals at oiled sites compared to 11% at unoiled sites Other studies conducted as part of the EVOS damage assessment program showed that seals in oiled areas became coated with oil (Lowry et al 1994) Many oiled seals acted sick and lethargic for the first few months after the spill Tests of bile and tissues showed that oiled seals were metabolizing petroleum compounds (Frost et al 1994) Microscopic examination indicated that some oiled seals had brain damage that would likely have interfered with important functions such as breathing, swimming, diving, and feeding (Spraker et al 1994) It was estimated that approximately 300 seals died because of the EVOS (Frost et al 1994) Hoover-Miller et al (2000) disputed the mortality estimate of Frost et al (1994), but they admit that the spill had effects on harbor seals and do not provide an alternative estimate of mortality

Harbor seals are one of the most common marine mammals in the EVOS GOA region In 1973, ADF&G estimated there were about 125,000 in this region based on harvest data, observed densities of seals, and the amount of available habitat (Pitcher 1984) The most recent population estimate for the GOA harbor seal stock, derived from intensive aerial surveys conducted by NMFS, is 29,175 (Ferrero et al 2000) Although the methods used to derive the two estimates were very different and they are not directly comparable, the difference does suggest that a large decline in harbor seal numbers has occurred in the GOA

Counts at individual haul-outs and along surveys routes established to monitor trends confirm the decline and provide some information on the temporal pattern of changes (Table 3 13) At Tugidak Island (south of Kodiak Island), average molt period counts declined by 85% from 1976 to 1988 (Pitcher 1990), followed by a period of stabilization before a population increase of about 5% per year during 1994 to 1999 (Small et al 1999) In eastern and central PWS, the number of seals at 25 trend index sites declined by 42% between 1984 and 1988 (Pitcher 1989) Trend counts at index sites have shown that the decline in that part of PWS continued at least through 1997, by which time there were 63% fewer seals than there were in 1984 (Frost et al 1999) Counts on the PWS trend route were fairly similar in 1994 to 1998 (Table 3 13), suggesting that the decline in that area may have stopped In the Kodiak trend area, harbor seal counts increased by 5 6% per year during 1993 to 1999 (Small et al 1999)

Table 3 13 Counts of Harbor Seals at Index Sites in the EVOS GOA Region

Year	Tugidak Island	PWS	Kodiak
1976	5 708	--	--
1977	4 618	--	--
1978	3 781	--	--
1979	3 133	--	--
1982	1 918	--	--
1984	1 469	2 488	--
1986	1 181	--	--
1988	966	1,875	--
1989	--	1 423	--
1990	882	1 282	--
1991	--	1 200	--
1992	820	1 133	--
1993	805	1 126	3 129
1994	800	981	3 478
1995	804	1 126	3 855
1996	819	962	3 322
1997	844	929	3 674
1998	880	1 053	4 247
1999	929		4 876

Source (Pitcher 1990) (Frost Lowry, Sinclair ver Hoef and McAllister 1994) (Frost et al unpublished) (Small R personal communication) year?

Counts have been adjusted to account for important covariates (see (Frost Lowry and ver Hoef 1999), Small et al in prep

Mortality of harbor seals caused by people because of fishery interactions, the EVOS, and hunting has been fairly well documented Each of these causes may be a contributing factor, but it seems unlikely that they could have caused such a widespread and major population decline Other factors that could be involved in the decline include disease, food limitation, predation, contaminants, and changes in habitat availability No strong scientific evidence has been produced, however, to suggest that any of these factors has been a primary cause (Sease 1992, Hoover-Miller 1994) A Leslie matrix model for population projection showed that large changes in vital parameters (reproduction and survival) must have occurred to cause the declines in abundance seen in PWS during 1984 to 1989, and that changes in juvenile survival are likely to have the greatest effect on population growth (Frost et al 1996)

The large decrease in harbor seal abundance in the GOA has been a major concern among scientists, resource managers, Alaska Natives, and the public After completion of damage assessment, the Trustee Council funded restoration studies to learn about the biology and ecology of harbor seals in the spill area, and to investigate possible causes for the decline (Frost and Lowry 1994, Frost et al 1995, Frost et al 1996, Frost et al 1997, Frost et al 1998, Frost et al 1999) At about the same time, Congress began providing funds to ADF&G to be used to investigate causes of the Alaskan harbor seal decline Those funds were used to initiate harbor seal research programs in Southeast Alaska and the Kodiak area, and to resume long-term studies on Tugidak Island (Lewis 1996, Small et al 1997, Small 1998, Small et al 1999, Small and Pendleton 2001) A major part of all those studies has been live-capturing seals and attaching SDRs to them to learn about their movements, foraging patterns, and behavior on land and at sea As part of the field studies, researchers have weighed and measured each seal, and have taken samples for studies of blood chemistry, disease, genetics, and diet. Some parts of those studies have been completed and published, some are in the analysis and reporting stage, and others are ongoing As discussed above, the results have added greatly to the understanding of harbor seals in this area and will continue to do so as more of the work is completed

Any time a wildlife population declines, it is a cause for concern For harbor seals in PWS and the GOA, however, the concern is magnified because the causes for the decline are unknown and because these seals are an important food and cultural resource of Alaska Natives In addition, the results of genetics studies are showing very limited dispersal between seals in adjacent areas, suggesting that harbor seals should be managed as a number of relatively small units So far GOA harbor seals have not been listed as depleted under the MMPA or as threatened or endangered under the ESA The listing status could change if recovery doesn't happen in some genetically discrete population units

Harbor seals may have great value as an indicator species of environmental conditions in the GEM region They are important in the food web, both as upper level predators on commercially exploited fishes and other fishes and invertebrates, and also as a food resource for killer whales and Alaska Native hunters Because they are non-migratory and have low dispersal rates, changes in their abundance and behavior should be reflective of changes in local environmental conditions in the areas they inhabit Further, they are relatively easy to study, and during the past 30 years a considerable amount of baseline data has been collected on their abundance, distribution, and other aspects of their biology and ecology

3.11.2.5 Sea Otter

Sea otters are the only completely marine species of the aquatic lutrinae, or otter subfamily of the family Mustelidae They occur only in coastal waters around the North Pacific rim, from central Baja California, Mexico, to the northern Islands of Japan The northern distribution of sea otters is limited by the southern extent of winter sea ice that limits access to foraging habitat (Kenyon 1969, Riedman and Estes 1990) Southern range limits are less well understood, but are likely related to reduced productivity at lower latitudes, increasing water temperatures, and thermoregulatory constraints imposed by the sea otter's dense fur

Three subspecies of sea otters are recognized *Enhydra lutris lutris* from Asia to the Commander Islands of Russia, *E l kenyoni* from the western Aleutians to northern California, and *E l nereis*, south of the Oregon (Wilson et al 1991) The subspecific taxonomy suggested by morphological analyses is largely supported by subsequent molecular genetic data (Cronin et al 1996, Scribner et al 1997) The distribution of mitochondrial DNA haplotypes suggests little or no recent female-mediated gene flow among populations Populations separated by large geographic distances, however, share some haplotypes (for example, in the Kuril and Kodiak islands), suggestive of common ancestry and some level of historical gene flow The differences in genetic markers among contemporary sea otter populations likely reflect the following

- Periods of habitat fragmentation and consolidation during Pleistocene glacial advance and retreat,
- Some effect of reproductive isolation over large spatial scale, and
- The recent history of harvest-related reductions and subsequent recolonization (Cronin et al 1996, Scribner et al 1997)

Sea otters occupy and use only coastal marine habitats The seaward limit of their feeding habitat, which is about the 100-m depth contour, is defined by their ability to dive to the sea floor Although sea otters may be found at the surface in deeper water, either resting or swimming, they must maintain relatively frequent access to shallower depths where they can feed In PWS, 98% of the sea otters are found in water with depths less than 200 m and sea otter abundance is inversely correlated with water depth, with about 80% of the animals observed in water less than 40 m deep (Bodkin and Udevitz 1999) Sea otters forage in diverse bottom types, from fine mud and sand to rocky reefs Although they may haul out on intertidal or supratidal shores, no aspect of their life history requires leaving the ocean Where present, surface-canopy-forming kelps provide preferred resting habitat In areas lacking kelp canopies, sea otters rest in groups or alone in open water, but may select areas protected from large waves where available Sea otters generally feed alone and often rest in groups of 10 or fewer, but also occur in groups numbering in the hundreds (Riedman and Estes 1990)

Relatively few data are available to describe relations between sea otter densities and habitat characteristics Maximum sea otter densities of about 12 per square kilometer (km^2) have been reported from the Aleutian and Commander islands (Kenyon 1969, Bodkin et al 2000) where habitats are largely rocky Maximum densities in Orca Inlet of PWS, a shallow soft-sediment habitat, are about 16 per km^2 Equilibrium, or sustainable densities ,likely vary among habitats, with reported values of about 5 to 8 per km^2 In PWS, sea otter densities vary among areas, averaging about 1 5 per km^2 and ranging from fewer than 1 to about 6 per km^2 (Bodkin and Udevitz 1999, USGS unpublished data)

The sea otter is the largest mustelid, with males considerably larger than females Adult males attain weights of 45 kg and total lengths of 148 cm Adult females attain weights of 36 kg and total lengths of 140 cm At birth, pups weigh about 1 7 to 2 3 kg and are about 60 cm in total length

Adult male sea otters gain access to estrous females by establishing and maintaining territories from which other males are excluded (Kenyon 1969, Garshelis et al 1984, Jameson 1989) Male territories vary in size from about 20 to 80 hectares Territories may be located in or adjacent to female resting or feeding areas or along travel corridors between those areas, and are occupied continuously or intermittently through time (Loughlin 1981, Garshelis et al 1984, Jameson 1989) Female sea otters attain sexual maturity as early as age 2, and by age 3 most females are sexually mature Where food resources may be limiting population growth, sexual maturation may be delayed to 4 to 5 years of age

Adult female reproductive rates range from 0 80 to 0 94 (Siniff and Ralls 1991, Bodkin et al 1993, Jameson and Johnson 1993, Riedman et al 1994, Monson and DeGange 1995, Monson et al 2000b) Among areas where sea otter reproduction has been studied, reproductive rates appear to be similar despite differences in resource availability Although copulation and subsequent pupping can take place at any time of year, there appears to be a positive relation between increasing latitude and reproductive synchrony (occurring simultaneously) In California, pupping is weakly synchronous to nearly uniform across months, in PWS, a distinct peak in pupping occurs in late spring

Reproductive output remains relatively constant across a broad range of ecological conditions, and pup survival appears to be influenced by resource availability, primarily food At Amchitka Island, a population at or near equilibrium density, dependent pup survival ranged from 22% to 40%, compared to nearly 85% at Kodiak Island, where food was not limiting and the population was increasing (Monson et al 2000b) Post-weaning annual survival is variable among populations and years, ranging from 18% to nearly 60% (Monson et al 2000b) Factors affecting survival of young sea otters, rather than reproductive rates, may be important in ultimately regulating sea otter population size Survival of sea otters more than 2 years of age is generally high, approaching 90%, but gradually declines through time (Bodkin and Jameson 1991, Monson et al 2000b) Most mortality, other than human related, occurs during late winter and spring (Kenyon 1969, Bodkin and Jameson 1991, Bodkin et al 2000) Maximum ages, based on tooth annuli, are about 22 years for females and 15 years for males

Although the sex ratio before birth (fetal sex ratio) is one to one (Kenyon 1982, Bodkin et al 1993), sea otter populations generally consist of more females than males Age-specific survival of sea otters is generally lower among males (Kenyon 1969, Kenyon 1982, Siniff and Ralls 1991, Monson and DeGange 1995, Bodkin et al 2000), resulting in a female-biased adult population

The sea otter relies on air trapped in the fur for insulation and an elevated metabolic rate to generate internal body heat To maintain the elevated metabolic rate, energy intake must be high, requiring consumption of prey equal to about 20% to 33 % of their body weight per day (Kenyon 1969, Costa 1982)

The sea otter is a generalist predator, known to consume more than 150 different prey species (Kenyon 1969, Riedman and Estes 1990, Estes and Bodkin in press) With few exceptions, their prey generally consist of sessile or slow moving benthic invertebrates such as mollusks, crustaceans, and echinoderms Preferred foraging habitat is generally in depths less than 40 m (Riedman and Estes 1990), although studies in southeast Alaska have found that some animals forage mostly at depths from 40 to 80 m A sea otter may forage several times daily, with feeding bouts averaging about 3 hours, separated by periods of rest that also average about 3 hours Generally, the amount of time a sea otter allocates toward foraging is positively related to sea otter density and inversely related to prey availability Time spent foraging may be a meaningful measure of sea otter population status (Estes et al 1982, Garshelis et al 1986)

NOTE TO PHIL from Lloyd Latin names of prey weren't given in the other sections – take them out of here?? This is an editorial decision that impacts all sections, so it can wait An author may choose to put Latin binomials in the text, or put them in Appendix as additions to Appendix A

Although the sea otter is known to prey on a large number of species, only a few tend to predominate in the diet, depending on location, habitat type, season, and length of occupation The predominately soft-sediment habitats of Southeast Alaska, PWS, and Kodiak Island support populations of clams that are the primary prey of sea otters Throughout most of Southeast Alaska, burrowing bivalve clams (species of *Saxidomus, Protothaca, Macoma, and Mya*) predominate in the sea otter's diet (Kvitek et al 1993) They account for more than 50% of the identified prey, although urchins (*S droebachiensis*) and mussels (*Modiolis modiolis, Musculus* spp) can also be important. In PWS and at Kodiak Island, clams account for 34% to 100% of the otter's prey (Calkins 1978, Doroff and Bodkin 1994, Doroff and DeGange 1994) Mussels (*Mytilus trossulus*) apparently become more important as the length of occupation by sea otters increases, ranging from 0% at newly occupied sites at Kodiak to 22% in long-occupied areas (Doroff and DeGange 1994) Crabs (*C magister*) were once important sea otter prey in eastern PWS, but apparently have been depleted by otter foraging and are no longer eaten in large numbers (Garshelis et al 1986) Sea urchins are minor components of the sea otter diet in PWS and the Kodiak archipelago In contrast, the sea otter diet in the Aleutian, Commander, and Kuril islands is dominated by sea urchins and a variety of fin fish (including hexagrammids, gadids, cottids, perciformes, cyclopterids, and scorpaenids) (Kenyon 1969, Estes et al 1982) Sea urchins tend to dominate the diet of low-density sea otter populations, whereas fishes are consumed in populations near equilibrium density (Estes et al 1982) For unknown reasons, sea otters in regions east of the Aleutian Islands rarely consume fish

Sea otters also exploit episodically abundant prey such as squid (*Loligo* spp) and pelagic red crabs (*Pleuroncodes planipes*) in California and smooth lumpsuckers (*Aptocyclus ventricosus*) in the Aleutian Islands On occasion, sea otters attack and consume sea birds, including teal (*Anas crecca*), scoters (*Melanita perspicillata*), loons (*Gavia immer*), gulls (*Larus* spp), grebes (*Aechmophoru soccidentalis*), and cormorants (*Phalacrocorax* spp) (Kenyon 1969, Riedman and Estes 1990)

Sea otters are known for the effects their foraging has on the structure and function of nearshore marine communities They provide an important example of the ecological "keystone species" concept (Power et al 1996) In the absence of sea otter foraging during the 20th century, populations of several species of urchins (*Strongylocentrotus* spp) became extremely abundant Grazing activities of urchins effectively limited kelp populations, resulting in deforested areas known as "urchin barrens" (Lawrence 1975, Estes and Harrold 1988) Because sea urchins are a preferred prey item, as otters recovered, they dramatically reduced the sizes and densities of urchins, as well as other prey such as mussels, *Mytilus* spp Released from the effects of urchin-related herbivory, populations of macroalgae responded, resulting in diverse and abundant populations of under-story and canopy-forming kelp forests Although other factors, both non-living (abiotic) and living (biotic), can also limit sea urchin populations (Foster and Schiel 1988, Foster 1990), the generality of the sea otter effect in reducing urchins and increasing kelp forests is widely recognized (reviewed in Estes and Duggins 1995) Further cascading effects of sea otters in coastal rocky subtidal communities may stem from the proliferation of kelp forests Following sea otter recovery, kelp forests provide food and habitat for other species, including fin fish (Simenstad et al 1978, Ebeling and Laur 1998), which provide forage for other fishes, birds, and mammals Furthermore, where present, kelps provide the primary source of organic carbon to the nearshore marine community (Duggins et al 1989)

Effects of sea otter foraging are also documented in rocky intertidal and soft-sediment marine communities The size-class distribution of mussels was strongly skewed toward animals with shell lengths smaller than 40 mm where otters were present, however, mussels with shell lengths larger than 40 mm comprised a large component of the population where sea otters were absent (VanBlaricom 1988) In soft-sediment coastal communities, sea otters forage on epifauna (crustaceans, echinoderms, and mollusks) and infauna (primarily clams) They generally select the largest individuals These foraging characteristics cause declines in prey abundance and reductions in size-class distributions, although the deepest burrowing clams (such as, *Tresus nuttallii* and *Panopea generosa*) may attain refuge from some sea otter predation (Kvitek and Oliver 1988, Kvitek et al 1992) Community level responses to reoccupation by sea otters are much less well studied in soft-sediment habitats that dominate much of the North Pacific, and additional research is needed in this area

A century ago, sea otters were nearly extinct, having been reduced from several hundred thousand individuals, by a multi-national commercial fur harvest They persisted largely because they became so rare that, despite exhaustive efforts, they were only seldom found (Lensink 1962) Probably less than a few dozen individuals remained in each of 13 remote populations scattered between California and Russia (Kenyon 1969, Bodkin and Udevitz 1999) By about 1950, it was clear that several of those isolated populations were recovering Today, more than 100,000 sea otters occur throughout much of their historic range (Table 3 14), although suitable unoccupied habitat remains in Asia and North America (Bodkin and Kenyon in press)

Trends in sea otter populations today vary widely from rapidly increasing in Canada, Washington, and Southeast Alaska, to stable or changing slightly in PWS, the Commander Islands and California, to declining rapidly throughout the entire Aleutian archipelago (Estes et al 1998, Estes and Bodkin in press) Rapidly increasing populations sizes are easily explained by abundant food and space resources, and increases are anticipated until those resources become limiting Relatively stable populations can be generally characterized by food limitation and birth rates that approximate death rates The recent large-scale declines in the Aleutian archipelago are unprecedented in recent times and demonstrate complex relations between coastal and oceanic marine ecosystems (Estes et al 1998) The magnitude and geographic extent of the Aleutian decline into the GOA are unknown, but the PWS population appears relatively stable The view of sea otter populations has been largely influenced by events in the past century when food and space where generally unlimited As food and space become limiting, however, it is likely that other mechanisms, such as predation, contamination, human take, or disease will play increasingly important roles in structuring sea otter populations

Table 3 14 Recent Counts or Estimates of Sea Otter (*Enhydra lutris*) Abundance in the North Pacific

Subspecies	Area	Year	Number	Status
E l lutris	Russia	1995-97	21 500	Stable in Kurils and Commander islands increasing in Kamchatka
E l kenyoni	Alaska USA	1994-99	100 000	Declining in Aleutians uncertain in GOA and increasing in Southeast
	British Columbia Canada	1997	1,500	Increasing
	Washington USA	1997	500	Increasing
E l nereis	California USA	1997	2 200	Uncertain
Total			125 700	

Source (Bodkin and Kenyon in press)

A number of predators include sea otters in their diet, most notably the white shark (*Carcharadon charcharias*) and the killer whale (*Orca orcinus*) Bald eagles (*Haliaeetus leucocephalus*) may be a significant source of very young pup mortality Terrestrial predators, including wolves (*Canis lupus*), bears (*Ursus arctos*), and wolverine (*Gulo gulo*) may kill sea otters when they come ashore, although such instances are likely rare Before the work of Estes et al (1998) predation was thought to play a minor role in regulating sea otters (Kenyon 1969)

Pathological disorders related to enteritis and pneumonia are common among beach-cast carcasses and may be related to inadequate food resources, although such mortalities generally coincide with late winter periods of inclement weather (Kenyon 1969, Bodkin and Jameson 1991, Bodkin et al 2000) Non-lethal gastrointestinal parasites are common, and lethal infestations are occasionally observed Among older animals, tooth wear can lead to abscesses and systemic infection, eventually contributing to death

Contaminants are of increasing concern in the conservation and management of sea otter populations throughout the North Pacific Concentrations of organochlorines, similar to levels causing reproductive failure in captive mink (*Mustela vison*), occurred in the Aleutian Islands and California, whereas otters from Southeast Alaska were relatively uncontaminated (Estes et al 1997, Bacon et al 1998) Elevated levels of butyltin residues and organochlorine compounds have been associated with sea otter mortality caused by infectious disease in California (Kannan et al 1998, Nakata et al 1998) Changes in stable lead isotope compositions from pre-industrial and modern sea otters in the Aleutians reflect changes in the sources of lead in coastal marine food webs In pre-industrial samples, lead was from natural deposits, in contemporary sea otters, lead is primarily from Asian and North American industrial sources (Smith et al 1990)

Susceptibility of sea otters to oil spills, largely because of the reliance on their fur for thermoregulation, has long been recognized (Kenyon 1969, Siniff et al 1982) and this was confirmed by the EVOS Accurate estimates of acute mortality resulting from the EVOS are not available, but nearly 1,000 sea otter carcasses were recovered in the months following the spill (Ballachey et al 1994) Estimates of carcass recovery rates ranged from 20% to 59% (DeGange et al 1994, Garshelis 1997), indicating mortality of up to several thousand animals (Ballachey et al 1994) Sea otter mortality in areas where oil deposition was heaviest and persistent was nearly complete, and through at least 1997, sea otter numbers had not completely recovered in those heavily oiled areas (Bodkin and Udevitz 1994, Dean et al 2000) Long-term effects include reduced sea otter survival for at least a decade following the spill (Monson et al 2000a), likely a result of sublethal oiling in 1989, chronic exposure to residual oil in the years following the spill, and spill-related effects on invertebrate prey populations (Ballachey et al 1994, Fukuyama et al 2000, Peterson 2000) As human populations increase, exposure to acute and chronic environmental contaminants will likely increase Improved understanding of the effects of contaminants on keystone species, such as sea otters, may be valuable in understanding how and why ecosystems change

Human activities contribute to sea otter mortality throughout the Pacific Rim Incidental mortality occurs in the course of several commercial fisheries In California, an estimated annual take of 80 sea otters in gill and trammel nets, out of a population numbering about 2,000, likely contributed to a lack of population growth during the 1980s (Wendell et al 1986) Developing fisheries and changing fishing techniques continue to present potential problems to recovering sea otter populations In Alaska, sea otters are taken incidentally in gillnet, seine, and crab trap fisheries throughout the state, but total mortality has not been estimated (Rotterman and Simon-Jackson 1988) Alaska Natives are permitted to harvest sea otters for subsistence and handicraft purposes The harvest is largely unregulated and exceeded 1,200 in 1993, with most of that from a few, relatively small areas In addition, an illegal harvest of unknown magnitude continues throughout much of the geographic range of sea otters

Sea otters occupy an important, and well documented, position as an upper-level predator in nearshore communities of the North Pacific In contrast to most marine mammals that are part of a plankton and fish trophic web, sea otters rely almost exclusively on benthic invertebrates Because both sea otters and their prey are resources

Relatively little work has been conducted in investigating relations between those physical and biological attributes that contribute to variation in productivity of nearshore marine invertebrates, such as the clams, mussels, and crabs that sea otters consume, and how that variability in productivity translates into variation in annual sea otter survival Given the observed variation in sea otter survival, and the recognized role of food in regulating sea otter populations, understanding these relations would provide some empirical measure of the relative contributions of "top-down" (predation) versus "bottom-up" (primary production) factors in structuring nearshore marine communities relatively sedentary, please correct preceding text they integrate physical and biological attributes of the ecosystem over small spatial scales Further, both sea otters and their prey occur nearshore, allowing accurate and efficient monitoring of sea otters, their prey, and physical and biological ecosystem attributes This suite of factors offers a strong foundation for understanding mechanisms, and interactions among factors that regulate long-lived mammalian populations Given that many populations of large carnivorous mammals are severely depleted worldwide, such an understanding would likely be broadly applicable to conservation and management of natural

3.11.3 General Research Questions

What are the factors responsible for the decline of marine mammal populations?

- What is the role of marine mammal predation (consumption) in structuring their prey populations (plankton, fish, and mammals)?

- What is the relation between abundance of marine mammal populations to the availability and quality of prey species?
- What is the relation between abundance of marine mammal populations and the removals of prey species by fishing?
- What is the relation between reproduction and abundance of marine mammal populations and contaminant burdens?
- How does variation in the amount of food produced affect the geographic distributions, fecundities and survivals of marine mammal populations?

What are the factors responsible for regulation of population size in sea otters?

- Can availability of food become limiting?
- Can predation, contamination, human take, or disease play important roles in structuring sea otter populations?

3.12 General Research Questions

3 12 1 Introduction

Organizing the research questions posed by the individual disciplines represented in this chapter is the first step in building the interdisciplinary team approach that GEM hopes to foster, as explained in Chapter 6, Volume I Accordingly, the general research questions have been organized to emphasize the need for scientists from different disciplines to work together to understand how the GOA works As explained more fully in the conceptual foundation discussion (Chapter 4, Volume II), the GEM program is to be built around the questions of how interannual and longer-period trends in the production and distribution of valued marine resources in the northern GOA reflect cycles in the meteorology, the underlying oceanography of the region, and the influences of man on the dynamics and structure of the ecosystem

3 12 2 General Research Questions

The following general research questions are organized under three major lessons from the scientific background Aspects important to detecting and understanding changes in all plant and animal species are covered here, although not all species are mentioned by name

3.12.2.1 The Importance of Weather

Patterns in current structure, upwellings and convergences, temperature, salinity, and density in the waters of the northern GOA are established in response to strong external meteorological conditions affecting the subarctic region of the North Pacific Ocean and through interactions with the coastal topography and the bathymetry of the shelf and coastal regions

a How variable–seasonally and annually–are the cross-shelf and along-shore flows over the shelf and inner coastal regions?

b Under what oceanographic conditions are shelf eddies formed, what are their sizes and how long do they persist?

c How are seasonal and interannual cycles in upper-layer stability influenced by the conditions of strong or weak Aleutian Low pressure systems?

d How frequently are deep bottom waters in coastal fjords renewed, and how is this process related to climate forcing on seasonal, annual and longer time scales?

e Under what conditions, where, and during which seasons are oceanographic frontal regions formed in the northern GOA? How are these regions affected by swings in the strength of the Aleutian Low Pressure system?

3.12.2.2 The Importance of Nutrient Transport

Primary productivity in the euphotic zone is controlled by amounts and supply rates of inorganic nutrients The deep waters of the GOA contain some of the highest nutrient concentrations found anywhere However, the seasonally permanent pycnocline between 110 and 150 m generally restricts deep mixing and access to this valuable pool

a How do shelf and coastal eddies, frontal regions and areas of upwelling and convergences affect the supply of inorganic nutrients to the upper layers under different conditions of ocean climate in the GOA?

b What are the processes by which deep and shallow coastal waters become enriched with nutrients each year? How are nutrient renewal processes influenced by the broader climate-forced oceanography of the GOA?

c What role does the input of fresh water along the northern coastline play in supplying nutrients and influencing recycling from deeper waters? How is this role affected by varying ocean climate on seasonal, annual, and longer time scales?

d How important and under what oceanographic and meteorological conditions are marine-derived nutrients brought into coastal watersheds and incorporated in the coastal ecology?

e What are the conditions that provide sufficient nutrient resupply to the surface waters in the fall to promote a fall plankton bloom?

f How does winter/early spring physical "preconditioning" of the upper layers promote or constrain plankton production through control of nutrient supply rates and photosynthesis in oceanic, shelf, and coastal waters?

g How is the energy of the diurnal tides used to promote nutrient resupply in the surface waters at selected locations in the northern GOA?

3.12.2.3 The Importance of Plankton Dynamics

In the northern GOA, open ocean and shelf/coastal plankton communities differ in their species composition and annual production By definition, deep and shallow currents distribute the plankton, and standing stocks occurring at specific times and places are the result of local productivity and the addition or dilution of stocks by advection

a Under what physical conditions and to what extent does the oceanic plankton community invade the shelf environment, including the coastal and inside waters? What role does the intruding plankton play in the ecology of the coastal waters?

b What is the biological nature of the boundary between the oceanic and shelf pelagic ecosystems, and how is the primary and secondary productivity in these regions phased through time and influenced by the state of the Aleutian Low?

c How is the efficiency of food-web transfer from plankton to fishes, birds, and mammals influenced by varying levels of the dominant macrozooplankton, including large calanoids, euphausiids, and amphipods?

d How is the time-varying spatial distribution of the dominant zooplankton reflected in seasonal, annual, and longer-period patterns in eddy formation, frontal regions, convergences/divergences, and cross-shelf and along-shore flows?

e What are the interacting physical and biological processes that establish levels of recruitment in plankton and nearshore benthic communities? How do these processes vary under different conditions of the Aleutian Low pressure system?

f How can the effects of human influences on the near-shore benthos be distinguished from natural perturbations?

3.12.2.4 The Importance of Trophic Dynamics

The transfer of energy in food webs (trophic dynamics) supporting fishes, birds, and mammals is influenced by the composition of the forage and its quality and availability The behaviors of forage species that result in seasonal swarming/schooling or layering provide enhanced opportunities for food web transfers External factors like fishing, hunting, and contaminant levels may significantly affect population structure and size, thereby altering food webs

a How does the species composition and quantity of small schooling fishes in shelf and coastal habitats reflect the state of the cycling ocean climate in the northern GOA?

b In what way do the conditions that favor the concentration of forage species also favor their levels of productivity?

c How do fluctuations in abundance and species composition of forage stocks and higher level consumers reflect their unique life history strategies under different conditions of ocean climate–winter, spring, andsummer spawners?

d How does interspecific competition for food resources among forage fishes affect their distributions and rates of production?

e How does the distribution and abundance of forage species reflect losses to predators?

f How do climate-forced shifts in the species composition and abundance of forage species control seabird populations?

g How can the influences of prey availability on seabird abundance be separated from the effects of regional scale properties unique to colony locations, like glaciers?

h What is the relationship between commercial fishing and the abundance of seabird populations?

i Do local trends in the abundance of murres and kittiwakes reflect mesoscale or regional scale climate and oceanographic processes affecting prey availability?

j To what extent are fish, seabird, and mammal stocks affected by top down influences, including fishing and other harvest practices?

k How is the recruitment to fish and shellfish stocks with pelagic eggs and larvae influenced by variable transport processes connecting with nursery areas?

l How do climate-influenced transport mechanisms influence the distributions of the drifting larvae of benthic populations relative to suitable settlement substrates?

m What life history strategies or other population characteristics of arrowtooth flounder cause this species to be so abundant and widespread?

n How well are the species composition, relative abundance and trophic structure of fish and shellfish communities understood based on current sampling and analysis procedures?

o How can long-term trends in salmon production be explained by climate-induced changes in ocean productivity and variations in fishing?

p How is salmon production controlled by ecological processes in the ocean? How can individual stocks be identified?

q How variable is the ocean growth, migratory timing and distribution of salmon, and how is this related to aspects of ocean climate?

r What are the annual levels of ocean production of salmon by region of origin?

s How is the abundance and distribution of marine mammals related to the availability of forage stocks?

t How is he abundance of marine mammal populations related to the removals of prey by fishing?

u How is the abundance of marine mammal populations related to the body burden of marine contaminants?

v Which life history stages of fishes, seabirds and marine mammals are most at risk to climate change and which to human influences?

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4. CONCEPTUAL FOUNDATION

In This Chapter

- Explanation and role of the conceptual foundation
- Description of leading GOA hypotheses
- Identification and interaction of principal marine ecological concepts
- Description of the central hypothesis and question

4.1 Introduction

The conceptual foundation is a working model, summed up in the form of a hypothesis and question, of how the marine ecosystems in the GOA produce biological resources The conceptual foundation does not provide a specific testable hypothesis for ecosystem change because doing so might lead to taking too narrow a view of the system in the face of tremendous uncertainty about sources of long-term changes Instead, this chapter reviews some basic assumptions about production in the oceans, presents a number of hypotheses about how various natural and human forces interact to cause change, discusses the changes in forcing and ecosystem components in various habitat types and regions in the northern GOA and then presents an overarching hypothesis about sources of change—the central hypothesis and questions Through synthesis and further insight from ongoing programs, in time a conceptual model for the program may eventually be specified This model should be broad and robust enough to be tested by the monitoring and research program and then accepted, modified, or eventually rejected without making the underlying data streams irrelevant to the contraction of a clearer picture of sources of change to the ecosystem

This chapter addresses the following topics

1. The role of the conceptual foundation in the GEM program
2. Current hypotheses about how multi-annual and multi-decadal changes in natural and human use factors may produce long-term changes in populations of valued animals
3. Some principal ecological concepts of marine ecosystems that explain generally how natural forces and human activities affect populations of organisms and biodiversity in marine ecosystems

4 Particular conditions in the GOA that appear to affect ecosystem production patterns across habitats–from the coastal watersheds to the central GOA Examples of these conditions are large inputs of nutrient-poor fresh water, strong atmospheric low pressure in winter, persistent coastal downwelling, and the presence of gyres and eddies

The conceptual foundation focuses on how the marine ecosystem in the GOA works

5 Regional ecological differences, such as those between PWS and Lower Cook Inlet, which may arise as a result of local differences in the interaction between physical forces (tides, winds, and currents), geography, oceanography, and human activities

6 The conceptual foundation summarized in a central hypothesis and question, applied across four habitat types

4.2 Role of the Conceptual Foundation in GEM

The conceptual foundation carries the information in the mission, goals, and historical record forward into the other GEM program elements and activities (Figure 4 1) Building on the mission and goals established by the Trustee Council, the foundation encapsulates the Trustee Council's understanding of how the GOA operates as an ecological system and how its biological resources, including highly valued populations of animals, are regulated Therefore, the conceptual foundation is at the philosophical and scientific center of the GEM program

The conceptual foundation is the product of ongoing synthesis and modeling, the latest scientific information, and an assessment of leading ecological hypotheses The central hypothesis and question summarize the current understanding of what controls changes in productivities of biological resources The conceptual foundation is not intended to be static, it will change as the understanding of the GOA marine ecosystem changes and will better reflect the realities of nature and the role humans play in the ecosystem Therefore, the conceptual foundation is an integral element in the adaptive management of the GEM program and in marine science

In summarizing these ideas, the conceptual foundation provides a model of reality Testing this model requires framing the hypotheses and questions that are the foundation for any monitoring and research program The intellectual framework of the GEM program is a hierarchy composed of a central hypothesis and question related to habitat types, specific questions for each habitat type, and ultimately, testable hypotheses based on the specific questions

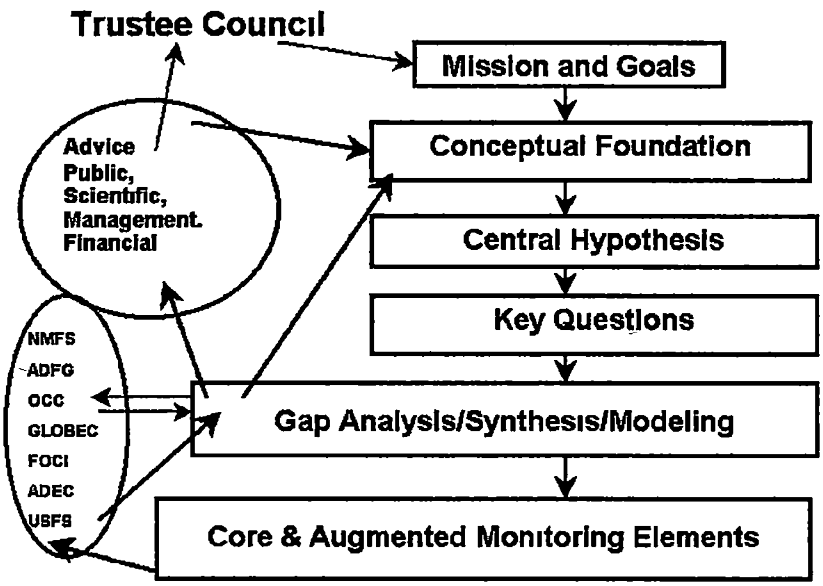


Figure 4 1 Selecting monitoring elements starts with the mission and goals established by the Trustee Council as expressed in the conceptual foundation, which is regularly updated by new information from a variety of sources

4.3 Some Leading Hypotheses

In the section that follows, a number of specific hypotheses about how natural forces and human activities control biological productivity are described These have been advanced in the scientific literature (see Chapter 3, Volume II)

4 3 1 Match-Mismatch Hypothesis

The essence of the match-mismatch hypothesis is as follows

- Populations of organisms are adapted to certain environmental conditions
- When those conditions change rapidly, predator and prey populations may not track in the same way
- As a result, transfer of energy into the higher levels of the food web is compromised

This hypothesis has been proposed by Mackas to explain changes in production with the slow shift to earlier emergence of *Neocalanus* copepods at Ocean Station P in the last several decades (Mackas et al 1998) The match-mismatch hypothesis was also invoked by Anderson and Piatt to explain ecological changes observed in a long time series of small-mesh trawl sampling around Kodiak Island and the Alaska Peninsula (Anderson and Piatt 1999)

4.3.2 Pelagic-Benthic Split

Eslinger et al (2001) suggested that strong inshore blooms of spring phytoplankton that occur in conditions of strong stratification put more biological production into the benthic ecosystem, in contrast to weaker, but more prolonged blooms, that occur in cool and windy growing seasons Under the latter conditions, it has been proposed that biological production is more efficiently used by the pelagic ecosystem and that relatively less of the production reaches the benthos It is conceivable that during a series of years in which one condition is much more prevalent than the other, food might be reallocated between pelagic-feeding and benthic-feeding species Or strong year classes of particular long-lived species might result either from conditions of strong stratification causing more biological production or weaker blooms, leading to dominance of the system by certain suites of species

4 3 3 Optimum Stability Window Hypothesis

Gargett (1997) proposed that there is a point in the range of water stability below which water is too easily mixed downward, resulting in less than maximum productivity, and above which the water is stratified to the extent that it resists wind mixing Gargett proposed that the fluctuating differences in salmon production between the California Current and subarctic gyre domains are ultimately the result of these two systems being on different parts of this response curve at different times

4 3.4 Physiological Performance and Limits Hypothesis

A number of explanations for long-term change more simply propose that the abundance of certain species, mainly fish, is a direct response to their physiological performance in different temperatures Under this hypothesis, the changes in dominance of cod-like fishes and crustaceans that were seen in eastern Canada around 1990 and in the northern GOA around 1978 were initially a response to warm (ascendancy of gadids) or cold (ascendancy of crustaceans) water temperatures In other words, the main agents of change are the direct effects of warmer water temperatures acting on physiological functions of individuals, in addition to the combined effects of freshwater input, winds, and temperature on ecological processes

4 3.5 Food Quality Hypothesis

The food quality hypothesis is also referred to as the junk food hypothesis It attributes declines of many organisms of higher trophic levels observed in the last several decades (harbor seals, sea lions, and many seabirds) to the predominance of suites of forage species that have low energy content (less lipid) than previous food sources (for example, gadids and flatfishes) Consistent with this hypothesis is evidence from the Trustee Council's APEX program, which showed that it takes about twice as much herring as pollock to raise a kittiwake chick to fledging during the nesting season With the relative rarity of capelin and sand lance in the diets of seabirds in PWS during the last several decades, it seems that many of the population declines might be at least partially attributable to the role of these fatty fish in seabird diets The change in food sources has been advanced for marine mammal populations that have been in decline

4.3 6 Fluctuating Inshore and Offshore Production Regimes Hypothesis

The GEM plan provides the first presentation of the model consisting of fluctuating inshore and offshore production regimes Although this model is closely related to the Gargett hypothesis of an optimum stability window, it proposes that under the same set of atmospheric forcing conditions opposite production effects are seen inshore and offshore Figure 4 2 illustrates some features of this model

FIGURE 4 2 is a series of figures illustrating the components of the J Allen "Gulf Ecosystem" figure Bob Spies will identify the figures

The model was developed as a result of observing during the last several decades that populations of many seabirds, harbor seals, and sea lions, which forage mainly in inshore waters, have been declining while marine survival of salmon and high levels of offshore plankton and nekton suggested that offshore productivity was very high It is proposed that the various manifestations of climate forcing have combined since about 1978 (positive Pacific Decadal Oscillation [PDO]) to make the ocean more productive offshore Characteristics of the offshore ocean include more upwelling of deep nutrients and a mixed surface layer that is shallower and more productive These same climatic conditions are proposed to have made the inshore areas of the GOA less productive During the positive PDO, greater freshwater supply (precipitation on the ocean and terrestrial runoff) results in greater-than-optimal nearshore stratification Also, during the positive PDO, greater winds cannot overcome the stratification during the growing season, but do inhibit the relaxation of downwelling Therefore, fewer nutrients are supplied to the inshore regime from the annual run up of deep water onto the shelf During a negative PDO, the opposite pattern in biological response results from a colder, less windy, and drier maritime climate

4 3 7 Incremental Degradation Hypothesis

Marine environments around urbanized areas (such as Los Angeles, Puget Sound, Boston Harbor, San Francisco Bay, and New York Bight) and watershed systems (Columbia River Basin and San Joaquin River) have highly altered ecosystems that contain invasive exotic species, individuals impaired by contamination, and fish populations that have been highly altered by the combined effects of various human alterations Although much of this degradation took place before policies for a sustainable natural environment were in place, it appears that this degradation occurred through a long period of time and as a result of the combined impacts of many different human activities To this day, no regional programs track the combined impacts of all human activities

4.4 Principal Ecological Concepts

Production at the base of the food web, referred to as primary productivity and strongly influenced by physical forces, ultimately determines ecosystem productivity However, the abundance of any particular population depends on three things immediate food supply (prey), removals (mortality), and habitat.

All animals and plants in the oceans ultimately rely on energy from the sun or, in some special cases, on chemical energy from within the earth The amount of solar energy converted to living material determines the level of ecosystem production (total amount of living material and at what rate it is produced) As a rule of thumb, populations of individual species (such as salmon, herring and harbor seals) cannot exceed about 10% of the biomass of their prey populations (about the average conversion of prey to predator biomass) Therefore, the amount of energy that gets incorporated into living material and the processes that deliver this material as food and energy to each species are key factors influencing reproduction, growth and death in species of concern Increases in prey, with other factors such as habitat being equal, generally allow populations to increase through growth and reproduction of individual members At the same time, there are factors that lead to decreases in populations–decreases in suitable habitat, decreases in growth and reproduction, and increases in the rate of removal (death) of individuals from the population As a result, the combined effects of natural forces and human activities that determine food supply (bottom-up forces), habitat (bottom-up and top-down forces), and removals (top-down forces) determine the size of the population of any animals of concern by controlling reproduction, growth, and death

4.4.1 Physical Forcing and Primary Production

The vast majority of the energy that supports ecosystems in the GOA comes from capture, or fixation, of solar energy in the surface waters How much of this energy is captured by plants in the ocean's surface layer and watersheds and passed on ultimately determines how much biomass and production occur at all levels in the ecosystem Capture of solar energy by plants in the oceans and watersheds and the conversion of solar energy to living tissue (primary production) depends on several interacting forces and conditions that vary widely from place to place, season to season, and year to year as well as between decades Needless to say, without a clear understanding of how these changes occur, it will not be possible to understand the most important aspects of ecological change in the GOA The process of capturing solar energy is explained below

First, in the ocean, primary production occurs only in the relatively shallow photic zone in which sunlight penetrates (a few hundred feet) In watersheds, cloud cover and shading play a larger role in variability of productivity Second, plants that fix this energy, by using it to make simple sugars out of carbon dioxide and water, depend on nutrients which are absorbed by the plants as they grow and reproduce Solar energy that is not captured by plants in the ocean warms the surface waters, making it less dense than the water beneath the photic zone, which causes layering of the water masses A continuous supply of nutrients to the surface waters is necessary to maintain plant production Likewise, terrestrial plants depend on nutrients carried from the ocean by anadromous fish Because the deep water of the GOA is the main reservoir of nutrients for shallow waters, and apparently also an important source for watersheds, the processes that bring nutrients to the surface and into the watersheds are key to understanding primary, and, therefore, ecosystem productivity Changes in nutrient supply on time scales of days to decades and space scales from kilometers to hundreds of kilometers have important impacts on primary production, generating perhaps as much as a thousand-fold difference in the amount of solar energy that is captured by the living ecosystem Nutrient supply from the deep water is influenced by the properties of the shallower water above (mainly because of the decreasing density of the water toward the surface) Nutrient supply is also influenced by physical forces that can overcome the density differences between deep and shallow water–namely, wind acting on the water surface and tidal mixing For watersheds, nutrient supply apparently depends strongly on biological transport of marine nitrogen by salmon, which die and release their nutrients in freshwater

As demonstrated in the scientific background in Chapter 3, Volume II, the knowledge of nutrient supply in the GOA, both how it occurs and how it may be changed on multi-year and multi-decadal scales, is very rudimentary As the energy of the wind and tides mixes surface and deeper water, it not only brings nutrients to the surface layers, but also mixes algae that fix the solar energy down and out of the photic zone, which tends to decrease primary production Therefore, other factors being equal, continuous high primary production in the spring-summer growing season is a balance between enough wind and tidal mixing to bring new nutrients to the surface, but not so much wind or tidal mixing that would send algal populations to deep water The seasonal changes in downwelling, solar energy, and water stratification that set up the annual plankton bloom are described in Section 3 6, Volume II, of the scientific background As noted in that section, however, it is not well understood how differences in physical forces from year to year and decade to decade change primary production many-fold in any particular place

4 4.2 Food, Habitat, and Removals

Increases in immediate food supply (prey) will translate to population increase, all other factors being equal The allocation of energy in each individual is key to growth of the population it belongs to Food supply is converted into population biomass through growth and reproduction of individuals in specific favorable habitats Therefore, factors in the habitat such as water temperature, distribution of prey, and contaminants that can influence the allocation of food energy to the following activities will influence the population size chasing and capturing prey, maintaining body temperature (for homeotherms), growth, and reproduction

Removals are all the processes that result in loss of individuals from the population, or mortality These processes include death from contamination, human harvest, predation, disease, and competition For example, harvest of a large proportion of the largest and most fecund fish in a population will soon decrease the population, as will a virulent virus or the appearance of a voracious predator in large numbers

Also included under the category of removals is any factor that negatively affects growth or reproductive rate of individuals, because such factors can decrease population size Contaminants are considered potential removals because of the following possible effects

- Causing damage that makes energy utilization less efficient and requires energy for repairs,

- Interfering with molecular receptors that are part of the regulatory machinery for energy allocation,
- Damaging immune systems that make disease more likely, and
- Outright killing of organisms at high concentrations

Habitats in marine and freshwater environments are ultimately controlled by temperature and salinity, as modified by many other biological, physical and chemical factors Basic physiological functions such as respiration and assimilation of nutrients from food occur only within certain boundaries of temperature and salinity As stated in Section 4 _ a number of hypotheses on the origins of long-term change relate the abundance of certain aquatic species to their physiological performance in different temperatures For example, changes in dominance of cod-like fishes and crustaceans in eastern Canada around 1990 and in the northern GOA around 1978 were explained as positive responses of gadids to increasingly warm temperatures Using the same reasoning, the ascendancy of crustaceans such as shrimp in the GOA in the 1950s and 1960s, and in eastern Canada during the 1990s, have been attributed to cooling water temperatures

On the basis of the first principles of physics, chemistry, and biology, temperature and salinity must be agents of change in biological resources through effects relating to physiological functions in individual plants and animals Effects on individuals add to the combined effects of freshwater input, winds, and temperature on ecological processes

4.5 Interactions of Principal Ecological Concepts by Habitat

4.5.1 From Watersheds to the Central Gulf

These ecological concepts can be applied directly to the GOA ecosystem to show how the system and its plant and animal populations are controlled Total annual primary productivity, natural controls on populations, and human activities change from the edge of the watershed to the central GOA These changes are related to the physical processes and geographic features depicted in Figure 4 3, a cross section of the GOA from the top of the eastern ringing mountains out past the continental shelf slope Some key biological features are also depicted in this figure

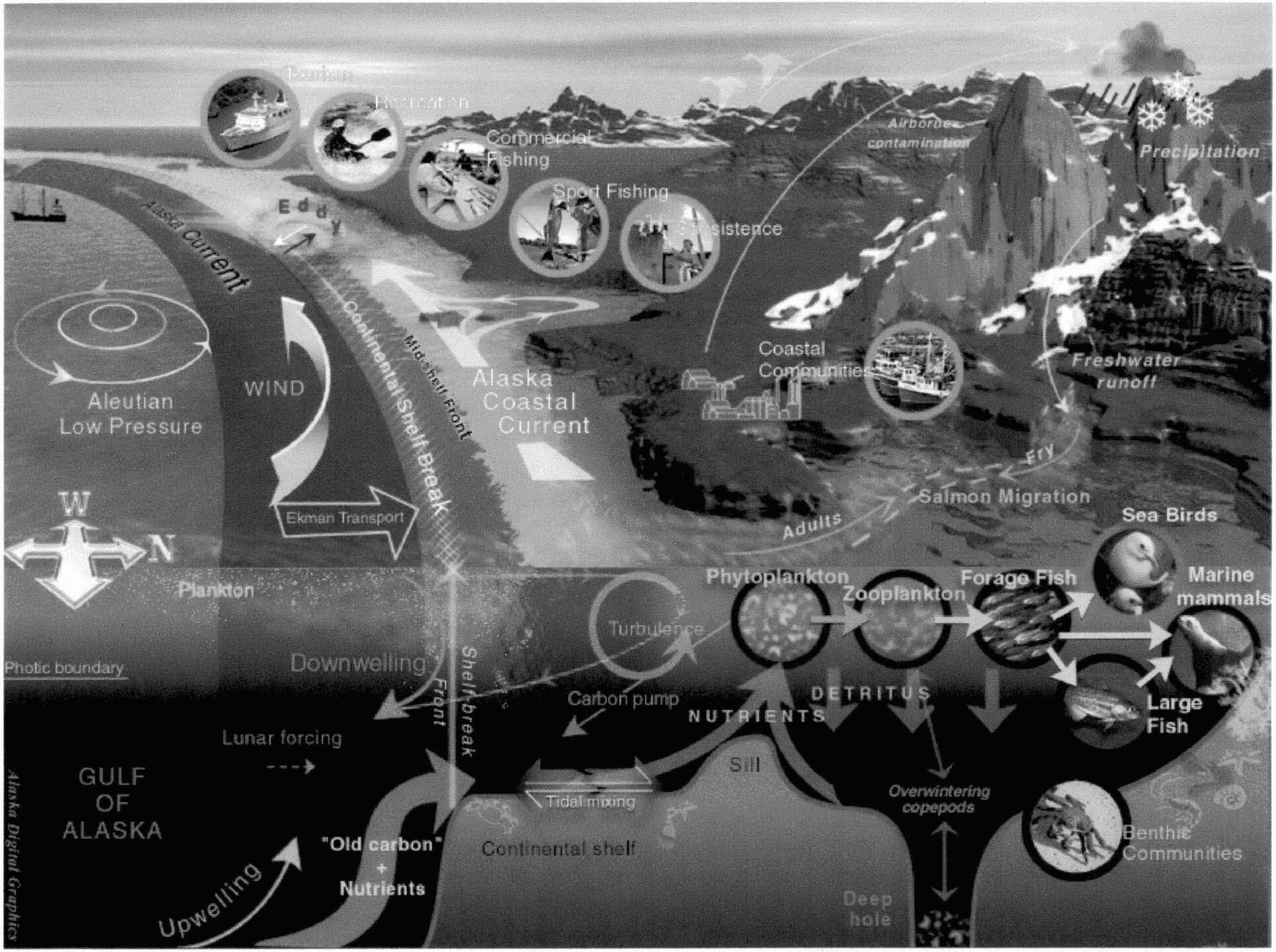


Figure 4.3 Diagram of the northern GOA showing connections among plants and animals, natural forces, and human actions. (J. Allen Alaska Digital Graphics)

4 4 2 Watersheds

Watersheds are lınked by geochemıcal cycles and common clımatıc forcıng to the marıne ecosystem Input of terrestrıal carbon contrıbutes to the carbon budget of the oceans In addıtıon, the ıncorporatıon of carbon dıoxıde by marıne plants acts as a pump that potentıally sequesters amounts of carbon for long perıods of tıme ın the oceans

4.5.2.1 Physıcal Forcing and Primary Productıon

Prımary natural forces are precıpıtatıon and ınsolatıon Watersheds depend on ımport of marıne nutrıents by anadromous fısh and other anımals Therefore, maıntenance of healthy salmon runs and populatıons of terrestrıal anımals that feed ın the nearshore marıne envıronment ıs key to healthy watershed ecosystems Woody debrıs and vegetatıon from land are also ımported to the marıne envıronment, provıdıng a carbon source and habıtat for some specıes The common effects of clımate also lınk these two systems Fresh water from coastal watersheds contrıbutes huge amounts of fresh water to the GOA and makes possıble the ACC–the sıngle most domınant and ıntegratıng feature of the physıcal envıronment on the contınental shelf

4.5.2.2 Food, Habitat and Removals of Valued Species

Human actıvıtıes ın the watersheds that remove natural vegetatıon can result ın soıl erosıon and ıts attendant effects on stream and coastal marıne lıfe Fresh water can carry contamınants to the marıne envıronment Sources of these contamınants can be of local orıgın–sewage and septıc wastes, ındustrıal and mılıtary wastes, motor vehıcles, and oıl from spılls–or ımported from dıstant sources and carrıed across the Pacıfıc Ocean by atmospherıc processes

4 5.3 Intertıdal and Subtıdal

The ıntertıdal and subtıdal–or nearshore–area ıs technıcally a part of the ACC regıme ın most places, except arguably ın some embayments, such as the fjord systems ın northern PWS But, because of the ımportance and vulnerabılıty of the ıntertıdal and shallow subtıdal areas and the dependence of so many valued specıes on nearshore habıtat, ıt ıs treated here separately from the ACC

4.5.3.1 Physıcal Forcıng and Prımary Productıon

The productıvıty of ıntertıdal and subtıdal marıne communıtıes depends on both fıxed algae and some other vascular plants ın shallow water, as well as free-floatıng phytoplankton Nutrıent supply to fıxed plants ıs not well characterızed, but presumably ıs controlled by oceanographıc processes and seasonal cycles of water turnover on the ınner shelf as well as some contrıbutıons from stream runoff Thıs process of nutrıent supply ıs essentıally the same as for nearshore phytoplankton Ultımately, as mentıoned ın Sectıon 3 5, Volume II, the run up of deepwater from the central GOA onto the shelf and some poorly characterızed processes for cross-shelf transport of the nutrıents are crıtıcal to growth of both fıxed and floatıng nearshore algae The nearshore waters can be depleted of nutrıents durıng the growing season if the warm surface layers where primary productivity is drawing down nutrients is not mixed with deeper waters by wind and tidal action Within-season variability in primary production, therefore, appears to depend on the previous late summer run up of deepwater onto the shelf, some poorly described cross-shelf transport processes, and within-growing season wind and tidal mixing

Cloud cover also is likely to be very important in regulating the amount of solar energy reaching the ocean surface Nearshore turbulence, which is the result of the prevailing climate and tidal action, promotes the growth of algae and phytoplankton. These plants are the food supplies for filter-feeding molluscs, such as clams and mussels, that are important sources of food for a variety of nearshore animals, such as sea otters and sea ducks Climate also directly affects intertidal and subtidal animals through changes of temperature, water salinity, and ice formation Ice formation is an important source of mortality and reduced growth of intertidal algae and some animal populations in some situations It is suspected that bottom-up forcing through variability of primary production is an important influence on intertidal invertebrate communities on the scale of decades, but there are no long-term data sets to examine this supposition If wave action is too intense, it can limit population growth, for example, waves during storms often throw large amounts of herring eggs (embryos) onto the beach where they die

In addition to these natural factors, human activities in the intertidal and subtidal area and human accidental releases of toxic materials have the potential to affect nearshore primary production At the present time, it appears that the influences of natural forces on basin and regional scales in nearshore ecosystem productivity are overwhelming and that human influences are negligible, except in local areas (such as harbor contamination)

4.5.3.2 Food, Habitat and Removals of Valued Species

A large number of intertidal and subtidal animal populations respond to both bottom-up and top-down natural forcing as well as to human activities Bottom-up forcing appears to have more documented effects on such populations as herring, pollock, shrimp, crab, salmon, and seabirds than have been documented for infaunal and intertidal animals There are good examples of population controls by removals (top-down influences) and many of these relationships, such as that between sea urchins and otters, are cited in Section 3 7, Volume II Disease possibly influences some populations, such as *Viral Hemorrhagic Septicemia* virus effects on Pacific herring in PWS

The intertidal and subtidal benthos is particularly vulnerable to human use through harvesting of various invertebrates, trampling, release of contaminants, road and home construction, and soil erosion At the present time, impacts of such activities appear to be localized because of the dispersed nature of human activities along the vast coastline of the northern GOA The nearshore sentinel populations may need to be monitored more closely, however, as Alaska's population and use of the nearshore zone expands in the future

4.5.4 Alaska Coastal Current

As noted above, the domain of the ACC in many cases starts at the shoreline and extends out to a frontal area several tens of kilometers onto the continental shelf. The inshore boundary of this current system is not precisely defined in this subsection because the nearshore aspects of the ecosystem have been covered above.

4.5.4.1 Physical Forcing and Primary Production

Because the ACC is a buoyant, low-salinity, eastern boundary current fed essentially by a line-source of fresh water along the length of the Alaska coastline, it offers a unique opportunity to study basin-scale physical forcing of biological production. Although one characteristic of the ACC is the draw-down of nutrients during the growing season to levels that are undetectable, the in-season variability, clearly driven by patterns in the aforementioned wind mixing, is very significant. A promising model developed by Eslinger et al. (2001) is capable of tracking the in-season variability of plankton production based on the physical characteristics of the water column and the wind field. The extent to which patterns of seasonal wind mixing are the major contributors to longer-term variability in primary productivity is not clear. Tidal mixing likely contributes to variability, as do other potential mechanisms that transport deep-water nutrients into shallow waters, for example, late-summer relaxation of Ekman transport and up-canyon currents.

Annual variability of nutrient supply likely has a great influence on long-term variability in primary production. For example, this influence would be consistent with the relationship between the Bakun upwelling index and pink salmon marine survival rates up to 1990 (see Section 3.6, Volume II) and the differences observed between the volumes of settled plankton in the 1980s and the 1990s (E. Brown, unpublished).

Another physical phenomenon that apparently affects biological production in the water column is eddies. Eddies have been documented in Shelikof Strait, for example, and greatly influence retention of larval pollock in a favorable environment. Beyond their study in the FOCI program, not much is known generally about eddies in the ACC and their biological influences. There are also eddies in Kachemak Bay, some of which are stratified at the surface by freshwater inputs that may similarly benefit pelagic species there and off Kayak Island southeast of PWS. The southerly and easterly winds that predominate during most of the year drive offshore water inshore (via Ekman transport), carrying offshore planktonic organisms close to shore and providing potential sources of food for nearshore organisms, such as juvenile pink salmon.

Finally, the outer edge of the ACC often forms a front with the water masses seaward of it. This front is characterized by strong convergence of offshore and inshore water masses and significant downward water velocities. It appears at times to concentrate plankton, nekton, fish, and birds, and is probably an important site for trophic interactions.

4.5.4.2 Food, Habitat and Removals of Valued Species

Many of the types of natural and human activities that affect the nearshore species apply also to the ACC This similarity is due in part to the fact that many species cross between the nearshore environment and deeper waters Bottom-up forcing appears to be of great importance, because areas of the ACC with high levels of chlorophyll a during the growing season and vigorous vertical mixing, such as Lower Cook Inlet, also support large populations of fish, seabirds and marine mammals The ACC is the main domain of the GOA for the productive fisheries for both pelagic and benthic species Consequently, human activities are potentially a quite large aspect of removals Other possible human impacts include contaminants and long-term global warming

4 5 5 Offshore: Alaska Current and the Subarctic Gyre

4.5.5.1 Physical Forcing and Primary Production

In the offshore areas of the Alaska Current and the subarctic gyre, forcing by winds associated with the Aleutian Low pressure system have a profound effect on production and shoreward transport of plankton Production and shoreward transport of plankton are determined by the following

- Upwelling at the center of the subarctic gyre,
- Depth of the mixed layer (freshwater and solar energy input set up the mixed surface layer where primary production takes place),
- Possible upwelling of nutrients along the continental slope and at the shelf break where the shelf break front may direct upwelled water toward the surface, and
- Formation of eddies along the shelf break that may incubate plankton in a favorable environment for production and be mechanisms of exchange between offshore and shelf water masses Individual eddies may persist for months and are therefore potentially important in any one growing season

The contrasts in biological production and shoreward transport of plankton between intense and relaxed Aleutian Low pressure conditions in the Alaska Current region and the subarctic gyre are profound In periods with more negative atmospheric pressure that is keyed by the northeastern movement of the ALP into the GOA in winter, the following interrelated physical changes are observed

- Acceleration of the cyclonic motion of the Alaska Current and subarctic gyre,
- Increased upwelling in the middle of the subarctic gyre (and possibly along the continental shelf),
- Entrainment of more of the west wind drift (southerly portion of the subarctic gyre) northward into the GOA, rather than into the California Current system,

- Warmer surface-water temperatures and increased precipitation and fresh water runoff from land,
- Freshening of the surface layer,
- Increased winds and Ekman transport, and
- Increased onshore downwelling

These phenomena are thought to cause the following biological changes

- The result of the shallower mixed surface layer is that the spring plankton production is likely higher (remember that nutrients may not be limiting in the subarctic gyre)
- Greater standing crops of zooplankton and nekton that have been observed are probably made possible by the higher productivity of the phytoplankton
- More food is available for the fish that feed on plankton and nekton, such as salmon
- Salmon populations track mean atmospheric pressure for the wintertime sea surface on scales of decades

In addition to the multi-decadal oscillations of atmospheric pressure, climate changes manifested in the northern GOA also include periodic El Niños and the long-term warming of the oceans El Niños have been associated with successful recruitment of a series of groundfish species, such as pollock, as well as some die-off of seabirds Because the El Niño phenomenon appears to be manifested solely in warming of the upper 200 m of the ocean, its biological effects are probably mediated through water stratification and its relationship to primary production and growth of larval fish

4.5.5.2 Food, Habitat and Removals of Valued Species

The Alaska Current is centered over the shelf break, an area of high biological activity The high concentrations of plankton observed at the shelf break, whether they result from accumulation of plankton originating further offshore, in situ production, or both, provide a rich resource for a variety of organisms and their predators It is not clear that juvenile salmon feed in this regime, but adults of all species certainly do Other prominent organisms include sablefish, myctophids (lantern fish), sea lions, some seabirds, and whales Well-developed benthic communities exist on the outer shelf, shelf break, and continental slope, including commercially exploited populations of shrimp, crab, cod, halibut, and pollock Some fishing activities, such as bottom trawling, have the potential to do habitat damage and possibly limit populations of animals associated with the sea bottom Issues associated with the balance between production and removals of commercially important species are of the utmost societal importance in Alaska and further ecological information, modeling, and synthesis centered on the Alaska Current regime is necessary

4.6 Regional Changes Resulting from Interacting Ecological Factors

In general, regional differences in populations of fishes, birds, and marine mammals in the northern GOA are well known, but the underlying interacting ecological factors that give rise to these differences are not as well understood In this section, some of the observed regional differences and some potential reasons underlying them are advanced These explanations of regional differences are based on incomplete or piecemeal evidence, but this speculation is important because it may lead to further study and analysis and to new understanding Comparative analysis of interacting factors in several regions may better clarify the role of various geographic features, physical forcing, and biological consequences in the northern GOA, as was emphasized in relation to seabirds (Section 3 9, Volume II) Because there is so much homogeneity in the ACC, in particular, what happens in PWS, along the Kenai Peninsula, in outer and middle Cook Inlet, and in the Shelikof Strait may well represent four different field experiments in the same body of water

One of the most prominent regional contrasts is the different levels of ecosystem productivity apparent in lower Cook Inlet and PWS It is relatively clear from satellite measurements of surface-water chlorophyll a and the large populations of forage fishes, seabirds, and marine mammals that occur there that the lower Cook Inlet area is extremely productive in the summer growing season relative to PWS Satellite data for the sea surface temperatures indicate that cold deep water, which is presumably also rich in plant nutrients, is on the surface whenever images are available, and in satellite images taken at the same times, PWS appears to have warmer surface water The strong mixing that brings deeper water to the surface in this area is probably largely tidal in nature Vigorous mixing is encouraged by

- The local geography and oceanography, such as the large tide range,
- The large volume of water that is exchanged with each tidal cycle, and
- The narrow entrances to outer Cook Inlet relative to the area of Cook Inlet

Another regional difference on a somewhat smaller scale occurs within Cook Inlet itself In Cook Inlet, studies of forage fish abundance and seabird populations at Gull Island on the eastern side and Chisik Island on the western side provide an interesting contrast that strongly suggests physical forcing on seabird populations At Gull Island, populations of all major seabirds have been increasing during the last 20 years, and at Chisik Island the opposite trend has occurred This difference appears to be caused by marine-influenced conditions near Gull Island where the food web probably has much greater access to deep-water nutrient sources At Chisik Island, however, the system is strongly influenced by nutrient-poor, silty freshwater runoff from the major glacial rivers of northern Cook Inlet, and only meager populations of forage fish exist within the foraging range of most species It appears that with a warmer climate and more runoff, the dynamic balance between fresher water coming down the western side of Cook Inlet and saltier offshore water entering Stevenson and Kennedy entrances has been shifted to make Chisik Island less productive and Gull Island more productive Eddies, which have been known to exist for some time near Gull Island in Kachemak Bay, have recently been shown to provide a less-dense surface lens in which forage fish favorable to seabirds reside

Another example of regional differences in geography and physical forcing shaping important differences in ecological production is the eddy system in Shelikof Strait. As mentioned above, this system has been extensively explored and modeled during the FOCI program This eddy system retains larval pollock in relatively favorable conditions for growth and allows them to eventually contribute to the important pollock fishery in the northern Gulf

The Trustee Council's SEA program, hatchery production records, and other studies, such as those carried out on kittiwake reproduction, have demonstrated important subregional ecological differences between northern and southern PWS as well as eastern and western PWS

The pattern of some differences may have changed on a decadal scale The following regional differences are apparent in PWS

- Residence time of water in different portions of PWS, with longer residence time in the northern portions of the sound that have more restricted water circulation,
- Degree of incursion of the ACC into the sound, which appears to vary annually,
- Glacial runoff, which is greater in the north and east, and
- Extent of subtidal habitat, which is greater in the eastern portions of PWS

4.7 Central Hypothesis and Questions by Habitat Type

4 7 1 Central Hypothesis

Natural forces and human activities working over global to local scales bring about short term and long lasting changes in the biological communities that support birds, fish, shellfish and mammals Natural forces and human activities bring about change by altering relationships among defining characteristics of habitats and ecosystems such as heat and salt distribution, insolation,

biological energy flow, freshwater flow, biogeochemical cycles, food web structure, fishery impacts, and pollutant levels

The central hypothesis states widely held beliefs about what drives changes in living marine-related resources in time and space Specific mechanisms that cause change are largely untested However, current speculations, supported by limited observations, are that forcing by winds, precipitation, predation, currents, natural competitors for food and habitat, fisheries, and pollutants change living marine-related resources over different scales of time and space through alteration of critical properties of habitats and ecosystems

Having an appreciation for the scales of time and space over which the processes responsible for biological production occur is essential for designing monitoring and research intended to detect and understand changes in the ecosystem To understand the composition and extent of ecosystems, it is necessary to ask and answer questions about the distances and time associated with the variation in the biological and physical phenomena As stated eloquently by Ricklefs (1990) (p 169), "Every phenomenon, regardless of its scale in space and time, includes finer scale processes and patterns and is embedded in a matrix of processes and patterns having larger dimensions " Indeed, spatial and temporal scales are part of the definitions of physical and biological processes such as advection and growth Taking account of spatial and temporal scales is critical to studying linkages between natural forces biological responses (Francis et al 1998)

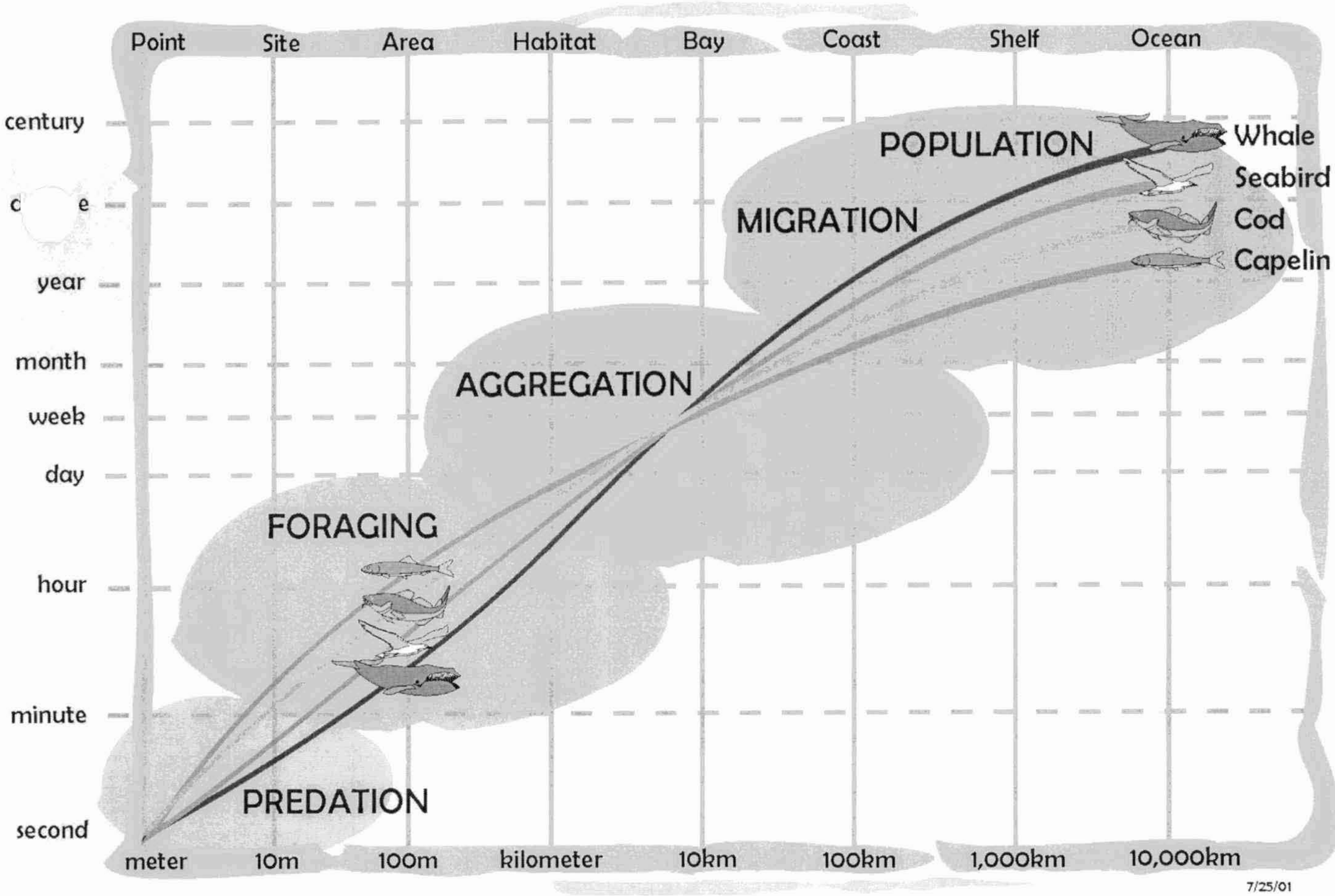
The central hypothesis easily can be converted into a central question designed to explore the means by which natural forces and human activities drive biological responses over different scales of time and space

What are the relative roles of natural forces and human activities, as distant and local factors, in causing short-term and long-lasting fluctuations changes in the biological communities that support birds, fish, shellfish, and mammals in the four key habitats of the GOA?

The following four habitat types, as formally defined in Chapter 3, Volume I, provide points of reference for studying the relations among species in spatially and ecologically separated habitats The intent is to implement monitoring that can, in the long term, help understand the relationships between productivity or community structure of a habitat and the other three habitats Thus, the central question can be specifically targeted to each of the habitats

Watershed (see Section 3 2, Volume I)

What are the relative roles of natural forces, such as climate, and human activities, such as habitat degradation and fishing, as distant and local factors, in causing short-term and long- lasting changes in marine-related biological production in watersheds?



Piatt figure

Intertidal and Subtidal (see Section 3 3, Volume I)

> *What are the relative roles of natural forces, such as currents and predation, and human activities, such as sediment and pollutant discharge, as distant and local factors, in causing short-term and long-lasting changes in community structure and dynamics of the intertidal and subtidal habitats?*

Alaska Coastal Current (see Section 3 4, Volume I)

> *What are the relative roles of natural forces, such as the variability in the strength, structure and dynamics of the ACC, and human activities, such as fishing and pollution, in causing local and distant changes in production of phytoplankton, zooplankton, birds, fish, and mammals?*

Offshore (Outer Continental Shelf and Alaska Gyre) (see Section 3 5, Volume I)

> *What are the relative roles of natural forces, such as changes in the strength of the Alaska Current and Alaskan Stream, mixed layer depth of the gyre, wind stress and downwelling, and human activities, such as pollution, in determining production of carbon and its shoreward transport?*

4.8 References

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5. MODELING

In This Chapter

- A survey of North Pacific models relevant to GEM
- Goals and purposes of gathering and analyzing data with models
- Use of a hierarchal strategy in decision-making
- Modeling strategies and methods

5 1 Introduction

Modeling and observing systems designed to support modeling efforts have been established in the GOA and North Pacific As a regional monitoring and research program, GEM seeks to build on the strengths of past and existing programs In this chapter, modeling strategies of established programs are reviewed to provide a starting point for the modeling component of the GEM program Identification of core variables used in these existing efforts provides an important contribution to developing the GEM monitoring program described in Volume I

Following the review of modeling efforts, the background necessary to implement a modeling program for GEM is developed This background includes presentation of explanations and discussion of the purposes of modeling, a hierarchical framework for organizing different types of models, options available in modeling strategies and methods, and the means of evaluating modeling proposals

5.2 Survey of Modeling

5.2.1 Modeling Strategies of Established Programs

This subsection provides statements summarizing modeling strategies The information is extracted from Web sites as noted

GOOS (Global Ocean Observing System)

> Linking user needs to measurements requires a managed, interactive flow of data and information among three essential subsystems of the IOOS [Integrated Coastal Ocean Observing System] (1) the observing subsystem (measurement of core variables and the transmission of data), (2) the communications network and data management subsystem (organizing, cataloging, and disseminating data), and (3) the modeling and applications subsystem (translating data into products in response to user

> needs) Thus, the observing system consists of the infrastructure and expertise required for each of these subsystems as well as that needed to insure the continued and routine flow of data and information among them

From "Toward a National, Cost-Effective Approach to Predicting the Future of our Coastal Environment, " a Position Paper of the U S GOOS Steering Committee, September 2000, PROLOGUE (http //www-ocean tamu edu/GOOS/publications/position html)

PICES (North Pacific Marine Science Organization)/NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography)

> Models serve to extrapolate retrospective and new observations through space and time, assist with the design of observational programs, and test our understanding of the integration and functioning of ecosystem components Clear differences were identified in the level of advancement of the various disciplinary models Atmosphere-ocean and physical circulation models are the most advanced, to the extent that existing models are generally useful now for CCCC [climate change and carrying capacity] objectives, at least on the Basin scale Circulation models in territorial and regional seas are presently more varied in their level of development, and may need some co-ordination from PICES Lower trophic level models are advancing, and examples of their application coupled with large-scale circulation models are beginning to appear There is a need for comparisons of specific physiological models, and for grafting of detailed mixed layer models into the general circulation models With upper trophic level models, there are several well-developed models for specific applications, but workshop participants felt there were as yet no leading models available for general use within the CCCC program This is an area that needs particular attention and encouragement from PICES

From http //pices ios bc ca/cccc/cccc/taskteam/modelws96 htm (Perry et al 1997)

GLOBEC (GLOBal Ocean ECosystems Dynamics)

> The physical models can be coupled with a suite of biological, biophysical and ecosystems models Development of biological models should occur concurrently with development of the physical model Four types of biological or biophysical models are recommended Linking outputs from each of these models will allow the examination of ecosystem level questions regarding

top down or bottom up controls in determining pelagic production in the Bering Sea

From http //globec oce orst.edu/groups/nep/reports/rep16/rep16 bs model html)

5 2 2 Core Variables for Modeling

Table 5 1 shows spatial domains, currencies, inputs, and outputs for models

5.3 Purposes of Modeling

The ultimate goal of both gathering data and developing models is to increase understanding Pickett et al (1994) ([Pace 2001] p 69) define this goal, in the realm of science, as "an objectively determined, empirical match between some set of confirmable, observable phenomena in the natural world and a conceptual construct"

A model—Pickett's "conceptual construct"—is useful if it helps people represent, examine, and use hypothetical relationships Data—Pickett's "confirmable, observable phenomena in the natural world"—can be analyzed with statistical tools such as the following Analyses of the variance (ANOVAs), regressions, and classification and regression trees (CARTs)

- Mathematical tools such as Fourier transforms or differential equations, and
- Qualitative models such as engineering "free body" diagrams, network diagrams, or loop models

Fundamental goals of statistical or mathematical analyses are to develop correlative, and perhaps even causal, relationships and an understanding of patterns and trends In particular, there is a need to distinguish between random variability, noise, and patterns or trends that can be used to explain and predict.

In other words, the goal of gathering and analyzing data is to improve our conceptual and analytical models of the world, and the goal of developing models is to represent and examine hypothetical relationships that can be tested with data

Table 5 1 Model Spatial Domains, Currencies, Inputs, and Outputs

Model Name/ Model Region	Model Spatial Domain	Inputs	Outputs/Currency
Single-species stock assessment models that include predation	Across EBS and GOA Pollock distributions	Fisheries data and predator biomass	Pollock population and mortality trends—number at age (and biomass at age)
Bering Sea MSVPA	The modeled region is the EBS shelf and slope north to about 61°N	Fisheries predator biomass and food habits data This model requires estimates of other food abundance supplied by species outside the model	Age-structured population dynamics for key species—numbers at age
BORMICON for the Eastern Bering Sea	The model is spatially explicit with 7 defined geographic regions that have pollock abundance and size distribution information	Temperature is included and influences growth and consumption	Spatial size distribution of pollock
Evaluating Alternative Fishing Strategies	U S Exclusive Economic Zone	Gear-specific fishing effort including bycatch	Biomass of managed fish species
Advection on larval pollock recruitment	Southeast Bering Sea Shelf	OSCURS surface currents (wind-driven)	Index of pollock recruitment
Shelikof Pollock IBM	Western GOA from just southwest of Kodiak Island to the Shumagin Islands shelf water column to 100 m	From physical model Water velocities wind field, mixed-layer depth water temperature, and salinity Pseudocalanus field (from NPZ model)	Individual larval characteristics such as age size weight location life stage, hatch date consumption respiration
GLOBEC NPZ 1-D and 3-D Models	Water column (0-100 m) Coastal GOA from Dixon Entrance to Unimak Pass 100 m of water column over depths < 2000 m 5-m depth bins x 20 km horizontal grid	Irradiance MLD Temperature diffusivity bottom depths water velocities (u, v w)	Diffusivity, ammonium nitrate detritus small and large phytoplankton, dinoflagellates tintinnids small coastal copepods, neocalanus and euphausiids (nitrate and ammonium) mmol/m^3 (all else) mg carbon/m^3
Steller Sea Lion IBM	Should be applicable to any domain surrounding a specific sea lion rookery or haul-out in the Bering Sea Aleutian Islands or GOA	The main input will be a 3D field of prey (fish) distribution derived either from hypothetical scenarios or (later) modeled based on acoustic data	Individual sea lion characteristics such as age location life stage and birth date are recorded Caloric balance is the main variable followed for each individual

Table 5 1 Model Spatial Domains, Currencies, Inputs, and Outputs

Model Name/ Model Region	Model Spatial Domain	Inputs	Outputs/Currency
Shelikof NPZ Model 1-D and 3-D Versions	Water column (0-100 m) GOA from southwest of Kodiak Island to Shumagin Islands 1-m depth bins for 1-D version 1 m depth x 20 km for 3-D version	Irradiance MLD temperature bottom depths water velocities (u v w)	Nitrogen phytoplankton Neocalanus densities Pseudocalanus numbers/m-3 for each of the 13 stages (egg 6 nauplıar, 6 copepodite)s
GOA Pollock Stochastic Switch Model	Shelikof Strait Gulf of Alaska	Number of eggs to seed the model Base mortality additive and multiplicative mort Adjustment parameters for each mort Factor	Number of 90-day-old pollock larvae through time
NEMURO	Ocean Station P (50°N 145°W) Bering Sea (57 5°N 175°W) and Station A7 off the east of Hokkaido island Japan (41 3°N 145 3°W)	15 state variables and parameters including 2 phytoplankton 3 zooplankton and multiple nutrient groups	Ecosystem fluxes are tracked in units of nitrogen and silicon
Eastern Bering Sea Shelf Model 1 Ecopath	500 000 km^2 in EBS south of 61°N	Biomass production consumption and diet composition for all major species in each ecosystem	Balance between produced and consumed per area biomass (t/km^2) Future work will explore energy (kcal/km^2) and nutrient dynamics
Eastern Bering Sea Shelf Model 2 Ecopath	500 000 km^2 in eastern Bering Sea south of 61°N		
Western Bering Sea Shelf Ecopath	300 000 km^2 on western Bering Sea shelf		
Gulf of Alaska Shelf Ecopath	NPFMC management areas 610 620 630 and part of 640		
Aleutian Islands Pribilof Islands Ecopath	Not determined		
Prince William Sound Ecopath	Whole Prince William Sound		

Table 5 1 Model Spatial Domains, Currencies, Inputs, and Outputs

Model Name/ Model Region	Model Spatial Domain	Inputs	Outputs/Currency

Source Table 2 in "North Pacific Models of the Alaska Fisheries Science Center and selected others " compiled by Kerim Aydin year?

Notes
BORMICON = Boreal Migration and Consumption Model
EBS = Eastern Bering Sea
GLOBEC = Global Ocean Ecosystem Dynamics
GOA = Gulf of Alaska
km = kilometer
kcal = kilo calorie
m = meter
MLD =
mmol = millimolar
MSVPA = Multispecies Virtual Population Analysis
NEMURO = North Pacific Ecosystem Model for Understanding Regional Oceanography
NPFMC = North Pacific Fisheries Management Council
NPZ = nutrient-phytoplankton-zooplankton
OSCURS = Ocean Surface Current Simulations
t = metric ton?
YD = days of year

need input to correct km^2 and m^3

One of the most useful applications of even relatively simple statistical and conceptual models is in experimental design that permits investigating the possible roles of various parameters and their interactions, ranking the relative importance of uncertainties that may need to be resolved (Fahrig 1991, Oosterhout 1998), and estimating impacts of sample size and observational error (Botkin et al 2000, Carpenter et al 1994, Ludwig 1999, Meir and Fagan 2000) Statistical models assess how the variability in one or more kinds of data relates to variability of others To answer the "why" and "how" questions, however, mechanistic models can be used to develop and test hypotheses about causes and effects (Gargett et al 2001) (Mechanistic in this use is intended to describe the philosophy of mechanism, especially explaining phenomena through reference to physical or biological causes) For monitoring and modeling to be useful for solving problems, they must contribute to improving decision-making (Botkin et al 2000, Hilborn 1997, Holling 1978, Holling and Clark 1975, Ralls and Taylor 2000)

Toward this end, one goal of the GEM program is to use models predictively to assist managers in solving problems It is important that expectations be realistic, however The mechanisms that drive ecological systems, particularly those related to climate and human activities, are not currently well enough understood for predictions about natural systems to be reliably successful It is not unreasonable to expect that predictive models that managers will be able to use to produce at least short-term reliable forecasts will eventually be developed, but advances in decision-support models will require a long-term commitment to advancing understanding on which those decision-support models will ultimately have to be based

Prediction is, however, an important goal of a modeling program even in the short run, because science advances with the development and testing of predictive hypotheses Mechanistic studies are essential to advancing understanding, but carrying out these studies requires defining cause-effect or predictive hypotheses, and then testing those predictions against subsequent data or events with analytical models

The fundamental goal of the GEM program is to identify and better understand the natural and human forces that cause changes in GEM species This research goal has a pragmatic purpose that can only be served, in the end, by linking correlative and mechanistic studies with the predictive needs of decision makers Decision-making, prediction, and understanding are inevitably linked, and maintaining that link can help keep a research program focused on its ultimate objectives, and help it to avoid narrow inquiry and the distractions of small temporary problems (Pace 2001)

An often-overlooked benefit provided by the process of developing a model is that it can, and probably should, facilitate communication among researchers, managers, and the public

To summarize, in the GEM program, the specific purposes of modeling are as follows

- Inform, communicate, and provide common problem definition,
- Identify key variables and relationships,
- Set priorities,
- Improve and develop experimental (monitoring) designs, and
- Improve decision-making and risk assessment

5 4 Hierarchical Framework

It is critical that the GEM program develop a hierarchical modeling strategy to ensure that short-term, smaller-scale decisions about monitoring and modeling studies will be consistent with the conceptual foundation and GEM program goals Smaller-scope research studies to test particular hypotheses and develop correlative relationships must fit within a larger synthesis framework connecting the more narrowly focused research disciplines Deductive studies to relate empirical data to synthetic constructs are just as important as inductive studies to elucidate general principles, and it is important that researchers keep straight whether they are investigating the meaning of the data, given the theory, or the validity of the theory, given the data Neither can be done unless modeling, monitoring, and data management strategies are developed together

As described in Chapter 4, Volume I, models for the purposes of the GEM program may be verbal, visual, statistical, or numerical Statistical models are also known as "correlative" and "stochastic," and numerical models are also known as "deterministic" and "mechanistic " Note that "prediction," "analysis," and "simulation" are terms that describe the use of models, and not necessarily their type (see 4, Volume I) The modeling hierarchy of the GEM program will provide links between observations and explanations, development of theory and design of experiments, and advancement of science and the practice of management The "top" of this hierarchy, the conceptual foundation, is the source of questions and hypotheses to be explored Statistical, analytical, and simulation models will be developed explicitly to link the "confirmable, observable phenomena in the natural world" to the "conceptual construct," as Pickett put it (Pace 2001, p 69)

For example, a visual model of the conceptual foundation is shown in an influence diagram in Figure 5 1, which shows the forces of change on the left and the objects of ultimate interest that are subject to change on the right In between the two are the intervening elements and relationships on which the human and natural forces act. It is the nature of the connections among these physical and ecological elements that is hypothesized to bring about the changes that the GEM program seeks to understand Therefore, these connections should provide the overall modeling structure

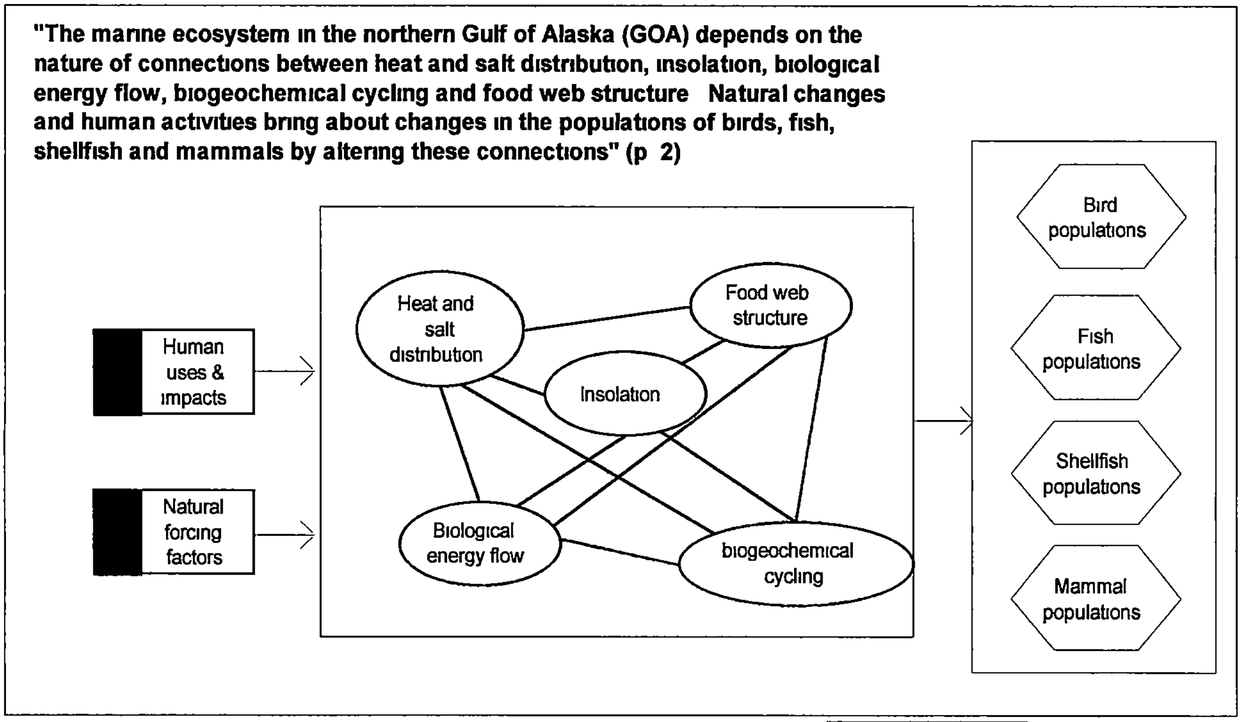


Figure 5 1 Influence diagram illustrating GEM draft conceptual foundation [This figure may be moved to conceptual foundation chapter]

This conceptual model is linked to the monitoring plan through the variables defined as "essential to monitor" in the conceptual foundation, illustrated in a network diagram in Figure 5.2. The analytical relationships between the monitored variables of Figure 5.2 and the conceptual foundation represented by Figure 5.1, are developed and investigated with statistical and analytical tools, called models.

The ultimate goal of GLOBEC's Northeast Pacific modeling appears to be a suite of computer models that represents an entire conceptual foundation. The way this is framed in programs like GLOBEC, the North Pacific Marine Science Organization (called PICES), and Global Ocean Observing System (GOOS) (see Section 5.2 of this chapter) is as linked physical and biological models representing the physical and biological worlds over time and space (marine as well as terrestrial). The NRC describes this idealized goal as follows (p. 16):

> Develop a whole-ecosystem fishery model as a guide to think about what needs to be monitored. Such a model would use current and historical data to relate yields to climate data and contaminant levels and might stress biological and physical endpoints (zooplankton/phytoplankton blooms, macrofauna populations) and climate and physical oceanography endpoints, in conjunction with modeling.

Such a conceptual framework can stimulate heated arguments, creative debate, and perhaps synthesis among researchers who have tended to work in somewhat independent fields with different theoretical foundations and languages (Zacharias and Roff 2000). On a pragmatic level, however, it is too general to help decision makers choose to fund one proposal over another.

A feasible way to proceed from what can be done now is through an iterative process framed by the conceptual foundation (Figure 5.3). The conceptual foundation should be the explicit source of hypothetical correlative and cause-and-effect relationships. Those relationships should be stated as hypotheses, and should be used to determine what needs to be measured and when, where, and how. If the monitoring and modeling plans are developed within this framework, the measurements can be compared to model predictions, the results can be used to update the scientific background and the monitoring plan, and the iteration can continue. This evolutionary process or adaptive feedback loop is illustrated in Figure 5.3.

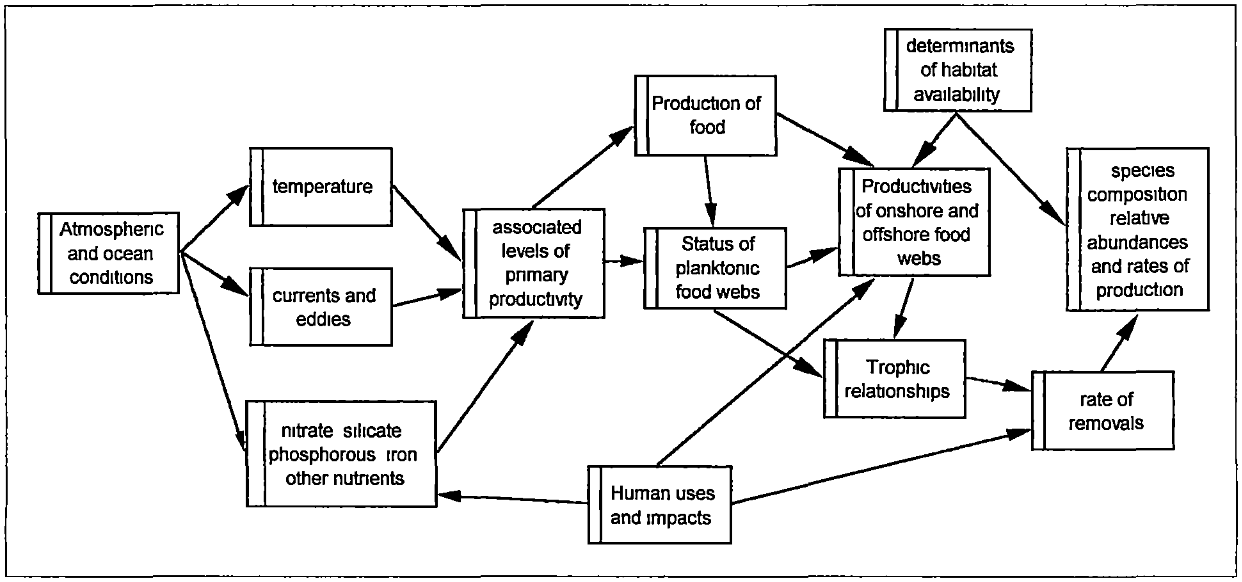
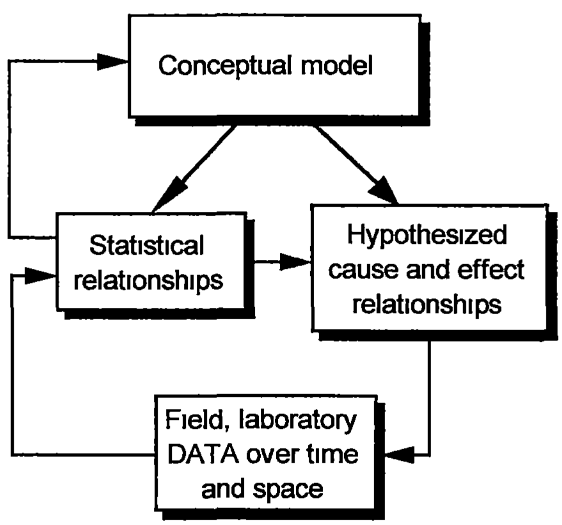


Figure 5 2 Linkages among system attributes that the conceptual foundation identified as "essential" to monitor This figure may be moved to conceptual foundation chapter



Feedback control (adaptive) system

Figure 5 3 Feedback control system linking the conceptual foundation, monitoring and modeling efforts

5.5 Defining and Evaluating Modeling Strategies

Modeling efforts of the GEM program for the short term will be developed as part of a long-term strategy defined by goals of the GEM program

To begin with, the modeling strategy must be consistent with GEM programmatic goals (Chapter 1, Volume I) They can be summarized to indicate that GEM modeling should accomplish the following

- Focus on filling gaps, thus avoiding duplication of efforts or "reinventing the wheel,"
- Emphasize synthesis,
- Depend as much as possible on already existing programs,
- Maintain focus on the key questions, and
- Emphasize efficiency

In developing a specific management strategy, it is often useful to think of it as a decision framework (Keeney 1992), and to start by defining an ideal For example, to satisfy GEM program goals efficiently, an ideal model would arguably require input data that are relatively easy to measure, readily available, and reliable indicators of change The cause-effect theory that drives the modeled system or species behavior would be based not only on statistically valid correlative studies, but also on plausible and well-developed mechanistic studies and their resulting theoretical constructs The model would produce credible predictions under plausible scenarios, and would help answer questions and raise new ones

This ideal model would be easy for other scientists and managers to comprehend, and it would be readily available for others to deconstruct, test, and critique The overarching conceptual model would be modularized so that components of it could be developed and tested relatively quickly by experts from multiple disciplines Ideally, data already available could be used to test and validate the components and their interactions, and could allow quick learning that could be used to redirect the modeling and monitoring strategies Sensitivity analysis of the components, and the interactions between the components, would be a highly productive source for subsequent model and monitoring plan development Model structure would be flexible and have robust mechanisms for assimilating new data and revising model structure As a result, short-term progress toward the long-term goals could be achieved and documented

A modeling strategy is the roadmap that provides the means for achieving the ultimate modeling goals An idealized model like the one described above is a useful step toward defining the attributes of an efficient, workable strategy Development of such an idealized model can produce a useful communication tool Table 5 2 identifies preliminary objectives and attributes derived from this idealized model that could be used to evaluate modeling strategies

Table 5 2 Potential Objectives and Attributes for Use in Evaluation of Modeling Strategies

Objective or Attribute	Supported by models that help
Relevance to key questions and hypotheses of the GEM program	Identify key variables and relationships Characterize uncertainty and noise impacts of process and observation error Elucidate general principles rather than narrow unique focus driven by short-term perceived crisis
Contribution to future model development	Inform communicate develop common problem definitions Set priorities clarify relative impacts of variables and relationships Improve and develop experimental (monitoring) designs Prioritize and elucidate impacts of uncertainties in data and in model structure and assumptions Increase utility of using simpler models to identify key variables and relationships to use in future models Advance the state of the art for example increase available methodologies by borrowing from other fields, particularly engineering and medicine tools such as neural nets genetic algorithms CARTs other kinds of regression (Jackson et al 2001)
Efficiency of approach	Synthesize exploit and integrate existing data and existing programs whenever possible for example from oceanographic programs such as NOAA OCSEAP GLOBEC and GOOS Identify and exploit uniqueness of GEM program opportunity for example no one else is doing it because it requires a very long time frame Elucidate links between things that are easy to measure and key indicators of change whatever they might be Elucidate links between correlations (which are usually easier to develop) and explanatory mechanisms (which are usually more difficult)
Maintenance and development of program support	Accessibility of models to end users other modelers Contribution to data management data assimilation effort Contribution to solving problems for resource managers and regulators

5.6 Modeling Methods

The modeling "niche" of the GEM program will be defined in part by a gap analysis, particularly focused on where it fits with established major regional programs, especially those of GLOBEC, GOOS, and PICES A very brief summary of the modeling approaches for these programs is provided in Section 5 2 of this chapter

The relationship between monitoring, models, and decision-making described here is consistent with the relationships of these programs The purpose of this section is not to define all the other modeling efforts that might be related to the GEM program A useful context is provided by a table compiled for GLOBEC by Aydin of NOAA (Seattle), which summarizes North Pacific models of the Alaska

Fisheries Science Center and others (see Section 5 2, Table 5 1, and North Pacific models in Appendix B) Correctly defining the GEM program niche is important to avoid duplication of effort and to make best use of work already being done by others

Developing a model should be perfectly analogous to designing a controlled experiment A useful model structure will be driven by the questions it needs to help people answer, not by the computer technology and programming expertise of model developers (although technology and expertise may impose constraints) As a general rule, useful models do not tend to be complex, in part because they must be comprehensible to be believed and used by decision makers That said, models based on laws of physics, which can be validated against those laws and either data or scale physical models, have advanced farther than ecological models in their ability to provide useful output from highly complex models

5 6 1 Linkages Among Models and Among Modelers

One of the most important challenges confronting GEM modelers will be to develop common languages and modeling frameworks that will allow them to resolve the temporal, mathematical, ecological, physical, and spatial sources of disconnects among the various academic paradigms This challenge will require significant commitment to improving communication skills, developing qualitative verbal or visual models, and using intuitive problem-structuring tools that combine different modeling techniques, such as network, systems, or loop models An additional benefit of this kind of approach is that these types of visual, qualitative models should be comprehensible to researchers from any scientific discipline, managers, and the public The attribute of being widely comprehensible will help facilitate the support of stakeholders

The feasibility of managing GEM as a realization of the conceptual foundation will depend in large part on the communication skills of experts in the components and linkages that make up the conceptual foundation Establishing effective communication among experts from different organizations is a widespread problem facing systems modelers (Caddy 1995), and the GEM program may be in a good position to help advance the cause by making it possible for diverse experts to work together Experts in these fields should bring substantial background capabilities to their work from their common language of mathematics and science learned in graduate school The modelers of the GEM program also should be required to demonstrate the ability to work with counterparts to develop a shared systems view and conceptual models

5.6 2 Deterministic Versus Stochastic Models

Detecting and understanding change requires that uncertainty and variability play a central role in the analyses (Ralls and Taylor 2000)

Two key questions that must be addressed by anyone trying to detect and understand change are the problems of Type I and Type II error Type I error is "seeing" something that is not really there, and Type II error is concluding something is not there, when it really is Dealing with these types of error in decision-making requires weighing the evidence that suspected change is caused by a (theoretically) definable pattern or trend or is "normal" process error, observation error, or some combination Equally important, and often overlooked, is how real indicators of change may be hidden by process or observation error or by incorrect assumptions about how things work

Dealing with uncertainty and variability in models requires at a minimum carrying out sensitivity analysis on simple deterministic models, with particular emphasis on model structure (Hilborn and Mangel 1997) But it is often more efficient and more useful to incorporate stochasticity into simple models Stochastic models need not necessarily be more data intensive than deterministic models Overlooking the assumptions required in choosing a mean (or median) or geometric mean, as a representative value for a deterministic parameter is one of the most widespread, but overlooked, sources of modeling error (Vose 2000) At least stochastic modeling requires that probability distributions be explicitly defined

Simplistic deterministic models can be every bit as misleading and improper as stochastic models (Schnute and Richards 2001), but because they are more familiar, and their single-number inputs and outputs are easier to think about than uncertainties and ranges, they may lead to false confidence on the part of decision makers Risk assessment in most fields requires analyzing probability distributions and uncertainties, not mean trajectories (Burgman et al 1993, Glickman and Gough 1990, Vose 2000)

One fundamental issue of interest to decision makers is often how best to prioritize research efforts A key part of such an issue is ranking the relative impacts of uncertainties on a decision In this case, it is possible that thoughtful sensitivity analysis carried out on a simple, deterministic model (or multiple models) may be adequate for the job, particularly as a first step in "weeding out" variables that are likely to be extraneous But developing a stochastic version of relatively simple models may be more efficient (Vose 2000) If care is taken to distinguish between environmental or process variation and observational or functional uncertainty, then statistical tools such as analysis of variance or regression can be used to investigate the relative impacts of uncertainties (Fahrig 1991, Law and Kelton 1991, Meyer et al 1986, Mode and Jacobson 1987a, Mode 1987b, Oosterhout 1998, Oosterhout 1996, Ruckelshaus et al 1997, Vose 2000) This approach can be very helpful in developing analytical structures as well as modeling plans It also lends itself well to decision analysis and risk assessment because it is similar to the "value of imperfect information" analyses widely used in risk assessment and decision analysis (Hilborn 1997, Keeney 1992, Punt and Hilborn 1997, von Winterfeldt and Edwards 1986)

5 6 3 Correlative Versus Mechanistic Models

The use of statistics-based tools such as regressions to make deterministic or probabilistic predictions will generally be easier than developing deterministic or stochastic biological models, because of a dearth of predictive "laws" of biology, let alone ecology Because statistics-based models are correlative, cause-and-effect explanations will eventually be needed if change is to be understood and predicted reliably Because some things are easier and more reliable to measure than others, simple models that can help develop correlative relationships between hard-to-measure parameters and easy-to-measure parameters may be of particular interest.

5.6.4 Modeling and Monitoring Interaction

Models should be developed to use and synthesize readily available data whenever possible This approach will also help identify data needs Similarly, whenever possible, monitoring plans should be developed to fit the models that will be used to analyze and interpret them Data management, assimilation, and synthesis should be key considerations for both monitoring and modeling

One useful way to incorporate data into improving an existing statistical or simulation model is with the Bayesian revision methods (Punt and Hilborn 1997, Hilborn 1997, Marmorek et al 1996) Bayesian methods might be useful to consider with respect to the question about how much emphasis should be put on annual forecasts, because Bayesian methods lend themselves well to incorporating incoming data into previous forecasts This entire approach also lends itself well to decision-analysis techniques

The GEM program shares the share the view of models as tools for assimilating data and optimizing data collection as expressed for the GOOS program (Intergovernmental Oceanographic Commission 2000, p 36)

> A validated assimilation model can be most useful in optimizing the design of the observing subsystem upon which it depends This underscores the mutual dependence of observing and modeling the ocean, i e , observations should not be conducted independently of modeling and vice versa For example the so-called "adjoint method" of assimilation can be used to gauge the sensitivity of model controls (e g , open boundary and initial conditions, mixing parameters) to the addition or deletion of observations at arbitrary locations within the model domain In this regard, Observation System Simulation Experiments (OSSEs) are becoming increasingly popular in oceanography as way of assessing various sampling strategies The model is first run with realistic forcing and model parameters The output is then subsampled at times and locations at which the observations were sampled These simulated observations are then assimilated into the model and the inferred field compared against the original field from which the "observations" were taken This allows the efficacy

of the assimilation scheme and sampling strategy to be evaluated (at least to the extent that the model is believed to be a reasonable representation of reality)

5 7 Evaluating Model Proposals

Model proposals should, of course, be evaluated within a decision-structured framework such as that outlined above and detailed in Table 5 2 Proposals must also demonstrate a high probability of actually producing what they propose to produce–meeting the objectives of the GEM modeling strategy A set of guidelines for evaluating model proposals will be developed for the GEM program in conjunction with development of the modeling objectives As a starting point, successful proposals will provide the following

- Define who will use the model and for what If the proposal is to continue or expand an existing model, it should describe who is currently using it and for what If relevant, the proposal should also identify who could be using it, for what, and why they are not able to use it now
- Define the questions the model is supposed to answer, and directly link those questions to the key questions and hypotheses of the GEM program
- Argue convincingly that the model structure is adequate for the purpose, and that there is not a better (cheaper, faster, more comprehensible, more direct) way to answer these questions
- Show some kind of schematic (flowchart) that is clear, complete, and concise
- Explain how uncertainty and variability will be represented and analyzed
- Describe the system characteristics that will be left out or simplified and how the analysis will evaluate the impacts
- Define data needs and show how the modeling effort will be coordinated with data assimilation and data management efforts
- Define validation approach
- Define how the modeling efforts will be communicated to other scientists, managers, and the public, and how input from model stakeholders will be incorporated into the effort, if appropriate

5.8 Conclusion

Feasibility and pragmatism in a new program like the GEM program dictate that walking will have to come before running and that focused, simpler models will have to come before large-scale, multi-disciplinary models Walking first means developing verbal and statistical models where numerical models cannot be developed because of a lack of data and understanding Learning to run requires developing coupled numerical biophysical models that accurately portray the ecosystem Running means using the biophysical models in a predictive sense The models must adapt to changes in the conceptual foundation (Chapter 4, Volume II), because the conceptual foundation is designed to change as new information is incorporated Nonetheless, no matter how many improvements are made, it is probably not reasonable to expect consensus on how that conceptual foundation should be used to develop a strategic modeling policy

In a constrained world, "consensus" in practice usually means accepting a strategy that enough decision makers find no more offensive than they can accept, optimization, on the other hand, means figuring out the tradeoffs necessary to achieve as many of the desired objectives as reasonably possible Adopting a decision-structured approach for the modeling strategy will help ensure that it is driven by the fundamental objectives of the GEM program, that the modeling questions are defined by the conceptual foundation, and the tradeoffs can be defined, weighed, and justified

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6. DATA MANAGEMENT AND INFORMATION TRANSFER

In This Chapter

- The role of data management
- The kinds of data to be used in GEM
- A description of GEM users and administrative support

Editorial note References GOOS document, a NASA document, and several Web sites The Web sites are included inline but may need to be moved to a bibliography

6.1 The Role of Data Management

The data management and information transfer component of GEM includes the following functions data receipt, quality control (QC), storage and maintenance, archiving and retrieval, and the systems necessary to automate as much of these procedures as possible This component also includes programs needed to create the custom data and information products that will be provided to the modeling and applications components, and to the users of this information Therefore, the data management system for GEM fits well into the definition established by C-GOOS (GOOS 2000)

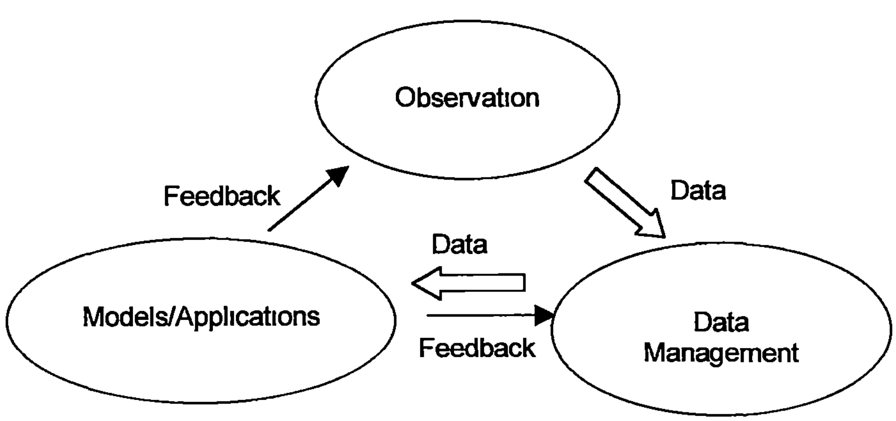

Figure 6 1 GOOS model of data management

The GOOS model is a general description of an end-to-end system that is based on the tripod of observation, data management, and models and applications, with the data management component acting as the intermediary between the observational component and the applications Data flows from observation through the management system to the modeling and applications component. In turn, the applications component informs and refines both the design of the observational component and the design of the data management system The monitoring plan may be altered to include new data, regions, or both that are identified during the modeling phase as key to understanding the natural system The interfaces and data products distributed by the data management system will also be refined with feedback from the applications

Scientific data management systems have grown rapidly since the advent of the World Wide Web Initially, projects or groups that collected or archived data made those available over the Web through simple interfaces based on the navigation of links These supply-oriented systems reflect the structure of the data that was made available by providing links to lists of data sets by years, data set name, or variable name Many of these systems are still in wide use, although newer systems include more sophisticated search options such as spatial and temporal selection However, these systems make few assumptions about the intended user community, and it becomes the users' responsibility to locate, evaluate, integrate, and pre-process the data into a form that is suitable for the target application

As the applications that use scientific data become more sophisticated, and the community is able to access and integrate large amounts of data to address a single problem, new data systems that address the data needs of specific user applications will be built The output of these systems will be higher-order products such as maps, graphs, visualizations, and data in interoperable formats NASA has funded some projects with a demand-oriented focus (ESIP NRA), and in the future, more user communities will find ways to build these types of targeted systems

The landscape of data product delivery will likely include large archives that supply data in a raw or partially pre-processed form Application-oriented sites will access data from these archive sites through a high bandwidth connection and may use intermediate sites, which provide value-added services that are not available from the originating archive Common data services available at the archive or through intermediate sites will include subsetting, reformatting, reprojection, regridding, and aggregation

Although predicting the evolution and the impact of the Web on scientific data delivery is speculative at best, the landscape of future data systems needs to be evaluated to understand the role of the data management component during the extended lifespan of GEM Initially, GEM will act as both a data archive and a user-focused delivery system, accepting and archiving data from the observational component and creating products that are customized to meet the needs of the habitat-specific applications During this phase, GEM will establish the procedures for assuring the quality of the data that are submitted to the archive as well as the operational details of ingesting data and making it available As the archive grows, older data sets will be moved to an archive such as the National Ocean Data Center (NODC) for permanent storage The GEM program will continue to maintain a meta-database that provides a data search interface to locate and access GEM data that is maintained by the originating project, the GEM archive, or the data archive at NODC

In the long term, however, the GEM program will likely turn over the entire archiving task to a center such as NODC that is better equipped to maintain the data for extended periods of time This transition is only possible after the data flow between the observational component and the applications component has been established and the tools and structures are in place to build the custom data products from a distributed set of data archives The GEM program will retain the meta-database and continue to provide custom data products and services to a set of targeted users

6.2 Characterizing the Data within GEM

Within the data management component, data is classified by the operations that must be applied to it during the archive and retrieval cycle This classification often cuts across the content-based classifications used during data analysis Although biologic data is more often collected by observation or laboratory work and physical data is frequently measured by instrument, there are significant exceptions A satellite image of ocean color that contains biologic variables will have more in common, in a data management context, with the physical variables in a Synthetic Aperture Radar image than to the phytoplankton results collected from the settled volume of a bottle sample The settled volume could include both physical and biologic results, but be retained by the data management system as a single data holding The meta-data and processing that are associated with the chemical and biologic data from the bottle sample will be nearly identical, as will the processing and meta-data associated with both types of satellite imagery

GEM will be collecting and processing a wide range of data from different collection and recording techniques that present different quality control and assurance challenges To classify these differences for the data management component, data can be separated into broad categories that reflect the handling and storage requirements These data categories include

- **Observational** data collected or recorded by an individual,
- **Measured** data collected by an instrument and stored in formatted files,
- **Modeled** data generated by a running computer model,
- **Geographic** or reference data used by a Geographic Information System, and

- **Remotely sensed** image data taken from a satellite or aerial platform

The following criteria are used to characterize these data types

- **Interoperability** how easily the data can be used in alternate applications,
- **Consistency** the degree of similarity between the data for different points,
- **Size of file** the size of the data for a single instance,
- **Number of files** the number of instances that make up the data set
- **Repeatability** whether or not the same data can be re-sampled,
- **Lag time** the length of time needed between collection and submission,
- **Alternative sources** whether the data is maintained at multiple sites, and
- **Meta-data** The content, format, or both of the meta-data

6 2 1 Observational Data

Observational data are collected by human observation, laboratory results, and manual data entry These data include species counts and locations and can include a large number of ad hoc observations of conditions or unrelated sightings These data are manually entered and capture a person's observations or calculations, which makes them less consistent, often complex, generally low volume, and occasionally error prone The observations are not repeatable and the formats are not customarily interoperable The lag time between collection and submission can be long if extensive lab or manual work is involved The meta-data describe the collection and or processing location and sometimes the conditions These data are often in a database management system (DBMS) or a spreadsheet, which forces a level of consistency that allows automated processing upon retrieval Examples of observational data sets from the GEM habitat themes (see Chapter 5, Volume I) include

Wetlands

- Lab results for stream chemistry
- Plant and animal observations from field study
- Isotopes of nitrogen and levels of phosphorus, silicon, and iron from a lab

Intertidal and Subtidal

- Species counts for substrate classification
- Lab results for chemical and biological oceanography

Alaska Coastal Current

- Lab results for chemical and biological oceanography

- Species counts for zooplankton
- Diet composition for nekton
- Nekton measurements from net tows
- Bird surveys

OCS/Alaska Gyre

- Lab results for chemical and biological oceanography
- Species counts for zooplankton
- Bird and mammal surveys

6 2 2 Measured Data

These data are mostly measurements of physical variables such as air temperature or salinity, but they may also include biologic variables as in the case of the acoustic measurements of the biomass of nekton or zooplankton These data are usually stored in files with formats that are set by the collection instrument The data files are consistent across the data set, but have a low level of interoperability with other systems Because data collection is automated, the size of the files and the number of the files can be large Usually, little special processing is involved, therefore, the lag time between collection and submission does not need to be long The meta-data include instrument details and conditions, and the data formats are standard enough to allow customized processing during retrieval Examples from the GEM habitat themes include

Intertidal and Subtidal

- Physical oceanographic variables

Alaska Coastal Current

- Lidar measurements
- Hydroacoustic plankton or nekton surveys
- Fluorescence measurements

OCS/Alaska Gyre

- Physical oceanography
- Hydro-acoustic plankton or nekton surveys
- Fluorescence measurements

6 2 3 Modeled Data

Numeric models, and to some degree statistical models, can generate a significant amount of data As an example, the circulation model can provide a snapshot of ocean current vectors across the GEM region, at many depths, for time steps as small as 10 minutes. Other models produce smaller result sets, but often these results are used by other models as input and must be cataloged and delivered by the data management component. However, unlike most other data sets, these data can be recreated and often are as the model matures. These data are consistent across the data set, can represent a high volume of data, and are not generally interoperable. The lag time between data generation and data submission (and even use) can be very short. The meta-data need to describe the classification and version of the model and may need to include relevant input parameters. The meta-data may be used to track the lineage of the output data, including the references to the input data and, if relevant, the models that created those input data. The modeled output data for GEM is not yet defined.

6.2.4 Geographic Data

These data are the reference data used by Geographic Information Systems (GISs) and include base layers such as elevation (bathymetry) and shorelines, but can also include soil types or habitat characterization. These data formats are rarely used to store data collected by a project, but are frequently used to display the information in the spatial context of a map. These data are usually interoperable across different systems and may be stored at several different locations. The meta-data are focused on the spatial definition and may include information about the resolution or precision of the data. GEM will not generally be ingesting these data from projects, but the program may store reference information in this format, which is also a prime format for custom data products created by the data management component.

6.2.5 Remotely Sensed Data

Remotely sensed imagery can come from satellite or aerial platforms. These are generally large files and may be used on a regular basis by the analysis being conducted by GEM. However, images from NASA or NOAA may not need to be archived if they can be retrieved again from the source. Aerial photography has also been used by EVOS projects to capture the spatial distribution of nekton in PWS. These images, along with satellite images, may in some cases be archived by the GEM program and provided to the application component. These data will require a large amount of storage and are quite interoperable with GIS and image-analysis tools. The meta-data describe the instrument and platform and often include details of the image quality and the spatial reference system. Examples in the GEM habitat themes could include:

Wetlands

- LandSat images of watersheds
- Moderate Resolution Imaging Spectroradiometer (MODIS) imagery
- Aerial photography

Intertidal and Subtidal

- Ocean color imagery from SeaWiFS
- Aerial photography

Alaska Coastal Current

- Ocean color imagery from SeaWiFS
- MODIS ocean products

OCS/Alaska Gyre

- Ocean color imagery from SeaWiFS
- MODIS ocean products

6.2.6 Impact on GEM

Although the data standards set by the GEM program will be similar across the data sets in a given type, each data set will have its own set of standards and QC and ingest processing As the GEM data management component becomes active, new data sets will be added to the archive For each new data set, GEM will set data standards and create the software to perform the QC against those standards The data management plan will outline what needs to be in place before a new data set can be added to the GEM archive

As each collection effort is funded and organized, a plan that outlines the data inventory and its submission schedule will be established In addition, the plan will include the procedures for performing the QC process and how discrepancies will be resolved

6.3 Characterizing the GEM User Community

During its lifetime, the GEM program will serve a large and diverse user community with needs that will vary from simple data download to the creation of tailored data and information products In most cases meeting the requirements of particular user groups will require detailed analysis and the creation of tailored products, but generalizations can be made about the types of applications for which GEM will provide data

The user groups interested in each application will have different levels of data analysis and reduction capabilities, and each will need to search for GEM data with different criteria Some applications require regular or periodic access to GEM data, and others are irregular or sporadic The largest discriminator between the applications, however, is the type of data products that GEM will create for them and the level of processing that will go into creating those products The following applications are relevant for all four of the main GEM habitat themes watersheds, intertidal and subtidal, ACC, and the Alaska gyre

1 Basic research and analysis is perhaps the most fundamental application of GEM data This activity will be done by researchers who are collecting data for GEM and by other researchers that are investigating the GEM region In general, this community will have a good understanding of GEM data and will be searching for specific variables within a region of interest Access is less likely to be irregular, but research applications expect access to data as soon as it can be made available, therefore, filet transfer protocol (ftp) or file-download of the original data will generally be sufficient

2 Modeling is also a critical application of GEM data Verbal and visual models will be drawn from research applications, but statistical and numeric models will require access to customized data products that are tailored to meet the needs of the model as closely as possible Most of the search criteria may be saved by the system and may be reused on a regular basis to execute the model with the most recent set of parameters The types of preprocessing could include reformatting, spatial or temporal aggregation, regridding, and reprojection

3 Resource management applications will increase in number through time and may become a common use of GEM data These applications will require a set of products separate from the modeling applications Management applications will be both periodic and sporadic, and the products may include reports, graphs, or maps Examples include regular stock analysis reports that are used by fisheries managers to set catch limits and or irregular access to watershed data that would be relevant to permit requests

4 Public outreach encompasses several different applications that GEM will be supporting to varying degrees These include providing public information about the state of the ecosystems that are being studied by GEM, as well as the general administration of the GEM program Other outreach activities will include supporting educational programs and possibly emergency response These applications can be supported with maps and graphs that describe various aspects of the central GEM themes Access is likely to be quite irregular and may be accomplished through the creation of a few standard maps and graphs on a regular basis

6.3.1 Supporting GEM Applications with User Interfaces

To support these applications, GEM will initially provide three different modes of access The initial design will include basic search and download, tailored product creation and display, and open map access For the most part, basic search and download will support research applications, tailored products will be used by both modeling and management applications, and open map access will support public outreach applications Together these three modes of access characterize many of the scientific data delivery systems available on the Web

Basic search and download is currently the most common method of accessing data on the Web Many projects have an interface that makes some level of search available and then allows data to be downloaded by clicking through to an ftp site or a Web page containing data links Examples include the following

- CIIMMS (http //info dec state ak us/ciimms/), which has been used successfully to provide basic access to meta-data and data relating to Cook Inlet,
- Systems such as GLIMPSE (http //lternet edu/data/), EMAP (http //www epa gov/emap/index html), and Beija-flor (http //beija-flor ornl gov/lba/), which provide basic access for the NSF Long Term Ecological Research program, the EPA Environmental Monitoring and Assessment Program, and the Large Scale Biosphere-Atmosphere Experiment in Amazonia sponsored in part by NASA, and
- The GLOBEC program, which provides basic data download through its own database (http //globec whoi edu/globec-dir/data-access html)

Although these systems provide different types of search criteria, and each has a different orientation, they all provide access to meta-data and, in most cases, the actual data collected by the program The GEM program can use one of these systems or something very similar to provide access to data soon after it is submitted to GEM Research applications are often focused on specific variables and regions,, and these basic systems meet the majority of those needs In addition, a basic search-and-download tool will provide the minimum access to GEM data and may support the other applications, including modeling, resource management, and public outreach Although budgetary constraints may require that the creation of custom map and data products be limited, the basic search-and-download functions will be supported as long as data is collected and archived by the GEM program

The meta-database maintained to support the basic search-and-download functions would also support access to remote database services that are funded by or relevant to GEM Remote databases like the EVOS hydrocarbon database and other databases maintained by the group that is conducting the data collection effort will be included in the GEM meta-database for searching purposes The data will then be available through the remote Web site set up to support those data

Map creation systems such as the Open GIS Consortium's Web Mapping Server (WMS) (http //www opengis org/techno/specs/01-047r2 pdf) and the ArcIMS system (http //www esri com/software/arcims/index html) from the Environmental Systems Research Institute (ESRI) make preprocessed maps available to users on the Web Both of these systems provide maps to Web browsers and to freely available viewers Because the WMS protocol is not tied to any particular vendor, it has been enjoying rapid acceptance and use in a wide range of applications In the future, the use of WMS in educational and outreach applications is likely to be very large

Once GEM has identified a set of standard map products that would be useful to the public or to particular educational programs, they will be available through one of these Internet map protocols These products will likely include base maps and general information maps, but might also include regular maps of the Alaska gyre or currents that affect the GEM habitats Web sites designed to support the educational program or the public interests will display these maps and may, in time, support more complicated map viewers that can access and overlay maps from other sites that are relevant to the goal of the Web site

Data products tailored to specific modeling and resource management applications will be the most useful facet of the GEM data distribution and also the most expensive to create It is not possible to create a single data distribution system that meets the wide range of user needs in modeling and resource management. Therefore, GEM will need to prioritize the products that are needed by particular groups and create them in sequence These products will be designed with the close involvement of the specific user community to which they are targeted and, initially, they may need to be created with a significant amount of manual effort. However, once automated, a separate Web-based interface that will be used by the target user group to create and download these products on a regular (or irregular) basis can be created In the future, after many of these products have been designed and the distribution of them automated, certain common functions will emerge and GEM will begin to build a library of data-processing utilities

Examples of modeling products include the reformatting and regridding of data to match the execution grid and time steps of the model Non-GEM data may be pulled from another site and integrated into data products Several different products may be generated at a time to meet the needs of a single modeling application The creation of a suite of products may be done by hand and may require that GEM start with algorithms that were written by the modeling group itself However, after the modeling group has used the products successfully several times, the process of creating the products could be automated and a simple interface built to allow the group to create and download the product If the requirements for the product are clear enough, the manual step may be bypassed

For resource management applications, a report or spreadsheet used to manage fish stocks may require access to several different data sets and the extraction and integration of different variables Unless the report is already in existence, it may require several attempts before a truly useful product can be created Once this is accomplished, the process could be automated The resource management office could trigger the report through a simple interface created for that product In this way, the application component of GEM will feedback information and tailor the design of the data management component.

In time, GEM will create a wide range of products to meet the specific needs of the GEM modeling and resource management communities The creation of each product will involve GEM staff and the interaction with the target user group Depending on the scope of the effort for each product, several tailored products could be created for the modeling and resource management community each year These products, coupled with the basic search and download and the Web-based map delivery services, will support a wide range of both specific and general data distribution needs

6 4 The Structure of the GEM Data System

The GEM data management system will address the issues related to the data types supplied by the observational component and the demand placed by the applications component As such, the data management system is positioned between the other two components and must develop and maintain an interface to both In addition, modeling and map creation applications will generate new data that will also be archived and delivered by the GEM data system

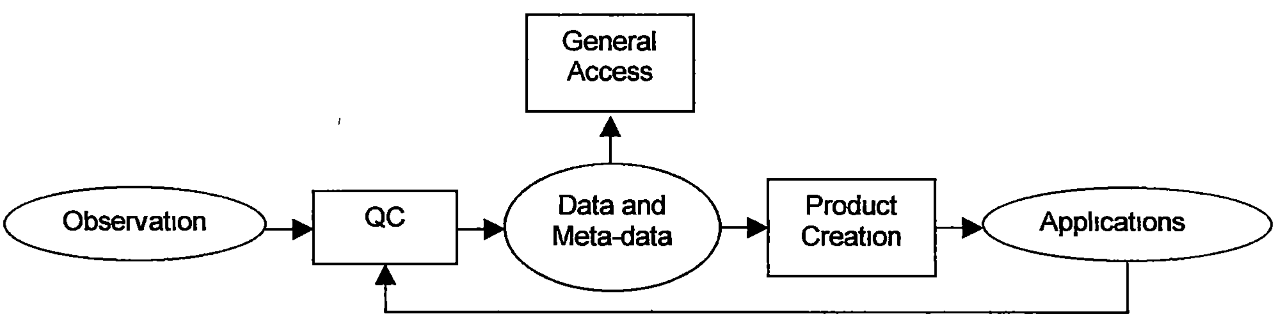

Figure 6 2 The GEM data system

6 4 1 Supply Side Support

To support the ingestion of data from the observational component of the GEM program, the data management system must provide QC of the meta-data (and to some degree the data) and quality assurance of the data and the meta-data Quality control will ensure that the meta-data comply with GEM standards and that valid values are supplied in formats that can be used to store that data in the GEM archive Values such as station identifier, date, and latitude and longitude need to be valid or fall within a reasonable range In general, each data type will have unique issues, and the GEM program will create new QC procedures and programs Through time however, some of the QC algorithms can be shared across data types The GEM program will also need to provide QC on some of the data values, such as species identification, but the submitter will do most of the QC for the data itself The validation provided by the data management component is done to ensure that data can be found and retrieved with the use of an accepted set of search criteria

Quality assurance includes the design of the QC processes and documentation of the QC activity The data management component of GEM will not be able to provide QC over most of the data, but it can ensure that the documentation of the submitters' QC is available along with the data The data management system will also provide quality assurance of the meta-data

6 4 2 Demand Side Support

On the applications side of the data management system, software modules will create the custom data products and standard maps These routines will not be developed all at once when the system is deployed, but through time, as the archive is populated with data and the user demands become clear Custom routines will integrate third-party software where possible These external routines may be commercial off the shelf (COTS) software or they may come from the growing library of free software available on the Web These custom routines will pull data sets from the GEM archive and other relevant data sources and provide preprocessing Examples of the types of operations include

- **Reformatting** Often, raw data may need to be reorganized to be usable by an application For example, an application may need multiple observations pulled into a single output file containing only those variables of interest from a subset of stations This file may also need to be ordered by date or species and written out in a comma-separated file that can be manipulated by a spreadsheet Other output formats may include GIS, image analysis formats or special binary formats for visualization applications

- **Aggregation or subsetting·** Modeling applications often need summary or averaged data These data sets may need to be merged or clipped to capture the temporal or spatial region of interest completely Some file formats support clipping, but many of these routines will be tailored to the input data Aggregation routines may come from the application space or they may simple average or sum calculations

- **Projection** Data are usually collected with latitude and longitude coordinates Some regional models use a map projection that preserves spatial relationships more accurately for the region Satellite data and other data may need to be projected or reprojected into a specific map projection for the application Software is available to perform some of these reprojection operations from both commercial and freeware sources

- **Map creation and visualization** Some data products may be best represented in the spatial context of a map or a graph The generation of these maps or the creation of a multidimensional or graph-oriented visualization requires data-extraction reduction and rendering Many software utilities are available to assist in this process

Most custom data products will require a user interface to allow the entry of parameters and trigger the creation of the product In most cases, these interfaces will be simple Web pages that support various pull-down menus to select input or display parameters Simple interfaces that are designed to support one or two data products are easier to use and maintain Through time, however, GEM will support a large number of custom products, and interfaces may need to be merged to reduce the overall maintenance load

6.4.3 Meta-Database Support

The core of the data system will be the meta-database and a data-storage component. The meta-database contains the descriptive information and is used to integrate access to the data by supporting cross-data set searching The ability to search for all data sets within a given spatial or temporal range, or all data sets containing particular variables, requires a single meta-database The QC routines will ensure that the meta-data submitted to the GEM program meets the standards necessary to support cross-data set search No data set will be added to the system unless it can be located with a search of this meta-database

The meta-database maintained by the GEM program will also support access to remote GEM archives that are maintained by individual researchers The GEM program will also evaluate whether to ingest meta-data about data sets that are relevant to the GEM system, but are not directly supported by GEM The ongoing gap analysis conducted by the GEM program will continue to reveal data sets and data-collection activities that complement the GEM mission One of the GEM goals is to integrate with those projects The data management system will reflect this integration by allowing users to locate relevant data that may not be archived by the GEM program

Most search and download systems include some level of meta-database support. The GEM program will evaluate the use of these existing systems, including the structure of the meta-database Because the population and use of the meta-database will be the central activity of the GEM data system, any existing system will need to be modified before it is used by GEM

6 4 4 Data Storage

The storage of the data in files or in another storage mechanism is a separate function of the data system that in time will require a significant amount of storage space The meta-database will contain pointers to the data itself, which may physically be in a separate storage facility The evolution of large archive technology has been rapid in the last few years, but GEM will be able to postpone the use of tape or optical media for several years until the space requirements demand it. The GEM program will evaluate the use of an external site to store the data as well as the use of GEM computing hardware Unlike the search of the meta-database that places a heavy computational burden on resources while returning a small amount of data, accessing the data itself requires no significant computation, but can return a large amount of data Therefore, the network connectivity is also an evaluation criterion for the data storage subsystem

The format of the data files will be defined and standardized in the GEM data management plan Although the QC procedures will not validate the scientific quality of the data, these programs will need to validate the format of the data Routines for creating data product require that input data files are in a recognizable format and contain data in a format that can be processed automatically

6 4 5 GEM Administrative Support

Managing the projects funded by and associated with GEM requires a project-oriented database (see Chapter 6, Volume I) The administrative information includes the original proposal, comments submitted by the review panel, status reports and notes, and the final report. This information will be valuable in the long term as the data collected by the project is evaluated in retrospect. The proposals and reports will contain the original hypotheses, as well as the problems that were encountered during data collection Future researchers will use this project history to understand the original goals of the project and issues that might affect data quality

Much of these administrative data a\is in the public record and will be made available over the Web The GEM meta-database will include the project specifications so that the data submitted by the project can be displayed along with the administrative details This link between the administration of the project and the data submitted would also allow the GEM program to evaluate whether all the data for a given project have been submitted