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.

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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 question
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 Acronyms and Web Links	
B	Appendix B Fish and Invertebrate Species from 1996 Trawl Survey of the Gulf of Alaska	
C	Appendix C North Pacific Models of the Alaska Fisheries Science Center and Selected Other Organizations	
D	Appendix D Gulf Ecosystem Monitoring and Research (GEM) Database	
E	Appendix E Glossary of Existing Agency Programs and Projects	

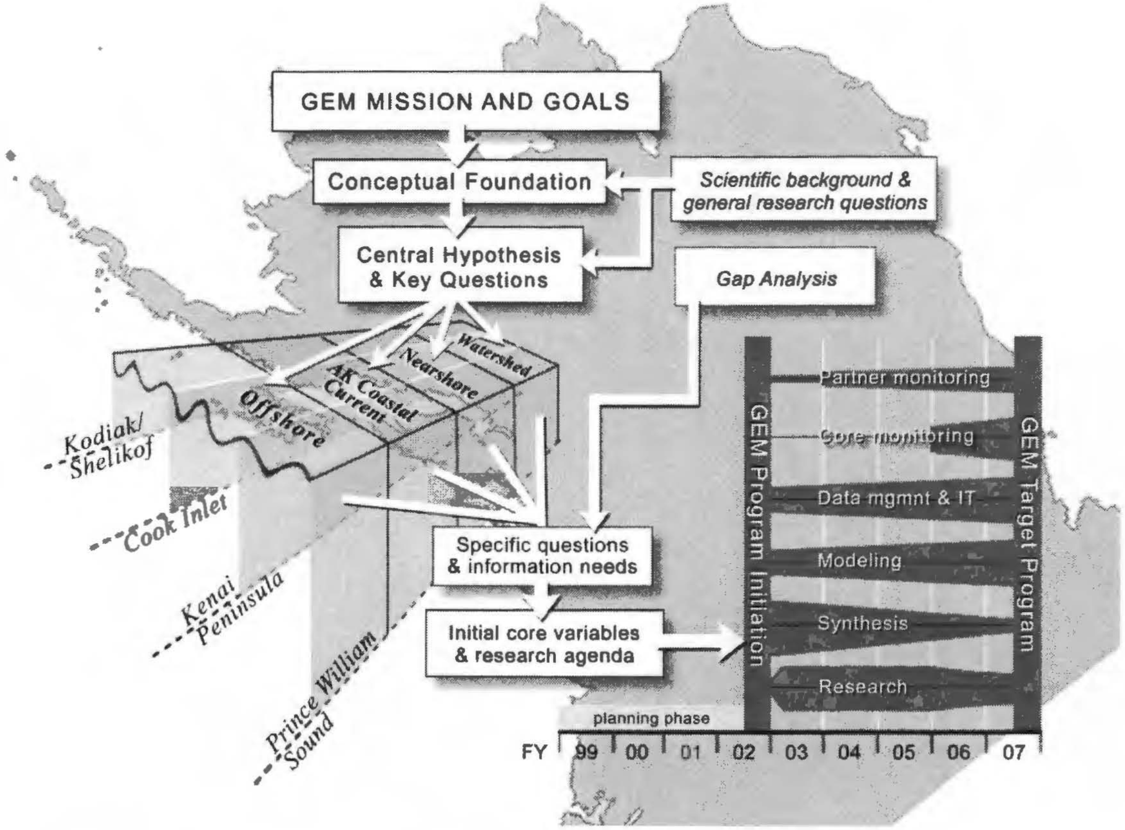

Figure O.1. An overview of the structure of the GEM Program Document showing the relation of key concepts to the habitat types and the schedule of implementation

CONTENTS

Figures

Tables

Appendices

1. BUILDING ON THE LESSONS OF THE PAST

In This Chapter

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

The Gulf Ecosystem Monitoring (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 Gulf of Alaska (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 eiders, Steller's eiders, 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 impacts lead 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, diversity, and productivity of marine populations The program focuses on the regulatory control of zooplankton dynamics on the biomass of many fish and shellfish

The GLOBEC Science Plan (U S GLOBEC 1997) describes an approach that uses a combination of field observations and modeling to concentrate on the middle and upper trophic levels of the ecosystem The GLOBEC goal is as follows "To advance our understanding of the structure and functioning of the global ocean ecosystem, its major subsystems, and its response to physical forcing so that a capability can be developed to forecast the responses of the marine ecosystem to global change "

The overarching concept is that marine and terrestrial ecosystems have close connections among energy flow, chemical cycling, and food web structure GEM monitoring activities will be consistent with these additional GLOBEC concepts

- Changes in abundances of birds, fish, shellfish, and mammals (higher trophic levels) usually reflect changes in physical and chemical processes,
- The actual effects on abundances of higher trophic level animals may depend on how these physical and chemical changes act on food production through effects on lower trophic level species,
- Changes in the dominant species at each trophic level are consistent with changes in the physical and chemical systems, and
- Understanding how the dominant species at each trophic level change through time requires knowledge of the energy and nutrient budgets of the ecosystem

1.4 Scientific Legacy of the *Exxon Valdez* Oil Spill (1989 to 2002)

Ecological knowledge gained in the years following the 1989 *Exxon Valdez* Oil Spill (EVOS) forms a substantial portion of the foundation of the GEM program The recovery status of each affected resource is based to the extent possible on knowledge of the resource's role in the ecosystem The scientific legacy of the *Exxon Valdez* Oil Spill Trustee Council (Trustee Council) creates the need to understand the causes of population trends in individual species of plants and animals through time and the need to distinguish human impacts from those of climate and interactions with related species

The studies supported by the Trustee Council since 1989 include more than 1,60 damage assessment studies costing more than $100 million, as well as hundreds of restoration studies costing approximately $170 million These studies have resulted in more than 400 peer-reviewed scientific publications, including numerous dissertations and theses In addition, hundreds of peer-reviewed project reports are available through the Alaska Resources Library and Information Services (ARLIS) and state and university library systems Many final reports are available in electronic format through the Trustee Council offices 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 and understanding stock structure

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 and settlement
- Status of injured resources and services
- Concerns with lingering oil effects

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 as of March 1999. More detail as of March 2001 are provided below.

2.1 Status of Recovery

Not Recovering

Eight species continue to be listed as not recovering: common loons, cormorants (pelagic, double-crested, and red-faced), harbor seals, harlequin ducks, killer whales (AB pod), and pigeon guillemots. The factors affecting their recovery status vary or are unknown.

Common Loon. Loons are long-lived, are slow-reproducing, and have small populations. Common loons in the spill area may number only a few thousand, including only hundreds in Prince William Sound (PWS). Yet carcasses of 395 loons were recovered following the spill, including at least 216 common loons. Boat surveys in the sound show no recovery through 2000.

Cormorant. Cormorants are large fish-eating birds that spend much of their time on the water or perched on nearby rocks. Three species typically are found within the oil-spill area: pelagic, double-crested, and red-faced. Post-spill counts showed significant declines in the estimated numbers of cormorants (all three

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

species combined) in PWS when compared to pre-spill populations Boat surveys in the sound show no recovery through 2000

Harbor Seal. Harbor seal populations in PWS and the GOA have declined by 80 percent in the last 20 years The declines may be related to environmental changes occurring since the late 1970s, but this is unclear The oil spill killed an estimated 300 seals, resulting in a 1-year drop of 43 percent in oiled areas of the sound The decline has continued at an average rate of about 3 3 percent from 1990 to 1999

Harlequin Duck. Harlequin ducks feed in intertidal and shallow subtidal habitats where most of the spilled oil was initially stranded Three years of data on overwintering adult female harlequins indicate significantly lower survival rates in oiled versus unoiled parts of the sound Researchers continue to view continued hydrocarbon exposure as a potential contributing factor to their lack of recovery

Killer Whale. The AB pod of killer whales, which lost 13 of 36 members in the 2 years following the oil spill, has yet to regain its former size, even though the overall size of the GOA population has increased since the spill The pod lost several adult females and juveniles, and it is expected to take many years for natural reproduction to make up for those losses The pod has increased by two members since 1996

Pigeon Guillemot. The pigeon guillemot population in PWS had declined before the spill, and it is estimated that 10 to 15 percent of the spill-area population may have died following the spill Surveys in the sound show no evidence of a post-spill population increase through 1998

Recovered

At the other end of the recovery scale are bald eagles and river otters These species have been declared "recovered" because their populations now appear healthy

Bald Eagle. An estimated 6,000 bald eagles live year-round or seasonally in PWS Although an estimated 250 eagles died during the spill, the population rebounded quickly and the bald eagle was formally designated as recovered in 1996

River Otter. River otters feed in intertidal areas, making them vulnerable to spilled oil Studies from 1989 to 1991 identified differences in the biochemistry and behavior of river otters in oiled and unoiled areas River otters were listed as recovered in February 1999 after 2 years in which differences were no longer measurable

Recovering

Several resources appear to be making clear progress toward recovery, but have not yet met specific recovery objectives These include black oystercatchers, common murres, marbled murrelets, mussels, Pacific herring, pink salmon, sea otters, sockeye salmon, clams, and intertidal and subtidal communities

Black Oystercatcher. It is estimated that there are only about 15,000 black oystercatchers worldwide, about 10 percent of which summer in PWS They spend their entire lives in the intertidal area and are highly vulnerable to spilled oil Oystercatchers appear to be reoccupying and nesting at once-oiled sites, and there are no oil-related differences in the productivity of black oystercatchers and survival to fledging of their chicks

Common Murre. About three-quarters of all the bird carcasses found after the spill were murres, and the losses resulted in declines of as much as 40 percent in local common murre populations By 1997, common murre colonies had bounced back to near pre-spill population levels Though the 1997 El Niño brought a temporary setback for the murres, the murre populations appear to be recovered now at the Barren Islands Surveys at the Chiswell Islands will take place in 2001

Marbled Murrelet. The marbled murrelet is listed as a threatened species throughout the Pacific Northwest, but is relatively abundant in Alaska It is estimated that as much as 7 percent of the marbled murrelet population in the spill area was killed by the spill Marbled murrelets declined before the spill, losing 67 percent of their population in PWS since 1972 Murrelet numbers in winter increased after the spill and productivity appears to be within normal bounds

Mussel Beds To protect mussel beds and the many species they harbor from additional injury, the beds were not cleaned after the spill. Twelve years later, oil persists in some mussel beds in PWS, providing potential pathways of oil contamination for sea otters, river otters, black oystercatchers, and harlequin ducks.

Pacific Herring. Some Pacific herring spawning areas were contaminated by oil, resulting in increased egg mortalities and larval deformities. Although the significance of these initial injuries to long-term population levels has not been established, sharp declines in herring numbers after the spill and little recovery since are cause for concern. Pacific herring in PWS suffered a dramatic collapse in 1993. The commercial herring fishery in the sound was closed for four successive years, opening again in 1997 and 1998. In 1999, the herring population suffered another setback and the commercial season was again closed in 1999 and 2000. Although it is highly unlikely that Pacific herring continue to be affected by any residual oil in the spill area, full recovery to pre-spill population levels awaits recruitment of a major new year-class of fish.

Pink Salmon. Overall, pink salmon are recovering well from the effects of the oil spill. There had been recent concerns about the sensitivity of early life stages of pink salmon to very low localized concentrations of crude oil, and on this basis the Trustee Council listed the pink salmon as recovering from the effects of the oil spill in 1999, the last time the injured species list was fully evaluated.

Sea Otter. An estimated 13,000 sea otters currently populate PWS. It is clear that recovery is under way for sea otters, with the exception of local populations in the most heavily oiled bays on Knight Island. The lack of recovery at Knight Island may reflect the extended time required for population growth for a long-lived mammal with a low reproductive rate and slow dispersal rate, but it also could reflect the effects of continuing exposure to hydrocarbons or a combination of both factors.

Sockeye Salmon. Nearly all commercial salmon fishing was closed throughout the spill region in 1989, allowing many more sockeye spawners than desirable to enter some watersheds. This produced an unusually high abundance of juvenile sockeye that depleted the food resources of the nursery lakes. The result was an overall decline in growth of juveniles and reduced rates of adult returns to some areas. Although the rates of adult returns appear to be returning to normal, accounting for returns from some of the affected brood years has yet to be completed.

Intertidal and Subtidal Communities. Intertidal and subtidal communities are well on their way to recovery, but recovery has generally been lagging in the upper intertidal zone. Subtidal communities include such species as eelgrass, starfish, and helmet crabs that remain nearshore but underwater at all times. Intertidal communities include the flora and fauna that live between the low- and high-tide lines, such as clams, *Fucus*, barnacles, and chitons.

Recovery Unknown

For some species, not enough is known about their original injury, current populations, reproductive success, and overall health to make a judgment on their recovery Species for which recovery is unknown are cutthroat trout, Dolly Varden, Kittlitz's murrelets, and rockfish

Cutthroat Trout. PWS cutthroat trout populations are small and geographically isolated Cutthroat trout, therefore, are highly vulnerable to exploitation, habitat alteration, and pollution In 1989 and 1990, following the oil spill, cutthroat trout in a number of oiled streams grew more slowly than in unoiled streams However, studies have since found inherent differences in growth between the eastern and western sound, and a fairly high degree of overall variability in growth Current information is not sufficient to quantify the possible injury to cutthroat trout, and their recovery status is unknown

Dolly Varden. Dolly Varden had some of the highest hydrocarbon concentrations of any fish studied in 1989 There is evidence that Dolly Varden in a number of oiled streams grew more slowly than in unoiled streams in 1989 and 1990 The degree of exposure makes it likely that Dolly Varden were injured by the spill, but the lack of historical data prevents quantifying those injuries and their recovery status is unknown

Kittlitz's Murrelet Kittlitz's murrelets are found only in Alaska and portions of the Russian Far East It is estimated that more than 1,000 individuals died from the oil spill, which would represent a substantial fraction of the world population Very little is known about this species Small population, low reproductive success, and affinity to tidewater glaciers (some of which are receding rapidly) are reasons for concern about the long-term conservation of Kittlitz's murrelet

Rockfish Relatively little is known about the complex of rockfish populations in the northern GOA Some dead adult rockfish were recovered following the oil spill, and autopsies indicated oil ingestion as the cause of death In addition, closures of salmon fisheries apparently increased fishing pressure on rockfish However, the original injury from the spill is uncertain, as are any long-term effects

Human Services. The lives of the people who live, work, and play in the areas affected by the spill were completely disrupted in the spring and summer of 1989 Commercial fishing families did not fish Those people who traditionally subsist on the fish, wildlife, and plants of the region could no longer trust what they were eating and turned instead to high-priced groceries Recreational opportunities were mostly shut down and the worldwide image of an attractive and pristine PWS was tarnished with oil

Twelve years later, a sense of normalcy is returning to the spill region, but residents, fishers, and the tourism/recreation industry have not fully recovered

The Trustee Council determined that the "human services" of commercial fishing, subsistence, recreation/tourism, and passive use will have recovered when the injured resources on which they depend are once again healthy and productive Because that level of recovery has not been achieved, each of these services is considered to be recovering

2.2 Concerns about Lingering Effects

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 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

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.

During the next several years, studies of lingering oil spill injury and recovery will increasingly be incorporated into 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 indicated by information developed in the long-term studies

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

2.3 References

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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

Summary of the Scientific Background for the Northern Gulf of Alaska

Introduction

The cold and turbulent Gulf of Alaska (GOA) is one of the world's most productive ocean regions. It sustains immense populations of seabirds, marine mammals, and fishes, and provides a way of life for tens of thousands of Alaskans. Indeed, the gulf is still wild, full of life, and deserves protection and wise management as one of the bio-gems of the planet.

Just why the GOA is so unusually productive remains unclear. The fish, birds, and mammals at the top of the food chain are supported by a diverse marine food web, dependent on the physical characteristics of an ever-changing ocean—one that experiences seasonal, annual, and longer-period extremes in weather and climate. The plant nutrients come from deep water, fueling production at the base of the marine food web. This production is eventually expressed in the stock size and production of higher-level consumers. Somehow, physical conditions in this region promote sufficient exchange between deep and shallow waters to bring these fertilizing elements to the surface, where they stimulate plant growth each year. To understand the gulf's complex ecosystem, and the productivity of its species big and small, will require more precise knowledge about the interactions between many biological and physical factors.

Fortunately, recent studies provide a scientific framework for the region and suggest a direction for future long-term research and monitoring. In aggregate, this new knowledge on how selected species interact with prey, predators and competitors—and most importantly, how these associations are influenced by shifts in ocean climate and human activities—provides exciting new possibilities for understanding this great ecosystem. This knowledge will help resource managers sustain populations of these species despite growing human influence in the region (possible climate change and elevated pollution levels) and the pressure of increased human use (harvests, recreational impacts, and population).

This summary describes the northern GOA ecosystem as it is now understood, and reveals gaps in current knowledge about the dynamics of higher-level productivity (A reader seeking greater detail is referred to the text in the full Scientific Background)

The Principal Habitats and Living Resources

The extent of damage resulting from the massive oiling of Prince William Sound and the coastal waters to the west in the spring of 1989 will never be fully known In the short term, Gulf Ecosystem Monitoring (GEM) studies will focus on the spill-affected resources that remain at risk But the *Exxon* Valdez Oil Spill Trustee Council (Trustee Council) has decided to commit its long-term support to a program of broader ecological research and environmental monitoring The effort will center on the major physical and biological phenomena that influence marine productivity in the principal habitats of the northern GOA For purposes of the GEM program, these habitats have been identified as

- The coastal watersheds,
- The intertidal and shallow subtidal zones to a depth of 20 meters,
- The Alaska Coastal Current (ACC), and
- The offshore areas embracing the continental shelf break and beyond to the continental slope and deep ocean basin

In these interacting environments, scientists will seek to understand how the dominant fishes, seabirds, and marine mammals use their critical habitats to sustain their populations in the face of cycling ocean climate, commercial and subsistence harvests, and threats from pollution and diseases

The Watersheds

The extensive coastal watersheds that drain into the northern GOA represent spawning and rearing habitat for anadromous species like Pacific salmon and eulachon, and nesting habitat for some seabirds like marbled murrelets The carcasses of spawned-out salmon supply substantial amounts of marine-derived nutrients to the poorly nourished streams, lakes, and rivers used for their reproduction In addition, dying salmon provide a food supply for many birds and mammals throughout the coastal range Bears, eagles and many gulls benefit locally from this extensive forage resource Analyses have also shown that marine-derived nitrogen from anadromous fishes leaves a detectable signal in many coastal plant communities

The human harvest of anadromous species may affect not only those species, but also all of the plants and animals touched by marine nutrients Therefore, understanding the distribution of marine nutrients by anadromous fish species puts a new dimension on fisheries management So, it is reasonable to ask to what extent human consumption of salmon effects the production of other plants and animals in the coastal watersheds. Moving beyond single-species management toward ecosystem-based management in coastal watersheds will require long-term monitoring of the flux of marine nutrients.

These same watersheds experience extensive human activity in addition to fishing. Large-scale logging and commercialization, including coastal settlements and towns, can alter or destroy some habitats. Expanding recreational activities in the coastal zone between Prince William Sound and Kodiak Island will also include additional land uses. Compared with other regions in North America, however, most watersheds in the periphery of the GOA are remote and relatively undisturbed.

The Intertidal and Subtidal

The intertidal and shallow subtidal habitats are represented by a variety of near-shore estuarine, fjord, and exposed coastal settings. These habitats range from precipitous and rocky, to gently sloping with muddy or sandy bottoms. The intertidal and shallow subtidal zones are among the most productive of marine habitats in the GOA. Here the annual growth of microalgae, seaweeds, and seagrasses supports many invertebrates that, in turn, are food for fishes, marine birds, and mammals. Guillemots and sea otters, for example, depend on the crabs, clams, and mussels, along with small benthic fishes, found in the intertidal and subtidal habitats. This specialized edge-zone habitat is also a nursery for juvenile pink and chum salmon, and juvenile Pacific herring for several months each year. Huge schools of spawning herring and capelin deposit their eggs in the shallows each spring. These mass spawnings induce a feeding frenzy that may last for a week or more. Gulls, kittiwakes, seals, sea lions, fishes, and a variety of large invertebrates gather to feed on the egg masses. The fish eggs are often eaten in huge numbers by shorebirds and other species that stop over in the region during the spring migration.

The intertidal and shallow subtidal zones may be at greatest risk to human activities. There is increasing use of vehicles, boats, and aircraft by recreationalists and sport fishermen to exploit these areas. In addition, floating pollutants and refuse, particularly plastic materials from the fishing industry, make landfall in the intertidal zone. Unlike the coastal watersheds that remain relatively unaltered at many locations, it is rare to walk the intertidal zone anywhere in the GOA and not see evidence of human activity. The degree to which these "footprints" result in environmental degradation is clear in the case of oil and toxic spills, but largely unknown for other pollution.

The Alaska Coastal Current

Hugging the inner third of the continental shelf, the ACC provides a sizeable and ecologically important transition zone between the shallow, nearshore communities and the huge outer-shelf and oceanic pelagic ecosystems. Fed by runoff from glaciers, snowmelt, and rainfall, the well-defined coastal current is a near-shore "river in the sea" with a freshwater output about one and a half times that of the Mississippi River It flows consistently to the north and west around the northern GOA from British Columbia to Unimak Pass on the Aleutian Chain The ACC, urged along by coastal winds, distributes subarctic plankton communities around the region and into protected inside waters such as Prince William Sound and lower Cook Inlet During the summer months, the ACC has local reversals and small eddies, which can concentrate plankton and small fishes in convergence zones, for foraging fish, birds, and marine mammals

The ACC is an important feeding habitat for many fish, birds, and mammals Most seabirds nest in coastal colonies or on islands where protection from predators is afforded by the isolation of rocky cliffs Because of this nesting behavior, the distribution and abundance of seabirds during their reproductive season is governed primarily by the availability of suitable, safe nesting sites and access to adequate prey Seabirds in the GOA are often grouped on the basis of their foraging behavior Surface feeders like kittiwakes obtain prey mostly in the upper 1 meter (m), coastal divers such as guillemots and murrelets exploit the shallow water column and nearshore seabed, while murres are deep divers capable of feeding in the water or on the bottom to depths of 200 m Seabirds feed close to colonies when opportunities arise, but most are also capable of flying a long distance to feed It is not unusual for coastal seabirds to fly to the outer shelf and shelf-break regions to feed themselves and their offspring

Marine mammals residing in the ACC are primarily fish eaters, although a few feed on bottom-dwelling invertebrates and some hunt other marine mammals or even seabirds Killer whales are either resident (fish eaters primarily) or transient (feeding mostly on other marine mammals) Seals, sea lions, and sea otters bear and protect their offspring in coastal rookeries sprinkled around the edge of the GOA and influenced by the ACC Fur seals and sea lions exploit a broad array of nearshore and oceanic habitats, although the juveniles appear to be more confined to the waters near rookeries By comparison, sea otters and harbor seals are almost sedentary in habit, usually ranging only short distances for food Juvenile and adult harbor seals hunt and consume a variety of fishes, squids, and octopus in mostly coastal habitats While sea otters can retrieve food from depths to 100 m, they rarely leave the shallow coastal areas where they live as generalist predators on a broad array of sessile or slow-moving macro-invertebrates, including clams, mussels, crabs, sea urchins, and starfishes

Many fishes and shellfishes also live, feed, and reproduce in the ACC Coastal rockfishes, Pacific herring, juvenile and adult walleye pollock, juvenile and adult salmon, adult cod, and many species of shrimps and crabs occur in protected fjords, inlets, bays, and sounds where they forage and/or reproduce, and where their early life stages feed and grow Halibut and lingcod occur abundantly in some seasons, and king crabs that feed and grow in deeper shelf and slope environments visit the shallower inner shelf to reproduce each year Because the eggs and larvae of many marine invertebrates and fishes drift with the plankton for weeks or even months, the flow of the ACC serves to distribute these forms to the variety of coastal habitats found around the edge of the gulf.

The same coastal flow that benefits so many species may also serve to distribute marine pollutants. Oil spilled in the northeastern corner of Prince William Sound by the *Exxon Valdez* entered the coastal flow and was carried hundreds of miles to the west, fouling beaches along the outer Kenai Peninsula, in lower Cook Inlet, on Kodiak Island, and along the southern Alaska Peninsula. A future toxic spill in shelf or coastal waters southeast of Prince William Sound could conceivably be spread across the entire northern GOA by the coastal flow.

Offshore: Mid-shelf and Deeper Waters

Arrowtooth flounder, Pacific ocean perch, walleye pollock, Pacific halibut and Pacific cod (in descending order of importance) composed the bulk of the trawl-caught stock of ground fishes in shelf and continental slope environments of the GOA in 1996. These waters, which begin at the outer edge of the ACC—about 20 to 30 miles offshore—delineate a huge marine ecosystem. East of Prince William Sound, the shelf is narrow, so the mid-shelf and deeper waters are close to the coast, about 30 to 50 miles. South and west of the sound, the shelf broadens to 100 to 120 miles in width before narrowing again south of the Alaska Peninsula and Aleutian Islands. These differences in shelf width provide seabirds, seals, and sea lions at some coastal locations with easy access to the deepwater environments for feeding purposes when needed; at other sites, access to the shelf edge and open ocean is much farther away. Spatial differences of this kind may be important to recognize when comparing the reproductive successes of birds and mammals in rookeries from different locations in the gulf.

Because the Alaska Current has it southern origins in the oceanic Subarctic Current, marine pollution and floating refuse from as far away as Asia, or originating from deliberate deep-ocean dumping or accidents at sea, can be swept north and westward around the shelf edge in the GOA. Trash from the international fishing industry operating 200 miles offshore is commonly found on beaches. Some of these pollutants can also be carried westward to the gulf in the atmosphere.

Intermediate Levels of the Food Web

Food webs are really pyramids with seabirds, marine mammals, and fishes at the top that depend initially on energy captured by marine plants at their base. Although there are hundreds—perhaps thousands—of different plant and animal plankters involved in the synthesis and initial transfer of organic matter through the food web, the pyramid of herbivores and predators narrows quickly.

The diets of seabirds, marine mammals, and fishes are composed of a relatively modest variety of small schooling fishes and macroplankters, but they are consumed in very large numbers. Seabirds are the clearest illustration. Out of the hundreds of fish species in the gulf, a substantial portion of the diets of seabirds consists mainly of smelts (capelin, eulachon, and rainbow smelt), juvenile herring, pollock and salmon, Pacific sand lance, Pacific sandfish, lanternfishes, and adult euphausiids In shallow waters, small benthic fishes like pricklebacks and gunnels are also important Many of these forage species are rich in fats, and almost all exhibit schooling behaviors that concentrate them for their bird, mammal, and larger fish predators Herring, capelin, sand lance, and lanternfish are probably preferred for their high caloric content Juvenile pollock, cod, and salmon are less preferred, despite their abundance, because of their lower energy content

Despite the ecological importance of macroplankton and small schooling fishes, the distributions, abundances, and forage requirements of these species are poorly understood The influence of climate change on their populations is also poorly known This is partly because routine censusing techniques are used primarily to count and map adult stocks of commercial importance, and ignore the smaller forage fishes Modern techniques that use high-speed mid-water and surface trawls, marine acoustics, LIDAR (light detection and ranging), aerial surveys, and monitoring the diets of top consumers like birds and large commercial fishes will make it possible to learn more about this vital link in the food web

Forage fishes are often taken in the bycatch of federal and state-regulated fisheries in the GOA, and while the proportion relative to the target species tends to be small, it may be ecologically significant in some cases Fisheries targeting herring, salmon, and pollock all have incidental catches of juveniles that might be avoided as the industry develops new equipment and techniques to minimize the impact of bycatch mortality Mortality of forage fishes associated with marine pollution and diseases is also poorly understood There is some evidence that the failure of herring in Prince William Sound to recover from oil spill injuries may be due, in part, to an abnormally high incidence of Viral Hemorrhagic Septicemia (VHS) and a marine fungus plaguing these stocks

Plankton and Linkages to the Physical Oceanography

Oceanic, shelf, and coastal plankton are the base of a vast food web supporting most seabirds, marine mammals, and fishes These tiny drifters are supplemented by rich populations of plants and mostly small benthic invertebrates that feed higher-level consumers in intertidal and shallow subtidal areas Although adult birds, fishes, and mammals rarely feed directly on plankton, there are notable exceptions, such as adult walleye pollock, Pacific herring, baleen whales, and some seabirds On the other hand, the plankton community does play a direct and important role during the early life history of most fishes Ichthyoplankters—larval and juvenile fishes and shellfishes—derive critical nutrition from the plankton, but are themselves also preyed upon by plankters, mostly small jellyfish

Because fish are highly vulnerable in the egg, larval, and early juvenile stages, only a fraction survive to join the adult populations Traditionally, this survival rate was estimated in field studies of the early life stages of fish, including the physical and chemical characteristics of the rearing waters These studies have led to several important ideas about critical ecological bottlenecks in the early development of fish larvae and juveniles linking changes in ocean currents and climate with distribution, growth, and survival. This direct tie to ocean climate creates an important "handshake" that extends through the food web to adult fish stocks. Unfortunately, the small number and patchy distribution of ichthyoplankters relative to the non-fish plankton creates some extremely serious difficulties with sampling and data interpretation that limit the early-life history approach.

The bloom of plankton each spring defines the cycle of marine production for that and succeeding years as the impact of the planktonic biomass moves through the food web. The plankton communities undergo huge seasonal changes in rates of photosynthesis and growth, and in their standing stocks each year. Initiated in the spring by a stabilizing upper layer and increasing ambient light levels, the phytoplankton community undergoes explosive growth during April, May, and June before being controlled by nutrient depletion, sinking, and zooplankton grazing. The organic matter produced in this burst of productivity mostly comprises a relatively small number of dominant species. In a similar way, shallow-water plants—microalgae, seaweeds, and sea grasses—provide much of the plant-derived organic matter in intertidal and shallow subtidal areas. In the late fall, plankton stocks plummet dramatically and remain low during winter and early spring.

The timing, duration and intensity of marine plant blooms are controlled largely by the physical structure of the water column. Depending on the variable conditions of any given spring, the plant bloom may be early or late by as much as 3 weeks. Warming and freshening of the surface layers in response to longer and brighter days promote intense photosynthesis. However, the seasonal stability of the upper layers that initiates the growth of phytoplankton stocks also restricts the vertical movement of dissolved nitrogen, phosphate, and silicon, resulting in a dramatic slowing of growth in early and mid-summer. Previous work suggests that winter-conditioned temperature and salinity influences plankton production, working in concert with spring weather conditions to establish the overall success of the spring bloom. Recent observations from moorings that monitor chlorophyll in the water indicate that a fall phytoplankton bloom also occurs in Prince William Sound in some years, but not others. This burst of production peaks in September and can last through November. The ecological importance of this late-season production and the physical forces that unleash the bloom are not yet understood.

By definition, the plankton are drifters, they have little or no mobility. Therefore, their geographical locations are determined primarily by ocean currents. However, because many zooplankters are capable of daily and/or seasonal vertical migrations of 100 m or more, these migrations may interact with vertical or horizontal currents in ways that create localized swarms and layers (patches) of plankton in the ocean. These patches provide food for birds, fishes, and marine mammals. Whales feeding on surface or subsurface swarms of large copepods or euphausiids, and adult pollock and herring filtering or gulping large calanoid copepods in surface layers, are examples of patch feeding Because the plankton can be concentrated or dispersed by ocean currents, fronts, and eddies, the physical oceanography plays a huge role in creating and maintaining "feeding stations" for marine birds, mammals, and fishes

The marine production cycle beyond the shelf edge is exceptionally complex Photic zone levels of nitrogen, phosphate, and silicon are apparently available in sufficient quantities to promote phytoplankton production during the spring, summer, and fall However, levels of chlorophyll (a measure of the concentration of living phytoplankton in the water) in the upper layers remain very low throughout the year at many locations In the coastal regions and inner shelf, there is a burst of chlorophyll—the "bloom"—each spring This bloom results from an imbalance between rates of phytoplankton growth and rates of plant loss to grazers or sinking Over the deep ocean and outer shelf, this burst/bloom does not usually occur, meaning that growth and loss rates of the plants are nearly equal, and that there is very little "excess" plant matter in the water to sink to the deep sea bed This balancing act in offshore waters has generally been attributed to the ability of the micrograzers to efficiently "crop down" the plant stocks and prevent blooms

It has been suggested that inorganic iron from atmospheric sources is limiting plant productivity to very small cell sizes at the ocean surface These microscopic plants are cropped efficiently by oceanic protozoans and other microconsumers Unlike the shelf and coastal plankton, where large chain-forming diatoms feed the macrozooplankton directly, the oceanic food web instead supports an additional level of tiny consumers that are then grazed by larger zooplankters On the basis of food-chain theory, this additional step at the base of the food web should reduce the open ocean's ability to feed consumer stocks higher in the food web The fact that the open GOA is the preferred feeding ground for a majority of salmon stocks with origins in North America and Asia suggests that an additional step in the food web does not compromise the region's ability to feed hundreds of millions of these fish each year

Very little is known about how the plankton community responds to human activity Some recent and dramatic shifts in phytoplankton stocks in the Bering Sea, associated with a summer warming trend, were accompanied by very noticeable declines in seabird survivals in the shelf environment These observations suggest that any increased climate warming due to human influence could alter high-latitude food webs with drastic effects for some consumers

Influences of Weather and Climate

Gulf organisms are influenced by a variety of currents, frontal regions, eddies, water temperatures, and salinities These conditions define the ocean state and reflect the influence of weather and climate From September through April each year, weather in the GOA region responds to the position and intensity of the Aleutian Low pressure system The cyclonic storms that develop in and around the

GOA in association with the Aleutian Low cause strong easterly winds to blow along the northern coastline The friction of these winds on the sea surface promotes a net shoreward flow in the upper 60 to 90 meters, and a counter-clockwise drift of the Alaska Gyre, the Alaska Current, Alaskan Stream, and Alaska Coastal Current The frequency and intensity of storms establishes a "conveyor belt," carrying ocean-derived plankton stocks shoreward, some reaching as far as the protected coastal waters By using carbon isotopes as indicators, a strong offshore signal can be found in inshore zooplankton and fishes at some locations In contrast, during June, July, and August, the conveyor belt slows or weakly reverses in response to the appearance of the North Pacific high-pressure system in the GOA The reversal of the conveyor belt over the outer shelf allows deep water below the surface to overrun the shelf break at some locations, providing a crucial source of deep nutrients and oxygen renewal for deep coastal areas

The location and intensity of the Aleutian Low is not constant When the low is intense, the weather is stormy with increased precipitation in the coastal mountains, and elevated sea levels and warmer water temperatures in the eastern GOA Under these conditions, described as the positive phase of a weather phenomenon called the Pacific Decadal Oscillation (PDO), the wind-induced cross-shelf transport increases, as does flow in the ACC During the long term, these conditions seem to favor production of salmon, pollock, cod, and flounder, but other species are disadvantaged, such as seabirds at many locations, some forage fishes, and shellfish like shrimp and crab When the PDO cycles back to its next negative phase—as it is predicted to do, with colder, less stormy, lower sea levels—conditions should favor the recovery of shellfish stocks, with salmon and gadid populations expected to slip into decline Why these populations fluctuate the way they do in response to changes in ocean climate is unknown However, the cycling of nature's laboratory from year to year, and through longer periods, provides a strong basis for a number of intriguing studies to search for and describe the underlying mechanisms that create change, and sometimes complete reversals, in fish, bird, and mammal abundance

Toward a More Functional Understanding of GOA Ecosystems

Current knowledge about coastal, shelf, and oceanic ecosystems supporting the living marine resources of the GOA is limited and skewed heavily toward structural elements—species lists, historical patterns of production (catch and harvest statistics), crude maps of distribution and abundance, some diet information, migratory behaviors, and, in a few cases, rates of production At the level of plankton, the seasonal cycle is quite well understood in relationship to factors like light and nutrients, but higher in the food web at the zooplankton level and that of the small schooling fishes, little information is available Therefore, with a few exceptions, the "puzzle pieces" are beginning to form reasonably coherent pictures at the top and bottom of the food web, but are absent or mostly missing from the middle regions of the web

The challenge for GEM will be to eventually understand how the major physical and biological components interact dynamically to produce the historical patterns in stock size and production of key species. Conventional population theory teaches that variability at the highest levels in food webs reflects the balance between reproduction and mortality (due to natural causes, predation, harvests, diseases, and pollution). A few statistical analyses point to significant correlations, however, between population levels and weather, climate, or physical oceanographic conditions, some apparently tied to recurring cycles like the PDO, the North Pacific Index (NPI), the 18.6 year Lunar Nodal Tidal Cycle, and episodic events like El Niño/La Niña. Unfortunately these intriguing and often ephemeral correlations suggest, but do not identify, the mechanisms behind these relationships. This critical missing information must be obtained at some point in comprehensive field and modeling studies that focus on selected ecosystem processes.

To be successful, these studies must be funded at levels sufficient to identify and collect the relevant data, and supported over periods of time that bridge the cycles in climate and ocean conditions. Few studies anywhere have been able to sustain their activities long enough, or were sufficiently comprehensive to meet these criteria. The GEM program will be unique in that regard and could assume a strong leadership role in taking the next bold steps in marine ecological research. In so doing, GEM will find ways to more fully exploit some emerging research "themes" that are suggesting new directions for process studies of large ecosystems.

1. Nature Is Complex

Food web theory has played a major role in shaping quantitative approaches to studying marine systems. Since the early 1940s, when aquatic communities were perceived as a linear series of interconnected levels—producers (plants), first-order consumers (herbivores), higher-level consumers (predators), and recyclers (bacteria)—this powerful idea has pointed to ever more sophisticated inquiries about how matter and energy are cycled through these systems. However, in the last few years, there has been a growing awareness that the inability to more fully understand how nature works may be tied to a number of simplifying assumptions that have always been made about living systems. It is now understood that at some level of detail, natural processes cannot all be adequately explained by strict linear theory. This means that unless the complexity of nature is acknowledged and that constraint dealt with in a realistic manner, the GEM program work will fall short, as will the ability to resolve resource management and other issues.

2. Survival Strategies Define Habitat Dependencies

There is a growing need to more fully understand what has been passed over as mostly "old science"—how the life history of a target species exploits the marine ecosystem during its entire life span. For example, most marine fishes begin life as tiny pelagic or demersal eggs followed by a drifting larval stage that may last for weeks or months. The drifting period is followed by successive juvenile and maturing older stages that may use different parts of the ecosystem from those that host the adults Understanding the entire ecological domain of a particular species will help establish the "connectiveness" needed to more fully understand how human influences and perturbations in climate and weather work their way though the marine ecosystem in the GOA

3. Use of Common Biological Currency

Oceanographers have traditionally used measures of carbon or nitrogen as common denominators to describe processes of organic matter synthesis and transfer at lower trophic levels At the other end of the food web, the fisheries literature tracks the abundance and biomass of exploited stocks, usually expressed in numbers or weight Recently, the energy content of species has been suggested as a useful measure for assessing the status of stocks and their principal prey Bioenergetic modeling is becoming more common and measures of whole body energy content easier to obtain For instance, the overwintering starvation mortality of juvenile Pacific herring residing in Prince William Sound can now be estimated through numerical analysis of the fat stores of the herring as they go into winter and the winter water temperatures

4. Problems of Time and Space

Attempts to understand how marine ecosystems react to climate and human influences pose huge sampling problems for systems on the scale of the GOA Current understanding suggests that the impacts of large-scale climate shifts and pollution are not uniform, but seem to be temporally and spatially distributed in ways that are not fully understood For example, seabird colonies at some locations do well, while others do not Two aspects may be important contributors to this uncertainty (1) variability in the timing, location, and duration of primary productivity each year as influenced by weather—a kind of "timing is everything" issue, and (2) spatial patchiness on a variety of length scales in forage stocks responding locally to changing temperature, salinity, currents, and other ocean characteristics This suggests that GEM will have to study a number of different environments at different times to fully understand the ecological ramifications of climate-driven change, and that care must be taken in generalizing about cause and effect within the region

5. Immigration or Emigration

Particularly for seabirds and marine mammals censused at nesting sites and rookeries, some population trends might be explained by migrations away from or to these locations If this is occurring, these migrations could pose serious problems in the interpretation of historical trends in the GOA Some believe that fish or shellfish stocks can also shift their distributions in response to environmental change, leading to increases in some areas and declines in others, although the overall stock production might remain unaltered This potential source of error must be addressed by GEM

6. Top-Down and Bottom-Up Controls

Historical approaches to studies of marine systems have led to a dichotomy of disciplines. Oceanographers have focused on the base of the food web and relationships with ocean physics and chemistry, whereas fisheries scientists have studied exploited stocks and, occasionally, the forage resources that support them. Top-down or bottom-up control has been debated endlessly for years without resolution. It is now beginning to be understood, that this is not an either/or problem, but rather one of process interaction. Top-down and bottom-up control of populations occurs simultaneously in all living systems and must be studied as such to refine understandings of system function. For example, recent studies of juvenile pink salmon in Prince William Sound have demonstrated that top-down losses to fish predators, such as adult pollock and herring, are modulated by the kinds and amounts of zooplankton available, a bottom-up function. The opportunistic pollock and herring prefer to feed on macrozooplankton when plentiful, thereby improving the chance of juvenile salmon to fatten up and escape their role as prey. However, when macrozooplankton is not abundant, pollock and herring begin augmenting their diets by feeding more heavily on small fishes, including juvenile salmon. In this way, bottom-up processes affecting the production of copepods not only help feed and fatten young salmon, but top-down processes of pollock feeding on copepods help protect the salmon fry.

Conclusion

In the final analysis, the GEM program will engage a complex ecosystem—a product of evolutionary adaptation through many thousands of years. This robust living assemblage exhibits different characteristics of species dominance, distribution, and abundance in response to short-term and longer-period changes in climate forcing and human influences. These different "states" have most recently been described as regimes. In the GOA, at least two dominant physical states—El Niño/La Niña—and PDO are known to affect the production cycles of several marine species. It is also likely that long-term warming of the North Pacific Ocean is having an as yet unassigned roles in ecological change. GEM proposes to investigate why some resources, but not others, benefit from these changing and interacting oceanic conditions. This understanding will ultimately provide information to more prudently exploit and/or conserve species of high value for all users. Knowing why a particular set of resources is performing at a given level of productivity will ultimately provide a means to more effectively manage the system under different states of species dominance and external influences. This ambitious goal will be addressed through a long-term commitment to innovative science, and the thoughtful application of results.

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 (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

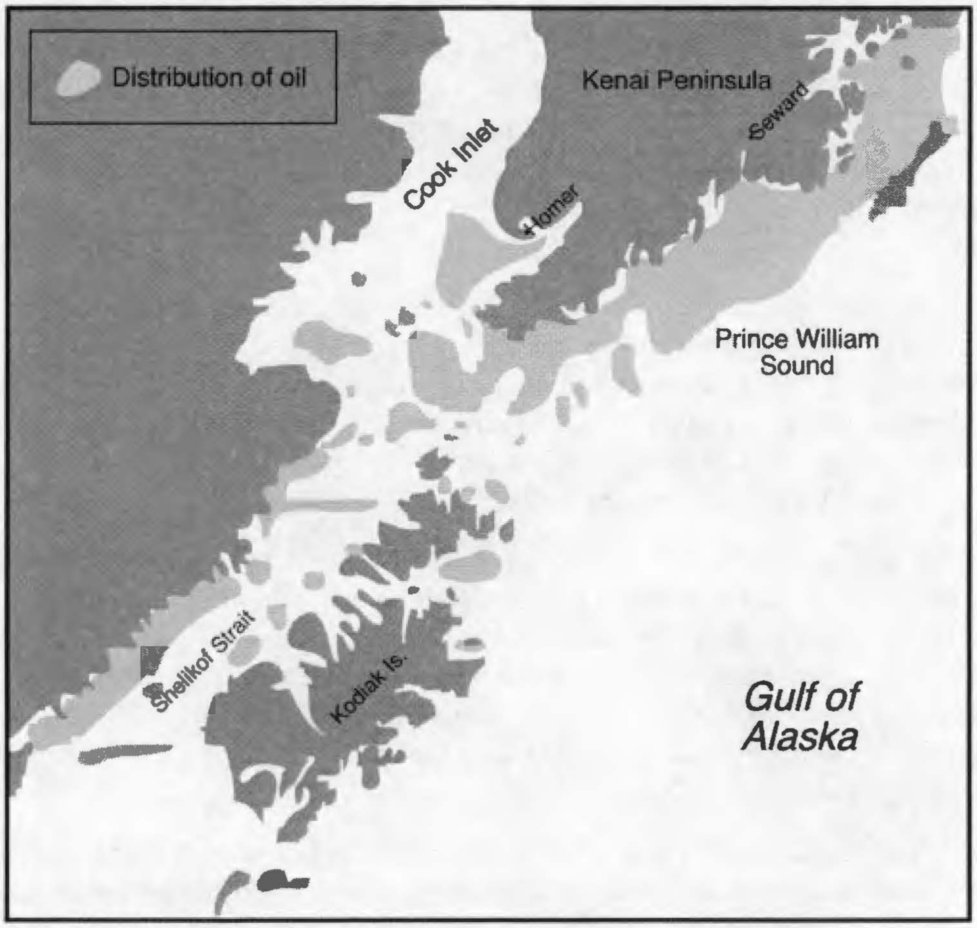


Figure 3.1 Distribution of oil from the *Exxon Valdez* oil spill.

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).

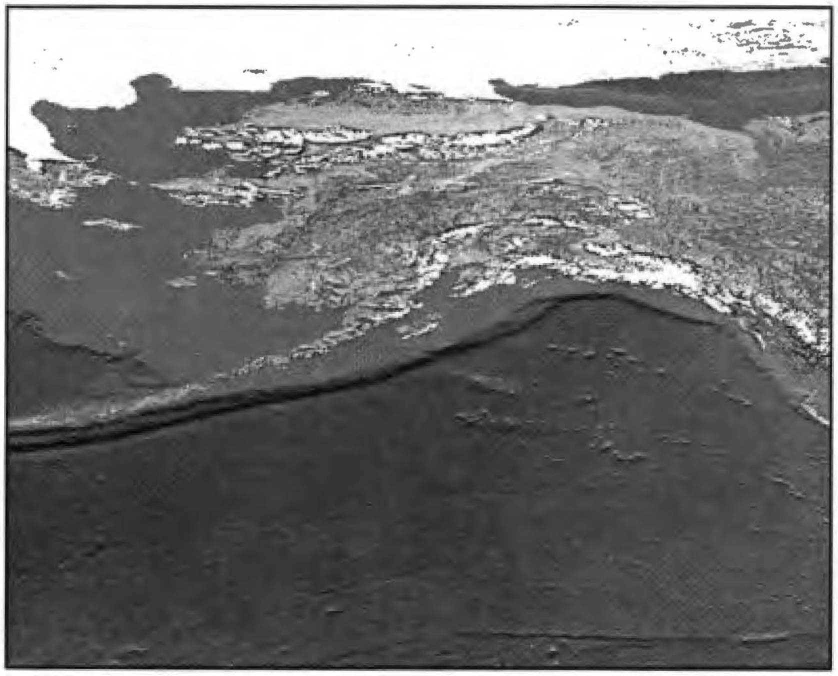


Figure 3.2 Satellite radar image of the northern Gulf of Alaska. Continental shelf, seamounts, and abyssal plain can be seen in relief. (Composite image from Sea-viewing Wide Field-of-view Sensor [SeaWiFS], a National Aeronautics and Space Agency remote-sensing satellite.)

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 Hurrell 1994)

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

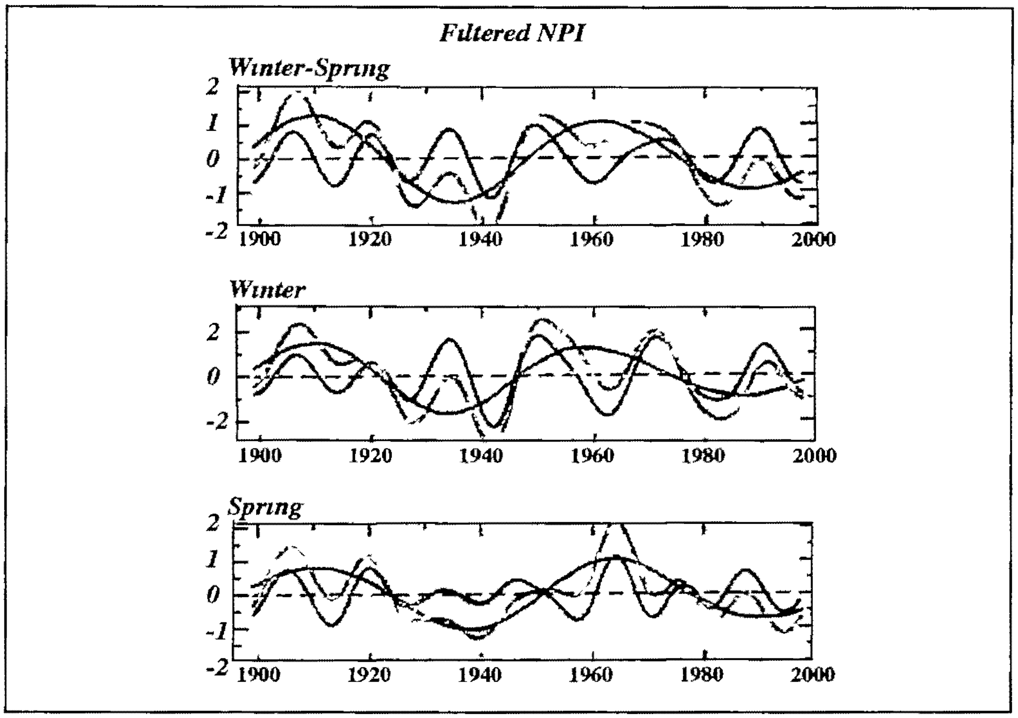


Figure 3 3 Filtered North Pacific Index in the winter-spring, winter, and spring seasons NPI is shown in hectoPascals, a measure of barometric pressure at sea level The three curves show the NPI band-pass filtered over intervals of 10 to 80 years, 10 to 30 years (bidecadal), and 30 to 80 years Source Minobe 1999

questions in paleoclimate 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

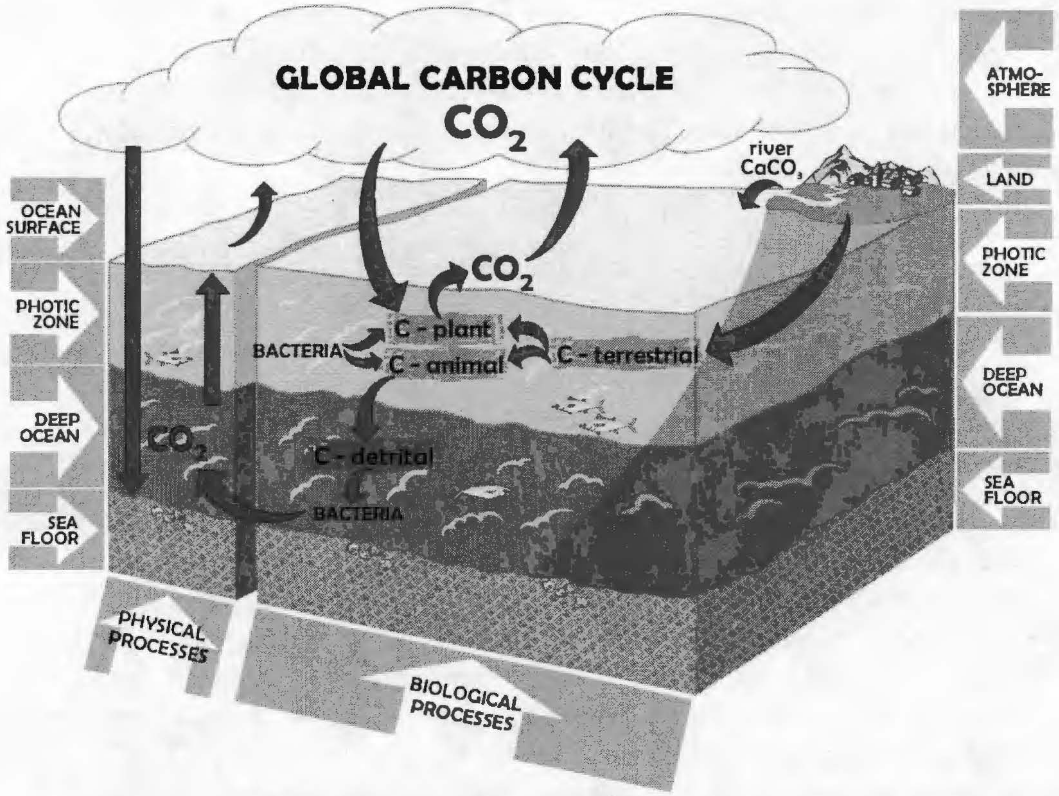


Figure 3.4 Global carbon cycle diagram showing the movement of carbon compounds of the atmosphere, land, marine photic zone, the deep ocean, and the sea floor.

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.

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.)

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.

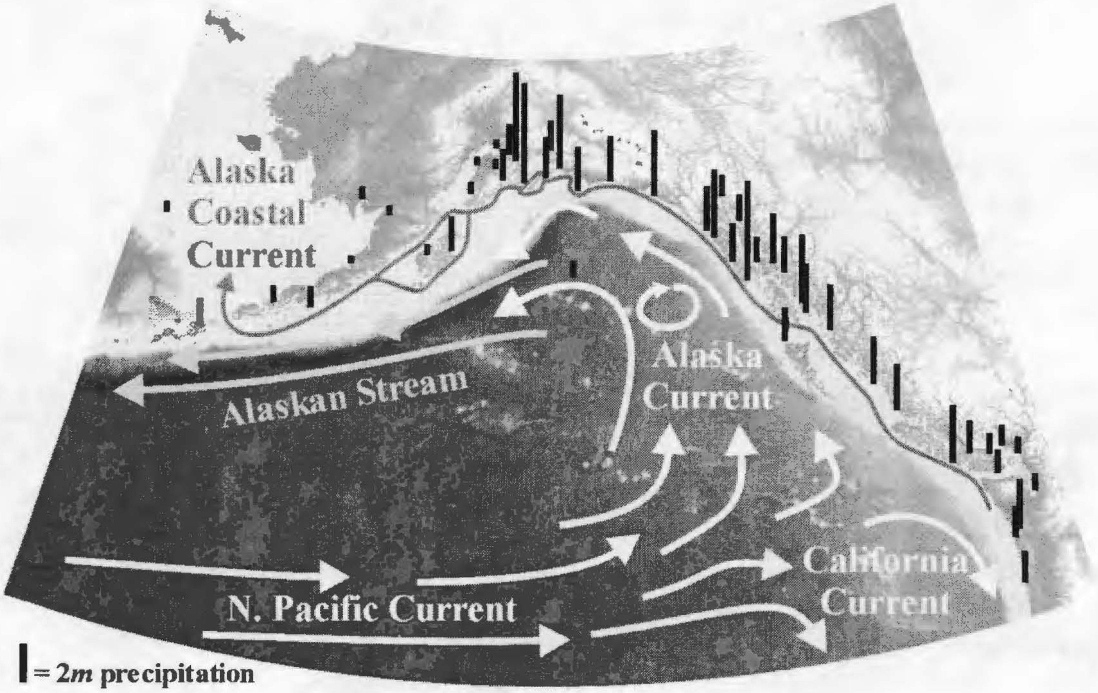


Figure 3.5 Schematic surface circulation fields in the Gulf of Alaska and mean annual precipitation totals from coastal stations (black vertical bars) and for the central gulf (Baumgartner and Reichel 1975).

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 Hurrell 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

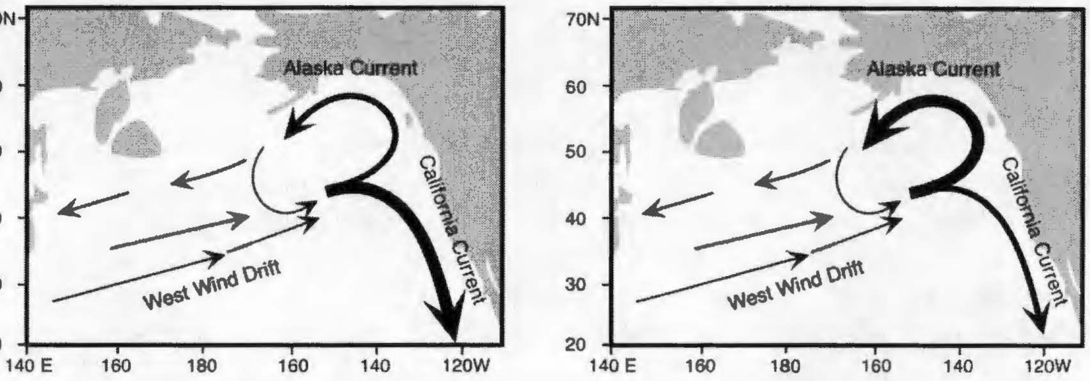


Figure 3.6 Oceanic circulation patterns in the far eastern Pacific Ocean proposed for negative PDO (left) and positive PDO (right) (Hollowed and Wooster 1992).

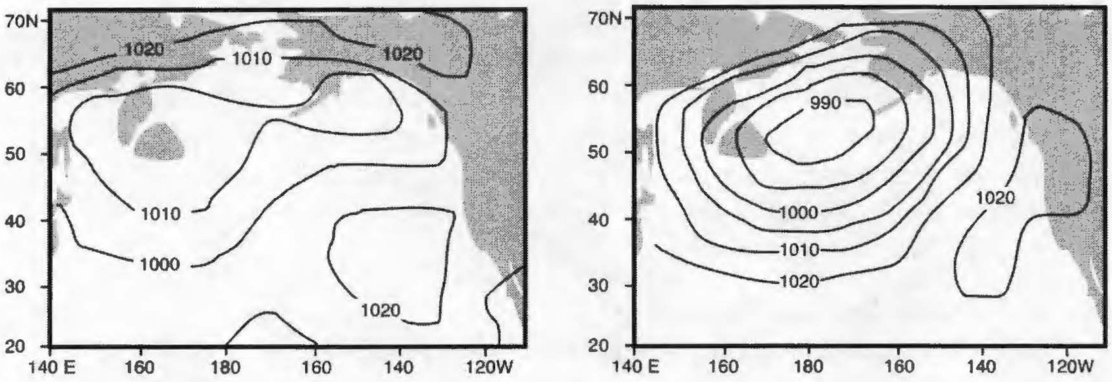


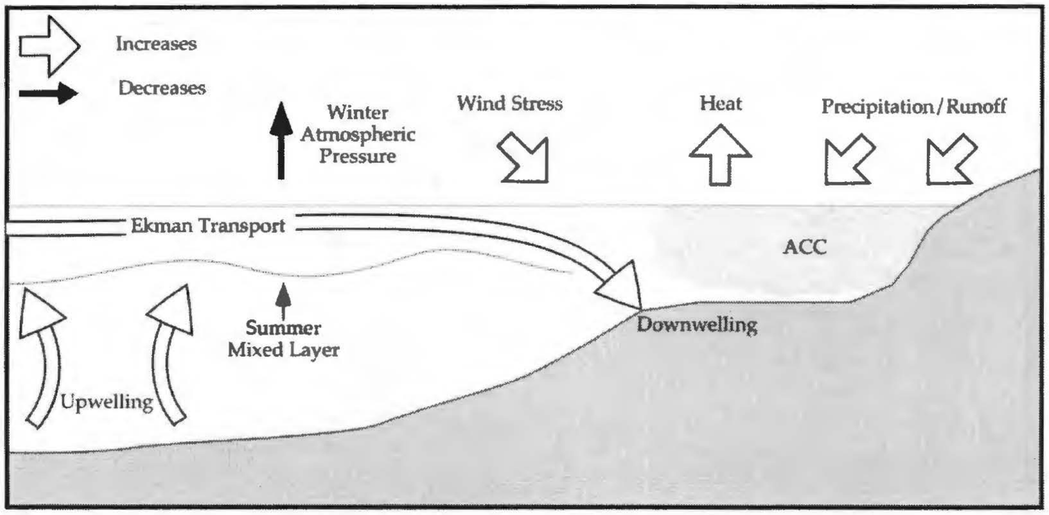
Figure 3.7 Mean sea-level pressure patterns from the winters of 1972 (left) and 1977 (right) (Emery and Hamilton 1985).

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.

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 Hurrell 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. 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 3.3). His

Positive PDO Index

Physics



Positive PDO Index

Biological Production/ Transport

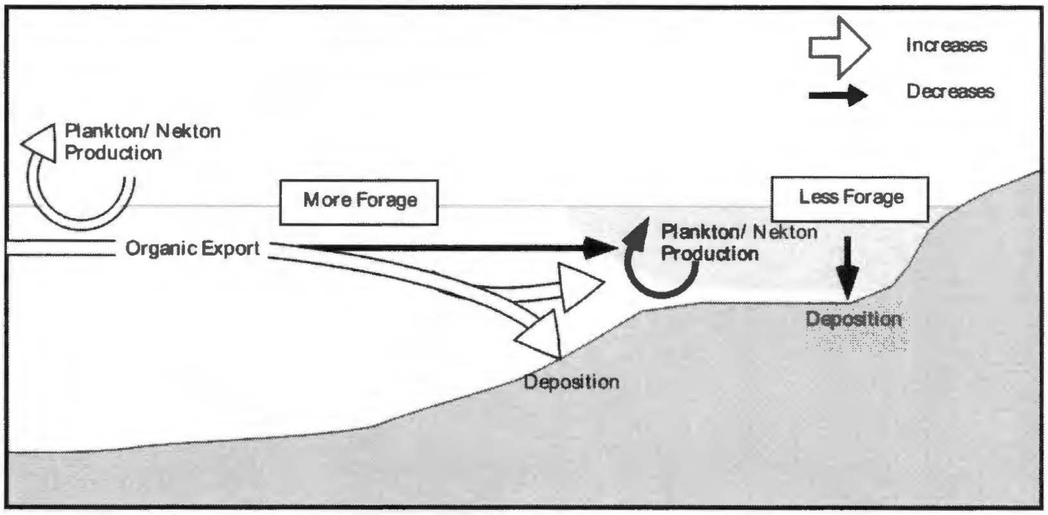


Figure 3.8 Schematic of physical processes during the winter in a positive PDO climatic regime in the Gulf of Alaska from offshore to nearshore areas showing the Alaska Current and the Alaska Coastal Current.

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

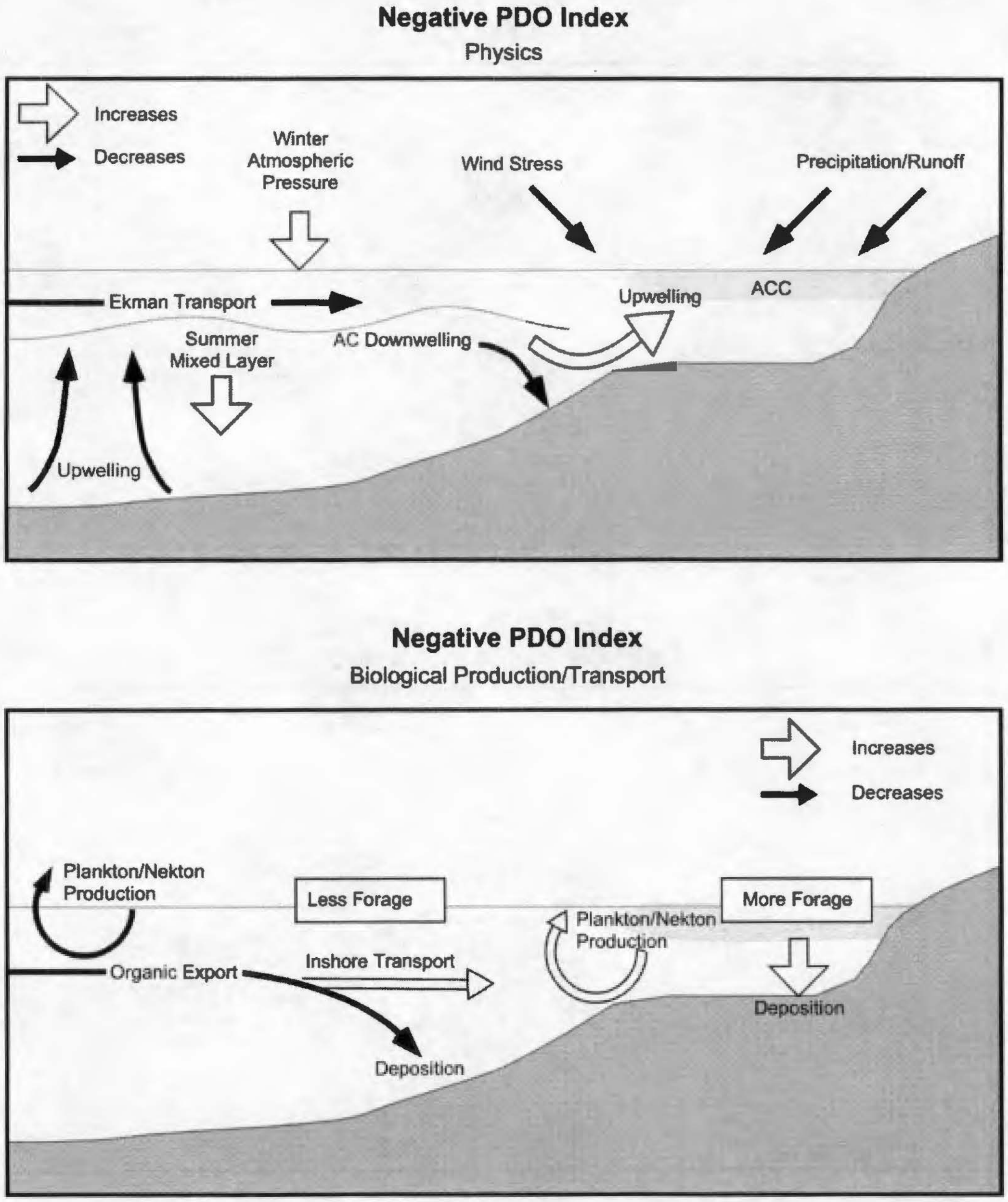


Figure 3.9 Schematic of physical processes during the winter in a negative PDO climatic regime in the Gulf of Alaska from offshore to nearshore areas showing the Alaska Current and the Alaska Coastal Current.

twentieth century (Richardson 1936, Klein 1957, Whittaker and Horn 1982, Wilson and Overland 1986).

3.2.3.3 El Niño Southern Oscillation

The ENSO is a weather 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). 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.

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). Experiments in artificial and natural streams have shown that chlorophyll a and the biomasses of the biofilm (bacteria and molds) and aquatic macroinvertebrates, such as insects, increase as the amount of salmon carcass biomass increases. Chlorophyll a has been observed to increase over the full range of carcass biomass , whereas increases in macroinvertebrates stop at some limiting value of carcass loading (Wipfli et al. 1998, Wipfli et al. 1999). Salmon carcasses stimulate production of multiple trophic levels, including decomposers, in watersheds by providing carbon and nutrients. In earlier studies of an Alaskan stream containing chinook salmon, Piorkowski (1995) supported the hypothesis of Wipfli et al. (1998) that salmon carcasses can be important in structuring aquatic food webs. In particular, microbial composition and diversity may determine the ability of the stream ecosystem to use nutrients from salmon carcasses, a principal source of marine nitrogen.

Marine nutrients and carbon move from the marine environment into terrestrial species in the watersheds of the GOA (Wipfli et al. 1999), as has been shown to be the case in anadromous fish-bearing watersheds elsewhere in the north Pacific region (Bilby et al 1996) 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),
- Opportunistic scavengers as riverine mink (Ben-David et al 1997a), wolf (Szepanski et al 1999), and martens (Ben-David et al 1997b), and
- Riparian zone plants such as trees (Bilby et al 1996)

In theory, any terrestrial plant or animal species that feeds in the marine environment or that receives nutrients from anadromous fish, such as harlequin duck or Sitka spruce, is a pathway to the watersheds for marine carbon and nutrients Species that contain marine nutrients are widely distributed throughout watersheds, 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) 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, Finney et al 2000)

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 (Figure 3.10). It includes a continental shelf area of about 3.7×10^5 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 (2.86×10^6 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 10) 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

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

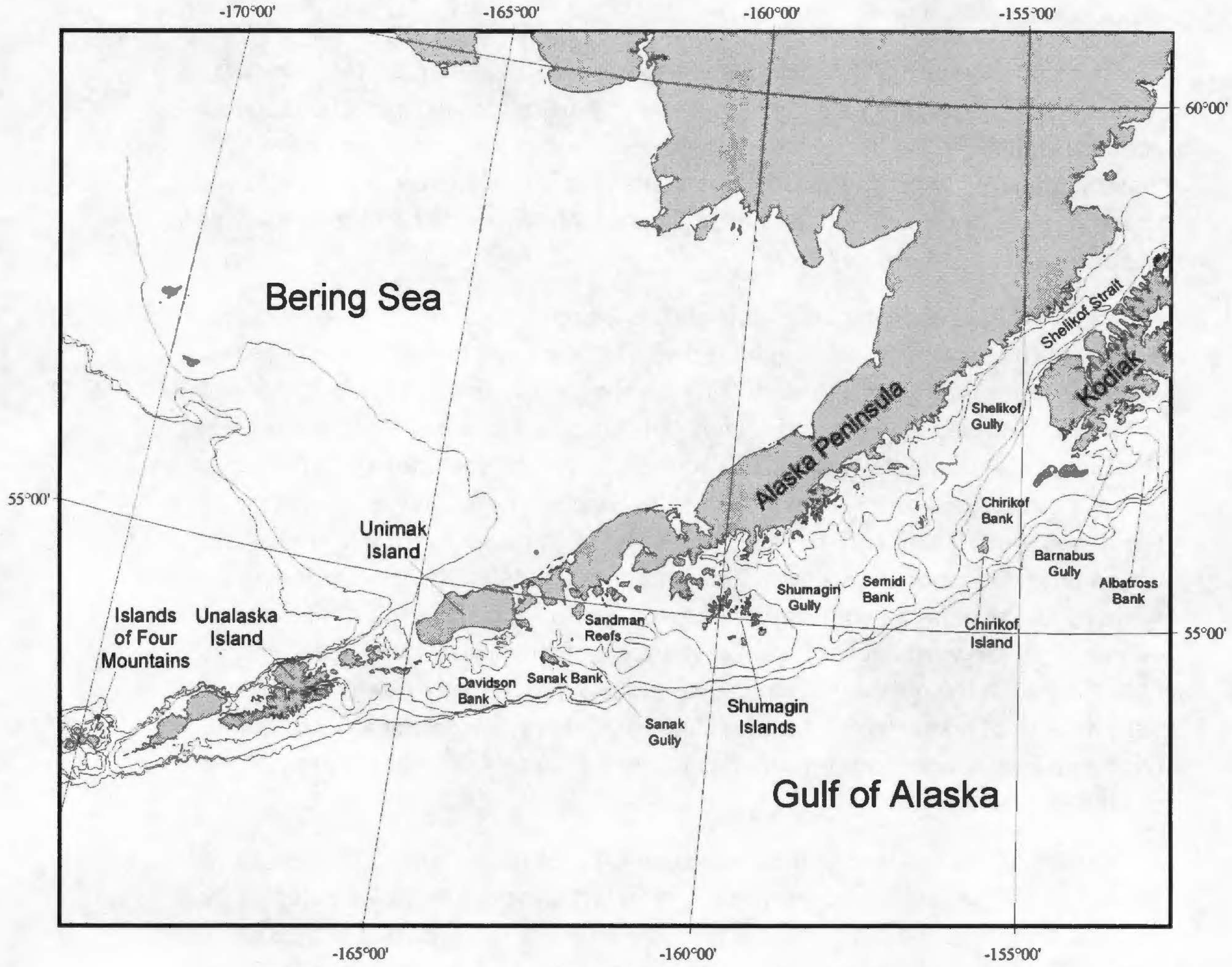


Figure 3.10a Shelf topography of the northern Gulf of Alaska and adjacent waters (Martin 1997).

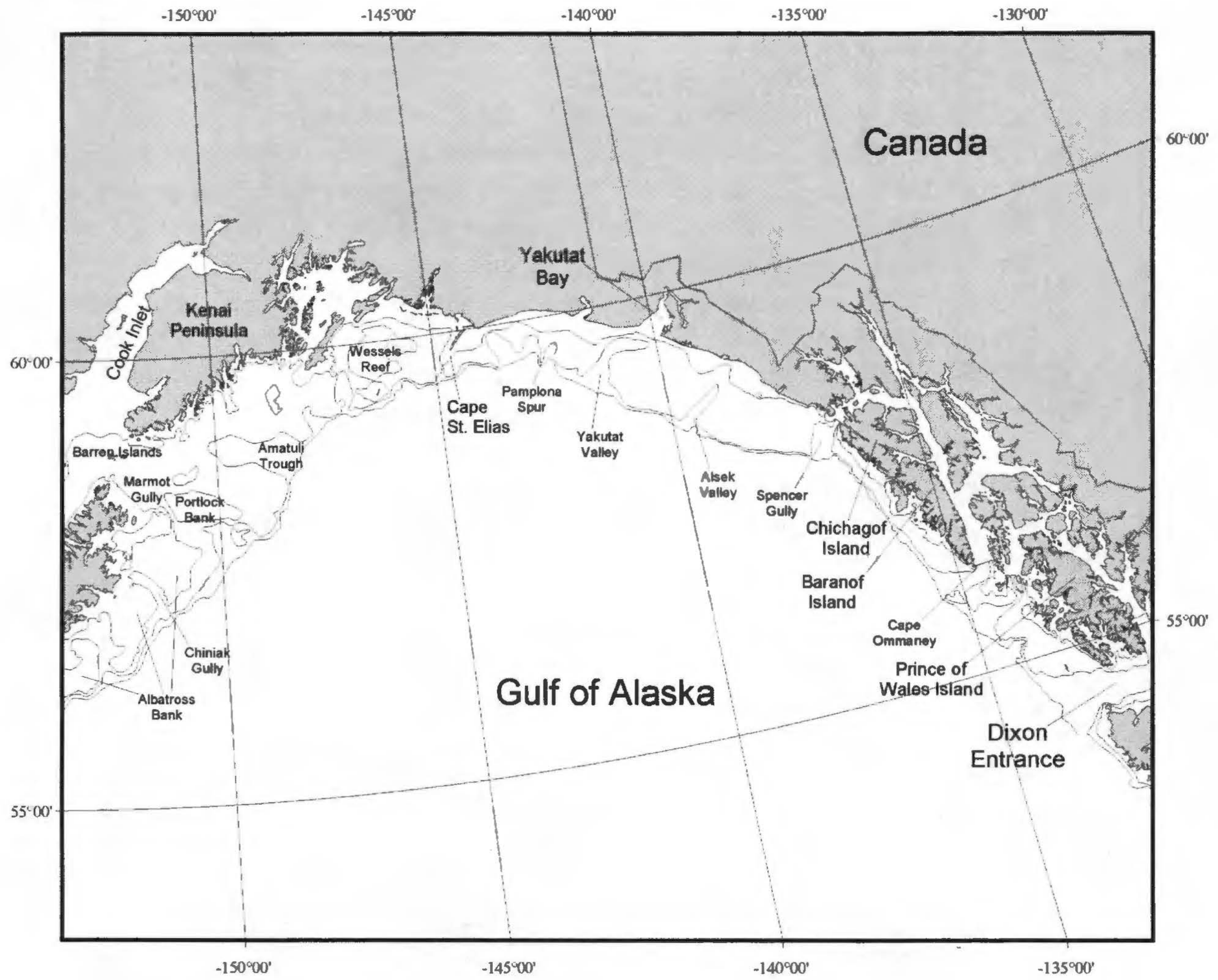


Figure 3.10b Shelf topography of the northern Gulf of Alaska and adjacent waters (Martin 1997).

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 3.11. 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.

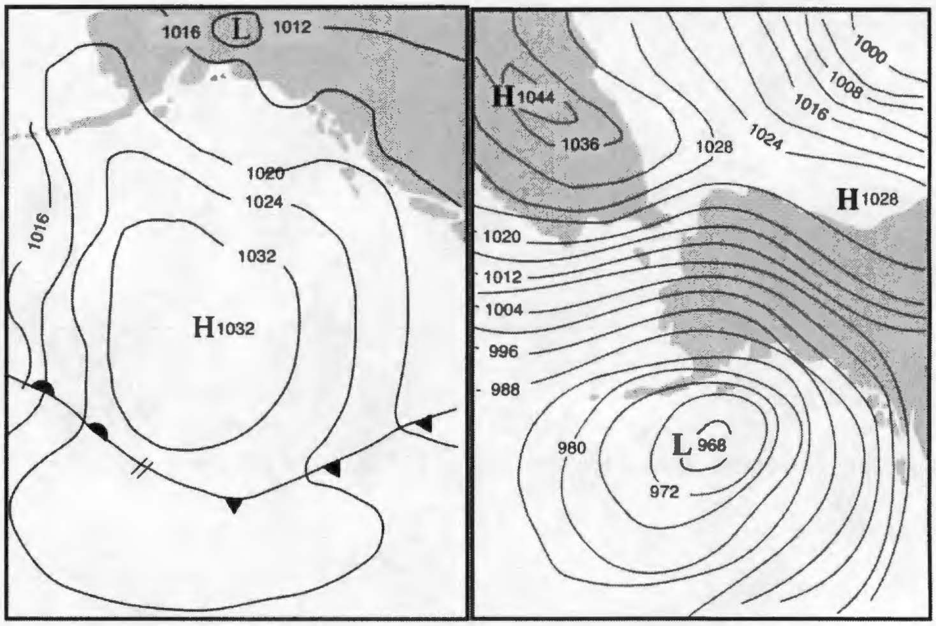


Figure 3.11 Typical summer (left) and winter (right) examples of the Aleutian Low and Siberian High pressure systems. Contours are sea-level pressure in millibars. (Hollowed and Wooster 1987)

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.

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.

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

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 3.12 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

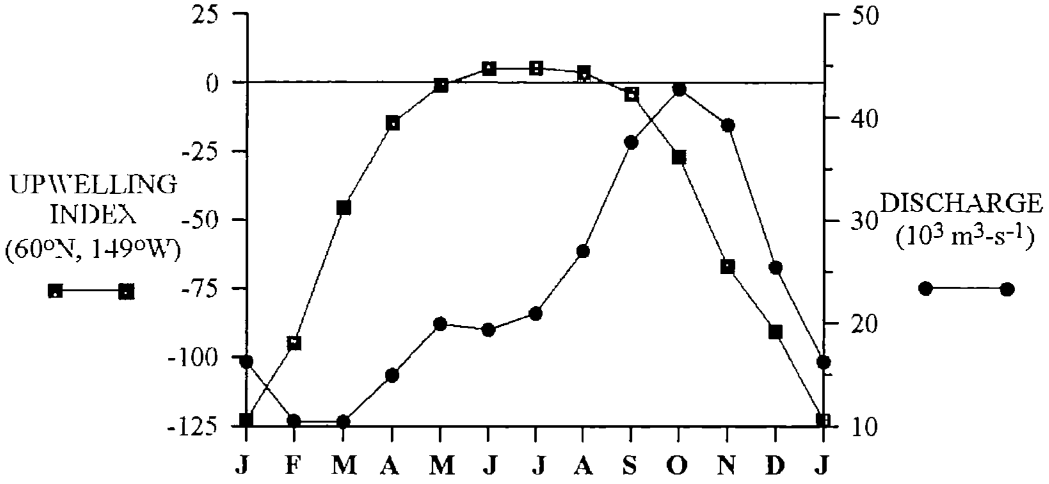


Figure 3 12 Mean monthly upwelling index, 1946 to 1999 (red), and mean monthly coastal discharge, 1930 to 1999 (blue) (Royer 1982, 2000) in the northern GOA Negative values of the Index imply onshore Ekman transport and coastal downwelling Discharge is shown in cubic meters per second, a measure of flow

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-yr^{-1}) are typical throughout the region, but rates in southeast Alaska and PWS exceed 4 m-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-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 12 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 12 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 scales 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 13) 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

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

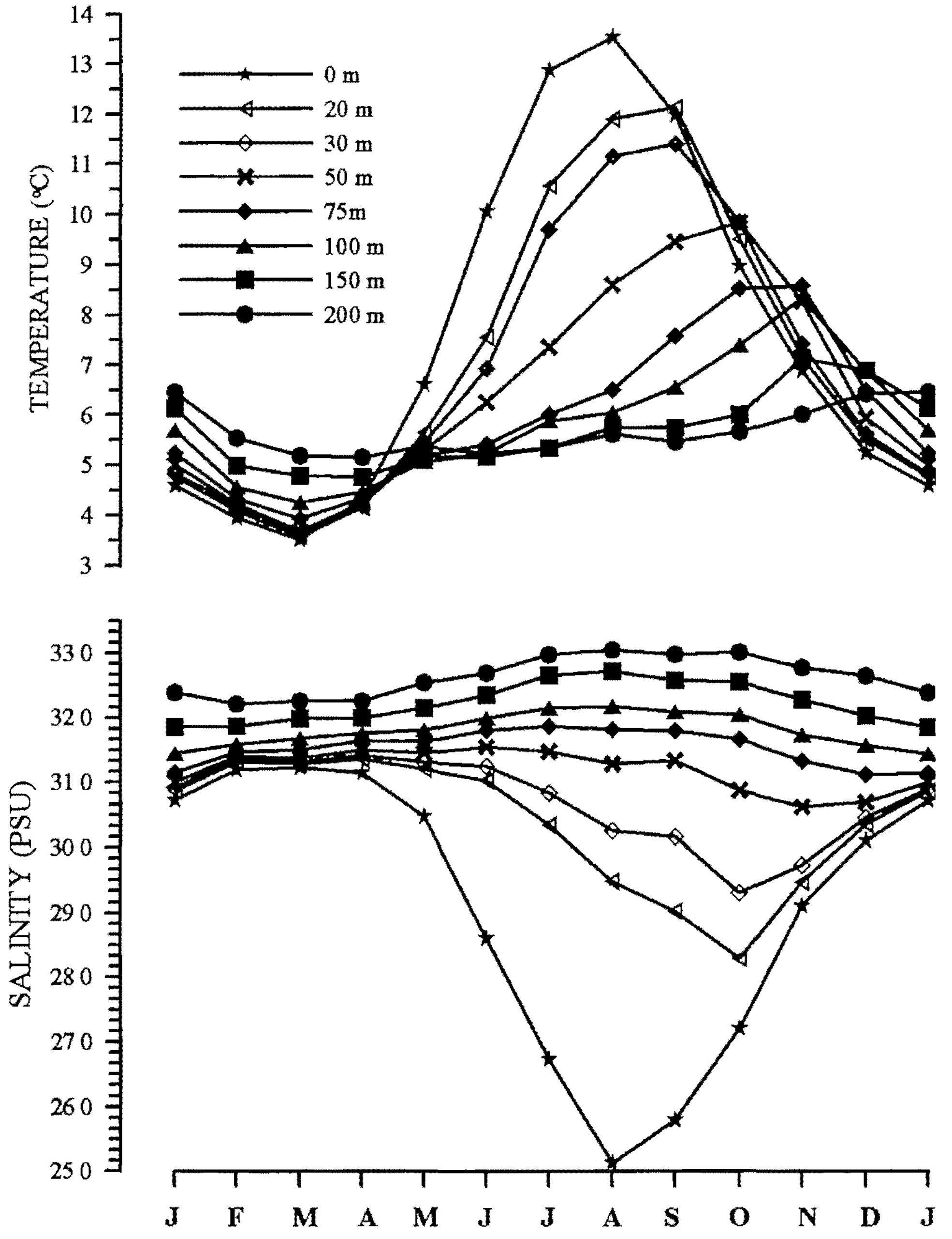


Figure 3 13 The mean annual cycle of temperature (upper) and salinity (lower) at various depths at station GAK1 on the inner shelf of the northern GOA The monthly estimates are based on data collected from 1970 through 1999 (The figure includes updated information [Xiong and Royer 1984])

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 14, 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

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 along-shore 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

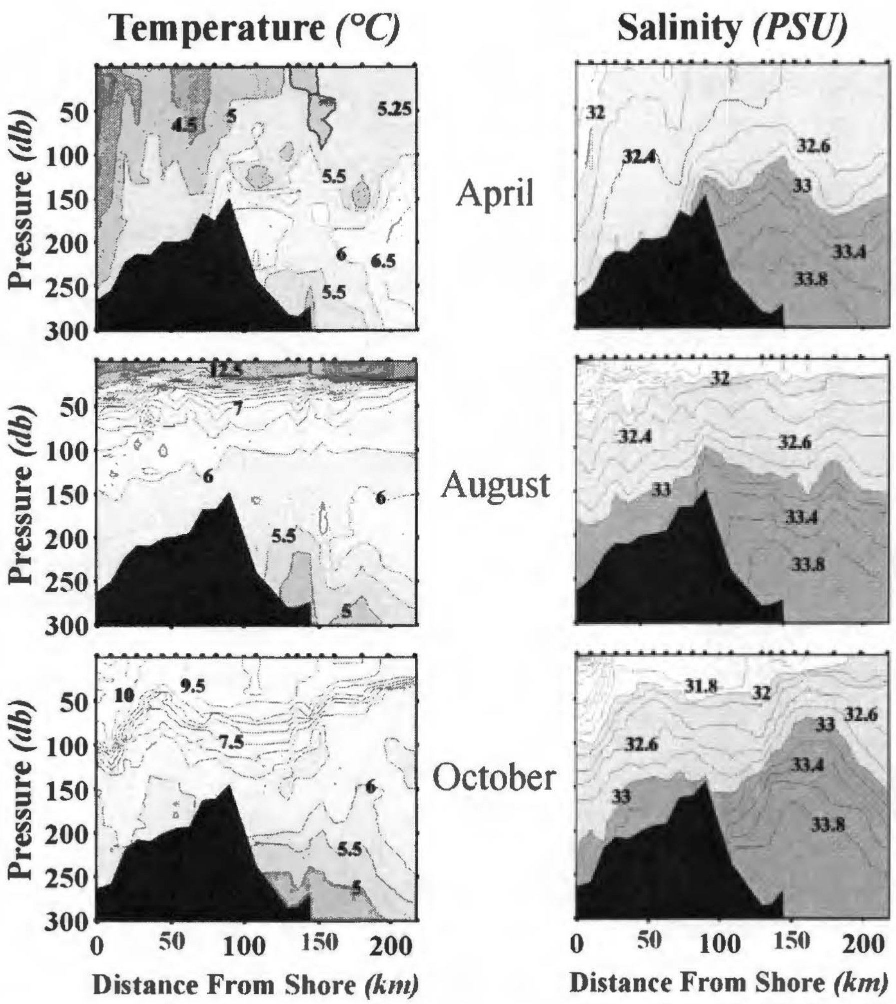


Figure 3.14 Seasonal cross-shore distributions of temperature (left) and salinity (right) along the Seward Line in the northern GOA. The graphs are based on data collected in 1999 as part of the GOA GLOBEC program (Weingartner 2001). The vertical axis is in pressure units (decibars [db]), with 1 db the equivalent of about 1 m.

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 (Ahlnäes et al. 1987);
2. Instabilities of the ACC (Mysak et al. 1981, Bogard 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 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

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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 14)

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, 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. 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. (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 35.4.4)

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

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

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 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).

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.

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.

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

Few measurements are available for variability of marine environment productivity in the northern GOA.

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 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) (Figure 3.15). 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 3.15) 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.

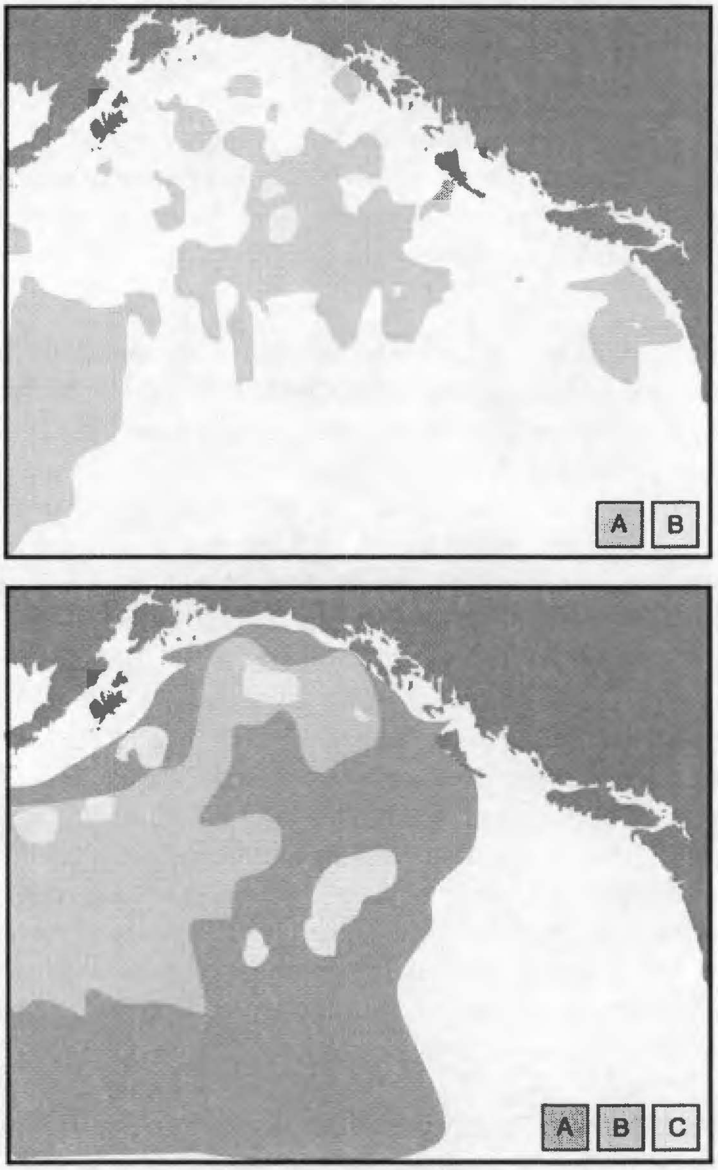

Figure 3.15 Biomass of plankton for the spring and summer period contrasted for a negative PDO period (top) and a positive PDO period (bottom). The shaded boxes present zooplankton biomass as follows: A represents 100 to 200 g/1,000 m^3; B represents 201 to 300 g/m^3, and C represents more than 300 g/m^3. (Brodeur and Ware 1992)

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).

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

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:

- 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 community on rocky shores of the GOA is also strongly influenced by larval distribution and recruitment. Recent studies by PISCO (see Appendix A for Web link) have shown that not only are the effects of competition and predation important in structuring benthic communities, but the sources and sinks of larvae are equally important Larval abundance and behavior, where they come from, how they respond to ocean conditions, where they are retained, where they are reflected, and the dynamics regulating their recruitment are all important processes that ultimately control what lives where Furthermore, knowledge about life histories is insufficient to make broad generalizations about the successes and failures of recruitment events

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

What are sources and rates of natural disturbance to these communities, and what are rates and patterns of recovery?

How variable is recruitment in space and time, and among planktonic species?

What is the relationship between recruitment rates and growth rates of filter feeders? Algae? Predators?

What are primary energy and nutrient sources of intertidal and benthic communities—in situ, upwelling, offshore, terrestrial runoff?

Under what conditions are populations limited by recruitment, food, space, natural disturbance, temperature, predators, competitors, and disease?

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, persistent organic pollutants (POPs) 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 (*Trichodon 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

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

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 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 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 et al 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 that sea ducks are not considered seabirds for the purposes of this discussion Most species of seabirds 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

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

Table 3.3 Nesting Seabirds in the Gulf of Alaska

English Name	Scientific Name	Abundance[1] (thousands)	Biomass[2] (tonnes)	Nesting Habitat[3]	Foraging Mode[4]
Northern fulmar	*Fulmarus glacialis*	440	268	Cliff	SF
Fork-tailed storm-petrel	*Oceanodroma furcata*	640	32	Burrow	SF
Leach's storm-petrel	*Oceanodroma leucorhoa*	1,067	53	Burrow	SF
Double-crested cormorant	*Phalacrocorax auritus*	3.3	6	Cliff	CD
Brandt's cormorant	*Phalacrocorax penicillatus*	0.086	0.2	Cliff	CD
Pelagic cormorant	*Phalacrocorax pelagicus*	21	40	Cliff	CD
Red-faced cormorant	*Phalacrocorax urile*	20	38	Cliff	CD
Unidentified cormorant	*Phalacrocorax* spp	15	29	Cliff	CD
Mew gull	*Larus canus*	15	11	Ground	SF
Herring gull	*Larus argentatus*	1	1	Ground	SF, S
Glaucous-winged gull	*Larus glauscescens*	185	241	Ground	SF, S
Black-legged kittiwake	*Rissa tridactyla*	675	270	Cliff	SF
Arctic tern	*Sterna paradisaea*	8.9	1.2	Ground	SF
Aleutian tern	*Sterna aleutica*	9.4	1.2	Ground	SF
Unidentified tern	*Sterna spp*	1.7	0.22	Ground	SF
Common murre	*Uria aalge*	589	589	Cliff	DD
Thick-billed murre	*Uria lomvia*	55	55	Cliff	DD
Unidentified murre[5]	*Uria spp*	1,197	1,197	Cliff	DD
Pigeon guillemot	*Cepphus columba*	24	13	Crevice	CD
Marbled murrelet	*Brachyramphus marmoratus*	200	48	Tree	CD
Kittlitz's murrelet	*Brachyramphus brevirostris*	+	+	Scree	CD
Ancient murrelet	*Synthliboramphus antiquum*	164	38	Burrow	CD
Cassin's auklet	*Ptychoramphus aleuticus*	355	71	Burrow	DD
Parakeet auklet	*Cerorhinca monocerata*	58	17	Crevice	DD
Least auklet	*Aethia pusilla*	0.02	0.0018	Talus	DD
Crested auklet	*Aethia cristatella*	46	14	Talus	DD
Rhinoceros auklet	*Cyclorrhynchus psittacula*	170	90	Burrow	DD
Tufted puffin	*Lunda cirrhata*	1,093	874	Burrow	DD
Horned puffin	*Fratercula corniculata*	773	425	Crevice	DD
Total		**7,826**	**4,423**		

[1] From U.S. Fish and Wildlife Service (USFWS), seabird colony database marbled murrelet in Gulf of Alaska from Piatt and Ford (1993)

[2] Based on weights of seabirds presented by DeGange and Sanger (1986)

[3] Principal type

SF = surface-feeder, CD = coastal diver, DD = deep diver, S = scavenger. From DeGange and Sanger (1986)

[5] Essentially all common murres

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 (Beissinger 1995) 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).

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
Increasing				
Gull Island[1]	Up	0.39	1	15
Prince William Sound[2]	Up	0.30	4	67
Barren Island[3]	Up	0.40	1	7
Stable				
Prince William Sound–Overall[2]	Level	0.18	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
Declining				
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	?

Colonies in PWS are divided into groups of increasing, stable and declining abundance, overall kittiwake abundance is stable in PWS.

[1] From J. Piatt (unpublished data)

[2] From D. Irons (unpublished data)

[3] From USFWS (unpublished data)

[4] From S. 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

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, 4 colonies have grown to large size, and 11 smaller colonies have declined, with some disappearing completely Five 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 18 chicks per pair since 1984 (Table 3 4) 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)

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 The consequences of inappropriate comparisons are 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

Crititcal 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 1986a, 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 1986a, Cooney 1986a, 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

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 B (see survey area map, Figure 3 10)

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 1986a). 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). 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 mind 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 1986b). 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 (see Figure 3.10 in Section 3.4.1). 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. draft).

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

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	-	-
Agonidae	8	12	8	9

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
Cyclopteridae	12	38	5	7
Bramidae	1	1	-	-
Pentacerotidae	1	1	-	-
Sphyraenidae	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 et al 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

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)

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

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

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 10) 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 (Rosenkranz 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 (Rosenkranz 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

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

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).

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 trends 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)

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

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

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

Sources: Hobbs et al. in press and Hobbs 2000

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 2000b) 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 2000b) 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 2000b) 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 (Sease and Loughlin 1999, NMFS 2000a) (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

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[1]
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

Sources Sease and Loughlin 1999 and NMFS 2000

Dashes indicate no count in that year

[1] Use counts in the Aleutian Islands made in 1977 and 1979

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)

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 2000b) 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 2000b) 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 2000b)

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 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 (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 Area

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

Sources: Pitcher 1990, Frost et al. 1994, Frost et al. unpublished, and Small 2001.

Counts have been adjusted to account for important covariates (Frost, Lowry, and ver Hoef 1999).

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)

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)

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

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

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 predation and primary production as controlling factors in structuring nearshore marine communities Due to the size of their home ranges, sea otters are relatively sedentary 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 encapsulates the understanding, in the form of a hypothesis and question, of how GOA ecosystems produce biological resources The conceptual foundation does not provide a specific model (testable hypothesis) for ecosystem change because of the 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, 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 constructing a clearer picture of ecosystem change

The conceptual foundation focuses on how the marine ecosystem in the GOA works.

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 factors and human activities may produce long-term changes in valued populations,

3 Some basic concepts of how natural forces and human activities affect biological production 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 (such as large inputs of nutrient-poor fresh water, strong

atmospheric low pressure in winter, persistent coastal downwelling, and the presence of gyres and eddies);

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, and human activities; and
6. The 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.

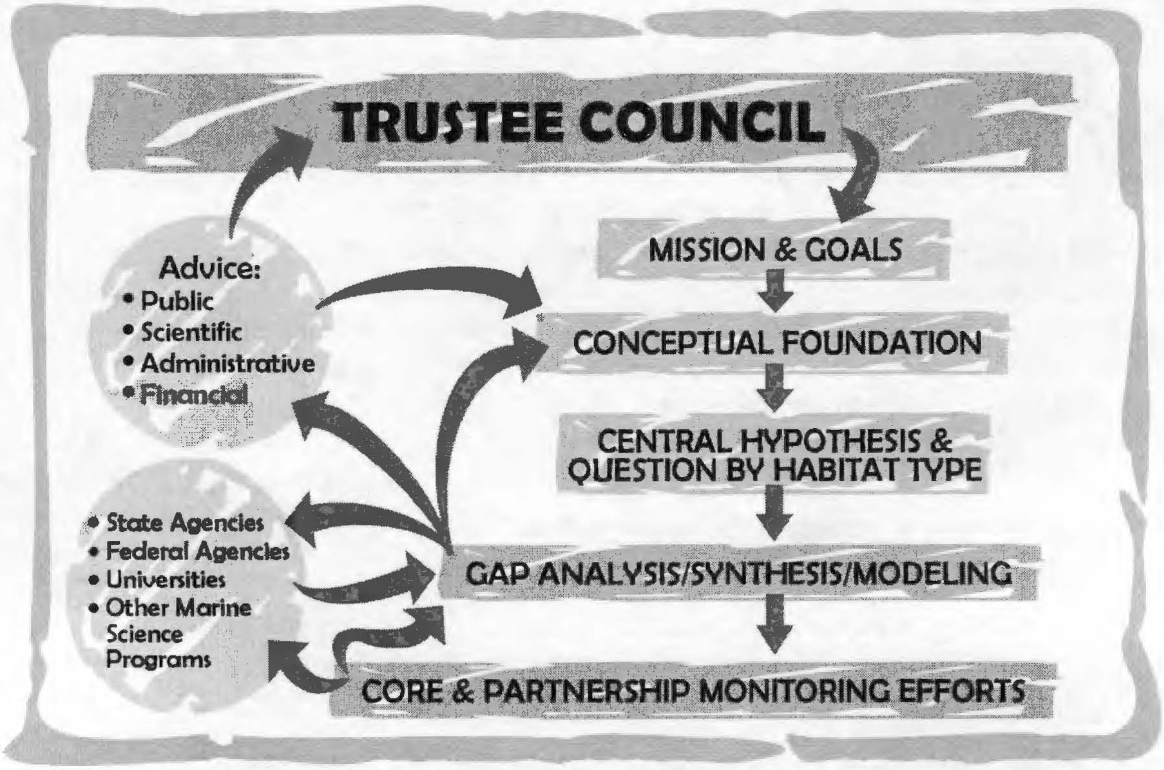


Figure 4.1 The process of selecting GEM monitoring efforts is a logical progression from the mission and goals, through the conceptual foundation, central hypothesis and question, gap analysis, synthesis and modeling, as influenced by input from various sources.

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 partial 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

4.3 Some Leading Hypotheses

In this section, a number of specific hypotheses about how natural forces and human activities control biological productivity are described Most of 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

- 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 and be reflected in changes in these populations Strong year classes of particular long-lived species also might result 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 at 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 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 higher trophic-level organisms 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 pollock as herring to raise a kittiwake chick to fledging during the nesting season (Piatt and Van Pelt 1998, Piatt 2000, Romano et al 2000) 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

The model was devêloped from observations 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, primary productivity, is strongly influenced by physical forces, and ultimately determines ecosystem productivity   However, the abundance of any particular population within the food web depends on three things   immediate food supply (prey), removals (mortality), and habitat

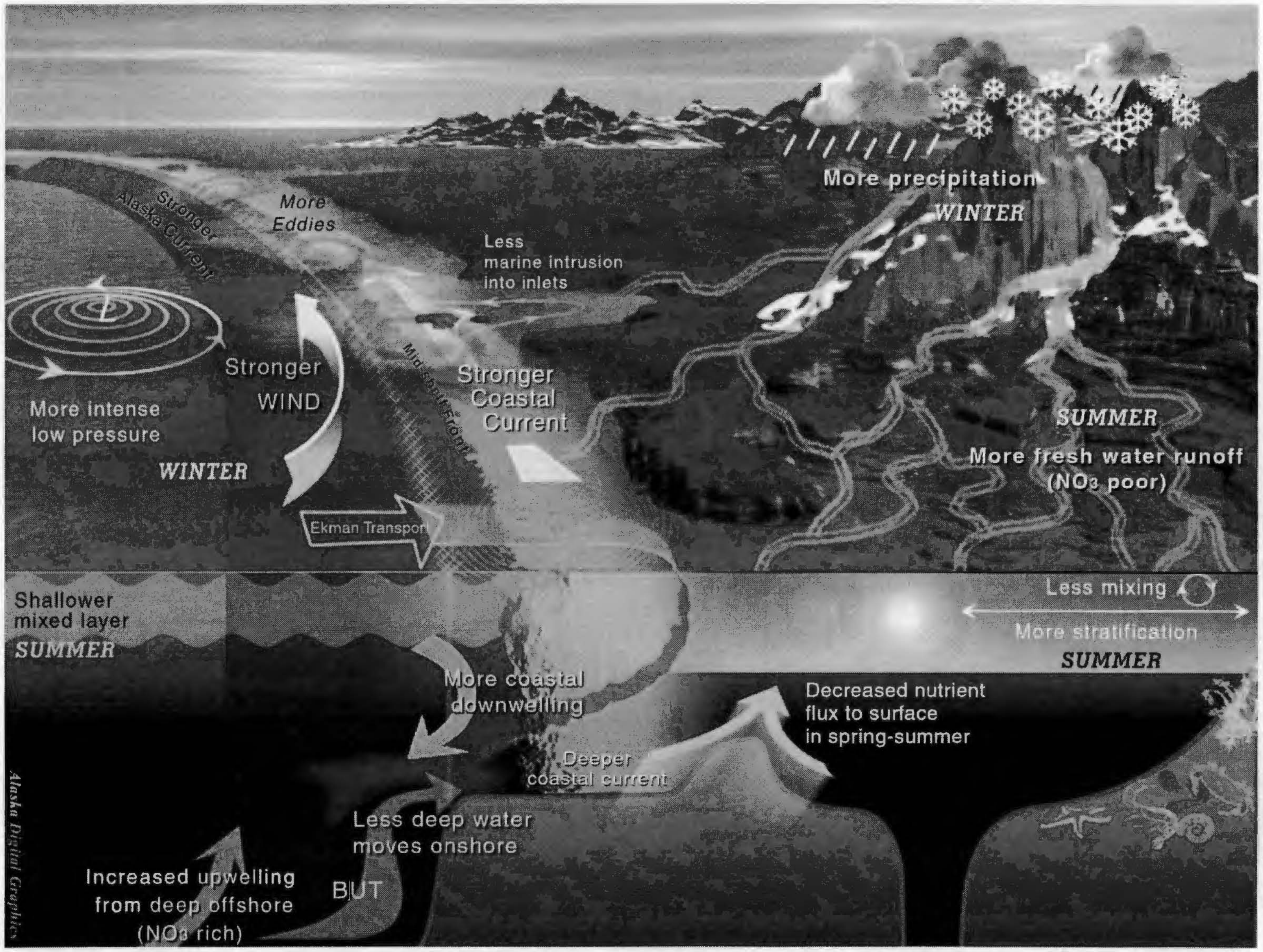


Figure 4.2a Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes: (a) in the physical processes during a positive PDO (strong wintertime low pressure), (b) the biological consequences of conditions in "a," (c) the physical changes in a negative PDO (weak wintertime low pressure) and (d) the biological consequences of conditions in "c."

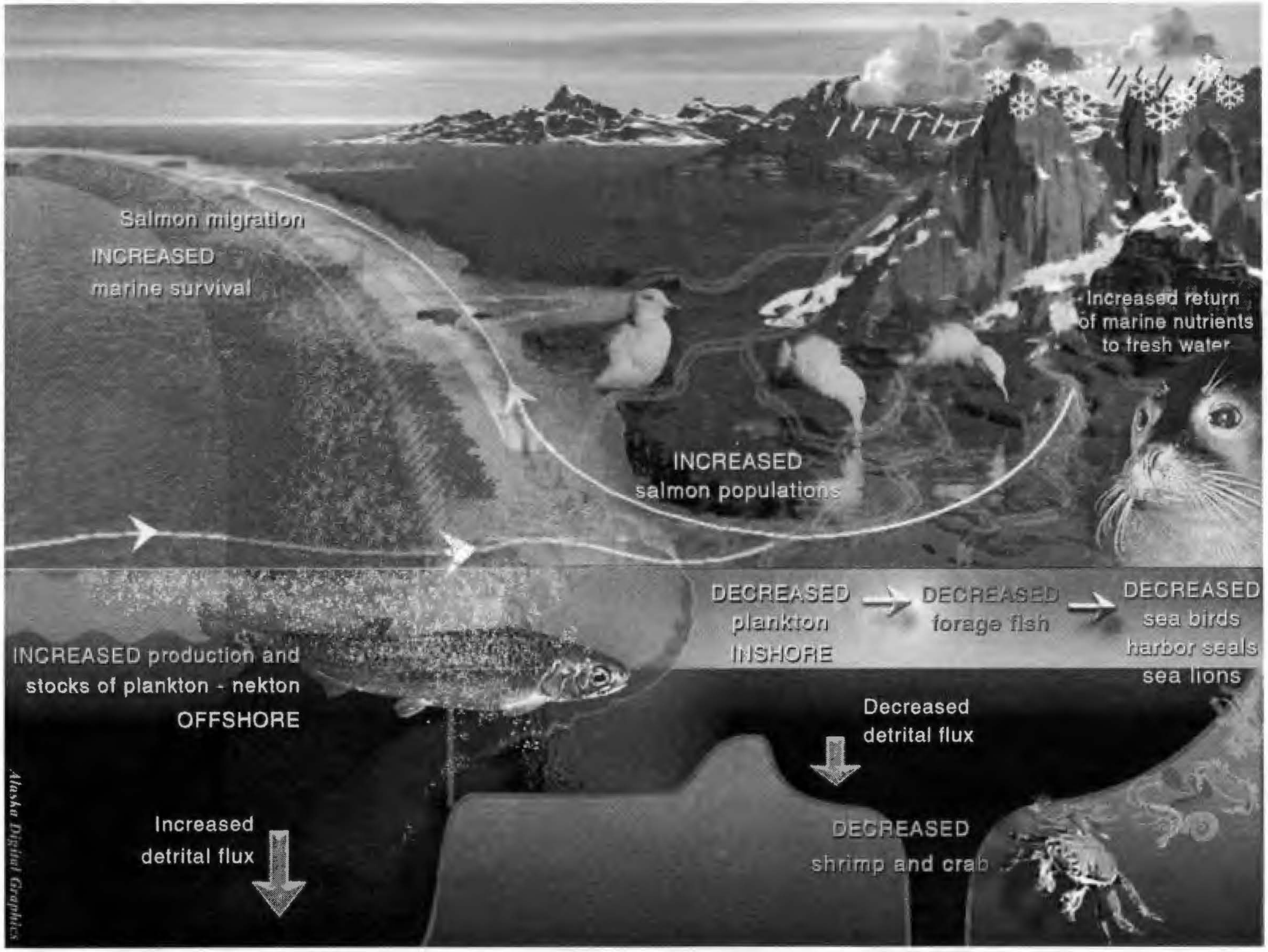


Figure 4.2b Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes: (a) in the physical processes during a positive PDO (strong wintertime low pressure), (b) the biological consequences of conditions in "a," (c) the physical changes in a negative PDO (weak wintertime low pressure) and (d) the biological consequences of conditions in "c."

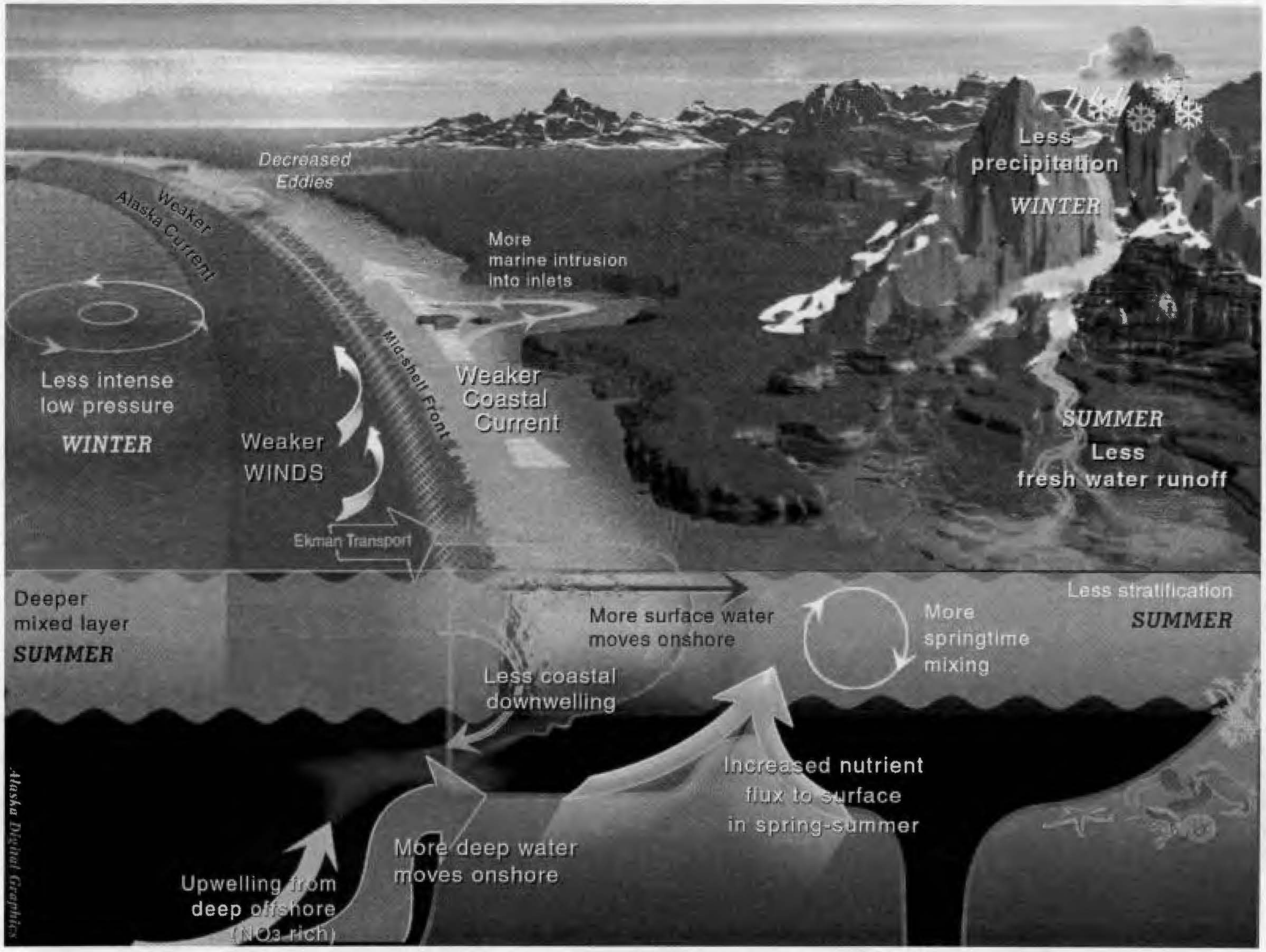


Figure 4.2c Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes: (a) in the physical processes during a positive PDO (strong wintertime low pressure), (b) the biological consequences of conditions in "a," (c) the physical changes in a negative PDO (weak wintertime low pressure) and (d) the biological consequences of conditions in "c."

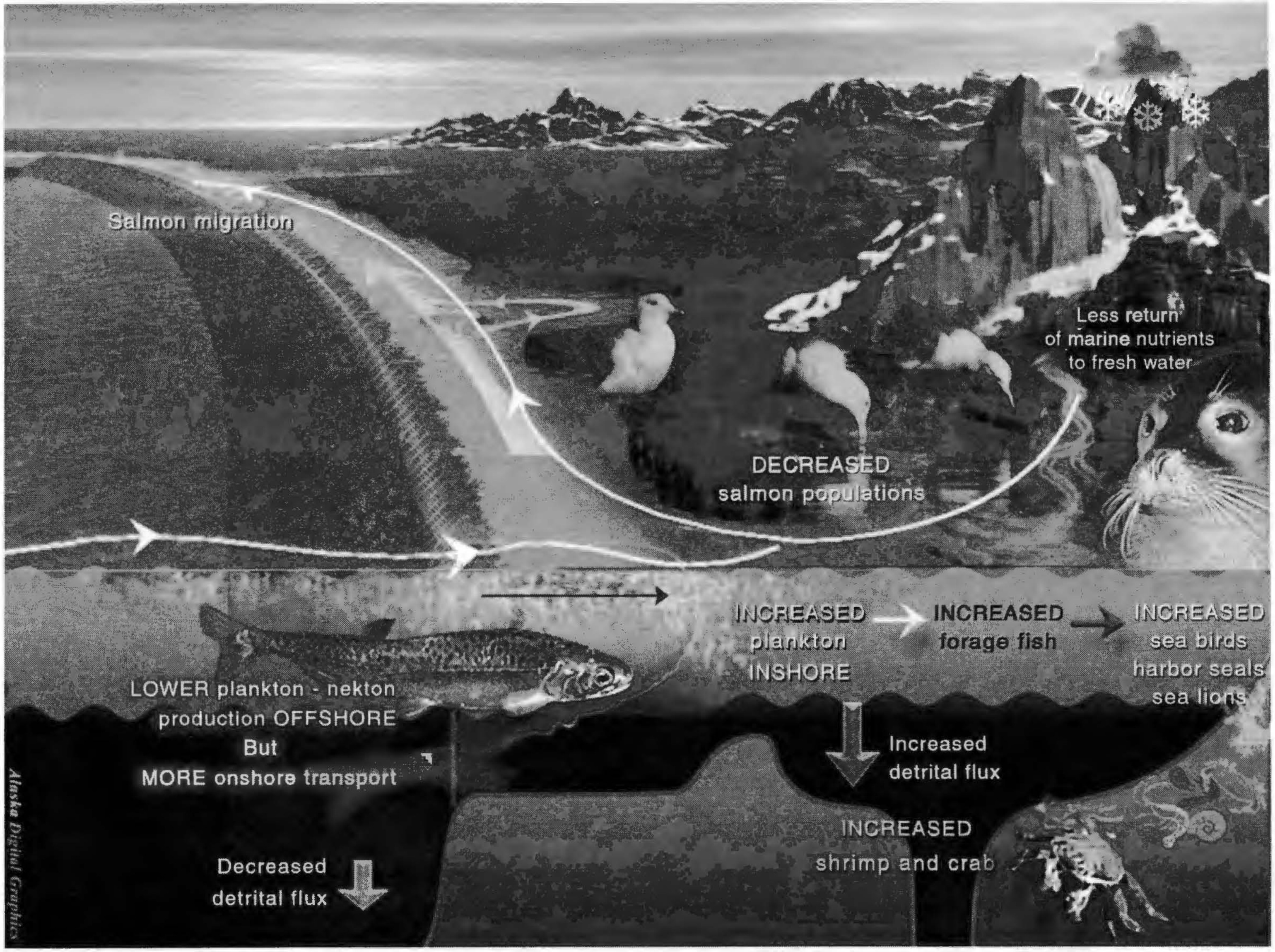


Figure 4.2d Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes: (a) in the physical processes during a positive PDO (strong wintertime low pressure), (b) the biological consequences of conditions in "a," (c) the physical changes in a negative PDO (weak wintertime low pressure) and (d) the biological consequences of conditions in "c."

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, loss of suitable habitat, decreases in growth, reproduction and immigration, and increases in the rate of removal (death and emigration) 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 animal populations 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 lit photic zone (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 spatial 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 well as other sources (such as nitrogen fixers).

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 and other physiological processes), 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 4.3, 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 Principal Ecological Concepts by Habitat

4.5.1 From Watersheds to the Central Gulf

The preceding ecological concepts can be applied directly to the GOA ecosystem to show how the system and its plant and animal populations are controlled. Taking the watersheds and marine areas of the GOA at a single glance, the importance of key geological features in shaping the natural physical and biological forces that control productivity is apparent (Figure 4.3). Note that features illustrated in Figure 4.3 are printed in bold in the following text. Natural forces are shaped by the surface topography of the Gulf. Storm tracks moving across the North Pacific from west to east can drive **Aleutian Low Pressure (ALP)** systems deep into the GOA until the

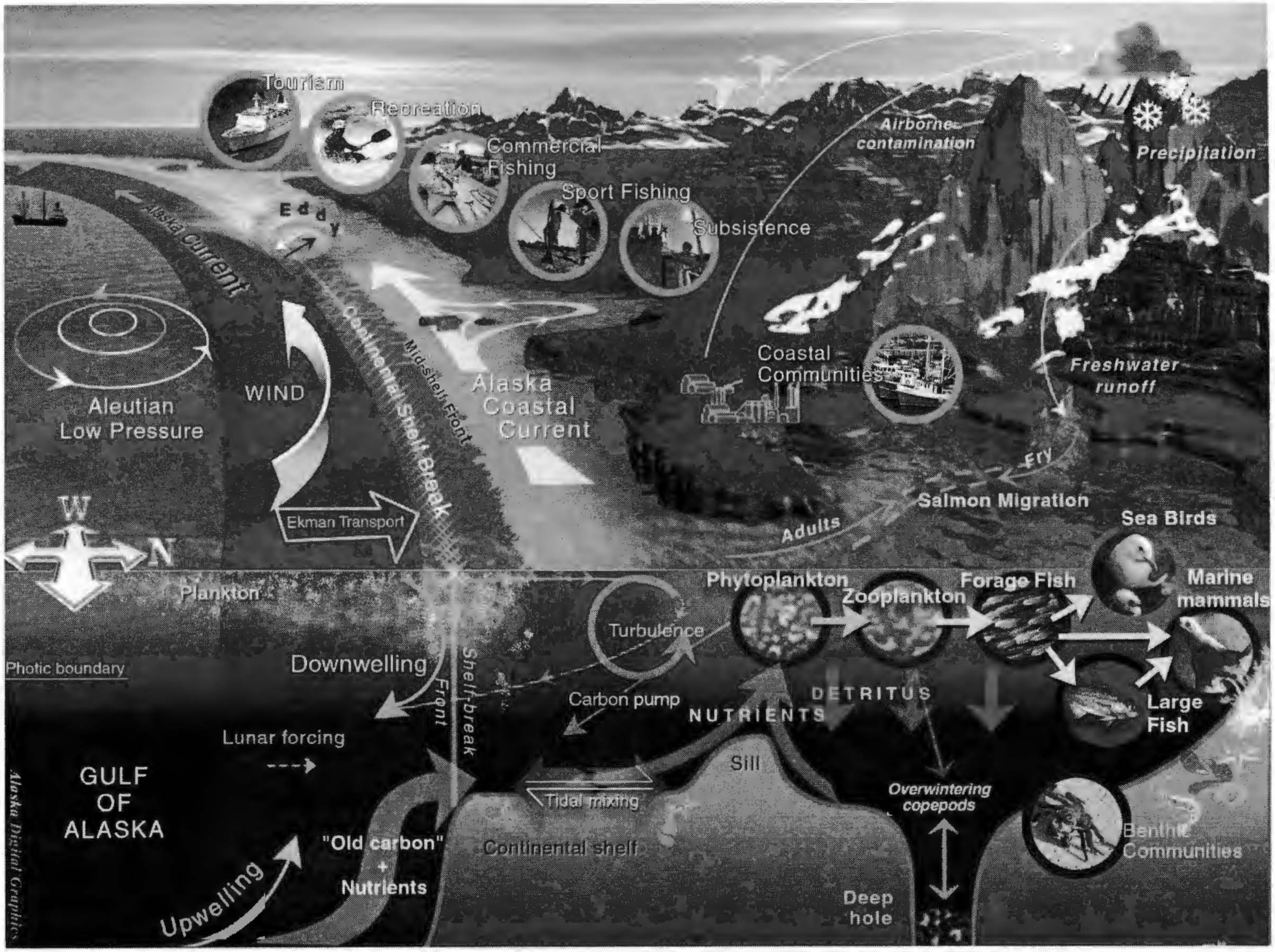


Figure 4.3 The physical and biological elements of the ecosystems of the northern GOA from the mountains surrounding the watersheds to the oceanic waters offshore.

encounter with **boundary mountains** causes the release of **precipitation** and **airborne contaminants** **Freshwater runoff** strengthens the **Alaska Coastal Current (ACC)** even as it brings airborne and terrestrial pollutants into the **watersheds** and **food webs**

Natural forces that control biological productivity are also shaped by the submarine topography (bathymetry) of the **continental shelf** Deep waters **upwell** across the **continental shelf break**, subsequently being carried across the **photic boundary** into areas of photosynthetic activity by the motion of surface currents, (ACC, **Alaska Current [AC]**), **lunar forcing**, the motion of the earth, and **tidal mixing** These deep waters carry **old carbon and nutrients** up into the food webs of the shelf and onshore areas Where the deep waters encounter islands, seamounts and **sills**, the resulting currents may deform the boundaries of the frontal zones of the ACC (**mid-shelf front**) and AC (**shelf-break front**), creating **eddies** that entrain plankton and other plants and animals for long periods of time (Figure 4 3)

Natural physical forces control productivity by limiting the amount of food and availability of habitats During the winter especially, the ALP produces **wind-driven** transport of surface marine waters (**Ekman transport**), bringing water onshore Movement of water onshore creates **downwelling** that takes plankton and associated nutrients out of the photic zone On the other hand, the wind may act to hold the nutrients dissolved in water and held in **detritus** in the photic zone in some areas, because wind also produces **turbulence** that mixes the surface water Turbulent mixing causes nutrients to be retained in surface waters, and retention increases production of **phytoplankton**, the base of the food web in surface waters Production of **zooplankton**, primary productivity, is the trophic connection (linkage) of phytoplankton to production of **forage fish**, which in turn links primary productivity to **seabirds**, **large fish**, **marine mammals**, and **benthic and intertidal communities** (Figure 4 3)

The biogeochemical cycle is an important collection of natural biological processes controlling the productivities of both marine and terrestrial environments The mechanisms that move carbon from the surface to the deep waters, are known collectively as the **carbon pump.** Atmospheric carbon moves into seawater as carbon dioxide to be incorporated by phytoplankton during photosynthesis Carbon also enters the sea as carbonates leached from the land by freshwater runoff, as plant debris, and as other biological input, such as immigrations of salmon (**salmon fry**) and other anadromous species Carbon moves to benthic communities and to deep water as detritus and emigrant animals (**overwintering copepods** and migrating myctophids) Emigrant animals (**adult salmon** and other anadromous species) also move marine carbon (and phosphorous and nitrogen) into the watersheds (Figure 4 3)

As illustrated by the interactions of biological and physical components of the biogeochemical cycle, natural biological forces modify the effects of natural physical forces on birds, fish, and mammals Because of biological-physical interactions, natural physical forces that cause changes in **primary productivity** do not necessarily cause proportional changes in populations of birds, fish, mammals, and benthic animals For example, the effects of physical forces on the amount of food available from primary productivity are modified through other natural forces, such as **predation and competition** among individuals, collectively known as the **trophic linkages.** Populations that respond strongly to physical forcing of primary productivity on approximately the same time scales are termed "strongly coupled," and those that exhibit variable responses are termed "weakly coupled" with respect to those physical variables Note that physical forcing changes not only the food available from primary productivity, but also the extent of habitats available for reproduction and feeding (Figure 4 3)

Human actions also serve to change the ways in which populations of plants and animals respond to the natural physical forces that affect the responses of reproduction, growth, and survival through limiting food and habitat Human actions such as water withdrawals, sewage discharge, and development of **coastal communities** change productivity by altering habitat availability and trophic linkages Fishing and other harvesting activities (**subsistence, sport, commercial**) affect death rates through removals Other forms of human action are more subtle, but no less effective, controls on productivity **Recreation and tourism** may alter growth and reproduction by disturbing rookeries and introducing pollutants **Commercial marine transport** may alter productivity by introducing pollutants oil spills) and noxious species as competitors and predators (Figure 4 3)

In summary, the GOA and its watersheds are part of a larger oceanic ecosystem in which natural physical forces such as currents, upwelling, downwelling, precipitation and runoff, acting over large and small distances, play important roles in determining basic biological productivity Natural physical forces respond primarily to seasonal shifts in the weather, and in particular to long-term changes in the intensity and location of the ALP system in winter Increased upwelling offshore appears to increase inputs of nutrients to surface waters, which increases productivity of plankton Increased winds appear to increase the transport of zooplankton shoreward toward and past the shelf-break How often and how much offshore zooplankton sources contribute to coastal food webs depends on natural physical and biological forces such as predation, migration, currents and structure of the fronts, formation and stability of eddies, degree and extent of turbulence, and responses of plankton to short and long-term changes in temperature and salinity

A wide range of human impacts interacts with natural biological and physical forces to change productivity and community structure in the GOA Human activities have the most direct and obvious impacts at those sites in watersheds and intertidal areas where human populations are high Nonetheless, some human activities affect populations of birds, fish, shellfish, and mammals far offshore, and also have impacts far from the sites of the actions In short, human activities and natural forces together act over global to local scales to drive and shape marine and terrestrial life in the GOA and its tributary watersheds Natural forces and human impacts, as exemplified by heat and salt distribution, insolation, biological energy flow, biogeochemical cycling and food web structure, fishery removals, pollutant inputs, and the relationships among them over time define the state of the marine ecosystem Natural forces and human impacts bring about changes in populations of birds, fish, shellfish, and mammals by altering the relationships among these state variables that define the marine ecosystem

4.5.2 Trophic Structure

The principal trophic groups of the northern GOA are represented by the analysis of Okey and Pauly for PWS (Okey and Pauly 1998b) The upper trophic levels (3 5+) are dominated by large vertebrates, including toothed whales, harbor seals and sea lions, seabirds, sharks, and fish species that are large as adults (Table 4 1) Primary consumers on trophic levels between 1 (primary producers) and 3 (tertiary) include jellyfish, zooplankters (including larvae of crustaceans and fish), infauna, and meiofauna The primary sources of food in the northern GOA are phytoplankton, macroalgae and eelgrass, and detritus The species of the dominant biomass are macroalgae and eelgrass, followed closely by shallow and deep infauna, deep epibenthos, and herbivorous zooplankton In terms of production per biomass (P/B), the dominant species groups are clearly the phytoplankton, followed by the herbivorous zooplankton In terms of food consumption per biomass (Q/B), invertebrate-eating birds top the list, followed by small cetaceans and pinnipeds, and herbivorous zooplankton Using this concept of the trophic structure of the northern GOA, data on the lower trophic levels (<3 5) are extremely important to detecting and understanding change in valued marine-related resources

Table 4 1 Representative Trophic Groups of the Northern GOA Arranged in Descending Order by Trophic Level

Group name	Trophic Level	Biomass (t km^{-2} year^{-1})	P/B (yr^{-1})	Q/B (yr^{-1})
Orcas	4 98	0 003	0 050	8 285
Sharks	4 81	0 700	0 100	2 100
Pacific halibut	4 59	0 677	0 320	1 730
Small cetaceans (porpoises)	4 52	0 015	0 150	29 200
Pinnipeds (harbor seal & sea lion)	4 45	0 066	0 060	25 550
Lingcod	4 33	0 077	0 580	3 300
Sablefish	4 29	0 293	0 566	6 420
Arrowtooth flounder adult	4 25	4 000	0 220	3 030
Adult salmon	4 17	1 034	6 476	13 000
Pacific cod	4 14	0 300	1 200	4 000
Arrowtooth flounder juvenile	4 01	0 855	0 220	3 030
Avian predators	3 89	0 002	5 000	36 500
Seabirds	3 78	0 011	7 800	150 60

Table 4.1 Representative Trophic Groups of the Northern GOA Arranged in Descending Order by Trophic Level

Group name	Trophic Level	Biomass (t km^{-2} year^{-1})	P/B (yr^{-1})	Q/B (yr^{-1})
Deep demersal fish (skates and flatfishes)	3 78	0 960	0 930	3 210
Pollock age 1+	3 76	7 480	0 707	2 559
Rockfish	3 74	1 016	0 170	3 440
Baleen whales	3 65	0 149	0 050	10 900
Salmon fry 0-12 cm	3 51	0 072	7 154	62 800
Nearshore demersal fish (greenling and sculpin)	3 35	4 200	1 000	4 240
Squid	3 26	3 000	3 000	15 000
Eulachon	3 25	0 371	2 000	18 000
Sea otters	3 23	0 045	0 130	117 000
Deep epibenthos	3 16	30 000	3 000	10 000
Capelin	3 11	0 367	3 500	18 000
Adult herring	3 10	2 810	0 540	18 000
Pollock age 0	3 07	0 110	2 340	16 180
Shallow large epibenthos	3 07	3 100	2 100	10 000
Invertebrate eating bird	3 07	0 005	0 200	450 500
Sandlance	3 06	0 595	2 000	18 000
Juvenile herring	3 03	13 406	0 729	18 000
Jellies	2 96	6 390	8 820	29 410
Deep small infauna	2 25	49 400	3 000	23 000
Near omni-zooplankton	2 25	0 103	7 900	26 333
Omni-zooplankton	2 25	24 635	11 060	22 130
Shallow small infauna	2 18	51 500	3 800	23 000
Meiofauna	2 11	**4 475**	4 500	22 500
Deep large infauna	2 10	28 350	0 600	23 000
Shallow small epibenthos	2 05	26 100	2 300	10 000
Shallow large infauna (clams, etc)	2 00	12 500	0 600	23 000
Near herbi-zooplankton	2 00	0 136	27 000	90 000
Herbi-zooplankton	2 00	30 000	24 000	50 000
Near phytoplankton	1 00	**5 326**	190 000	0 000
Offshore phytoplankton	1 00	**10 672**	190 000	0 000
Macroalgae/eelgras	1 00	125 250	5 000	0 000
Inshore detritus	1 00	3 000	-	-
Offshore detritus	1 00	4 500	-	-

Notes Bold values were calculated by the Ecopath software

P/B is production per biomass Q/B is food consumption per biomass

Source Table 74 (Okey and Pauly 1998a)

4.5.2 Watersheds

Watersheds are linked by geochemical cycles and common climatic forcing to the marine ecosystem Input of terrestrial carbon contributes to the carbon budget of the oceans Likewise, marine contributions of nutrients appear to be important to growth of aquatic and terrestrial plants in watersheds

4.5.2.1 Physical Forcing and Primary Production

Primary natural forces are precipitation and insolation Watersheds depend on import of marine nutrients by anadromous fish and other animals Therefore, maintenance of healthy salmon runs and populations of terrestrial animals that feed in the nearshore marine environment is key to healthy watershed ecosystems Woody debris and vegetation from land are also imported to the marine environment, providing a carbon source and habitat for some species The common effects of climate also link these two systems Fresh water from coastal watersheds contributes huge amounts of fresh water to the GOA and makes possible the ACC–the single most dominant and integrating feature of the physical environment on the continental shelf

4.5.2.2 Food, Habitat and Removals of Valued Species

Human activities in the watersheds that remove natural vegetation can result in soil erosion and its attendant effects on stream and coastal marine life Fresh water can carry contaminants to the marine environment Sources of these contaminants can be of local origin–sewage and septic wastes, industrial and military wastes, motor vehicles, and oil from spills–or imported from distant sources and carried across the Pacific Ocean by atmospheric processes

4.5.3 Intertidal and Subtidal

The intertidal and subtidal–or nearshore–area is technically a part of the ACC regime in most places (the next habitat to be considered), except arguably in some embayments, such as the fjord systems in northern PWS But, because of the importance and vulnerability of the intertidal and shallow subtidal areas and the dependence of so many valued species on nearshore habitat, it is treated here separately from the ACC

4.5.3.1 Physical Forcing and Primary Production

The productivity of intertidal and subtidal marine communities depends on both fixed algae and some other vascular plants in shallow water, as well as free-floating phytoplankton. Nutrient supply to fixed plants is not well characterized, but presumably is controlled by oceanographic processes and seasonal cycles of water turnover on the inner shelf as well as some contributions from stream runoff This process of nutrient supply is essentially the same as for nearshore phytoplankton Ultimately, as mentioned in Section 3 5, Volume II, the run up of deepwater from the central GOA onto the shelf and some poorly characterized processes for cross-shelf transport of the nutrients are critical to growth of both fixed and floating nearshore algae The nearshore waters can be depleted of nutrients during 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 attached 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 sea 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, discharge 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 is clearly driven by patterns in the aforementioned wind mixing, and 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 onshore 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 in the 1990s (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 (Bogard et al 1994, Bailey et al 1997) 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 ALP system has 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 ALP 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, and
- 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, 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 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

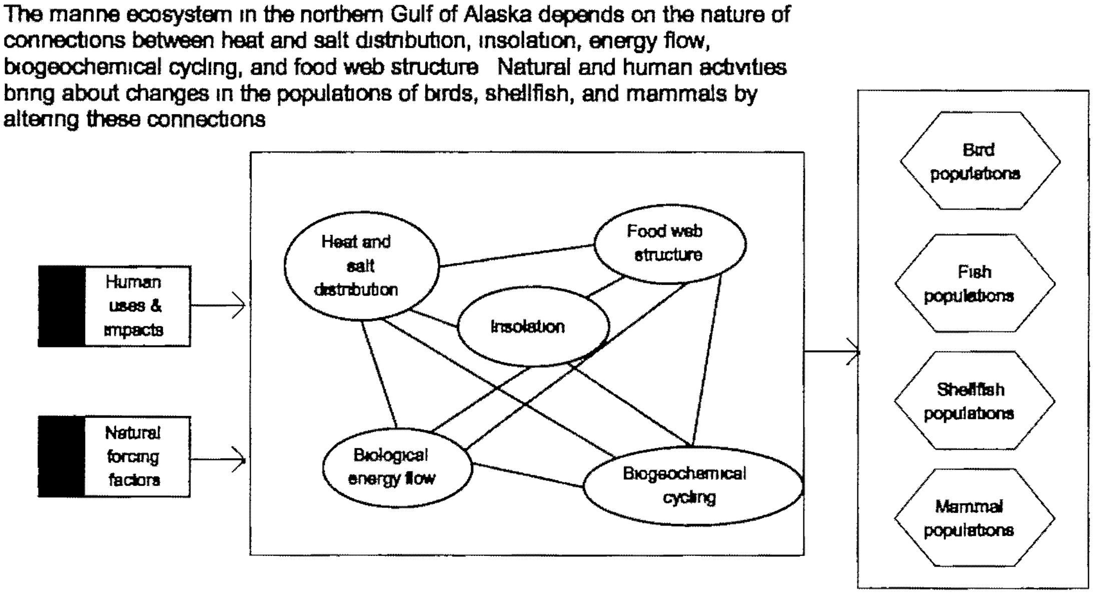
4.7 Central Hypothesis and Questions by Habitat Type

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 (Figures 4.4 and 4.5).



The marine ecosystem in the northern Gulf of Alaska depends on the nature of connections between heat and salt distribution, insolation, energy flow, biogeochemical cycling, and food web structure. Natural and human activities bring about changes in the populations of birds, shellfish, and mammals by altering these connections.

Figure 4.4. Relations among major parts of the GEM conceptual foundation

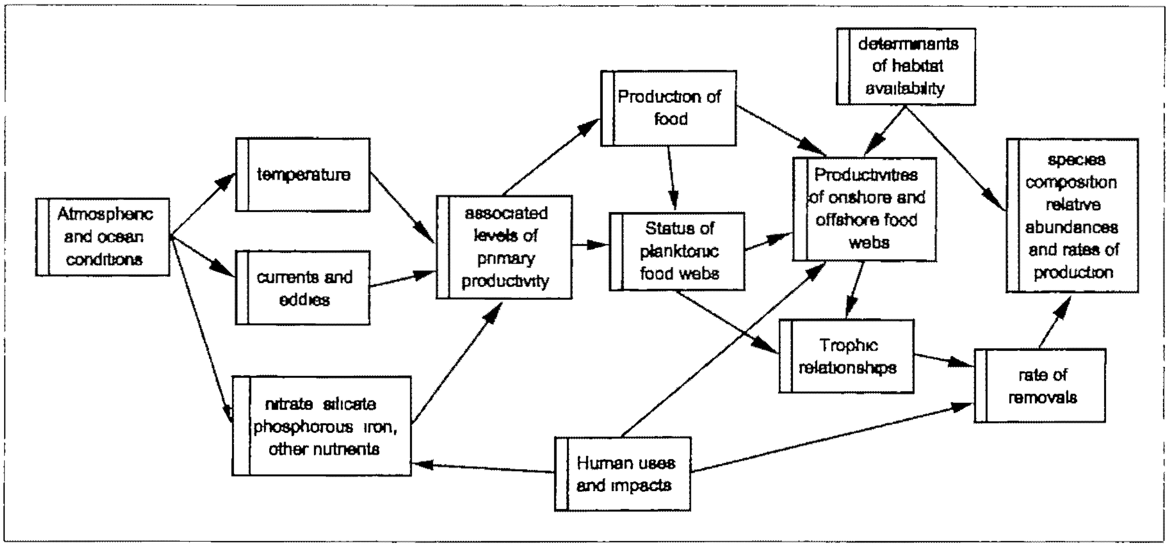


Figure 4 5 Possible connections among specific mechanisms and agents of change in living marine-related resources

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 (Figure 4 6) 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 and biological responses (Francis et al 1998)

The central hypothesis is easily 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 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

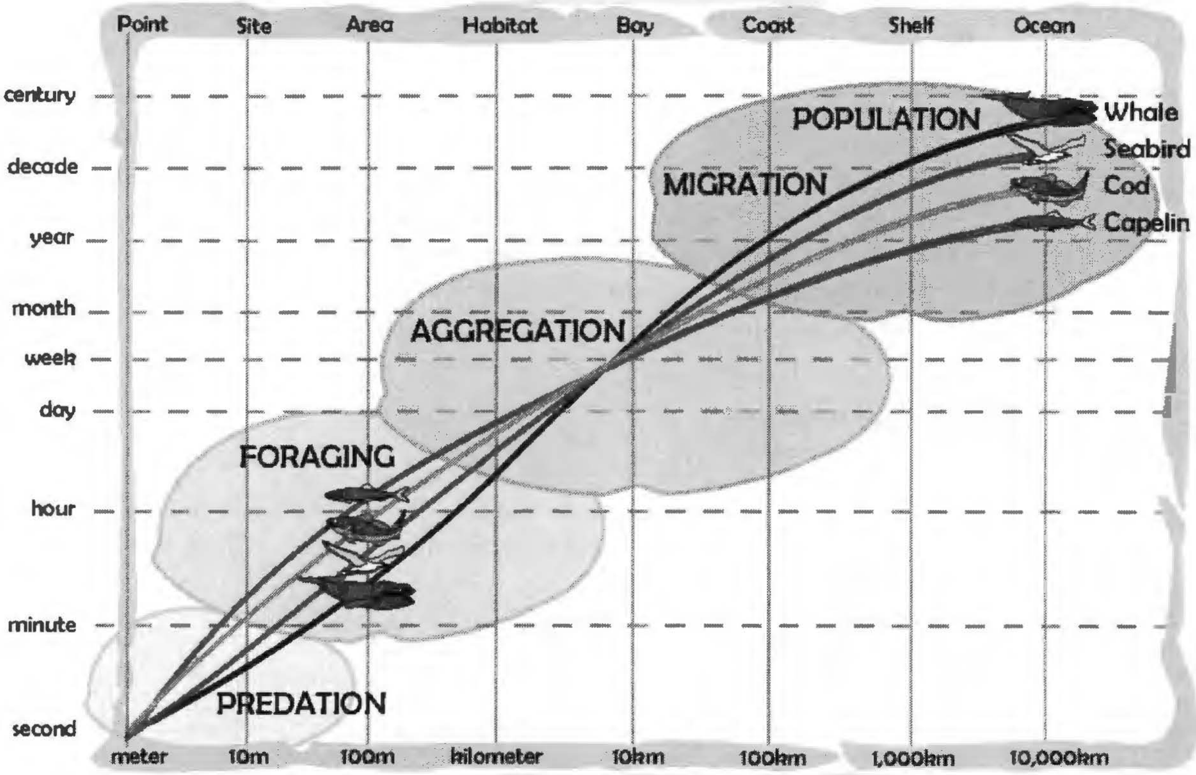


Figure 4.6 Scales of time and space corresponding to key elements and processes in ecosystems of the GOA. Illustration provided by John Piatt.

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?***

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 small-scale development and increased urbanization) 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?***

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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 hierarchical 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

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 several of the most relevant North Pacific 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

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

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 3-D 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 nauplIar, 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 Appendix C prepared by Kerim Aydin

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

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 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

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

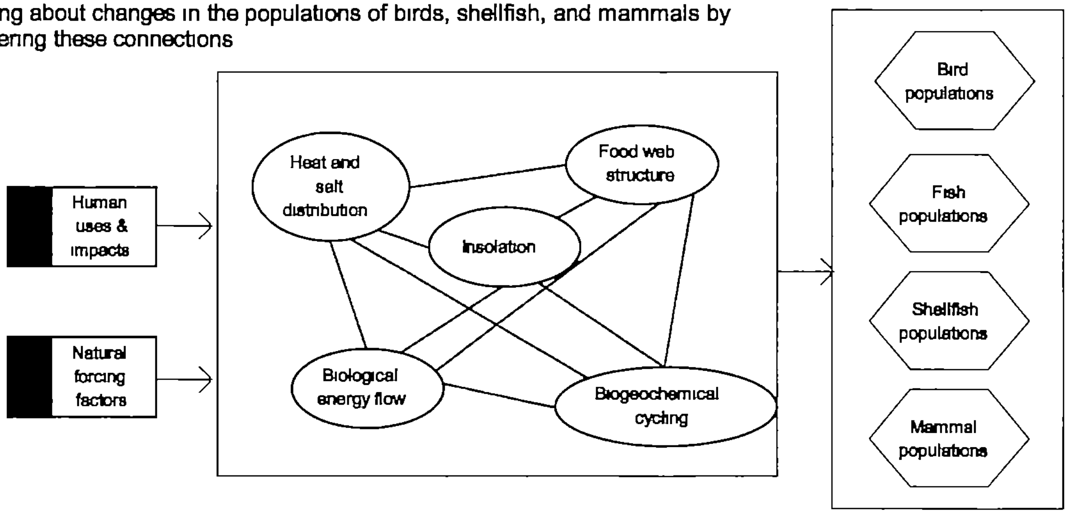

The marine ecosystem in the northern Gulf of Alaska depends on the nature of connections between heat and salt distribution, insolation, energy flow, biogeochemical cycling, and food web structure Natural and human activities bring about changes in the populations of birds, shellfish, and mammals by altering these connections

Figure 5 1 Influence diagram illustrating GEM draft conceptual foundation

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 (NRC 2000 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.

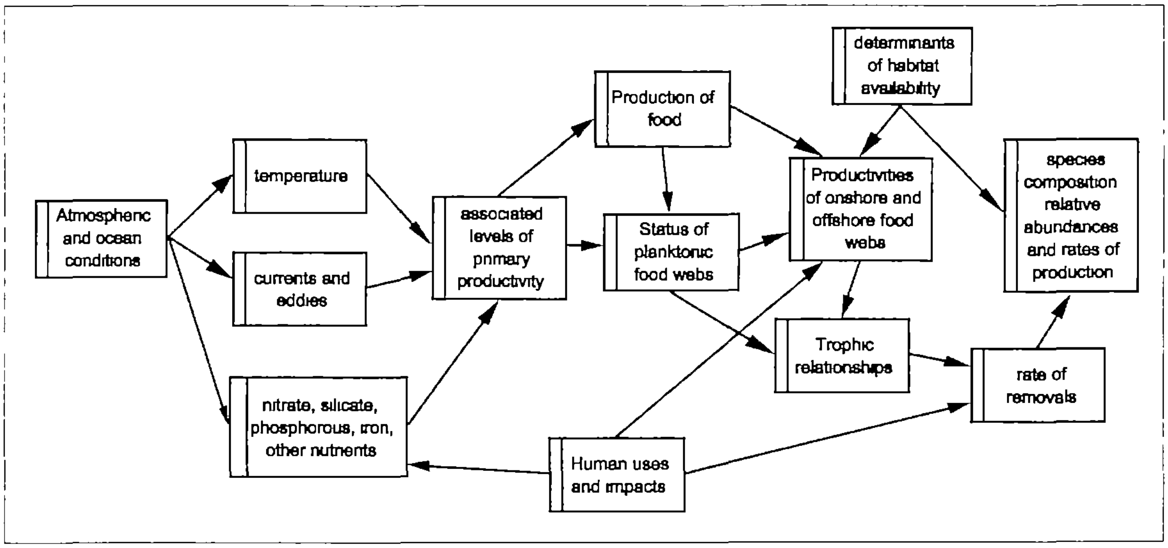
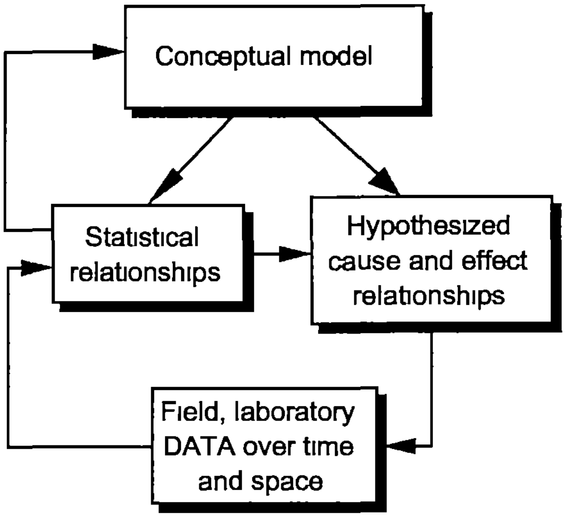


Figure 5 2 Linkages among system attributes that the conceptual foundation identified as "essential" to monitor



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 implementation 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 C) 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

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)

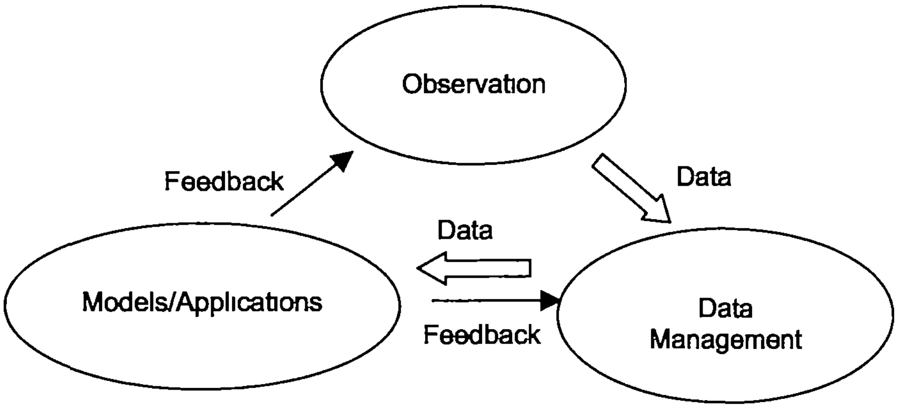

Figure 6 1 GOOS model of data management

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 may 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 will 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 would 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 are classified by the operations that must be applied to them during the archive and retrieval cycle This classification often cuts across the content-based classifications used during data analysis Although biologic data are more often collected by observation or laboratory work and physical data are 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

- **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 are 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 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

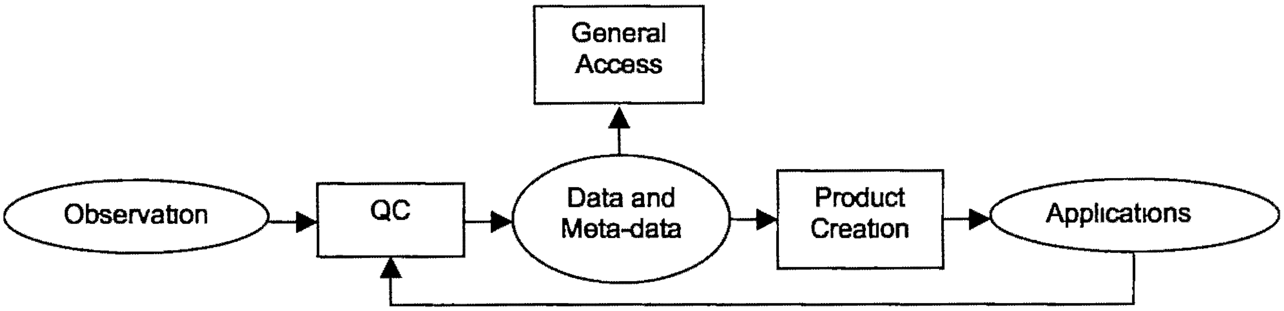

Figure 6 2 The GEM data system

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 are 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

6.5 Reference List

GOOS 2000 Strategic design plan for the coastal component of the Global Ocean Observing System UNESCO GOOS Report No 90