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

The GEM Program Document

July 9, 2002

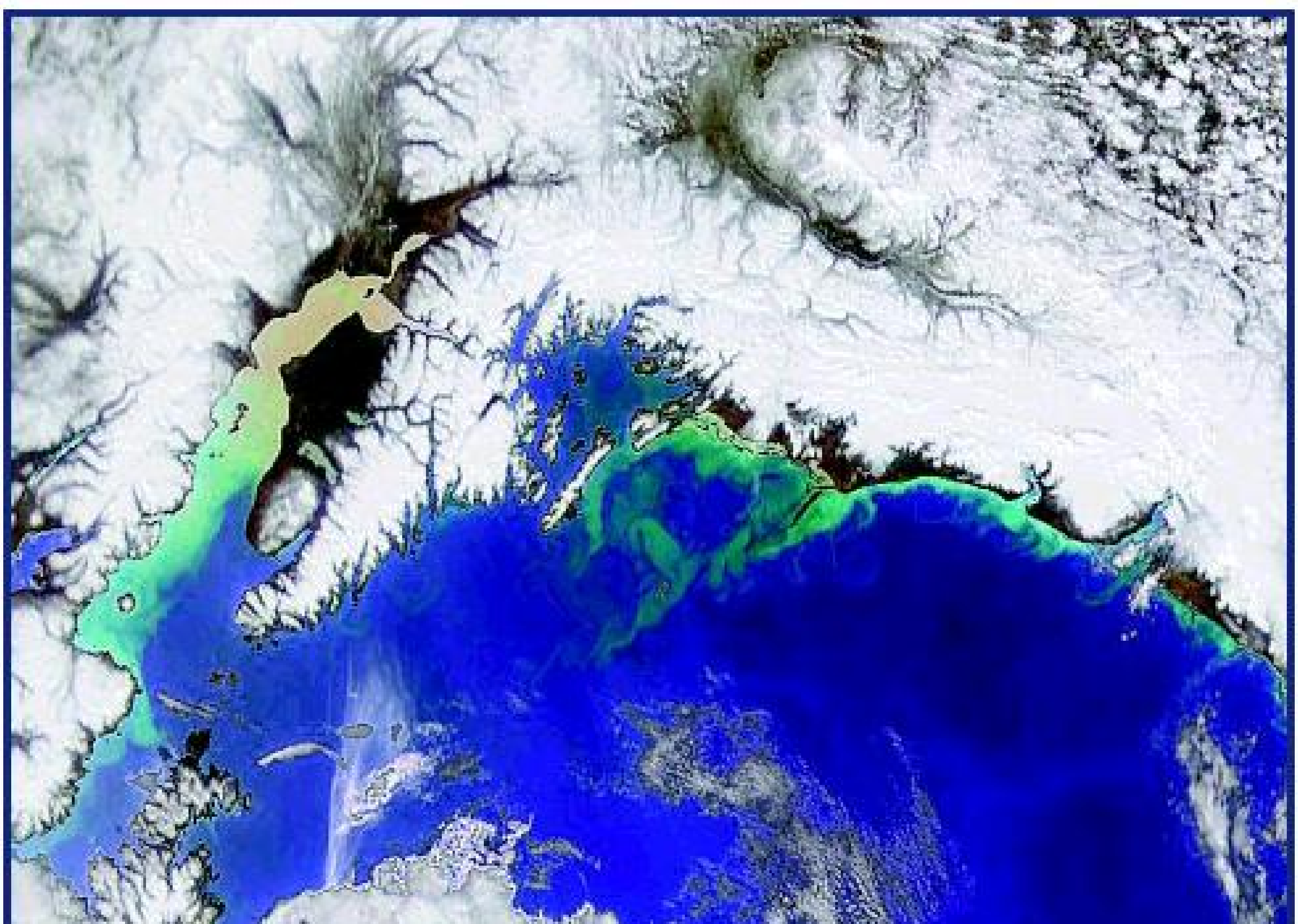

Photo courtesy the SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE Corporation

ACKNOWLEDGMENTS

The primary authors of the GEM Program Document are Molly McCammon, Phil Mundy, and Bob Spies. Editors for the document were Molly McCammon, Phil Mundy, Katharine Miller, and Bob Walker. Thanks to Bob Spies and Judy Griffin for editorial work on earlier versions. Cherri Womac has been instrumental in proofing and formatting the entire document.

Credit goes to the scientific and technical authors of the following portions: Chapters 2 and 6 – Phil Mundy and Bob Spies; Chapter 7 – Ted Cooney, Jim Bodkin, Anne Hollowed, Lloyd Lowry, Phil Mundy, Peter Olsson, Charles Peterson, Bob Spies, Alan Springer, Tom Weingartner, Jim Richardson and Gregg Erickson; Chapter 8 - Gretchen Oosterhout; Chapter 9 – Charles Falkenberg; Appendix B – Bob Spies; Appendix C – Geoff Shester; Appendix D – Joe Sullivan, Dede Bohn, Veronica Christman, Sandra Schubert, and Phil Mundy; Appendix E – Kerim Ayden; Appendix F - Michael H. Martin; Appendix G – Phil Mundy and Cherri Womac; Appendix H – Bob Spies.

A special appreciation goes to the National Research Council's Committee to Review the Gulf of Alaska Ecosystem Monitoring Program: Michael Roman, Chair, Don Bowen, Andria A. Elskus, John J. Goering, George Hunt, Seth Macinko, Donal Manahan, Brenda Norcross, J. Steven Picou, Thomas C. Royer, Jennifer Ruesink, and Karl Turekian. The committee was ably staffed by Chris Elfring, David Policansky and Ann Carlisle.

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

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

ACRONYMS AND TERMS MOST FREQUENTLY USED

ACC: Alaska Coastal Current

ADEC: Alaska Department of Environmental Conservation

ADF&G: Alaska Department of Fish & Game

Aleutian Low: Aleutian Low Pressure System

ANHSC: Alaska Native Harbor Seal Commission

ARLIS: Alaska Resources Library and Information Services

ARMRP: Alaska Regional Marine Research Plan

APEX: The Alaska Predator Ecosystem Experiment

CARTs: classification and regression trees

CPR: Continuous Plankton Recorder

CPUE: catch per unit effort

CRRC: Chugach Regional Resource Commission

DDT: dichlorodiphenyltrichloroethane

ENSO: El Niño Southern Oscillation

EPA: U.S. Environmental Protection Agency

ESA: Endangered Species Act

FGDC: Federal Geographic Data Committee

FOCI : Fisheries Oceanography Coordinated Investigations

ftp: file transfer protocol

GAK1: Gulf of Alaska station 1 located at the mouth of Resurrection Bay (60 N, 149 W)

GEM: Gulf of Alaska Monitoring and Research Program

GIS: Geographic Information System

GLOBEC: Global Ocean Ecosystem Dynamics

GLOBEC NPZ: nutrient-phytoplankton-zooplankton

GOA: Gulf of Alaska

IOC: Intergovernmental Oceanographic Commission

KBNERR: Kachemak Bay National Estuarine Research Reserve

LIDAR : light detection and ranging

MMPA: Marine Mammal Protection Act

MODIS: Moderate Resolution Imaging Spectroradiometer

NEP: National Estuary Program

NMFS : National Marine Fisheries Service

NMML: NMFS National Marine Mammal Laboratory

NASA: National Aeronautics and Space Administration

NOAA: National Oceanic and Atmospheric Administration

NODC: National Ocean Data Center

NPAFC: North Pacific Anadromous Fish Commission

NPI: North Pacific Index

NRC: National Research Council

NVP: The Nearshore Vertebrate Predator Project

OCC: Ocean Carrying Capacity

PAC: Public Advisory Committee

PAG: Public Advisory Group

PCB: polychlorinated biphenyls

PDO: Pacific Decadal Oscillation

PWS: Prince William Sound

PWSAC: Prince William Sound Aquaculture Corporation

PWS-SEK: Prince William Sound-Southeast Kenai

QC: quality control

SCOR: Scientific Committee on Oceanic Research

SDRs: satellite-linked depth recorders

SEA: The Sound Ecosystem Assessment

SeaWiFS: Sea-viewing Wide Field-of-view Sensor

SOIREE: Southern Ocean Iron Release Experiment

STAC: Scientific and Technical Advisory Committee

TEK: Traditional Ecological Knowledge

Trustee Council: ***Exxon Valdez*** Oil Spill Trustee Council

USFS: U.S. Forest Service

USFWS: U.S. Fish and Wildlife Service

USGS: U.S. Geological Survey

WDFW: Washington Department of Fish and Wildlife

WKP: Western Kenai Peninsula

WMS: Open GIS Consortium's Web Mapping Server

OVERVIEW OF THE GEM DOCUMENT

The Gulf of Alaska Ecosystem Monitoring and Research (GEM) Program document describes the basic monitoring and research program and the scientific background behind the development of essential program components. Chapters 1 through 5 explain the basic motivations for the program, conceptual foundation, tools and strategies for achieving program goals, and program implementation and management. Chapters 6 through 9 present the factual basis for the program including detailed descriptions of two important components of the program: 1) modeling (Chapter 8) and 2) data management and information transfer (Chapter 9). Table O.1 identifies the question addressed by each chapter and the products provided.

Table O.1 Contents of the GEM Program Document

Chapter	Title Question Addressed	Products
1	Vision *Why do this and what do we hope to achieve?*	Mission and goals Geographic scope, funding and governance
2	Conceptual Foundation *How do we think the ecosystem works?*	Central hypothesis Habitat types and time-space scales
3	Tools and Strategies *What information do we need and how do we get it?*	Tools: Gap Analysis, Synthesis, Research, Monitoring, Modeling, and Data Management Strategies: Community Involvement and Traditional Knowledge, and Resource Management Applicability
4	Program Implementation *Where are we going to start and how will we proceed? (This chapter is expected to change over time.)*	Potential questions by habitat type Program implementation and partnering
5	Program Management *What are the processes and policies for monitoring and research?*	Program administration Roles and responsibilities of the GEM components
6	Introduction to the Scientific Background *What are the theories and principles on which the conceptual foundation is based?*	Leading hypotheses in marine ecosystems Principal ecological concepts and theories

Table O.1 Contents of the GEM Program Document

Chapter	Title Question Addressed	Products
7	Scientific Background: Physics, Biology, Human Uses and Economics *Comprehensive review of the current state of scientific knowledge of Gulf of Alaska ecosystems*	Overview of physical, chemical, and biological characteristics of the Gulf of Alaska Status of non-human populations, predators, and prey Status of human activities and socio-economics in the GOA
8	Modeling *What is the role of modeling in GEM?*	Modeling definitions and options for program implementation
9	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	Acronyms and Web links	
B	Recovery Status of Injured Resources	
C	EVOS Tribal and Community Involvement	
D	GEM Database	
E	Glossary of Existing Agency Programs and Projects	
F	North Pacific Models of the Alaska Fisheries Science Center and Other Selected Organizations	
G	Fish And Invertebrate Species From 1996 NMFS Trawl Survey Of The Gulf Of Alaska	
H	Collected Research Questions	

CONTENTS

Figures

Tables

EXECUTIVE SUMMARY

On March 24, 1989, the ***T/V Exxon Valdez*** ran aground on Bligh Reef in Prince William Sound, spilling almost eleven million gallons of North Slope crude oil. The event was the largest tanker spill in U.S. history, contaminating approximately 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, the Exxon Corporation agreed to pay the United States and the State of Alaska $900 million over ten 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 ***Exxon Valdez*** Oil Spill Trustee Council (Trustee Council) was formed to administer the restoration funds, and in 1994 the ***Exxon Valdez*** Oil Spill Restoration Plan was adopted to guide the development and implementation of a comprehensive, interdisciplinary recovery and rehabilitation program.

The knowledge and experience gained during years of biological and physical studies in the aftermath of the ***Exxon Valdez*** oil spill (EVOS) confirmed that understanding the sources of changes in marine resources and ecosystems requires putting those changes into an historical context. Toward this end, in March 1999 the Trustee Council dedicated approximately $120 million for long-term monitoring and ecosystem-based research within the area affected by the 1989 oil spill, which is generally the northern Gulf of Alaska (GOA), including Prince William Sound, Cook Inlet, Kodiak Island, and the Alaska Peninsula. This new program is called the GEM (the Gulf of Alaska Ecosystem Monitoring and Research) Program, and its mission is to:

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

The Trustee Council identified five major goals necessary to accomplish this mission:

- Detect: Serve as a sentinel (early warning) system by detecting annual and long-term changes in the marine ecosystem, from coastal watersheds to the central gulf;
- Understand: Identify causes of change in the marine ecosystem, including natural variation, human influences, and their interaction;
- Inform: Provide integrated and synthesized information to the public, resource managers, industry and policy makers in order for them to respond to changes in natural resources;

- Solve: Develop tools, technologies and information that can help resource managers and regulators improve management of marine resources and address problems that may arise from human activities; and
- Predict: Develop the capacity to predict the status and trends of natural resources for use by resource managers and consumers.

Given the size and complexity of the northern GOA ecosystem and the available funding, the GEM Program alone can not meet these goals. For that reason, the Trustee Council adopted a set of additional goals for implementing the program. These call for the GEM Program to:

- Lead the way in integrating, synthesizing, and interpreting monitoring and research results to form and convey a “big picture” of the status of and trends in the GOA ecosystem;
- Track work of other entities relevant to understanding biological production in the GOA and coordinate GEM with those efforts;
- Leverage funds to augment ongoing monitoring work funded by other entities;
- Involve other government agencies, non-governmental organizations, stakeholders, policy makers, and the general public in a collaborative process to achieve the mission and goals of GEM;
- Increase community involvement and local and traditional knowledge in order to enhance long-term stewardship of living marine resources; and
- Facilitate application of GEM research and monitoring results to benefit conservation and management of marine resources.

To fully achieve its mission, GEM must provide information that enables resource-dependent people, such as subsistence users, recreation users, and commercial fishers, to better cope with changes in marine resources. The data and information produced by GEM during its first decade may not totally solve problems for the public, commercial interests, resource managers, and policy makers faced with environmental change. Nonetheless, as information accumulates, the ability for GEM to provide problem-solving information and tools can and must increase.

The GEM Program is based on the current state of knowledge about the natural factors and ecological impacts of human activities that cause change in the GOA. Within the northern GOA, offshore and nearshore marine, estuarine, freshwater and terrestrial environments interact with geologic, climatic, oceanographic, and biologic processes to produce highly valued natural bounty and exceptional beauty. The GOA provides habitat for diverse and abundant populations of fish and shellfish, marine mammals and seabirds. It is a major source of seafood for the entire nation, as well as for Alaska Natives, who rely on it for subsistence and cultural purposes. It is also a source of beauty and inspiration for those who love nature and part of the "lungs" of the planet for recycling of oxygen and carbon to and from the atmosphere. As a result of both human influences and natural processes, these important attributes are continually changing.

Populations of important marine resources in the northern GOA have undergone major changes, especially since the late 1970s. Salmon catches of all species, and especially of sockeye, have remained near record levels for two decades, with annual catches significantly greater than those in the three decades ending in 1979. Shrimp and red king crab have fallen to extremely low levels in the gulf since 1980, in sharp contrast to the very high levels in the two prior decades. Kodiak's red king crab fishery, once among the world's richest, has been completely closed since 1984. As shrimp and crab declined, cod, pollock and flatfish, such as arrowtooth flounder, have rapidly increased. Some marine mammals associated with the gulf, such as sea lions, harbor seals and overwintering fur seals, have steadily declined since 1980. Other species, such as sea otters and elephant seals, have been on the rise for more than a decade. Colonies of seabirds, such as black-legged kittiwakes, common murres and cormorants have shown declines since about 1980 in some coastal localities, such as Prince William Sound and central Cook Inlet, but not in others. Overall, many species and populations associated with nearshore habitats in the GOA have declined since about 1977, whereas species and populations having access to offshore gulf habitats have generally increased.

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, play important roles in determining basic biological productivity. Natural physical forces are shaped by the surface topography of the GOA and the submarine topography of the continental shelf and respond primarily to seasonal shifts in the weather, and in particular to long-term changes in the intensity and location of the Aleutian Low Pressure system. Increased upwelling offshore appears to increase inputs of nutrients to surface waters, which in turn increases productivity of plankton, the basis of the food chain and the primary food source for all marine life. Increased winds appear to increase the transport of zooplankton shoreward toward and past the continental 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, fronts, and eddies, degree and extent of turbulence, and responses of plankton to short and long-term changes in temperature and salinity.

The ecological impacts of a wide range of human uses and activities interact with these natural forces to change the productivity and community structure in the GOA. More than 70,000 people live within the area directly affected by the oil spill, and two to three times that number use the area seasonally for work and recreation. When combined with the population of the nearby centers of Anchorage and Wasilla, plus nearly a million tourists who visit the state each year, it becomes clear that the natural resources of the GOA cannot be immune to the pressures associated with human uses and activities.

Human activities have the most direct and obvious impacts at those sites in watersheds and intertidal areas where human populations are high. Crude oil and fuel tanker traffic, increasing tourism and recreational use, expanded road building, and growing commercial and sport fishing pressure could have increasing effects on marine resources and ecosystems. Some human activities affect populations of birds, fish, shellfish, and mammals even far offshore, and also have impacts far from the sites of the actions. Large scale fishing that occurs in international waters impacts Alaska resources. In addition, recent evidence of persistent organic pollutants and heavy metals in fish and wildlife tissues in the gulf indicate that this region is not immune from worldwide concerns about potential effects of contaminants on marine organisms and on human consumers, particularly Alaska Native subsistence users.

In short, human activities and natural forces act together over local and global scales to drive and shape marine and terrestrial life in the GOA and its tributary watersheds. This conceptual foundation is summarized into a central hypothesis that will guide the GEM Program:

> ***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, biogeochamical cycles, food web structure, fishery impacts, and pollutant levels.***

This broad, interdisciplinary hypothesis states what is thought to be known in general, prepares the way for questions that test the validity of this knowledge and serves as a flexible framework for determining the type of monitoring and research activities that will be undertaken in implementing the GEM Program.

Since the gulf ecosystem under consideration is extremely complex and consists of thousands of species, it also will not be possible for GEM to answer all, or even most, of the questions that could be posed about the GOA. Four habitat types, representative of the GEM region, have been identified as themes around which the interdisciplinary monitoring and research activities that address GEM's central hypothesis will be organized. These habitat types are: watersheds, the intertidal and subtidal areas, the Alaska Coastal Current, and the offshore areas (the continental shelf break and the Alaska Gyre). The habitats are composed of identifiable, although not rigid, collections of characteristic microhabitats, resident and migratory species, and physical features. The decision to use habitats as a mechanism for stratifying funds and allocating resources will require the GEM

Program to ensure that such cross-habitat processes and linkages as freshwater flow and cross-shelf nutrient transport are not forgotten or ignored.

The GEM central hypothesis can be translated into a hypothesis for each of these habitat types. However, before they can be used to guide research, they need to be further refined into questions which can then be used to identify a core set of measurements for long-term monitoring. The GEM Program will use the tools of gap analysis, synthesis, and modeling to develop a series of initial research questions and to continually refine and implement GEM's long-term core monitoring program. The "flagship" of GEM will be a long-term monitoring program that will be maintained even if funding levels vary. The monitoring component will be complemented by strategically chosen research projects. These projects will follow up on lingering effects of the ***Exxon Valdez*** oil spill, explore questions and concerns that arise out of interpretation of the monitoring data, especially in trying to understand the causes of change, and provide key information and tools for management and conservation.

To further develop the program, the Trustee Council will use two major strategies: incorporating community involvement and traditional knowledge and focusing on resource management applications. Communities and stakeholders must be involved at all levels of the program. The Trustee Council believes that encouraging local awareness and participation in research and monitoring enhances long-term stewardship of living marine resources. In addition, traditional and local ecological knowledge can provide important observations and insights about changes in these resources. In order to enhance the information managers and stakeholders use to cope with these changes, the GEM Program will seek to acquire data with significant potential for use in resource management applications.

The hypotheses, research questions, tools and strategies will all be used to develop a Science Plan for GEM. The goal of the Science Plan is to implement a long-term monitoring program to detect and understand change over time within the northern Gulf of Alaska ecosystem. The Science Plan will develop over time and include an implementation schedule; partners doing related monitoring or research; models to synthesize results and transfer information to users; core monitoring variables; and core monitoring activities.

The GEM Program will be administered by the Trustee Council's core professional staff, based in Anchorage, Alaska. Funds will be provided by the Trustee Council's investment fund, managed as an endowment, with the annual program funded by investment earnings after inflation-proofing. The Trustee Council's executive director will oversee the financial, program management and administrative, scientific, and public involvement aspects of the program. The Trustee Council and staff will actively solicit advice on science and policy matters, including review of monitoring and research activities, from experts, including a Scientific and Technical Advisory Committee (STAC), and from the public, including the Trustee Council's Public Advisory Committee.

The STAC will play a key role in guiding the GEM Program and ensuring a high degree of scientific credibility is maintained. Subcommittees composed of scientists, resource managers, stakeholders, and other experts and community members will be established to assist the STAC. The STAC and subcommittees will work with resource managers, stakeholders, the scientific community and the public to refine a common set of priorities for research and monitoring in the northern gulf.

Independent peer review of the GEM Program is essential for a high-caliber scientific program. Participation in research and monitoring is expected to be completely open to competition. All data must be documented, archived, maintained, and readily accessible to other scientific users and the public. In order for GEM to be successful, it will be necessary to integrate, synthesize, and interpret monitoring and research results to form and present a "big picture" of the status of and trends in the northern GOA ecosystem. One approach is through the use of periodic "State of the Gulf" and "State of the North Pacific" workshops and reports. Another is use of the GEM web site. The Trustee Council is committed to public input and outreach as vital components of the long-term GEM Program.

Data management and information transfer policies are an integral part of GEM Program management. Clear and effective approaches to gathering information and making it widely available in understandable formats are essential to the successful operation of the GEM Program. Because the program is a regional program with goals of cooperation, coordination, and integration with existing marine science programs, data policies are to be compatible with, and similar to, existing norms for state, federal, and nongovernmental marine science programs.

The GEM Program cannot be the sole solution to problems facing the northern Gulf of Alaska ecosystem. However, a permanent fund, dedicated to monitoring the long-term health of a marine ecosystem, is totally unique and provides an unparalleled opportunity to increase our understanding of the functioning of this system. The Trustee Council views the GEM Program as a permanent legacy of its efforts to restore the northern Gulf of Alaska from the effects of the 1989 ***Exxon Valdez*** oil spill. And for that reason, the Trustee Council believes that the program must be justified on what it can teach policy makers, resource managers, and the public about options for directing human behavior to achieve the GEM mission "to sustain a healthy and biologically diverse marine ecosystem and the human use of the marine resources in that ecosystem."

1. VISION

In This Chapter

- Origin of the GEM Program
- Mission and Goals Identified for the Program
- Geographic Scope, Funding and Governance
- Building on Lessons of the Past

1.1 Introduction

On March 24, 1989, the ***T/V Exxon Valdez*** ran aground on Bligh Reef in Prince William Sound, spilling almost eleven million gallons of North Slope crude oil. The event was the largest tanker spill in U.S. history, contaminating approximately 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, the Exxon Corporation agreed to pay the United States and the State of Alaska $900 million over ten 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 ***Exxon Valdez*** Oil Spill Trustee Council (Trustee Council) was formed to administer the restoration funds, and in 1994 the ***Exxon Valdez*** Oil Spill Restoration Plan was adopted to guide the development and implementation of a comprehensive, interdisciplinary recovery and rehabilitation program.

Thirteen years after the spill, total recovery has still not been achieved. Appendix B presents the current information regarding the recovery status of resources injured by the spill. There are still two main concerns about lingering effects of the spill. The first is the potential effect of pockets of residual oil in the environment. The second concern is the ability of a population to fully recover by overcoming changes in the population dynamics resulting from the initial oil-related mortalities and the interaction of these effects with other kinds of changes and disturbances in the marine ecosystem.

The knowledge and experience gained during years of biological and physical studies in the aftermath of the ***Exxon Valdez*** oil spill (EVOS) confirmed that a solid historical context is essential to understand the sources of changes in valued natural resources. Toward this end, in March 1999 the Trustee Council dedicated approximately $120 million for long-term monitoring and ecosystem-based research in the northern Gulf of Alaska (GOA). This new program is called the

GEM (Gulf of Alaska Ecosystem Monitoring and Research) Program. Funding for the GEM Program comes from an endowment, with an annual program funded through investment earnings, after allowing for inflation-proofing and modest growth of the corpus.

A program rooted in the science of a large-scale ecological disaster is uniquely suited to form the foundation for ecosystem-based management. In making the decision to allocate these funds for a long-term program of monitoring and research, the Trustee Council explicitly recognized that complete recovery from the oil spill may not occur for decades, and that full restoration of these resources will most likely be achieved through long-term observation and, as needed, restoration actions. The Trustee Council further recognized that conservation and improved management of these resources and services would require substantial ongoing investment to improve understanding of the marine and coastal ecosystems that support the resources, as well as the people, of the spill region. Improving the quality of information available to resource managers should result in improved resource management. In addition, prudent use of the natural resources of the spill area without compromising their health and recovery requires increased knowledge of critical ecological information about the northern GOA. This knowledge can only be provided through a long-term monitoring and research program that will span decades, if not centuries.

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

1.2 Mission

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

Consistent with this mission and with the ecosystem approach to restoration adopted by the Trustee Council in the 1994 ***Exxon Valdez*** Oil Spill Restoration Plan, the mission of the GEM Program is to:

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

In pursuit of this mission, the GEM Program will accomplish the following:

- Sustain the necessary institutional infrastructure to provide scientific leadership in identifying research and monitoring gaps and priorities;
- Sponsor monitoring, research, and other projects that respond to these identified needs;

- Encourage efficiency in and integration of GOA monitoring and research activities through leveraging of funds and interagency coordination and partnerships; and
- Promote local stewardship by involving stakeholders and having them help plan, guide, and carry out parts of the GEM Program.

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

1.3 Goals

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

1. Detect: Serve as a sentinel (early warning) system by detecting annual and long-term changes in the marine ecosystem, from coastal watersheds to the central gulf; and
2. Understand: Identify causes of change in the marine ecosystem, including natural variation, human influences, and their interaction.

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

3. Inform: Provide integrated and synthesized information to the public, resource managers, industry and policy makers in order for them to respond to changes in natural resources; and
4. Solve: Develop tools, technologies and information that can help resource managers and regulators improve management of marine resources and address problems that may arise from human activities.

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

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

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

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

- Lead the way in integrating, synthesizing, and interpreting monitoring and research results to form and convey a "big picture" of the status of and trends in the GOA ecosystem;
- Track work of other entities relevant to understanding biological production in the GOA and coordinate GEM with those efforts;
- Leverage funds to augment ongoing monitoring work funded by other entities;
- Involve other government agencies, non-governmental organizations, stakeholders, policy makers, and the general public in a collaborative process to achieve the mission and goals of GEM;
- Increase community involvement and local and traditional knowledge in order to enhance long-term stewardship of living marine resources; and
- Facilitate application of GEM research and monitoring results to benefit conservation and management of marine resources.

The substantial experience of the EVOS Restoration Program indicates that these six implementation goals are reasonable, necessary, and attainable.

1.4 Geographic Scope

Consistent with the Restoration Plan, GEM Program activities will occur within the area affected by the 1989 oil spill, which is generally the northern GOA, including Prince William Sound (PWS), Cook Inlet, Kodiak Island, and the Alaska Peninsula (Figure 1.1). Recognizing that the marine ecosystems affected by the oil spill do not have discrete boundaries, some monitoring and research activities may extend into adjacent areas of the northern GOA.

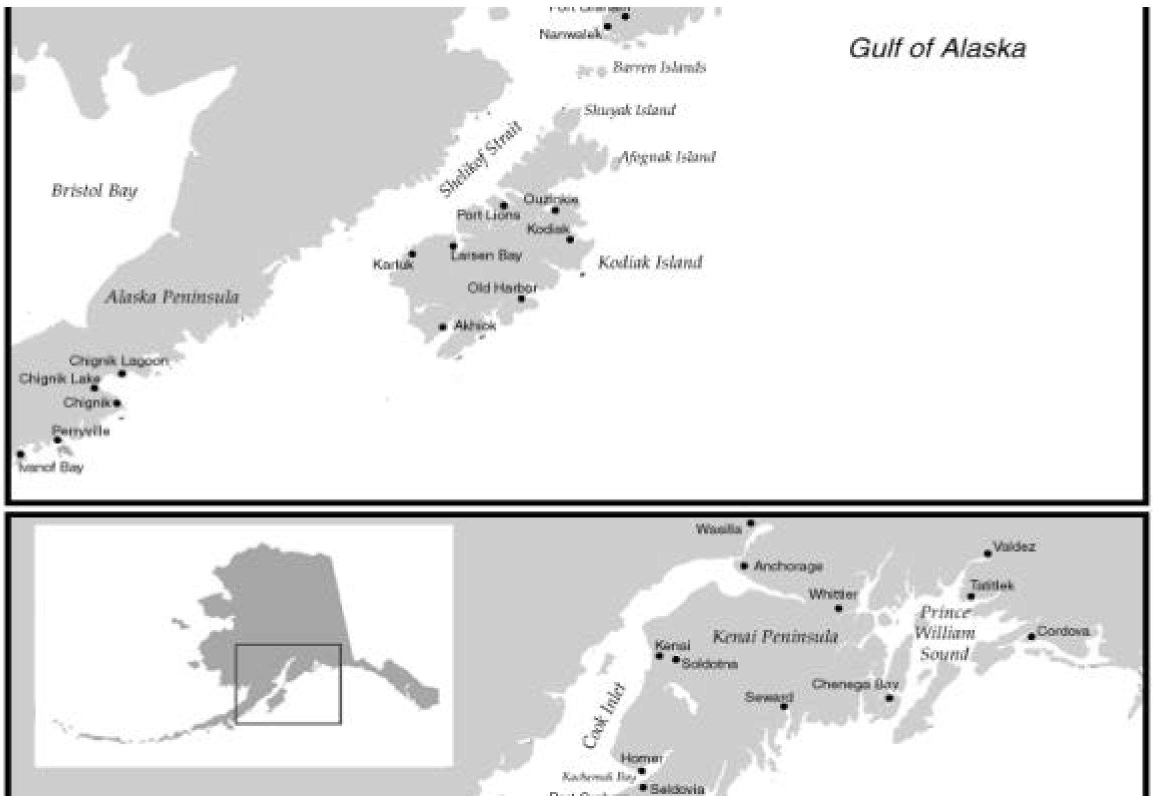

Figure 1.1 Map of the spill area showing the location of communities.

The primary geographic focus of GEM will be the four habitat types that contain the ecosystems of the northern GOA. These habitats are the watersheds, intertidal and subtidal, Alaska Coastal Current (ACC), and offshore (the continental shelf break and the Alaska Gyre).

Although GEM has a regional outlook, the waters of the GOA are connected to adjacent waters. Waters from the shelf and basin of the GOA eventually enter the Bering Sea and the Arctic Ocean through the Bering Strait. Waters from the west coast states (California, Oregon, and Washington), Canada and southern Alaska also feed into the northern GOA. Consequently, the program will be of vital importance in understanding the downstream Bering Sea and Arctic Ocean ecosystems, as well as the upstream southern GOA. In addition to the linkages provided by the movements of ocean waters, the GOA is linked to other regions by the many species of birds, fish, and mammals that move through these regions. It is also becoming increasingly clear that environmental conditions in the GOA, such as levels of persistent organic pollutants, as well as the temperature of GOA waters, can originate many thousands of miles away.

The Trustee Council is aware of the trade-offs between the size of the area to be studied and the frequency and intensity of the monitoring and research that can be conducted there. In selecting core variables for long-term research and monitoring, the GEM Program will need to ensure that measurements are conducted at the spatial and temporal scales necessary to achieve the desired goals of the program. For this reason, much thought must be given to the selection of the variables and the identification of the subset of the northern GOA that can reasonably be monitored by a program the size of GEM. It is anticipated that partnering with other agencies and programs will help extend the GEM research area beyond that which GEM could fund on its own. However, because of its critical importance to meeting the program's goals and objectives, core monitoring based on a set of core variables will be fully supported by the GEM Program.

1.5 Funding and Governance

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

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

The trustees established the Trustee Council to administer the restoration fund. The state trustees serve directly on the Trustee Council. The federal trustees each have appointed a representative in Alaska to serve on the Trustee Council. The representatives currently are the Senior Advisor to the Secretary for Alaskan Affairs (Department of the Interior), the Alaska Director of the National Marine

Fisheries Service (National Oceanic and Atmospheric Administration), and the Supervisor of the Chugach National Forest (U.S. Department of Agriculture). All decisions by the Trustee Council are required to be unanimous.

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

1.6 Building on Lessons of the Past

The GEM Program is not the first attempt to look at large areas of Alaska's marine ecosystems from a broader perspective. The ***Exxon Valdez*** Oil Spill Restoration Program, as well as a number of other programs, provides valuable guidance. This section briefly describes some of these programs and their relevance to the development of GEM.

1.6.1 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. ARMRP goals express the scientific needs of the Alaska region as of 1992 and are still relevant to the GEM effort:

Goals of other major programs are relevant to the GEM effort.

- 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.

1.6.2 Bering Sea Ecosystem Research Plan (1998)

The Bering Sea has received considerable 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 is consistent with the vision of the federal-state regulatory agencies for the ***Bering Sea Ecosystem Research Plan*** (DOI et al. 1998a), which states: "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.

1.6.3 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 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 GLOBEC concepts.

1.6.4 Scientific Legacy of the *Exxon Valdez* Oil Spill (1989 to Present)

Ecological knowledge gained in the years following the 1989 ***Exxon Valdez*** Oil Spill forms a substantial portion of the foundation of the GEM Program. In 1994 the ***Exxon Valdez*** Oil Spill Restoration Plan was adopted to guide the development and implementation of a comprehensive, interdisciplinary recovery and rehabilitation 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 1,600 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 500 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 2002). 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 2002).

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. 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.

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 $6 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.

1.6.5 Trustee Council Commitment to Traditional Knowledge and Community Involvement

From 1995 –2002, the Trustee Council provided almost $2 million to the Chugach Regional Resources Commission to facilitate the involvement of local communities in the oil spill restoration program and improve communication between spill area residents, community councils, regional organizations, scientists and the tribal community. The facilitators and coordinators have been active participants in all the GEM planning workshops and meetings. This project has also funded the development of natural resource management plans in several villages, which tribal representatives believe are a necessary step before incorporating tribal concerns into the GEM Program.

This long-term project (1995-2002) was designed to:

- Increase meaningful involvement of spill area communities in the Trustee Council restoration efforts / process;

- Provide information to communities regarding data and scientific research performed by the Trustee Council science program;
- Improve communication of findings and results of restoration efforts to spill area residents, village councils, and the appropriate regional organizations;
- Promote the inclusion of community-based projects, as well as community involvement in science projects throughout the life of the restoration effort;
- Work with the formation of local natural resource management programs that will focus on the stewardship and management of injured resources and lands; and
- Develop a means to compile and utilize western science and traditional wisdom in a cooperative manner to further the restoration process in ways that are sensitive to the needs of the communities.

The Chugach Regional Resources Commission coordinated this project by employing community facilitators in ten communities, and a spill area-wide community involvement coordinator who facilitated communication between the communities, the Trustee Council, and scientists.

Also since 1995, the Trustee Council has funded Youth Area Watch programs through the Chugach School District and Kodiak Island Borough School District. These programs involve youth from local spill area communities in the science behind the restoration effort. As of 2002, 168 students have participated in the Prince William Sound and Kodiak programs with students participating in such projects as harbor seal biosampling, seabird momitoring, collection oceanographic data on cruises, and analyzing chemicals found in intertidal mussels.

In 1994 the Trustee Council received its first call from a community resident to incorporate Traditional Ecological Knowledge (TEK) of spill area residents into the restoration program. Two years later, the Trustee Council's 1996 annual restoration workshop had TEK as its theme, and led to a set of protocols for incorporating TEK into restoration projects developed by a committee of Alaska Natives and others and approved later that year by the Trustee Council. The Trustee Council has provided funds each year since 1995 toward the goal of incorporating TEK into the restoration program. Efforts have included:

- Developing a TEK handbook and reference guide for biologists documenting the sources of TEK in the spill area and incorporating it into a western science approach.
- Providing funds for Chugach Regional Resource Commission (CRRC) to contract with TEK expert Henry Huntington for seven years. He has worked directly with Alaska Native elders and hunters as well as scientists to bridge the gap between these two different approaches to understanding the natural world. A result of this process is that several EVOS projects

incorporate TEK directly into their data sets and results, including projects on community natural resource management, fish and seabird studies, and a series of films about Alutiiq culture (see examples below).

- Conducting two workshops to develop tribal management programs and bringing several scientists to spill area communities to share information.

Examples of projects incorporating TEK as a result of Trustee Council efforts include:

- Scientist Jody Seitz conducted an extensive project involving TEK. Researchers interviewed thirty-nine spill area community members to document the historical distribution of forage fish such as juvenile herring, sand lance, capelin, and eulachon. This information was mapped and provided to the APEX and SEA researchers. The results were extremely valuable because they could not have been obtained from other historical sources or from current data collection efforts.

- Scientist Dan Rosenberg solicited local participation from communities and conveyed results of his research on surf scoters, an important subsistence resource. The project idea came from local communities. Rosenberg worked with community members throughout all stages of the project, from project design to writing the final report.

- The Trustee Council provided funding support to the Alaska Native Harbor Seal Commission, which uses Alaska Native hunters to conduct biosampling of harbor seal tissues using lab-approved techniques. In 1999, the commission reached an agreement with the National Marine Fisheries Service to co-manage harbor seal populations.

- Three videos have been produced with Trustee Council funds to provide the public information about TEK and concerns about subsistence use after the oil spill. The first two, ***Alutiiq Pride: A Story of Subsistence*** and ***Changing Tides in Tatitlek*** describe subsistence methods, interview Alaska Native people who experienced the spill first hand, show actual subsistence hunts, and illustrate the importance of subsistence in Alutiiq culture. The third documents the communities of Chenega Bay and Ouzinkie in relation to the effects of the oil spill, residual oil in the spill region, and concerns about paralytic shellfish poisoning toxins, natural toxins found in clams harvested for food. These videos were distributed at no charge to all schools in Alaska via their school districts, all spill area tribal councils, and any other library or school in the U.S. upon request.

The Trustee Council funded Elders/Youth Conferences in 1995 and 1998 that brought together Alaska Native elders, youth, other subsistence users, scientists, and managers to share ideas about subsistence issues and facilitate community involvement. The Trustee Council paid for four people from each of twenty spill area communities to attend each conference. Participants shared stories, voiced frustration, and asked scientists questions about subsistence issues. They also developed ideas for youth to get more involved through spirit camps, internships, and educational opportunities. These workshops facilitated collaboration between communities of the spill area, while concerns and ideas generated at the conference were reported to the Trustee Council.

Additional details on the Trustee Council's tribal and community involvement efforts are included in a report in Appendix C.

1.7 References

ARMRB. 1993. Alaska Regional Marine Research Board, Alaska research plan. School of Fisheries and Ocean Sciences, University of Alaska. Fairbanks.

DOI, NOAA, and ADF&G. 1998a. Draft Bering Sea ecosystem research plan. Alaska Department of Fish and Game, Commercial Fisheries Division. Juneau.

DOI, NOAA, and ADF&G. 1998b. Bering Sea ecosystem - a call to action. Alaska Department of Fish and Game, Commercial Fisheries Division. Juneau.

EVROFAB. 2002. ***Exxon Valdez*** Oil Spill Restoration Office bibliography of final and annual reports. Anchorage, Alaska, ***Exxon Valdez*** Oil Spill Trustee Council.

EVROTCB. 2002. ***Exxon Valdez*** Oil Spill Restoration Office bibliography of published oil spill investigations. Anchorage, Alaska, ***Exxon Valdez*** Oil Spill Trustee Council.

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

U.S. GLOBEC. 1997. Global Ocean Ecosystems Dynamics (GLOBEC) science plan. IGBP Secretariat, The Royal Swedish Academy of Sciences. Stockholm, Sweden.

United States of America and State of Alaska. 1991. Memorandum of agreement and consent decree, A91-081 CIV.

2. CONCEPTUAL FOUNDATION AND CENTRAL HYPOTHESIS

In This Chapter

- Conceptual Foundation
- Central Hypothesis
- Habitat Types and Time-Space Scales
- Central Hypothesis by Habitat Type

2.1 Introduction to the GEM Conceptual Foundation

The intellectual framework of the GEM Program is a hierarchy composed of a conceptual foundation, central hypothesis, habitat-specific hypotheses, research questions, and ultimately, testable hypotheses based on the specific questions (Figure 2.1). Four habitat-specific hypotheses, based on the central hypothesis, form the core of the GEM monitoring plan. The conceptual foundation provides an overarching explanation, or verbal model, of how the Gulf of Alaska (GOA) ecosystems produce biological resources. As such, the conceptual foundation is not itself a testable hypothesis on the sources of change in ecosystems, but rather, the origin of hypotheses, both general and testable. Habitat-specific hypotheses are based on assumptions about how natural and anthropogenic factors influence ecosystem functioning within each of the habitat types, recognizing that different factors may be important in different habitats. This chapter presents the narrative of the GEM conceptual foundation for the GOA, addresses cross-habitat connections and regional variability, and adapts the narrative of the conceptual foundation to describe the four habitat types used by GEM.

2.1.1 The GOA at a Glance

The conceptual foundation for the GOA ecosystem explains how its plant and animal populations are controlled through time. A broad, interdisciplinary conceptual foundation serves as a flexible framework for determining the type of monitoring and research activities that will be undertaken in implementing the GEM Program. The conceptual foundation is the product of syntheses of the latest scientific information and an assessment of leading ecological hypotheses. It

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

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.

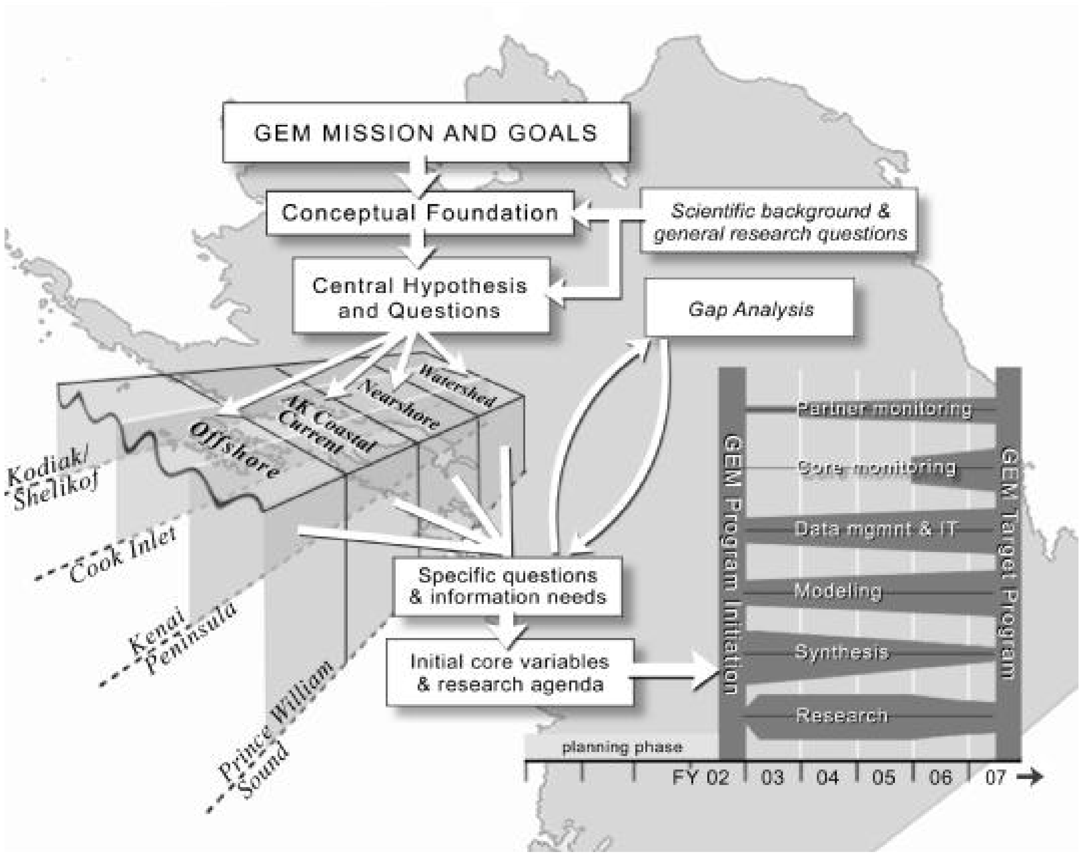

Figure 2.1. Overview of the GEM Program structure showing the relation of key concepts to the habitat types, implementation tools, and the schedule of implementation.

Specific citations to the scientific literature are omitted for the sake of brevity, however these may be found in the scientific synthesis of Chapter 7. Taking the watersheds and marine areas of the GOA together at a single glance, the importance of key geological features in shaping the natural physical and biological forces that control productivity is apparent (Figure 2.2). Note that features illustrated in Figure 2.2 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 Systems (Aleutian Low) deep into the GOA until the 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

Figure 2.2 The physical and biological elements of the ecosystems of the northern GOA from the mountains surrounding the watersheds to the oceanic waters offshore.

boundary into areas of photosynthetic activity by the motion of surface currents, (Alaska Coastal Current, 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.

Natural physical forces control productivity by limiting the amount of food and availability of habitats. During the winter especially, the Aleutian Low 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, secondary 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.

The biogeochemical cycle is an important collection of natural biological and physical 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 fish such as myctophids). Emigrant animals (adult salmon and other anadromous species) also move marine carbon (and phosphorous and nitrogen) into the watersheds.

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.

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. The economy of Alaska depends heavily on extraction of natural resources (primarily oil, fish, and shellfish followed by timber and minerals). Fishing and other extractive uses (subsistence, sport, commercial) affect death rates through removals. Other forms of human action are more subtle, but no less effective, controls on productivity. In the Northern Gulf of Alaska, recreation and tourism, oil and gas development, logging, road building and urbanization, marine transportation and subsistence harvests are all activities that have the potential to affect fish and wildlife populations and habitat. 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 exotic species as competitors and predators. Currently, the human impact on Alaska's marine ecosystems is relatively small compared to impacts in most of the developed world. Even here, however, natural resource managers have concerns about localized pollution, the potential impacts of some fisheries, extreme changes in some fish and wildlife populations, and the little known impacts of contaminants and global warming.

In summary, Figure 2.2 shows that 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 Aleutian Low 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. Approximately 71,000 full-time residents live within the area directly affected by the oil spill and two to three times that number use the area seasonally for work and recreation. The spill area population, combined with that of the nearby population centers of Anchorage and Wasilla, totals more than 60percent of the state's 627,000 permanent residents. When the resident population is combined with the more than one million tourists who visit the state each year, it becomes clear that the natural resources of the GOA cannot be immune to the pressures associated with human uses and activities. 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.

Because of the tremendous uncertainty about sources of long-term changes, the conceptual foundation does not provide a specific model (testable hypothesis) for ecosystem change. Rather, the GEM conceptual foundation is designed to be broad enough to serve as a tool to organize thinking and research over long time periods, to encompass ecosystem interconnections, and to link information from traditional knowledge and scientific disciplines. It takes into account both oceanic and terrestrial ecosystems and addresses the influence of climate and human activity in influencing biological productivity within these interconnected systems. By using this broad, scientifically grounded conceptual foundation, the GEM Program will be able to adapt to changes in understanding ecosystem processes without having to sacrifice long-term research and monitoring goals (NRC 2002).

The GEM Program will, however, need to develop specific testable hypotheses, as derived from a general, or central hypothesis, in order to implement the monitoring and research program. As a start on a central hypothesis, consider the one provided by the National Research Council (NRC 2002, p. 27), as follows,

> ***The Gulf of Alaska, its surrounding watersheds, and human populations are an interconnected set of ecosystems that must be studied and monitored as an integrated whole. Within this interconnected set, at time scales of years to decades, climate and human impacts are the two most important driving forces in determining primary production and its transfer to upper trophic-level organisms of concern to humans.***

The NRC summary identifies climate and human impacts as the two most important determinants of biological production, among the many forcing factors recognized as significant in the conceptual foundation. Nonetheless, the biological communities that support the birds, fish and mammals are subject to a variety of biological and physical agents and factors of change, any one of which can at times play an important, and even dominant, role in controlling populations of birds, fish, shellfish and mammals. A formal statement of the central hypothesis that starts with and considers the full suite of forcing factors is needed to allow research and monitoring to identify the most important forcing factors for species and habitats of the GEM region.

2.2 The Central Hypothesis and Habitat Types

Identifying the forcing factors, human and natural, that drive biological production requires framing hypotheses and questions that point the way for a scientific monitoring and research program. The central hypothesis formally states widely held beliefs about what drives changes in living marine-related resources in time and space:

> ***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.***

Although widely accepted as fact, the specific mechanisms that cause change are largely untested in the GEM region, and the relative importance of the forcing factors is unknown. 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 2.3 and 2.4).

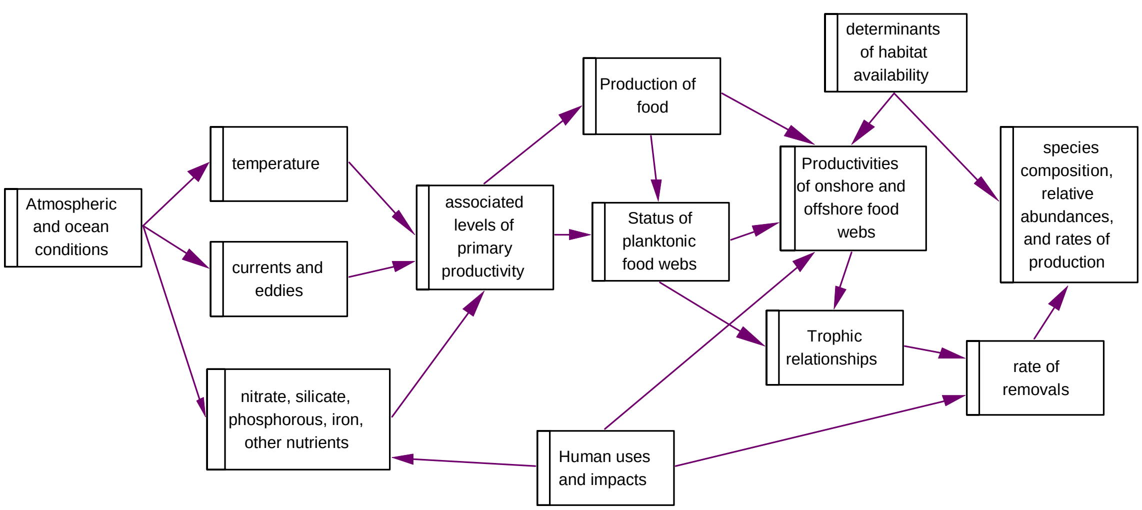

Figure 2.3 Possible connections among specific mechanisms and agents of change in living marine-related resources.

Although the central hypothesis may appear to be a bland statement of the obvious, it is an essential first step in applying the scientific method to address the many open, and sometimes highly contentious, scientific questions about whether, and to what extent, human activities are responsible for degradation of habitats and declines in populations of animals. The central hypothesis states what is thought to be known in general, preparing the way for questions that test the validity of this knowledge. For example it is reasonable to ask of the central hypothesis, “What are the natural forces and are they equally important in all types of habitat?” Critically examining the starting point through posing and answering questions, is intended to point out the need for more specific hypotheses, which in turn lead to more specific questions, and so forth.

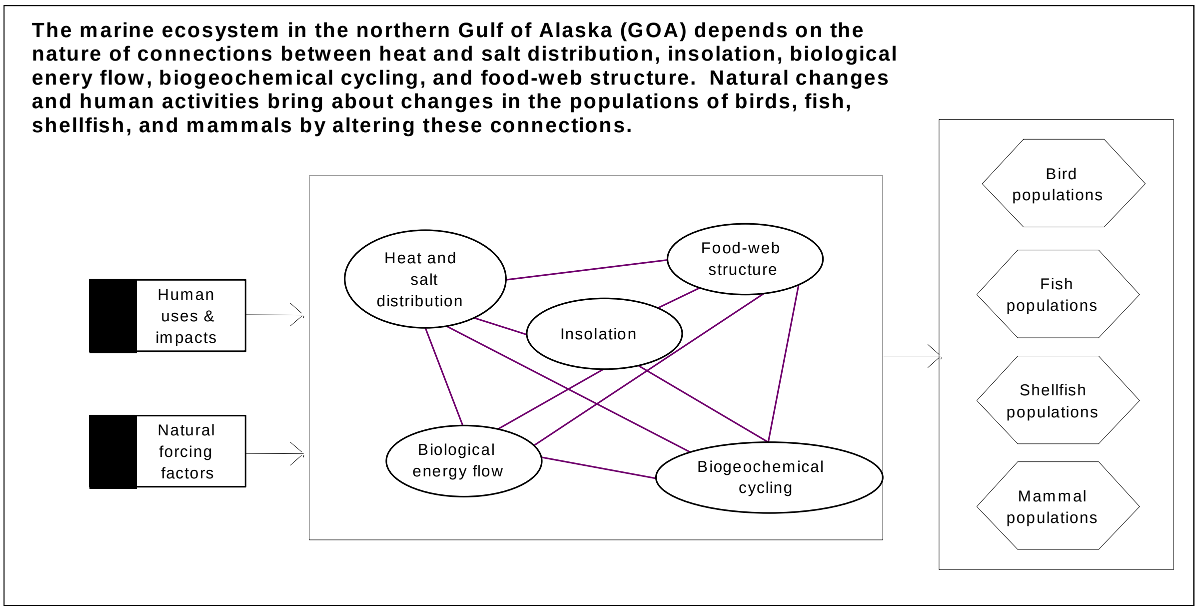

Figure 2.4 Relations among major parts of the GEM conceptual foundation.

The central hypothesis is given more specificity through adaptation to habitat types in the following section. Before adding specificity to the central hypothesis, the habitat types need definition, and the context of conducting studies at time-space scales appropriate to the phenomenon needs to be provided.

To better organize the GEM Program, four habitat types, representative of the GEM region, have been identified as themes around which the interdisciplinary monitoring and research activities that address GEM’s central hypothesis will be organized. These habitat types are: watersheds, the intertidal and subtidal areas, the ACC, and the offshore areas (the continental shelf break and the Alaska Gyre). These habitats were selected after evaluating information about how natural forces and human activities control biological productivity in the northern GOA (Chapters 6 and 7). The habitats are composed of identifiable, although not rigid, collections of characteristic microhabitats, resident and migratory species, and physical features. The physical locations are described below:

§ Watersheds—freshwater and terrestrial habitats from the mountains to the extent of a river’s plume.

- § Intertidal and subtidal areas—brackish and salt-water coastal habitats that extend offshore to the 20-m depth contour.
- § ACC—a swift coastal current of lower salinities (25 to 31 psu) typically found within 35 km of the shore.
- § Offshore—the continental shelf break (between the 200-m and 1,000-m depth contours) and the Alaska Gyre in waters outside the 1,000-m depth contour.

The decision to use habitats as a mechanism for stratifying funding and allocating resources will require the GEM Program to ensure that cross-habitat processes and transfers are not forgotten or ignored. 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 2.5). 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.

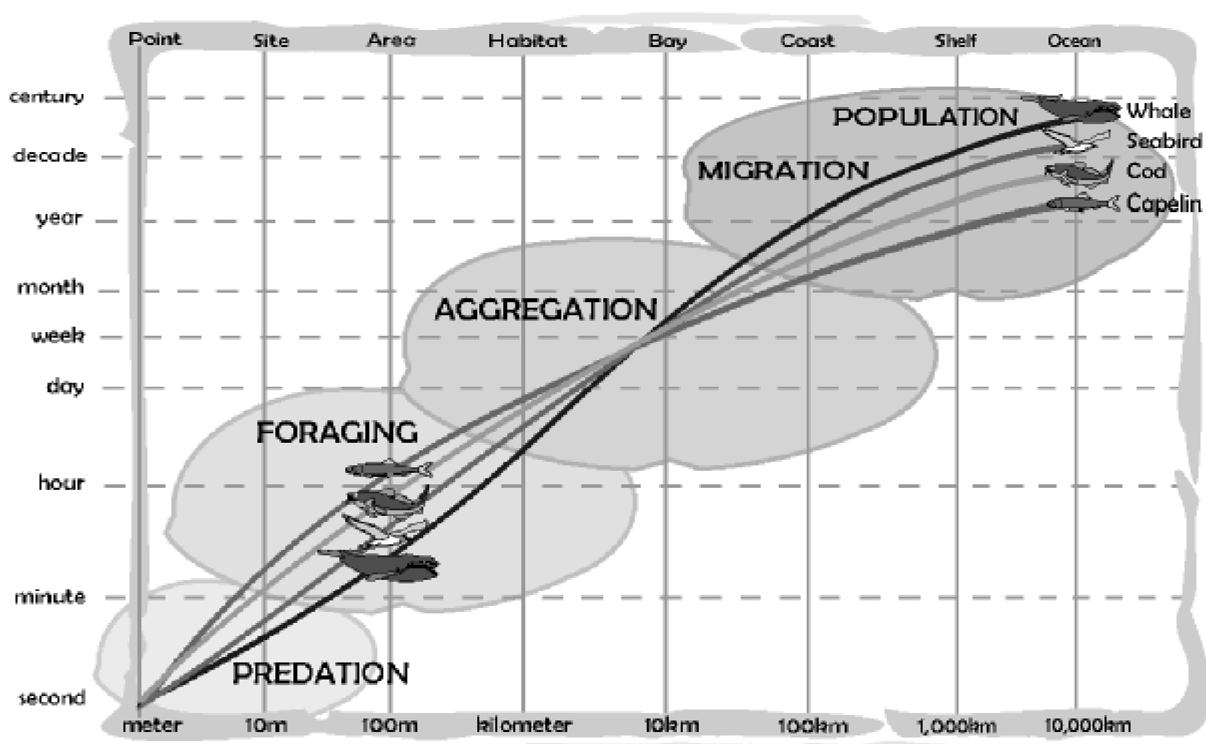

Figure 2.5 Scales of time and space corresponding to key elements and processes in ecosystems of the GOA. *Illustration provided by John Piatt.*

Taking account of spatial and temporal scales is critical to studying linkages between natural forces and biological responses (Francis et al. 1998).

Cross-habitat linkages and processes will be incorporated into the GEM Program in several ways that will be described in more detail in later chapters. The primary mechanisms for ensuring they are addressed will be through ongoing synthesis of research results and oversight by the Scientific and Technical Advisory Committee. It is also expected that modeling efforts will be regional in focus rather than habitat specific.

2.2.1 Central Hypothesis by Habitat Type

The central hypothesis is adapted to each habitat type:

Watersheds:

> ***Natural forces (such as climate) and human activities (such as habitat degradation and fishing) serve as distant and local factors in causing short-term and long-lasting changes in marine-related biological production in watersheds.***

Intertidal and Subtidal:

> ***Natural forces (such as currents and predation) and human activities (such as increased urbanization and localized pollution) serve 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 (ACC):

> ***Natural forces (such as variability in the strength, structure and dynamics of the ACC) and human activities (such as fishing and pollution) cause local and distant changes in production of phytoplankton, zooplankton, birds, fish, and mammals.***

Offshore:

> ***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) play significant roles in determining production of carbon and its shoreward transport.***

As noted above, these hypotheses can be used as a general guide to monitoring and research, but they need to be further refined into questions which identify a core set of measurements for implementation of long-term monitoring and research. In Chapter 4 the habitat-type hypotheses are examined through specific questions that lead to preliminary recommendations on what information needs to be gathered, as a starting point for the GEM Program. Basic definitions of the tools for implementing the program, as provided in Chapter 3, are needed before launching into the details of implementation found in Chapter 4.

Before moving on to the definition of implementation tools, it should be noted that information for developing these specific questions into a monitoring and research program comes from many sources, including analysis of ongoing and existing research results, evaluation of agency monitoring programs and activities, and input from a variety of interest groups including scientists, resource managers and the communities. Over the long-term one of the most valuable resources for identifying research questions may be the legacy of scientific information and results from community involvement projects from the ***Exxon Valdez*** Oil Spill Restoration Program. The following chapter describes the process by which gap analysis, synthesis, and research are used to implement the GEM Program and guide selection of variables for long-term monitoring. Chapter 4 introduces potential research questions that may be used to begin development of the GEM Science Plan

2.3 References

Francis, R.C., S.R. Hare, A.B. Hollowed, and W.S. Wooster. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the northeast Pacific. Fisheries Oceanography 7: 1-21.

NRC. 2002. A century of ecosystem science: planning long-term research in the Gulf of Alaska. Washington, D.C., National Academy Press.

Ricklefs, R.E. 1990. Scaling patterns and process in marine ecosystems. Pages 169-178 in Sherman, K., L.M. Alexander, and B.D. Gold, editors. Large marine ecosystems: patterns, processes and yields. American Association for the Advancement of Science, Washington, D.C.

3. TOOLS AND STRATEGIES

In This Chapter

- Tools: Gap Analysis, Synthesis, Research, Monitoring, Modeling and Data Management
- Strategies: Community Involvement and Traditional Knowledge, and Resource Management Applicability

3.1 Introduction

The hypotheses presented in Chapter 2 are refined into a series of initial research questions through the use of gap analysis, synthesis and research, as supported by modeling and data management. These tools also will be used to continually refine and implement GEM's long-term core monitoring program. To further develop the program, the Trustee Council will use two major strategies: incorporation of community involvement and traditional knowledge, and potential for resource management applicability (Figure 3.1).

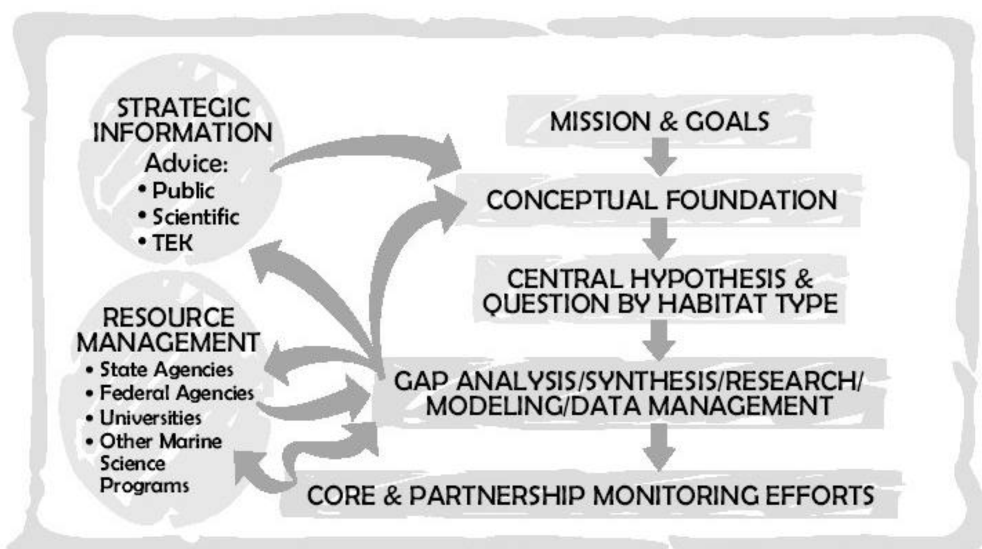

Figure 3.1 GEM Structure

This chapter defines and discusses these tools and strategies and explains how each will be used to implement the GEM Program.

3.2 Program Tools

Research questions emerge from a consideration of the central hypothesis and the hypotheses for each habitat presented in the previous chapter. Potential research questions and the information necessary to answer them are presented in Chapter 4. The recommendations on the information needed were developed through a process of "gap analysis," as defined in the following section and as supported by information in Appendix D. From the starting point of preliminary questions and the information needed to answer them (Chapter 4), the GEM Program is intended to follow a path of synthesis, research, and monitoring to detect, understand, and, eventually, predict changes in living marine-related resources of the northern Gulf of Alaska (GOA). Modeling and data management are critical elements in evaluating and managing the GEM long-term research program, and will closely support synthesis and research activities.

3.2.1 Gap Analysis

In the process of starting the GEM Program, key hypotheses about how the GOA ecosystem functions were evaluated and refined into a set of potential questions for each of the primary habitat types in the GOA (Chapter 4). The major information gathering programs in the North Pacific (Appendix D) were reviewed to identify where they are collecting data that could be used to answer the questions, and where there were gaps in the information that would need to be filled by future research. This ongoing identification of information needs, or gap analysis, is an important part of the process of identifying the starting points for monitoring and research, for avoiding duplicating the efforts of others, and for continuing to refine the program as it progresses. This analysis will continue during implementation of the GEM Program, with initial general questions being replaced by increasingly specific questions as knowledge about the ecosystem increases.

It is important to have a clear understanding of how the nature of the question determines the nature and outcome of the gap analysis. The gap analysis has four essential parts: a question, identification of information necessary to answer the question, a survey of relevant available information, and identification of gaps in the available information.

The first part, the question, is fundamental to the gap analysis and defines the survey of all relevant information needed to answer it. A general question calls for a general gap analysis, and a more detailed question calls for a more detailed gap analysis. The gap analysis seeks to identify what information is currently being collected that could help answer the question and what information, for which no data are being collected currently, is needed to answer the question. The data gaps become the priorities for focusing research and monitoring activities.

A continuing gap analysis, supported by a regularly updated database of current and historical information-gathering projects in the GOA and adjacent areas, is essential to implementing the GEM Program. This analysis will be performed by the staff and researchers and will be key to finding new partners for monitoring activities, identifying new opportunities for research and synthesis, and providing increased opportunities for collaboration, without risking duplication of effort or the possibility of failing to obtain needed data. In the short term, this database will provide information needed to select core monitoring variables and locations. In the longer term, the supporting database will become a valuable tool for resource managers, policy makers, other scientists, stakeholders, and the general public. As the GEM Program moves from the general hypotheses about what controls and connects biological production within and between habitats, and toward specific questions and testable hypotheses, the gap analysis will become highly specific.

3.2.2 Synthesis

A second starting point for developing the GEM Program is synthesis, because all good science ultimately involves synthesis. In the words of biologist E. O. Wilson (1998):

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

Synthesis builds on and updates the current understanding of the northern GOA. It brings together existing data from any number of disciplines, times, and regions to evaluate different aspects of the GEM Program's conceptual foundation, central hypotheses, and related ideas. Synthesis has three broad uses. First, it is used to provide direction for developing hypotheses to be tested and, combined with research and monitoring, to update and refine the program structure and implementation plan. In this respect, synthesis is an ongoing evaluative process throughout the life of the GEM Program that will help to ensure that the program is meeting its goals and objectives. Second, synthesis is used as a tool to inform stakeholders and the public about the developing understanding of the factors responsible for change in the marine environment. Some of the most important synthesizers of GEM monitoring and research will be the public. Synthesis will be useful in workshops, meetings, publications, and other methods for communicating information to the public. And third, synthesis is used to help solve resource management problems, by identifying new applications of existing information or by identifying opportunities to solve existing problems by collecting new information. Synthesis is a logical place to begin the cycle of monitoring and research, but once used to initiate a project or component, it becomes a companion to monitoring and research and an ongoing part of the overall program.

For the purposes of the GEM Program, synthesis is distinguished from research and from retrospective analysis, a form of research. Unlike research, synthesis does not necessarily start from a specific hypothesis or question. Instead, synthesis takes an interdisciplinary approach to evaluating existing information or data to identify potential new applications and uses. As such, synthesis is a critical component in ensuring that cross-disciplinary and cross-habitat linkages and processes are adequately considered during research and monitoring. Synthesis may be supported by various forms of retrospective analysis (discussed below).

3.2.3 Research

Research is defined under GEM as collecting relatively short time series of new observations to evaluate a testable hypothesis relating to the conceptual foundation or a specific aspect of the monitoring program. In the early stages of GEM Program implementation, research will be critical in helping to identify the core variables around which the long-term monitoring activities will be developed. For example, when synthesis, modeling, or other analysis indicates the need for measuring a core variable, research may be necessary to understand how to gather the data in a specific locality and/or to determine and evaluate the appropriate measurement technology. Research may build on or use existing data and may also build models. Testing current understandings through research provides the basis for making changes to the monitoring program.

Retrospective analysis is treated in the GEM Program as a specialized form of research, sometimes used as an integral component of synthesis, that employs existing time series data to evaluate a testable hypothesis or other questions of similar specificity relating to monitoring, often supported by statistical modeling. Retrospective analysis contributes to building numerical models and to synthesis.

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

The short-term end point for GEM Program synthesis and research is implementation of core monitoring activities that are refined as suggested by new information. The continuing roles for synthesis and research, as supported by modeling, are to advance understanding of the relationships among and within the habitat types of the ecosystems, plant and animal species, physical and chemical oceanographic processes, and climate in the northern GOA in accordance with the conceptual foundation. Continual refinement and testing of hypotheses, synthesis across geographic areas and species, and modeling of biological and physical processes are expected. As seen in Figure 3.1, synthesis is expected to play a dominant role in defining the monitoring program during the early years of the program, with the relative amount of revenues devoted to synthesis declining as long-term monitoring sites are selected and implemented. Synthesis will nonetheless continue to be important indefinitely, as a means for understanding and improving the flow information produced by the monitoring programs.

3.2.4 Monitoring

As defined for the purposes of the GEM Program, monitoring is the action of repeatedly collecting long-time series observations. At the level of data acquisition, monitoring differs from research primarily in the length of time over which the measurements are taken, and the nature of methods and devices employed. Monitoring differs from research by employing methods and devices that are "tried and true," whereas research may use experimental devices or novel methods to acquire data. For example, observations now considered monitoring, such as satellite observations of sea surface height, were once seen as novel research. Such satellite observations remain in the research domain to some extent, as efforts to refine the spatial resolution of the available data continue.

The decision on what and where to monitor is based on the results of research and synthesis to identify core variables. The development of long time series of data is essential to detecting and understanding change in the ecosystem. When combined with research and modeling, monitoring can demonstrate how ecosystems change over time and in response to various inputs. As such, it provides a sound scientific basis for making a variety of management decisions potentially affecting ecosystem resources. Appropriate temporal and spatial scales for the hypotheses being analyzed are important aspects of detecting change, and, are therefore, key considerations in the design of monitoring.

Monitoring in the GEM Program will be organized into core monitoring and partnership monitoring. Because of its critical importance to meeting the program's goals and objectives, ***core monitoring*** based on a set of core variables will be fully supported by the GEM Program. ***Partnership monitoring*** is envisioned to extend the GEM core monitoring program by teaming with partners involved in research that is also relevant to the hypotheses that GEM will be testing. Partnership monitoring will be partially supported by leveraging GEM resources with the resources of the partner organization.

The end point for monitoring is a geographically distributed network gathering data on the state of the marine ecosystem in the GEM region, using spatially structured survey methods. This implies a broad spatial scale for monitoring, as a combination of GEM with that of other entities. These data are transformed into information for user groups by using synthesis, research, modeling, data management, and information transfer.

3.2.5 Modeling

Modeling is used to make the relationships between the parts and processes of the ecosystem clear, and as such, serve as a critical element in making connections between habitats and across disciplines. Models are tools for organizing data and telling a story and can be written in a variety of media as verbal, visual, statistical, or numerical models. In the GEM Program, the specific purposes of modeling are to help accomplish the following:

- Inform, communicate, and provide common problem definition;
- Identify core variables and relationships;
- Set priorities;
- Improve and develop experimental designs to attain monitoring objectives;
- Evaluate cross-habitat linkages and transfers; and
- Improve decision-making and risk assessment.

Modeling, monitoring, and data management strategies need to work in concert for each to be fully effective (Figure 3.2). Modeling is a pivotal link between monitoring and data management and information transfer on the one hand, and synthesis and research on the other. Modeling feeds back information to the monitoring program in the form of recommendations on how the monitoring system can be made more effective. Modeling also helps interpret data for the use of synthesis and research activities.

There are numerous synonyms for the types of models defined for the purposes of the GEM Program. Verbal models are also known as “qualitative” and

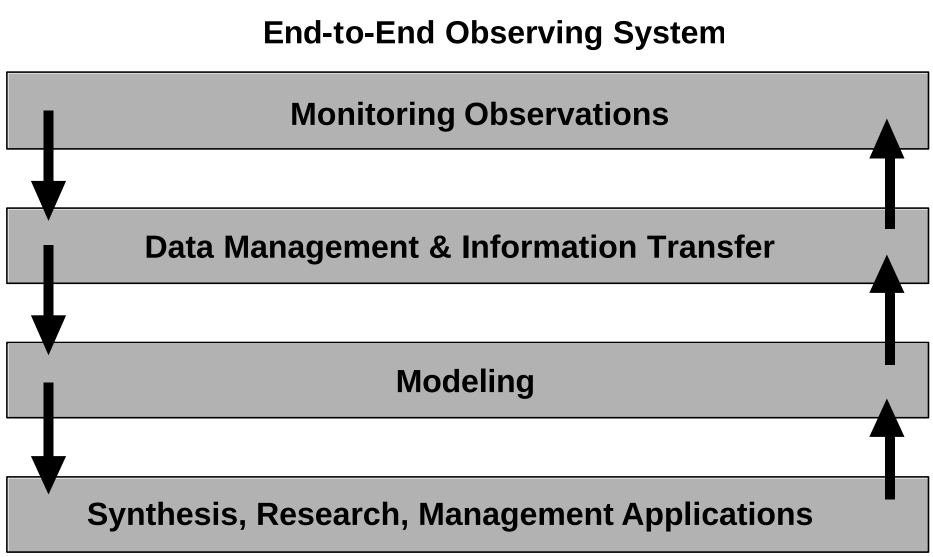

Figure 3.2 The End-to-End Observing System in which the monitoring observations are linked by data management and information transfer to end users, including modeling, synthesis, research, and management applications. *(Adapted from Tom Malone [U.S. GOOS Steering Committee 2000])*

"conceptual"; statistical models are also known as "correlative" and "stochastic"; and numerical models are also known as "deterministic" and "mechanistic." Note that "prediction," "simulation," and "analysis" are not types of models, but uses of models. For example, the use of any kind of statistical or numerical model to reproduce the behavior of a process, such as population growth, is known as a simulation. All four types of models will be used in the GEM Program. In the near-term, however, models of biological phenomena are expected to be mostly verbal, visual, and statistical, whereas models of physical and chemical phenomena are likely to be primarily numerical, in addition to being verbal and statistical.

The long-term modeling end points for monitoring, synthesis, and research in GEM are working biophysical models that make managers, policy makers, and resource users aware of changes in natural resources, help them understand the human and natural origins of these changes, and give them some idea of what to expect in the future. A detailed discussion of the definitions and strategies for modeling in the GEM Program is provided in Chapter 8.

3.2.6 Data Management and Information Transfer

Data management and information transfer are the processes of acquiring in the field, receiving in the office, formatting, and storing data; providing quality control and assurance; developing and managing databases; and making the data understandable and available to users (See also Chapter 9). It includes the development of information products based on interpreted data and the delivery of these products, including user interfaces. The immediate objective of data management and information transfer is to ensure that the data collected by projects under GEM are well documented, safely stored, and accessible to the public within a reasonable period of time after collection. An ongoing objective of data management and information transfer in the GEM Program is to achieve to the greatest extent possible the documentation, storage and public access for past data acquired with ***Exxon Valdez*** Oil Spill (EVOS) funds under the Natural Resource Damage Assessment and Restoration programs of the Trustee Council.

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

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

- Support cross-disciplinary integration of physical and biological information, and traditional knowledge within a structured, decision-making framework;
- Support synthesis, research, and modeling that evaluate testable hypotheses on the roles of natural forces and human activities in controlling biological production; and

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

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

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

Information transfer products will depend on the nature of the monitoring and research activities that are yet to be chosen. Possibilities for these products, based on the experience of other monitoring and research programs, are discussed in Chapter 9 and could include models and measures relevant to determining the productivity of key species such as salmon.

3.3 GEM Program Strategies

The previous section discussed the standard tools that will be used to develop and evaluate data and manage information in the GEM Program. This section presents two strategies that also will be important in guiding the GEM Program: incorporating traditional knowledge and community involvement, and potential for resource management applicability. These strategies will be applied to the GEM Program as a whole and will influence the way that the tools presented in the previous section are used.

3.3.1 Incorporating Community Involvement and Traditional Knowledge

Community involvement and the incorporation of traditional knowledge in the GEM Program are critical to the program's long-term success. The significance of traditional knowledge is becoming increasingly recognized (IUCN 1986, Martinez 1994, Kimmer 2000) and can play a role in providing early warning signs of ecosystem change (Ford 2001). Local residents are expected to provide ecological knowledge that can be incorporated into established scientific models. They also can be a source of research questions which help ensure research that is relevant to both ecological and community needs. Community-based monitoring efforts can efficiently collect essential data and build local stewardship as well as long-term support for the GEM Program.

The EVOS settlement requires meaningful public involvement in all Trustee Council programs, as well as a Public Advisory Committee. Residents of coastal communities have a direct interest in scientific and management decisions and activities concerning the fish and wildlife resources and environments on which they depend for their livelihoods and sustenance (Huntington 1992). The Trustee Council believes that encouraging local awareness and participation in research and monitoring enhances long-term stewardship of living marine resources.

Community involvement can occur in many ways. Several approaches have been tried in the EVOS restoration program and elsewhere in Alaska and other northern regions, and GEM will draw on these experiences to design specific processes for involving communities and their expertise(Huntington 2000, Brown-Schwalenberg et al. 1998, Fehr and Hurst 1996, Hansen 1994, Brooke 1993). One avenue is through active membership on the 20-member Public Advisory Committee, made up of representatives of tribal and incorporated communities, stakeholders, scientists and members of the general public. Another is through active participation of public members on various scientific subcommittees and work groups and during targeted workshops to help plan and guide the GEM Program as it develops. Other ways include having citizens, students and communities implement local monitoring activities.

Traditional and local ecological knowledge can provide important observations and insights about changes in the status and health of marine resources (Huntington 1998). With Trustee Council funding, Alaska Native tribes in the GEM research area are currently developing natural resource plans that will help identify important resources and potential threats and be useful in designing local monitoring schemes that help answer key questions for the GEM Program.

The Trustee Council has always listened closely to the views and interests of the people living in the spill-affected region, and responded to their concerns consistent with the legal restrictions of the EVOS settlement funds. Under the terms of the settlement, restoration funds can only be used to respond to injuries to the public's natural resources – not injury to individuals or to communities. However, the communities have the well being of these resources at heart, and any program to provide for the long-term health of the resources, has the benefit of providing for the long-term health of the local communities.

3.3.2 Potential for Resource Management Applicability

The GEM Program is intended to increase and enhance the information managers and stakeholders use to cope with changes in natural resources. To accomplish this, GEM will seek to acquire data with significant potential for use in resource management applications, ensure that data is converted into useful information in a timely manner, and invite research and synthesis projects that both involve and benefit natural resource management agencies.

Salmon fishery management illustrates management concerns that are common to most natural resources. The typical salmon fishery operates on a resource that depends on a variety of habitat types (freshwater, nearshore, and offshore) during the course of its life cycle (Figure 3.3). Management of the salmon fishery requires detecting and understanding the consequences for production of habitat management decisions (Box 1.9, Figure 3.3) throughout the salmon's life cycle. GEM seeks to provide data relevant to answering specific questions about how a range of habitat types function to produce salmon and other species. The cyclic nature of the salmon fishery in time and space makes it clear that biological production in one habitat type cannot be understood in isolation from production in the other habitat types in which the salmon completes its life cycle. GEM questions are directed at understanding not only specific mechanisms of production in representative habitat types, but also the connections among habitat types.

GEM questions are directed at understanding not only specific mechanisms of production in representative habitat types, but also the connections among habitat types.

The management applications actually achieved will depend on a variety of factors, including the degree to which resource managers participate in the review, development, and implementation of the GEM Program.

3.4 Conclusion

The tools and strategies described above are used together to make the GEM Program scientifically sound, compatible with other programs, relevant to communities and resource managers, and open to the information local residents may provide. Using the tools and strategies to implement the GEM Program is addressed in following chapter.

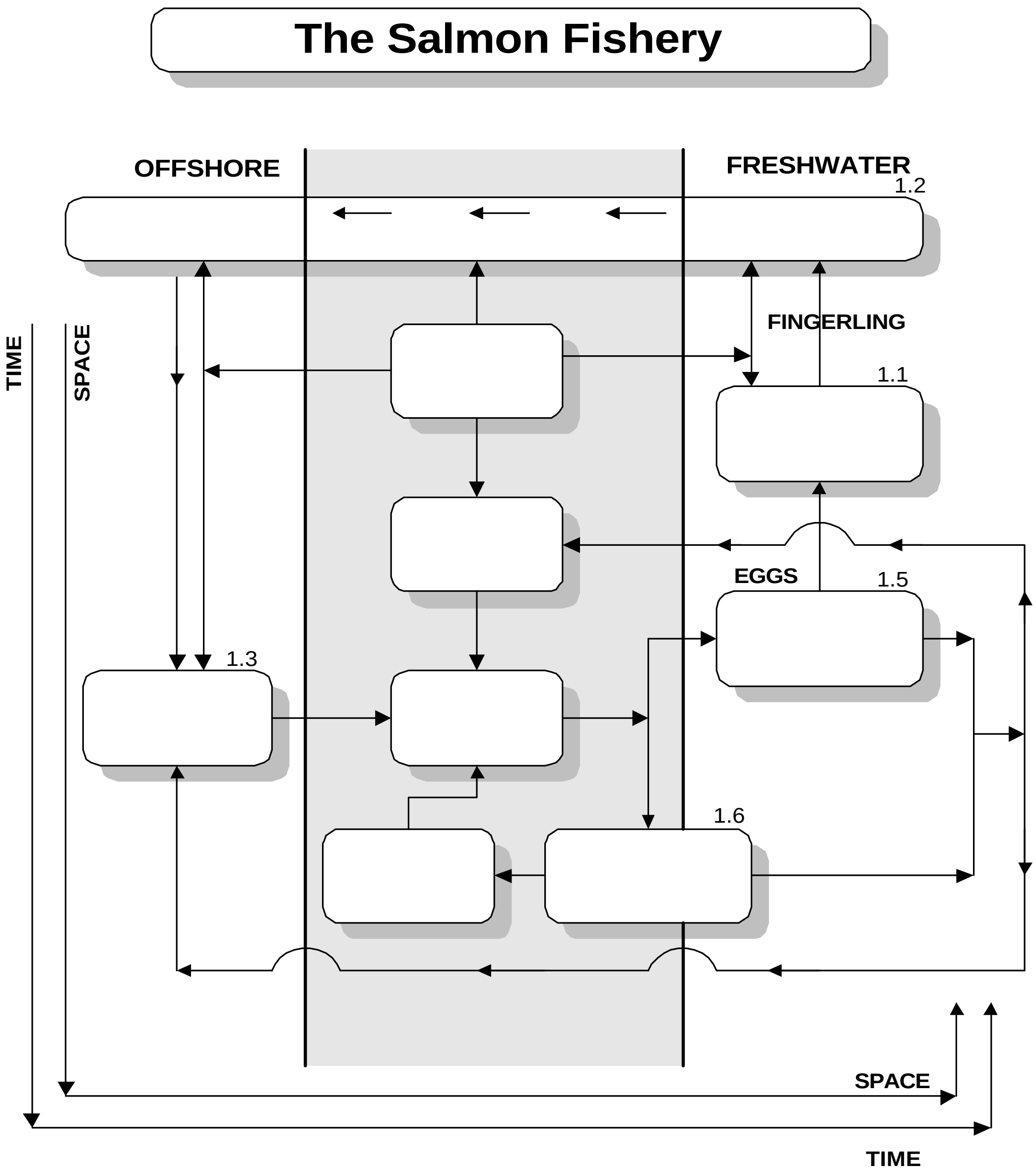

Figure 3.3 Diagram of the salmon fishery with life cycle stages, harvest, and habitat management decisions in geographic and temporal contexts *(Mundy 1998)*.

3.5 References

Brooke, L.F. 1993. The participation of indigenous peoples and the application of their environmental and ecological knowledge in the Arctic environmental protection strategy. Inuit Circumpolar Conference. Ottawa.

Brown-Schwalenberg, P., H.P. Huntington, and H. Short. 1998. Traditional knowledge and environmental recovery: experiences from the Exxon Valdez oil spill. Bridging traditional ecological knowledge and ecosystem science, August 1998, Flagstaff, AZ.

Fehr, A. and W. Hurst. 1996. A seminar on two ways of knowing: indigenous and scientific knowledge. Inuvik, NWT, Aurora Research Institute.

Ford, J. 2001. The relevance of indigenous knowledge to contemporary sustainability. Northwest Science Forum 75: 183-188.

Hansen, B. 1994. Report on the seminar of integration of indigenous peoples and their knowledge. Reykjavik, Iceland, Copenhagen: Ministry for the Environment (Iceland), Ministry of the Environment (Denmark), and the Home Rule of Greenland (Denmark Office).

Huntington, H.P. 1992. Wildlife management and subsistence hunting in Alaska. Belhaven Press. London.

Huntington, H.P. 1998. Observations on the utility of the semi-directive interview for documenting traditional ecological knowledge. Arctic 51: 237-242.

Huntington, H.P. 2000. Using traditional ecological knowledge in science: methods and applications. Ecological Applications 10: 1270-1274.

IUCN. 1986. (International Union for Conservation of Nature) Tradition, conservation and development. Occasional newsletter of the Commission on Ecology's Working Group on Traditional Knowledge. No. 4. International Union for Conservation of Nature. UK.

Kimmer, R.W. 2000. Native knowledge for Native ecosystems. Journal of Forestry 98: 4-9.

Martinez, D. 1994. Traditional environmental knowledge connects land and culture. Winds of Change 89-94.

Mundy, P.R. 1998. Principles and criteria for sustainable salmon management. Alaska Department of Fish and Game. http://www.cf.adfg.state.ak.us/geninfo/pubs/ pubshome.htm

Myers, K.W., R.V. Walker, H.R. Carlson, and J.H. Helle. 2000. Synthesis and review of U.S. research on the physical and biological factors affecting ocean production of salmon. Pages 1-9 in Helle, J.H., Y. Ishida, D. Noakes, and V. Radchenko, editors. Recent changes in ocean production of Pacific salmon. North Pacific Anadromous Fish Commission Bulletin, Vancouver.

NRC. 2002. A century of ecosystem science: planning long-term research in the Gulf of Alaska. Washington, D.C., National Academy Press.

Ricklefs, R.E. 1990. Scaling patterns and process in marine ecosystems. Pages 169-178 in Sherman, K., L.M. Alexander, and B.D. Gold, editors. Large marine ecosystems: patterns, processes and yields. American Association for the Advancement of Science, Washington, D.C.

U.S. GOOS Steering Committee. 2000. Third meeting of the U.S. GOOS steering committee June 29-30, 2000 Huntington Beach, California. U.S. GOOS.

Wilson, E.O. 1998. Consilience: the unity of knowledge. Vintage Books, A Division of Random House, Inc. New York.

4. PROGRAM IMPLEMENTATION

In This Chapter

- Introduction to the GEM Science Plan
- Conceptual Foundation by Habitat
- Key Questions by Habitat
- GEM Program Implementation

This chapter describes the starting point for developing the GEM Science Plan. As such, it should be considered a work in constant progress. Once completed the GEM Science Plan will be periodically updated in response to direction from the Scientific and Technical Advisory Committee, its subcommittees, and using input from communities and the general public (see Chapter 5). Changes to potential research questions during the early years of the program could be substantial.

4.1 Introduction

Before the general hypotheses developed and presented in Chapters 2 and 3 can be used to guide the GEM research and monitoring program, they need to be refined into a set of specific research questions, and the research questions need to be evaluated to determine what data need to be collected and analyzed to answer them. The process and timelines for defining, asking, and getting the data to answer the questions, also known as research and monitoring, is described by the GEM Science Plan, which does not now exist.

The goal served by the Science Plan is to implement a long-term monitoring program, which can only be done after the requisite synthesis and research have been completed.

This chapter is the first step in developing the Science Plan. It extends the GEM conceptual foundation (through the primary physical and biological processes, and human activities believed to be most important in affecting change in the Gulf of Alaska [GOA]) to each general habitat type. From this information, and building on the habitat hypotheses, a series of potential questions have been developed that can be used as a starting point for identifying initial research activities. The potential research questions presented in these sections are meant to capture some of the main uncertainties in how fluctuations in the northern GOA ecosystem influence the distribution and abundance of valued organisms. They do not attempt to capture the entire scope of potential research questions. Instead, they address discrete aspects of the conceptual foundation and are starting points for identifying research activities. As knowledge of the ecosystem increases, the research questions are expected to gain greater specificity and refinement through ongoing hypothesis testing, gap analysis, and identification of specific information needs. It is expected that the potential research questions will change as a result of the Scientific and Technical Advisory Committee (STAC) process described in Chapter 5.

Following the habitat-specific research questions is an initial implementation plan for the GEM Program during a 5-year period, from FY 03 to FY 07. This plan incorporates the following elements:

- A ***proposed schedule for implementation***, FY 03 to FY 07, for core and partnership activities, models, and data management.
- Lists of probable or ***prospective partners*** that are actively doing related monitoring or research in the habitat type.
- Development of ***models*** as a way to synthesize monitoring and research results and transfer information to end users.
- ***Candidate (possible) core monitoring activities*** recommended based on the conjunction of partnership opportunities and opportunities for measuring biological and physical quantities related to the key question and information gaps.
- ***Candidate (possible) core variables*** recommended based on approaches suggested by the literature reviewed in the scientific background (Chapter 7).

The proposed schedule for implementing GEM monitoring activities in the watershed, intertidal/subtidal, and Alaska Coastal Current (ACC) habitat areas is similar, but modeling and data management needs differ in each habitat. For offshore research, GEM will primarily be involved in partnering activities, since research offshore is already being undertaken by a number of other large-scale programs. As a result, the schedule for implementation largely is dependent on the implementation schedules for partner programs.

4.2 Watersheds

4.2.1 Conceptual Foundation for Watersheds

Watersheds are linked by biogeochemical 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 and animals in watersheds.

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 exported 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 Alaska Coastal Current–the single most dominant and integrating feature of the physical environment on the continental shelf.

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.

Key Hypothesis: ***Natural forces (such as climate) and human activities (such as habitat degradation and fishing) serve as distant and local factors in causing short-term and long-lasting changes in marine-related biological production in watersheds.***

4.2.2 Potential Watershed Questions:

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

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

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

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

c. What are the levels of contaminants entering and leaving watersheds along marine-related pathways?

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

4.2.3 Program Implementation

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

Table 4.1 presents the proposed schedule for implementation.

Table 4. 1 Proposed Implementation Schedule for Watershed Habitat

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

Notes:

c = core (GEM Program supported) activity

p = partnership (jointly supported) activity

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

Candidate core monitoring activities: Kenai River watershed, Karluk River watershed.

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

4.2.4 Prospective Partners and Partner Activities

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

4.2.5 Models

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

4.2.6 Candidate Core Monitoring Activities

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

4.2.7 Candidate Core Variables

Isotopes of nitrogen in plants and animals and sources of reduced iron are candidates for core variables, based on work described in the scientific background under marine-terrestrial connections and chemical oceanography (Chapter 7). In watersheds of the GEM region, where nitrogen limits productivity, marine nitrogen in anadromous fish species, principally salmon, could be an important driver of watershed productivity. Phosphorus and iron from salmon may also be important to watershed productivity, but direct measures of the origin of these elements are not available. Indirect measures might be, for example, phosphorus or iron concentration per gram of fish times average fish weight times return number. A decade of work on the role of iron in primary productivity in marine areas suggests that geophysical and biological processes in watersheds may contribute to marine productivity. Processes in the watersheds may limit marine productivity by controlling the availability of precursors of reduced iron.

4.3 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 Prince William Sound (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.

4.3.1 Conceptual Foundation for Intertidal and Subtidal

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 Chapter 7, Section 5.3, the runup 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 mollusks, such as clams and mussels, which 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.

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 Chapter 7.12.2.5. 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.

Key Hypothesis: ***Natural forces (such as currents and predation) and human activities (such as increased urbanization and localized pollution) serve as distant and local factors, in causing short-term and long-lasting changes in community structure and dynamics of the intertidal and subtidal habitats.***

4.3.2 Potential Intertidal and Subtidal Question:

a. What is the variability of selected plant and animal populations in the intertidal and subtidal zones?

Specific Information Needs:

- Variability in numbers and diversity of fixed algae and invertebrates in several regions, such as PWS, Kachemak Bay, and Kodiak Island.
- Relative availability of larval dispersal stages.
- Measures of the cycling of carbon, nutrients, and contaminants in key species such as ***Fucus***.
- A detailed map of intertidal plant biomass during the growing season on a wide spatial scale.

- Monitoring of clam populations.
- Measurements of population processes of sea otters.
- Identification and measurement of human impacts of concern.

4.3.3 Program Implementation

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

Table 4.2 presents the proposed schedule for implementation.

4.3.4 Prospective Partner Activities

Partner activities in FY 03 will be the supporting monitoring programs already in place, such as monitoring of individual species for basic biology and contaminant loads, surveys of species composition and distribution, surveys of substrates, and measurements of physical oceanography. Starting in FY 04, partners will be encouraged to assist in funding research to further site selection. These research activities will extend through FY 06, terminating after the monitoring station is fully operational in FY 07 (Table 4.2).

4.3.5 Models

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

Table 4. 2 Proposed Implementation Schedule for Intertidal and Subtidal Habitat

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

Notes:

c = core (GEM Program supported) activity

p = partnership (jointly supported) activity

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

Candidate core monitoring activities: Kachemak Bay (lower Cook Inlet), Green Island (PWS)

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

4.3.6 Candidate Core Monitoring Activities

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

4.3.7 Candidate Core Variables

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

4.4 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.

4.4.1 Conceptual Foundation for ACC

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 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 Chapter 7) 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 Fisheries Oceanography Coordinated Investigations (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.

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.

Key Hypothesis: ***Natural forces (such as variability in the strength, structure and dynamics of the ACC) and human activities (such as fishing and pollution) cause local and distant changes in production of phytoplankton, zooplankton, birds, fish, and mammals.***

4.4.2 Potential Alaska Coastal Current Questions:

a. What is the annual variability of strength, location and dynamics of the ACC?

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

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

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

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

Specific Information Needs:

- ***Chlorophyll a*** measurements.
- Information on phytoplankton species composition.

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

Specific Information Needs: Information about zooplankton biomass and species composition.

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

Specific Information Needs:

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

f. What are the major factors affecting long-term changes in sea bird populations?

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

g. What are the major factors affecting long-term changes in harbor seal populations?

Specific Information Needs:

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

4.4.3 Program Implementation

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

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

Table 4.3 presents the proposed schedule for implementation.

4.4.4 Prospective Partner Activities

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

Table 4. 3 Proposed Implementation Schedule for Alaska Coastal Current Habitat

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

Notes:

c = core (GEM Program supported) activity

p = partnership (jointly supported) activity

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

Candidate core monitoring activities: GAK1, Hinchinbrook Entrance, Montague Strait

Candidate core variables: temperature, salinity, fluorescence, plankton, forage species

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

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

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

4.4.5 Models

Several hydrographic and circulation models have been or are being developed for the ACC (see also Chapter 8, and Appendix F). Models of the relationship of marine planktonic production to water column structure were developed in the EVOS SEA program (Eslinger et al. 2001) and are expected eventually to be developed further under the GEM Program.

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

Models of particular interest from the FOCI program are the 1-D and 3-D versions of the Shelikof NPZ models, and the GOA Walleye Pollock Stochastic Switch Model (SSM) (see Chapter 8, and Appendix F). The Shelikof NPZ models are a set of coupled (biological and physical) models designed to examine hypotheses about pollock recruitment in the Shelikof Strait region. The Pollock SSM is a numerical simulation of the process of pollock recruitment. Of particular interest to the GEM Program is the identification by the SSM of three specific agents of mortality: wind mixing, ocean eddies, and random effects. Ecopath models developed by Okey, Pauly, and others at the University of British Columbia are also of interest, especially for PWS, but also for the GOA continental shelf and slope (excluding fjord, estuarine, and intertidal areas) (see Appendix F).

4.4.6 Candidate Core Monitoring Activities

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

4.4.7 Candidate Core Variables

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

4.5 Offshore: Alaska Current and the Subarctic Gyre

4.5.1 Conceptual Foundation for Offshore

In the offshore areas of the Alaska Current and the subarctic gyre, forcing by winds associated with the Aleutian Low Pressure System (Aleutian Low) 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 Aleutian Low conditions in the Alaska Current and the subarctic gyre are profound. In periods with more negative atmospheric pressure that is keyed by the northeastern movement of the Aleutian Low 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 Niño's and the long-term warming of the oceans. El Niño's 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.

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 salmon 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.

Key Hypothesis: ***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) play significant roles in determining production of carbon and its shoreward transport.***

4.5.2 Potential Offshore Questions:

a. What is the annual variability in the production of zooplankton in the offshore areas?

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

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

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

c. What is the role of the Pacific High Pressure System in determining the timing and duration of the movement of dense slope water onto and across the shelf to renew nutrients in the coastal bottom waters?

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

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

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

e. Does iron limitation control the species and size distribution of the phytoplankton communities in the offshore areas?

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

4.5.3 Program Implementation

As with the ACC portion of the program, results of GLOBEC research need to be carefully considered before implementation of long-term monitoring in this broad habitat type. This deliberate approach is reflected in the emphasis on synthesis for this habitat type in the early years of the proposed schedule for implementation (Table 4.4).

4.5.4 Prospective Partner Activities

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

4.5.5 Models

The GLOBEC NPZ 1-D and 3-D models are discussed above in Section 4.4.5. A broader model addressing NPZ for the entire North Pacific is the North Pacific Ecosystem Model for Understanding Regional Oceanography, in which fluxes of nitrogen, silicon, and carbon will be tracked (see Appendix F).

Table 4. 4 Proposed Implementation Schedule for Offshore Habitat

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

Notes:

c = core (GEM Program supported) activity

p = partnership (jointly supported) activity

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

Candidate core monitoring activities: GLOBEC stations, Valdez-Long Beach Line, and other ships of opportunity.

Candidate core variables: nutrients, detritus and plankton, temperature, and salinity.

4.5.6 Candidate Core Monitoring Activities

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

4.5.7 Candidate Core Variables

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

4.6 Conclusions: Moving the GEM Program Forward

To maintain the value of the long-term monitoring program, data collection and sampling protocols will necessarily be conservative, changing only with demonstration of substantial need, and then only after careful deliberation. Therefore, it is critical that GEM choose its monitoring projects with caution and deliberation . The process envisioned will select research projects in the early years of the program that show promise of leading eventually to inclusion in the long-term monitoring program. Research will be focused around initial research questions developed through the STAC and subcommittee processes (see Chapter 5), using the questions provided in this chapter as a starting point for deliberation. In the initial years of the program, research projects will be selected through a solicitation process. The Trustee Council will issue the request for proposals with recommendations from the STAC, the Public Advisory Committee and community involvement (see Chapter 5). As the GEM Program matures, requests for proposals may become increasingly targeted toward requests for specific research and monitoring projects and capabilities. However, a portion of the available funds will continue to be allocated to the innovative synthesis and research proposals necessary to maintain high standards of scientific rigor and cost effectiveness. Workshops and subcommittees will be important mechanisms to involve the public, including resource managers, communities and other stakeholders, in selecting research and monitoring activities.

4.7 References

Bailey, K.M., P.J. Stabeno, and D.A. Powers. 1997. The role of larval retention and transport features in mortality and potential gene flow of walleye pollock. Journal of Fish Biology 51: 135-154.

Bogard, S.J., P.J. Stabeno, and J.D. Schumacher. 1994. A census of mesoscale eddies in Shelikof Strait, Alaska during 1989. Journal of Geophysical Research 99: 18243-18254.

Brown, E. unpublished. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Eslinger, D., R.T. Cooney, C.P. McRoy, A. Ward, T. Kline, E.P. Simpson, J. Wang, and J.P. Allen. 2001. Plankton dynamics: observed and modeled responses to physical factors in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1): 81-96.

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

5. PROGRAM MANAGEMENT: ADMINISTRATION, PUBLIC AND COMMUNITY ADVICE AND INVOLVEMENT, SCIENTIFIC GUIDANCE, AND DATA POLICIES

In This Chapter

- Program Administration
- Providing for Public and Community Advice and Involvement
- Process for Providing Scientific Advice, Review and Management
- Establishing Data Management Office and Policies

5.1 Administration

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

The GEM Program will be administered by a core professional staff that is not directly affiliated with any particular agency, institution, or program. This is currently the case with the management of the ***Exxon Valdez*** Oil Spill Trustee Council Office (Figure 5.1). An executive director will oversee the financial, program management and administrative, scientific, and public involvement aspects of the program. The executive director and staff, while housed for administrative purposes in a single government agency, will work under a cooperative agreement for all six trustees. The Trustee Council and staff will actively solicit advice on science and policy matters, including review of monitoring and research activities, from experts, including the Scientific and Technical Advisory Committee (STAC), and from the public, including the Public Advisory Committee (PAC).

5.1.1 The Work Plan

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

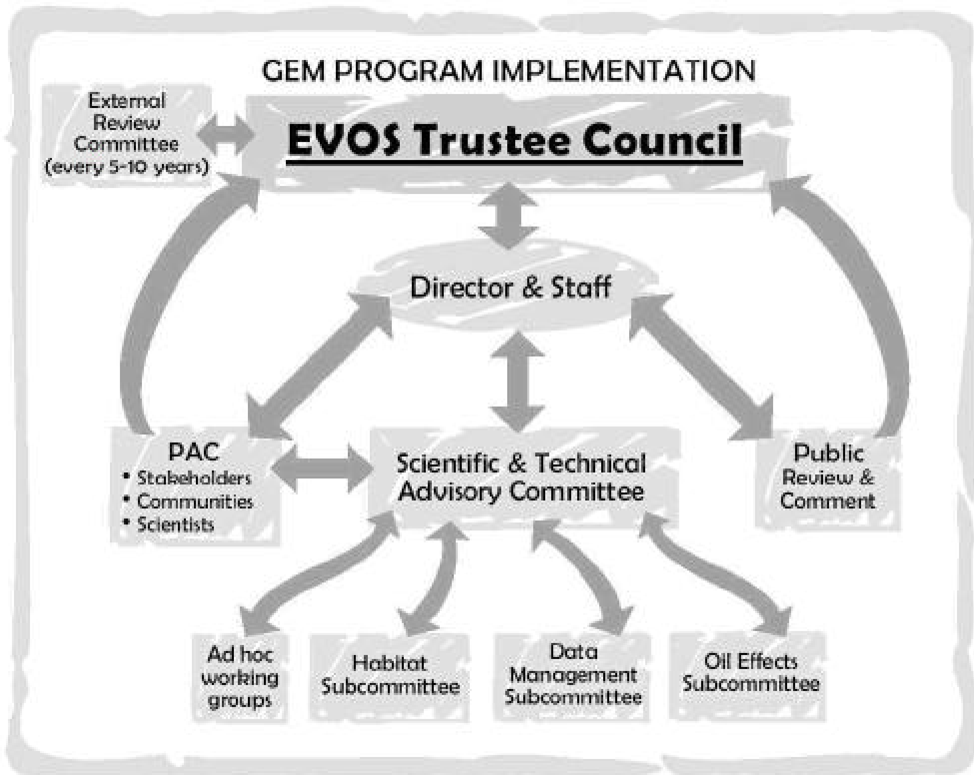

Figure 5.1 The organizational elements involved in GEM implementation. Modified in response to comments from the Nation Research Council.

5.1.2 Proposal Development and Evaluation Process

The proposal development and evaluation process will have the following elements or steps, which are also shown in Figure 5.2. As implementation of the GEM Program begins, however, these steps may be modified as efficiencies and improvements are found.

- A "State of the Gulf" workshop will be held periodically, at which the current status of the health of the Gulf of Alaska (GOA) ecosystem will be assessed. Project investigators, peer reviewers, resource managers, stakeholders, and the public will be invited to this meeting, at which research and monitoring results will be presented and discussed. In some years, this workshop will be replaced by or augmented with a process of consultations and workshops with various committees and work groups of science and public advisors to evaluate and affirm or revise priorities.
- An ***Invitation to Submit Proposals***, which will specify the types of proposals that are priorities for consideration to implement the mission and goals of the GEM Program, will be issued periodically. Research proposals are envisioned to be of finite duration and have short-term goals (for example, 2 to 5 years). Monitoring projects will be evaluated and renewed on longer time scales (such as once every 5 years). The ***Invitation(s)*** will be the vehicle

for notifying the scientific community, the public and others that proposals will be considered during a certain period of time.

- Proposals received in response to the ***Invitation*** will be circulated for technical peer review (see below). In addition, proposals will be reviewed by the STAC and appropriate subcommittees for their ability to contribute to the information-gathering needs of the central hypothesis and questions, and also for how they contribute to meeting the programmatic goals and strategies of the Trustee Council (see Chapters 1 and 3), such as promoting community involvement, developing resource management applications, and leveraging funds from other sources. Past performance of principal investigators will be assessed. Staff will also review all budgets.
- Comments from the PAC and the general public will be solicited. A reasonable period of time for public comment will be built into the review process.
- The executive director will present to the Trustee Council the recommendations of the STAC and PAC, a summary of any additional public comment, and additional recommendations if appropriate.

The Trustee Council, after receiving advice from its public and scientific advisors and staff, will vote on which proposals to fund.

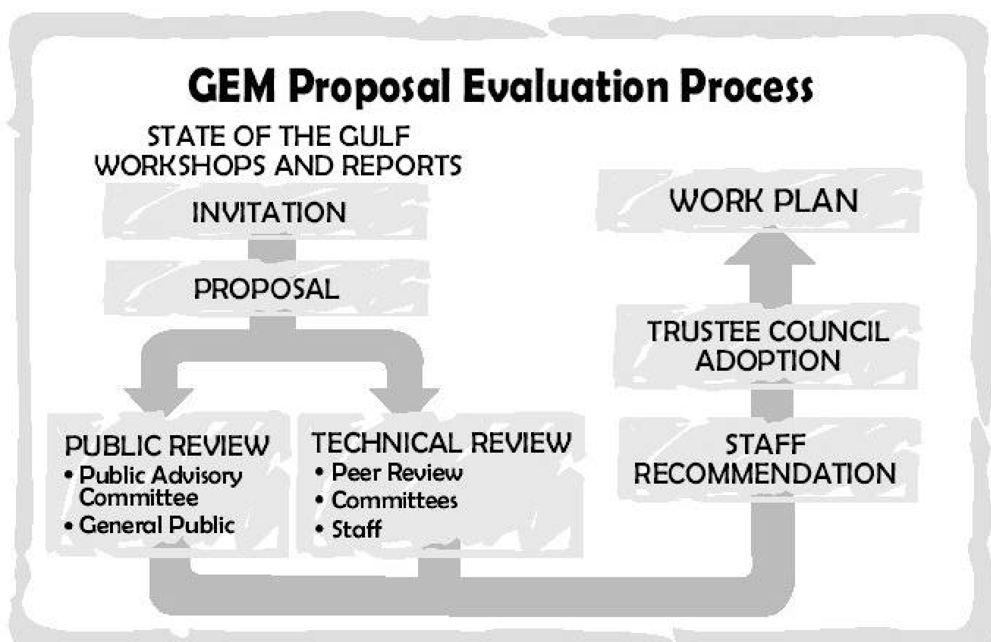

Figure 5.2 GEM Proposal Evaluation Process

5.1.3 Reports and Publications

Annual and final reports will be required for all projects, following established procedures. To ensure that investigators are making satisfactory progress toward project objectives, staff will review annual reports. In addition, annual reports may possibly be sent out for independent peer review. Final reports will be subject to independent peer review, and comments from the independent peer reviewers must be addressed in the final versions of final reports. All final reports will be archived at the Alaska Resources Library and Information Service (ARLIS) and available on the Trustee Council's web page.

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

5.1.4 Peer Review

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

Special review panels may be convened from time to time to evaluate and make recommendations about aspects of the GEM Program. At other times, special panels may meet with project investigators and others to fully explore particular topics, problems, or projects.

5.1.5 External Program Review

The Trustee Council is committed to review of the program by an outside entity, such as the National Research Council, at periodic intervals. This review will look at the program's structure and implementation to ensure that the GEM mission and goals are being achieved.

5.2 Public and Community Advice and Involvement

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

The Trustee Council is committed to public input and public outreach as vital components of the long-term GEM Program. Figure 5.1 illustrates the role of public participation in the GEM Program.

5.2.1 Public Advisory Committee

The Public Advisory Group (PAG) in effect from 1991 – 2002 has 17 members representing 12 interest groups and the public at large, as well as two ex-officio members from the Alaska Legislature. The charter for a new Public Advisory Committee (PAC) will be certified in September 2002. The PAC will consist of 20 members, representing 14 distinct public interests. The PAC will meet at least twice a year to provide broad program and policy guidance to the Trustee Council and staff on the overall development and progress of the GEM Program. The group will take an active role in setting priorities and ensuring that the overall program is responsive to public interests and needs.

5.2.2 Public Advice

The Public Advisory Committee is not the only source of public advice for the Trustee Council. Opportunities for public advice and comment are incorporated throughout the process. The Trustee Council is a public entity subject to the State of Alaska Open Meetings Act and corresponding federal laws. All meetings are public, noticed to the public, and include a formal public comment period. Newsletters, annual reports, public meetings in communities in the spill-affection region, and the Trustee Council's Web site (www.oilspill.state.ak.us) are all tools to promote and encourage public input and participation.

5.2.3 Public and Community Involvement

The Trustee Council is committed to incorporating public and community involvement in the GEM Program at all levels. This means not just providing advice on proposals and policies, but involving communities early on in developing research hypotheses and questions and helping decide what variables to monitor and in what locations.

Developing a program that includes extensive community involvement will be a challenge, and will necessarily evolve over time. The Trustee Council is funding several planning projects in FY 02-FY 03 to further develop ways to better incorporate local and community involvement in the GEM Program.

Ongoing efforts include, but are not limited to, these elements:

- Community meetings where community members are asked to identify and provide information on issues and questions that are most important to them.
- Public, stakeholder and community membership on the Public Advisory Committee. Expansion of the committee size to allow greater participation by communities and stakeholders.
- Community representation on all subcommittees and work groups used in developing and implementing the GEM Program. Making funding available to encourage participation in subcommittees and work groups.

- Joint meetings between the Scientific and Technical Advisory Committee and the Public Advisory Committee to foster communication between scientific interests and community interests.
- Membership of at least one STAC member on the PAC.
- A proposal solicitation and review process that encourages community-based proposals.
- The inclusion of community-based monitoring programs and traditional knowledge in the GEM Program, especially in the watershed and intertidal/subtidal habitats.

5.3 Scientific Advice, Review and Management

In addition to peer review of individual proposals and public review and advice, a committee and work group approach will be used to guide GEM Program development and implementation.

5.3.1 GEM Science Director

The GEM Program Science Director will work closely with other scientific advisory bodies, and will be the staff member tasked with overseeing implementation of the science program and informing interested communities of the program's results. The Science Director will work with other Trustee Council staff in overseeing implementation of research and monitoring activities, ensuring timely delivery and dissemination of research results, and maintaining the GEM database. The Science Director makes recommendations to the Executive Director and the Trustee Council on program implementation and development.

5.3.2 Scientific and Technical Advisory Committee (STAC)

The STAC is a standing committee that is expected to provide the primary scientific advice to the Executive Director on how well the collection of proposed monitoring and research projects (the work plan) and the GEM Program meet the mission and goals of the program and test the conceptual foundation.

The STAC has three primary functions:

1. Provide leadership in identifying and developing testable hypotheses relevant to the conceptual foundation of the GEM plan, consistent with the mission, goals and policies of the Trustee Council.
2. Make recommendations to the Executive Director and GEM Science Director on preparation of the science program and implementation plans; proposal solicitation and peer review; and selection of research, monitoring, synthesis, modeling and other studies best suited to meeting the goals of the GEM Program.

3. Provide support and oversight to subcommittees and ad hoc work groups as needed (see below).

The STAC is composed of emeritus and senior scientists and others selected primarily for their broad expertise and leadership who serve for four-year, staggered renewable terms. At least one of the scientists serving on the STAC also serves on the PAC. The STAC members are not principal investigators for GEM projects. Institutional and professional affiliations are of interest in selecting members, because connections to other marine science programs are valuable for ensuring collaboration and coordination on GEM Program implementation. The GEM Science Director is a co-chair and non-voting member of the STAC.

5.3.3 Subcommittees

Subcommittees are standing committees organized to address specific aspects of the GEM Program, to facilitate coordination among scientists, resource managers, and the public and communities, and to help the STAC provide leadership and oversight for the program.

The functions of the subcommittee(s) are to:

- Recommend to the STAC testable hypotheses, items for invitation and peer reviewers;
- Identify and help guide implementation of core monitoring stations and variables that are relevant to the key questions and testable hypotheses;
- Advise on, or possibly convene special review panels or work groups about, aspects of the GEM Program.

The subcommittees are composed of scientists, resource managers, educators, and community members selected for knowledge, expertise or familiarity with the issue around which the subcommittee is created. For example, subcommittees could be developed around each of the broad habitat types (watersheds, intertidal and subtidal, Alaska Coastal Current (ACC), and offshore) or just one overall habitat, lingering oil effects, data management systems and information technology, modeling, monitoring or other GEM Program areas. Subcommittee members can be principal investigators on current GEM funded projects. Institutional, professional, and other affiliations will also be of interest in selecting members to promote collaboration and cooperation.

5.3.4 Work Groups

The STAC and subcommittees may periodically form ad hoc work groups to develop specific products as requested. Work groups could also be charged with solving a particular problem in a finite amount of time, such as the proper location of an oceanographic mooring.

5.3.5 Workshops

The STAC or subcommittees may recommend organizing workshops to provide input on core variables for monitoring, research activities, community involvement strategies, and other program elements. The GEM Program anticipates that workshops will play an important role in implementing the science program and disseminating the results of GEM research to resource managers and communities.

5.4 Data Management and Information Transfer

The Data Management Office will be an essential component of the GEM Program. The office will be headed by a Data Systems Manager who will evaluate continuously the evolving information management needs of the GEM Program, and identify and recommend cost-effective solutions to the Executive and Science directors. Over time the mix of in-house supporting staff and out-sourced tasking may vary, but there will be a long-term commitment to providing consistent and high quality data management support (data quality, archive, and analysis) to the GEM Program. Staff in the Data Management Office will coordinate with other agencies in regard to data management and information transfer, manage computing resources, develop software programs, and maintain web sites in support of the GEM Program. In addition, staff in the Data Management Office will be responsible for developing and ensuring compliance with data policies and procedures.

Data management and information transfer policies are an integral part of GEM Program management. Clear and effective approaches for information gathering, archiving and dissemination are essential to the successful operation of a long-term ecosystem science project such as the GEM Program. Because the GEM Program is regional in geographic scope, with goals of cooperation, coordination, and integration with existing marine science programs, data management and information transfer policies are to be compatible with, and similar to, existing norms for state, federal, and nongovernmental marine science programs. Whenever possible, existing norms will be adapted or adopted for use by the Trustee Council. Standards adopted by the Federal Geographic Data Committee, GLOBEC, and the U.S. Environmental Protection Agency's (EPA) Environmental Monitoring and Assessment Program (EMAP), and other organizations will be considered for developing GEM data management and information transfer policies. (Options and procedures for data management and information transfer are considered in more detail in Chapter 9.)

The GEM data management and information transfer policies will incorporate the following broad elements:

- A commitment to making data and models available in a well documented and understood form.

- Full and open sharing of data and models at low cost, after verification and validation.
- Timely availability of data and models.
- Acceptance of and adherence to the data policies as a condition for participation in the GEM Program and receipt of funding.
- Adherence to data collection and storage standards.
- Availability of data and models on the GEM public web site, or through a national public archive.
- Long-term archiving of all data and models in a designated storage facility.
- Proper metadata, including identification of the origin of all data and models with a citation.

6. INTRODUCTION TO THE SCIENTIFIC FOUNDATION

In This Chapter

- Ø Leading Hypotheses in Marine Ecosystems
- Ø Principal Ecological Concepts

6.1 Introduction

GEM's mission, as defined in Chapter 1, is to:

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

As developed in response to this mission, a comprehensive, general conceptual foundation is the basis for the GEM Program (Chapter 2). The validity of the conceptual foundation is essential to the success of the GEM Program by virtue of its use to generate the hypotheses and questions that drive monitoring and research. Chapter 6 begins the process of establishing the scientific credentials of the conceptual foundation by presenting the leading hypotheses on structure and function of marine ecosystems and the principal ecological concepts on which it is based. Chapter 7 continues and concludes that process with a presentation and synthesis of relevant scientific literature.

6.2 Some Leading Hypotheses

This section reviews leading hypotheses that explain changes in biological production as a result of natural and human activities.

6.2.1 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).

6.2.2 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.

6.2.3 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.

6.2.4 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.

6.2.5 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 Alaska Predator Ecosystem Experiment 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 Prince William Sound (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.

6.2.6 Fluctuating Inshore and Offshore Production Regimes Hypothesis

Although the fluctuating inshore and offshore production regimes 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. Figures 6.1a-d illustrate some features of this model.

The model was developed 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.

Figure 6.1a Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes in the physical processes during a positive PDO (strong wintertime low pressure).

Figure 6.1b Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes in the biological consequences of conditions during a positive PDO (strong wintertime low pressure).

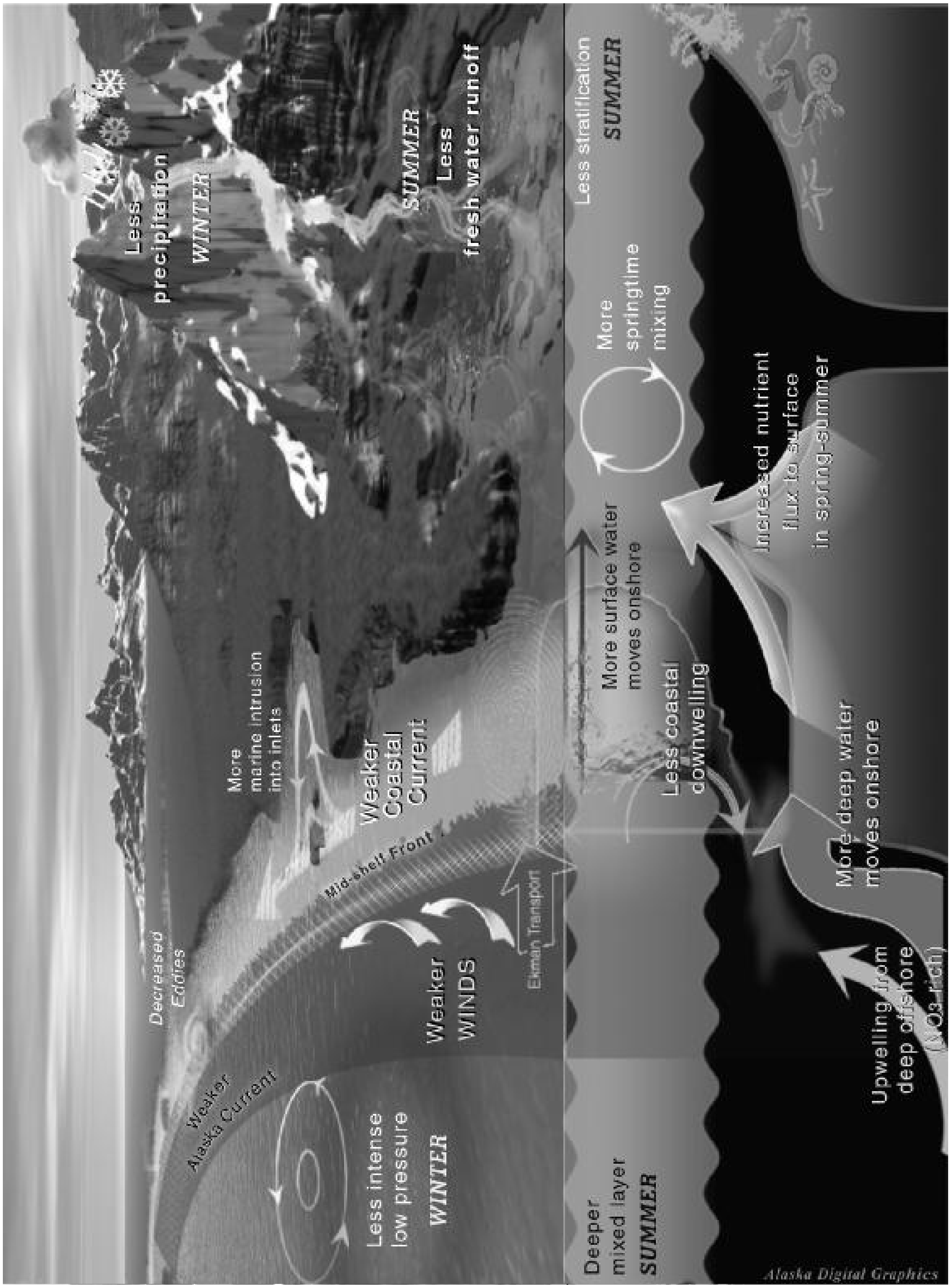

Figure 6.1c Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes in the physical changes during a negative PDO (weak wintertime low pressure).

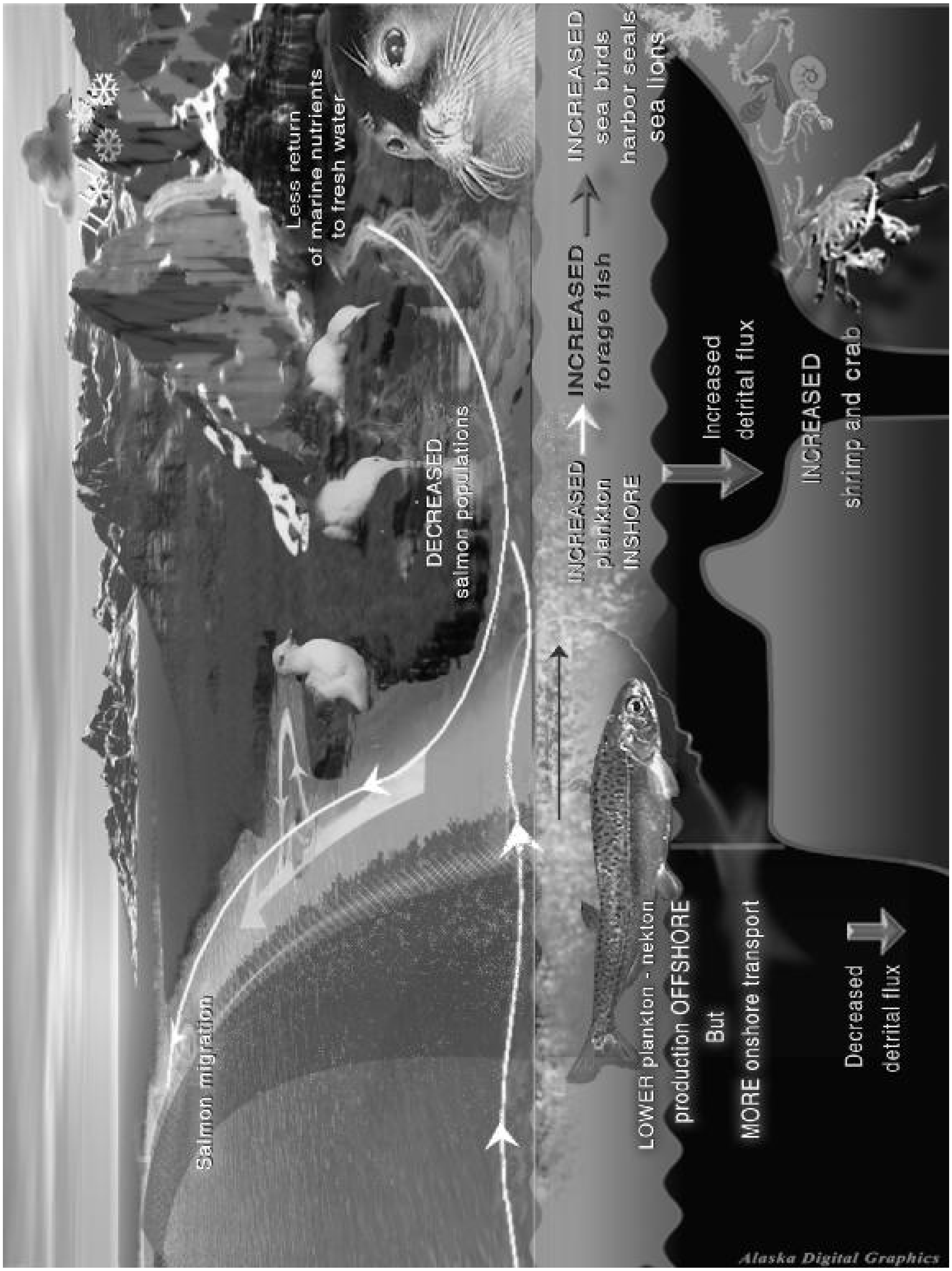

Figure 6.1d Schematic of proposed fluctuating inshore and offshore production regimes in the GOA showing relative changes in the biological consequences of conditions during a negative PDO (weak wintertime low pressure).

6.2.7 6.2.7 Human Impacts Hypotheses

Hypotheses on human impacts explain alterations of ecosystems as the result of human activities. Changes in species composition, alteration of the relative abundances of species and their food species, and changes in production and productivities of populations of plants and animals are widely accepted as being consequences, to some degree, of human activities (Jackson et al. 2001). An important, constant dilemma in the history of natural resource management is distinguishing between human and non-human causes of fluctuations in production of biological resources through time (Mangel et al. 1996, NRC 1999). Indeed, this classic dilemma is the origin of the central hypothesis for GEM. A large body of existing hypotheses, summarized below, view specific human activities, such as harvesting and pollution, as causes of changes in biological production that are direct or indirect sources of mortality for plant and animal populations, including those of humans.

6.2.7.1 Theory of Sustainable Fishing

According to the theory of sustainable fishing, it is possible to strike a balance between the losses caused by human and natural forces, and the gains due to reproduction and growth, such that the abundance of a species in an area remains constant through time. Also known as the ***deterministic theory of fishing*** (Quinn and Deriso 1999), this theory has intellectual origins in the equation of logistic population growth first introduced in this context in 1837 (Quinn and Deriso 1999), and in even older concepts of population regulation that can be traced to the late eighteenth century (1798). It is well known that the ideal of a constant population size regularly producing predictable amounts of biomass for human consumption in perpetuity is rare in the case of wild populations (1973) (Ricker 1975, Quinn and Deriso 1999). Nonetheless, this ideal is the basis for the legal, scientific and popular concepts of sustainable uses of all types of renewable natural resources, and it motivates the need for GEM to distinguish between, and to help quantify, natural and human caused sources of mortality.

The original basic theory of sustainable fishing has been expanded to include the concept that the process of fishing sustainably for one species may not constitute fishing sustainably for other species (Quinn and Deriso 1999). For example, one of the operating hypotheses for investigations of causes for decline of the Steller sea lion in the Gulf of Alaska by the National Marine Fisheries Service (NMFS 2002) is that the declines are due to commercial fisheries out-competing the sea lion for food. Starvation and associated nutritional stress are hypothesized to be direct agents of mortality and causes of lowered reproductive rates.

Fisheries are also hypothesized to compete with terrestrial species by lowering the overall productivity of watersheds in the GEM region and adjacent areas, thereby also reducing the production of salmon that originate in those watersheds (Finney 1998, Finney et al. 2000, Gresh et al. 2000, Finney et al. 2002). Transport of nutrients from the marine environment to the watersheds by anadromous species, principally Pacific salmon, is thought to be important for sustaining the overall productivity of some types of watersheds, including the salmon species themselves (Mathisen 1972, Kline et al. 1990, Kline et al. 1993, Bilby et al. 1996, Mathisen et al. 2000). Note that application of the deterministic theory of fishing without inclusion of nutrient-effects could lead to a downward spiral in the annual production of the salmon species being managed, instead of the constant population predicted by the theory (Finney et al. 2000). As the salmon fishery removes nutrients from the watershed, the carrying capacity of the watershed for salmon is lowered, thereby causing the deterministic theory of fishing to prescribe to managers a lower "sustainable" level of spawners. The lower level of spawners means even less nutrients and a lower level of productivity for the watershed. Lower productivity means an even lower estimate of "sustainable" spawners from the theory, leading to less nutrients for the watershed, and a downward spiral in salmon production.

6.2.7.2 Ubiquitous Distribution and Northern Concentration of Anthropogenic Contaminants Hypothesis

Transport of contaminants from sites of release in lower latitudes by atmospheric and oceanic processes and through biologic pathways concentrates anthropogenic contaminants in northern ecosystems in even the most remote, uninhabited regions of the northern hemisphere, including the GEM region (Crane and Galasso 1999). Contaminants produced by human activities in human-populated areas, principally radionuclides, organochlorines, and heavy metals, alter ecosystems in all parts of the world by changing rates of biological production (productivities), as agents of direct and indirect mortality. For example, one of the operating hypotheses for investigations of causes for decline of the Steller sea lion in the Gulf of Alaska by the National Marine Fisheries Service (NMFS 2002) is that the declines are due to reproductive impairment and mortality resulting from contaminants from distant and local sources. Also in the GEM region, two organochlorines, polychlorinated biphenyls (PCB) and the pesticide dichlorodiphenyltrichloroethane (DDT), were found to be transported to remote localities in the Copper River drainage (circa 63^0 N 145^0 W) by migratory fish species and by wind (Ewald et al. 1998). Both DDT and PCB concentrations per individual increase as they move through the food chain, with both at times being found in very high concentrations near the top of the food chain in birds and mammals, including humans. DDT is well known to cause reproductive impairment, especially in birds. Metabolites of DDT (p,p' –DDE) were found in blubber taken by biopsy of killer whales in Prince William Sound in concentrations high enough (21 – 210 ppm) to suggest reproductive impairment and infant mortality, and relatively high concentrations of other organochlorines were also found (Ylitalo et al. 2001). PCB is known to cause pathological changes in reproductive and immune systems. For example, relatively high concentrations of PCB in the milk fat of Inuit women are consistent with the high incidence of infectious disease among Inuit infants in Arctic Quebec, Canada (Dewailly et al. 1993).

6.2.7.3 Anthropogenic Distribution of Exotic Species Hypothesis

According to this hypothesis, human transport of vertebrate and invertebrate species causes changes in ecosystems by radically changing species composition and relative abundances of species through alterations of food web (trophic) pathways and interactions. The food webs of the GEM region appear to be susceptible to alteration by certain freshwater and anadromous fish species that are known to be able to complete their life cycles at these latitudes: Atlantic salmon, northern pike, and yellow perch (ADF&G 2002). Anthropogenic introductions of both northern pike and yellow perch have been documented, and Atlantic salmon have become established to the south in British Columbia as a result of failed pen rearing operations. In addition, a number of other vertebrate and invertebrate animal species and a number of freshwater and salt marsh plants may be able to establish themselves in the GEM region if introduced (ADF&G 2002).

6.2.7.4 Cumulative Human Effects Hypothesis

Individual instances of fishing, introduction of contaminants, transport of exotic species, and other human impacts that are not alone sufficient to cause discernible changes in the ecosystem are inexorably accumulated through time to levels that can and do profoundly alter the habitats and trophic pathways of the ecosystem, thereby reducing production of many animal and plant species. As a corollary, cumulative effects are directly proportional to human population density and they can reach levels that prohibit any sustainable human use of certain species (Mangel et al. 1996). For example, many salmon populations near and adjacent to human centers in the Pacific Northwest (California, Oregon , Washington, Idaho) are now categorized by the federal government as threatened or endangered, and can no longer provide a harvestable surplus with respect to humans, (Stouder et al. 1997), whereas salmon populations in areas of low human densities are producing historical record-high levels of harvest (Mundy 1996). Further it is self-evident that 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 impacts. It appears that this degradation occurred over a long period of time and as a result of the combined impacts of many different human activities.

6.3 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.

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 percent 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.

6.3.1 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 7, 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 7.1.4, 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.

6.3.2 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 6.2, 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. The preceding ecological concepts have been applied directly to the GOA ecosystems to show how the system and its plant and animal populations are controlled in the conceptual foundation, Chapter 2.

6.3.3 Trophic Structure

The principal trophic groups of the northern GOA are represented by the analysis of Okey and Pauly for PWS (Okey and Pauly 1999). 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 6.1). 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 6.1 Representative Trophic Groups of the Northern Gulf of Alaska Arranged in Descending Order by Trophic Level

Group name	Trophic Level	Biomass ($t\ km^{-2} \cdot year^{-1}$)	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
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

Table 6.1 Representative Trophic Groups of the Northern Gulf of Alaska 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})
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 1999)

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 Aleutian Low 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. This understanding of the mechanisms affecting change in the GOA provides the basis for developing a key hypothesis about the GOA ecosystem that will form the conceptual foundation around which the GEM Program is focused.

6.4 References

ADF&G. 2002. Draft Aquatic Nuisance Species Management Plan. Ginny Fay.

Anderson, P.J. and J.F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series 189: 117-123.

Bilby, R.E., B.R. Fransen, and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 164-173.

Crane, K. and J.L. Galasso. 1999. Arctic environmental atlas. Washington, D.C. U.S. Naval Research Laboratory, Office of Naval Research.

Dewailly, E., P. Ayotte, S. Bruneau, C. Laliberte, D.C.G. Muir, and R.J. Nortstrom. 1993. Inuit exposure to organochlorines through the aquatic food chain in Arctic Quebec. Environmental Health Perspectives 101: 618-620.

Ewald, G., P. Larsson, H. Linge, L. Okla, and N. Szarzi. 1998. Biotransport of organic pollutants to an inland Alaska lake by migrating sockeye salmon (***Oncorhynchus nerka***). Arctic 51: 40-47.

Finney, B.P. 1998. Long-term variability of Alaska sockeye salmon abundance determined by analysis of sediment cores. North Pacific Anadromous Fish Commission Bulletin 388-395.

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

Finney, B. P., Gregory-Eaves, I., Douglas, M. S. V., and Smol, J. P. 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. Nature 416: 729-733.

Gargett, A. 1997. Optimal stability window: A mechanism underlying decadal fluctuations in north Pacific salmon stocks. Fisheries Oceanography 109-117.

Gresh, T., J. Lichatowich, and P. Schoonmaker. 2000. An estimation of historic and current levels of Salmon production in the northeast Pacific ecosystem: evidence of a nutrient deficit in the freshwater systems of the Pacific northwest. Fisheries 25: 15-21.

Jackson, J.B., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629-638.

Kline, T.C., J.J. Goering, O.A. Mathisen, P.H. Poe, and P.L. Parker. 1990. Recycling of elements transported upstream by runs of Pacific salmon: I. •^{15}N and •^{13}C evidience in Sashin Creek, Southeastern, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 47: 136-144.

Kline, T.C., J.J. Goering, O.A. Mathisen, P.H. Poe, P.L. Parker, and R.S. Scalan. 1993. Recycling of elements transported upstream by runs of Pacific salmon: II. •^{15}N and •^{13}C evidence in the Kvichak River watershed, Bristol Bay, Southwestern, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 50: 2350-2365.

Mackas, D.L., R. Goldblatt, and A.G. Lewis. 1998. Interdecadal variation in developmental timing of ***Neocalanus plumchrus*** populations at Ocean Station P in the subarctic North Pacific. Canadian Journal of Fisheries and Aquatic Sciences 55: 1878-1893.

Malthus, T. 1798. An Essay on the Principle of Population, editor. J. Johnson, in St. Paul's Church-Yard. London.

Mangel, J., L.M. Talbot, G.K. Meffe, M.T. Agardy, D.L. Alverson, J. Barlow, D.B. Botkin, G. Budowski, T. Clark, J. Cooke, R.H. Crozier, P.K. Dayton, D.L. Elder, C.W. Fowler, S. Funtwicz, J. Giske, R.J. Hofman, S.J. Holt, S.R. Kellert, L.A. Kimbal, D. Ludwig, K. Magnusson, Malayang III, C., C. Mann, E.A. Norse, S.P. Nothridge, W.F. Perrin, C. Perrings, R. Peterman, G.B. Rabb, H.A. Regier, J.E. Reynolds, K. Sherman, M.P. Sissenwine, T.D. Smith, A. Starfield, R.J. Taylor, M.F. Tillman, C. Toft, J. Twiss, R. John, J. Wilen, and T.P. Young. 1996. Principles for the conservation of wild living resources. Ecological Applications 6: 338-362.

Mathisen, O.A. 1972. Biogenic enrichment of sockeye salmon lakes and stock productivity. Verhandlungen der Internationalen Vereinigung für Theoretische and Angewandte Limnologie 18: 1089-1095.

Mathisen, O.A., J.J. Goering, and E.V. Farley. 2000. Nitrogen and carbon isotope ratios in sockeye salmon smolts. Verrh. Internat. Verein. Liminol. 27: 3121-3124.

May, R. M. 1973. Stability and complexity in model ecosystems, editor. Princeton University Press. Princeton, N.J.

Mundy, P.R. 1996. The Role of Harvest Management in the Future of Pacific Salmon Populations: Shaping Human Behavior to Enable the Persistence of Salmon. Pages 315-330 Naiman, R.J. and D. Stouder, editors. Chapman Hall, New York, USA.

NMFS. 2002. Principle Hypotheses Surrounding the Steller Sea Lion Decline (SSLI).

NRC. 1999. Sustaining Marine Fisheries. National Academy Press. Washington, D.C.

Okey, T.A. and D. Pauly. 1999. Trophic mass balance model of Alaska's Prince William Sound ecosystem, for the post-spill period 1994-1996. EVOS restoration project 98330-1 annual report. The Fisheries Centre, University of British Columbia. Vancouver.

Piatt, J.F. 2000. Survival of adult murres and kittiwakes in relation to forage fish abundance, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 99338). U.S. Geological Survey, Alaska Biological Science Center. Anchorage, Alaska.

Piatt, J.F. and T.I. Van Pelt. 1998. Survival of adult murres and kittiwakes in relation to forage fish abundance, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 98338). U.S. Geological Survey. Anchorage, Alaska.

Quinn, T.J. and Richard B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press.

Ricker, W. E. 1975. Computation and interpretation of biologocal statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191: 1-382.

Romano, M.D., D.D. Roby, J.F. Piatt, and A. Kitaysky. 2000. Effects of diet on growth and body composition of nestling seabirds, ***Exxon Valdez*** oil spill restoration project final report (Restoration Project 98163N). U.S. Geological Survey, Oregon Cooperative Fish and Wildlife Research Unit, and Oregon State University. Corvallis, Oregon.

Stouder, D.J., P.A. Bisson, and Robert J. Naiman (editors). 1997. Pacific salmon and their ecosystems: status and future options. Chapman and Hall. New York.

Ylitalo, G.M., C.O. Matkin, J. Buzitis, M.M. Krahn, L.L. Jones, T. Rowles, and J.E. Stein. 2001. Influence of life-history parameters on organochlorine concentrations in free-ranging killer whales (***Orcinus orca***) from Prince William Sound, Alaska. The Science of the Total Environment 281.

7. SCIENTIFIC BACKGROUND: PHYSICS, BIOLOGY, HUMAN USES AND ECONOMICS

In This Chapter

- Overview of Physical, Chemical, and Biological Characteristics of the Gulf of Alaska
- Discussion of Climate, and Physical, Geological, Chemical and Biological Oceanography
- Discussion of Status of Non-human Populations, Predators, and Prey
- Discussion of Status of Human Activities and Socioeconomics in the Gulf of Alaska

7.1 Introduction

The scientific background is a comprehensive review of the current state of scientific knowledge of the Gulf of Alaska (GOA) ecosystem upon which the Gulf Ecosystem Monitoring (GEM) Program is based. Its body of scientific knowledge includes the socioeconomic, physical, chemical, and biological characteristics of the GOA, the status of major animal species, and the state of human impacts in the GOA. It provides the underpinning for the GEM conceptual foundation and central hypothesis, and it will provide reference material for initiating the research and monitoring programs. The scientific background also includes the scientific information that led to current hypotheses introduced in Chapter 6.

The information in Sections 7.2 through 7.5 Marine Mammals is current as of August 2001. Sections 7.14 and 7.15 are current as of July 2002.

7.2 Summary of the Physical and Biological Background for the Northern Gulf of Alaska

7.2.1 Introduction

The cold and turbulent 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 (Table 7.1), 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.

Table 7.1 Representative Trophic Groups of the Northern Gulf of Alaska 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
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

Table 7.1 Representative Trophic Groups of the Northern Gulf of Alaska Arranged in Descending Order by Trophic Level

Group name	Trophic Level	Biomass (t km$^{-2}\cdot$ year^{-1})	P/B (yr^{-1})	Q/B (yr^{-1})
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)

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. (Greater detail is provided following this summary in the full Scientific Background.)

7.2.2 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, 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 cyclic ocean climate, extensive commercial and subsistence harvests, and threats from pollution and diseases.

7.2.2.1 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.

7.2.2.2 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.

7.2.2.3 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.

7.2.2.4 Offshore: Mid-shelf and Deeper Waters

These waters, which begin at the outer edge of the adjacent ACC region—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. 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.

The dominant flow in the offshore is counterclockwise, and it is designated the Alaska Current. Because the Alaska Current has its 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.

7.2.3 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.

7.2.4 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 three 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 euphusiids, 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.

7.2.5 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 (Aleutian Low). 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.

7.2.6 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:

7.2.6.1 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.

7.2.6.2 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.

7.2.6.3 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.

7.2.6.4 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.

7.2.6.5 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.

7.2.6.6 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.

7.2.7 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. 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.

7.3 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).

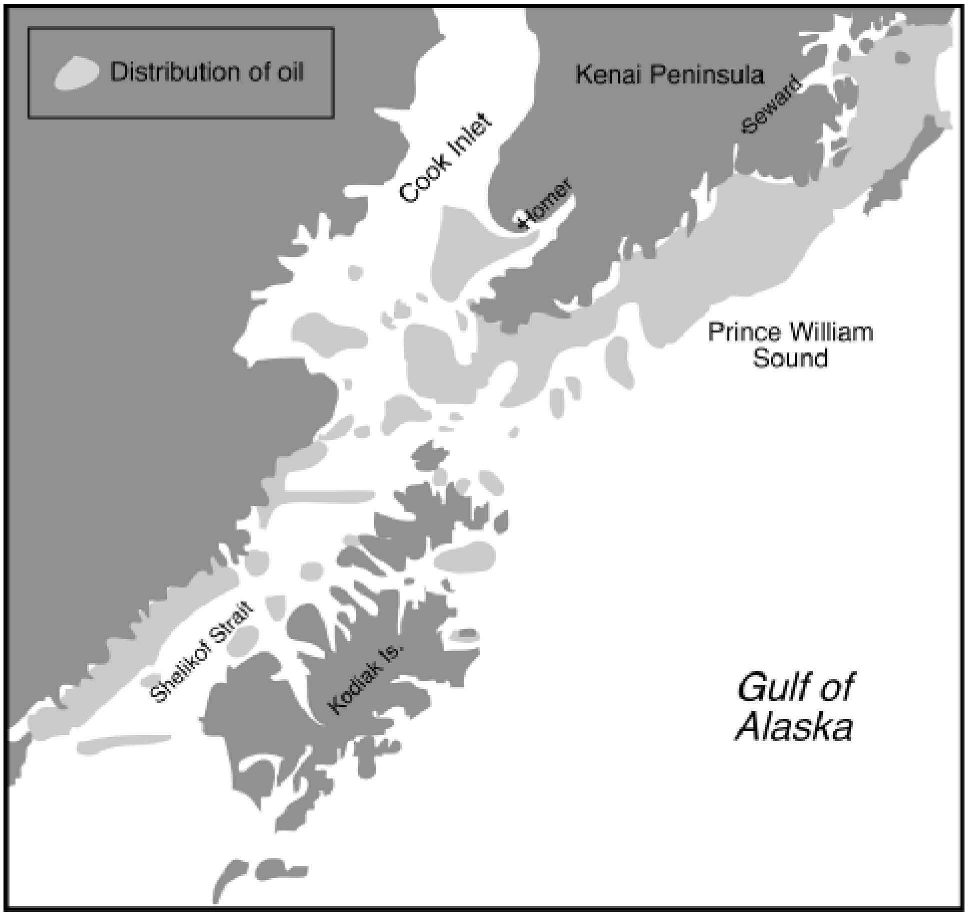

Figure 7.1 Distribution of oil from the *Exxon Valdez* oil spill.

The area of the GOA directly affected by the EVOS (Figure 7.1) 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 Prince William Sound (PWS) are the Skeena and Nass (Canada), the Stikine, Taku, Chilkat, Chilkoot, Alsek, Situk, and Copper. All major and nearly all smaller watersheds in the GOA region support anadromous fish species. For example, although PWS proper has no major river systems, it does have more than 800 independent drainages that are known to support anadromous fish species.

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

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

The GOA shoreline is bordered by a continental shelf ranging to 200 meters (m) in depth (Figure 7.2). 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

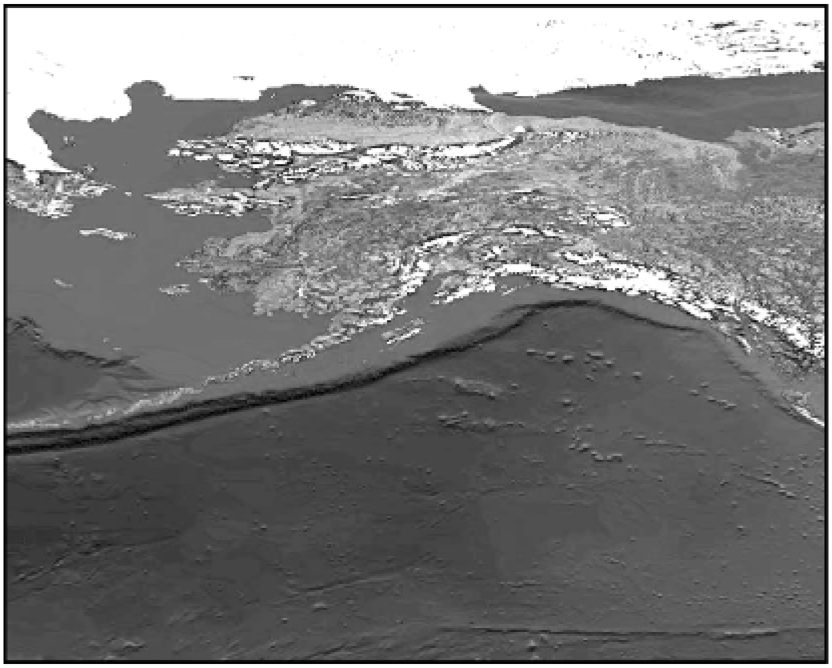

Figure 7.2 Satellite radar image of the northern Gulf of Alaska. Continental shelf, seamounts, and abyssal plain can be seen in relief. (Composite image from Sea-viewing Wide Field-of-view Sensor [SeaWiFS], a National Aeronautics and Space Agency remote-sensing satellite.)

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).

7.4 Climate

7.4.1 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 Southeast 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 of 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 regional 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 (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 7.3) (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 two million years (Hays et al. 1976). The amount of solar radiation reaching earth changes periodically, or oscillates, in response to variations in the path of the earth's orbit about the sun. Geographic and seasonal changes in solar radiation caused by periodic variations in the earth's orbit around and orientation toward the sun have been labelled "Milankovich cycles," which are known to have characteristic frequencies of 100,000, 41,000, and 23,000 years (Berger et al. 1984). Shifts in the periodicity of long-term weather patterns correspond to shifts from one Milankovich cycle to another. How and why shifts from one Milankovich cycle to another occur are among the most important questions in paleoeclimate research (Hays et al. 76, Rutherford and D'Hondt 2000).

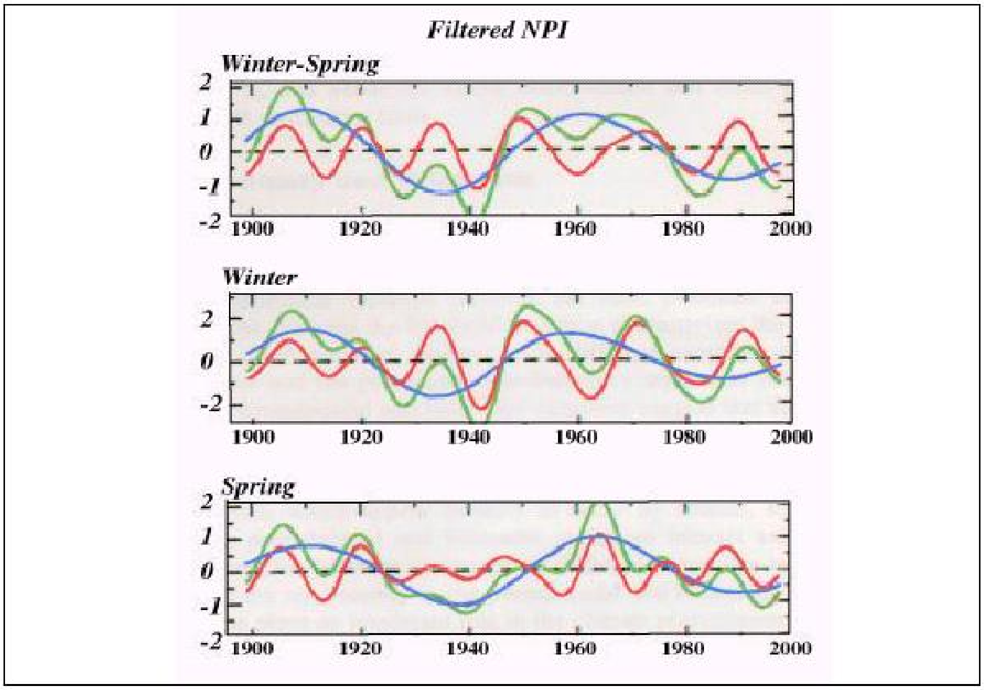

Figure 7.3 Filtered North Pacific Index in the winter-spring, winter, and spring seasons. NPI is shown in hectoPascals, a measure of barometric pressure at sea level. The three curves show the NPI band-pass filtered over intervals of 10 to 80 years, 10 to 30 years (bidecadal), and 30 to 80 years. Source: Minobe 1999.

7.4.2 Long Time Scales

7.4.2.1 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.

7.4.2.2 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). 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. 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.

7.4.2.3 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 7.4) are not sufficient to account for the magnitude of the changes in atmospheric carbon dioxide between major climate changes, such as glaciations.

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

Areas where nitrates and phosphates do not limit phytoplankton production, such as the Southern Ocean (60°S), can have very large effects on the global carbon cycle through the action of the biological pump. When stimulated by the micronutrient iron, the biological pump of the Southern Ocean becomes very strong because of the presence of ample nitrate and phosphate to fuel photosynthesis, as demonstrated by the Southern Ocean Iron Release Experiment

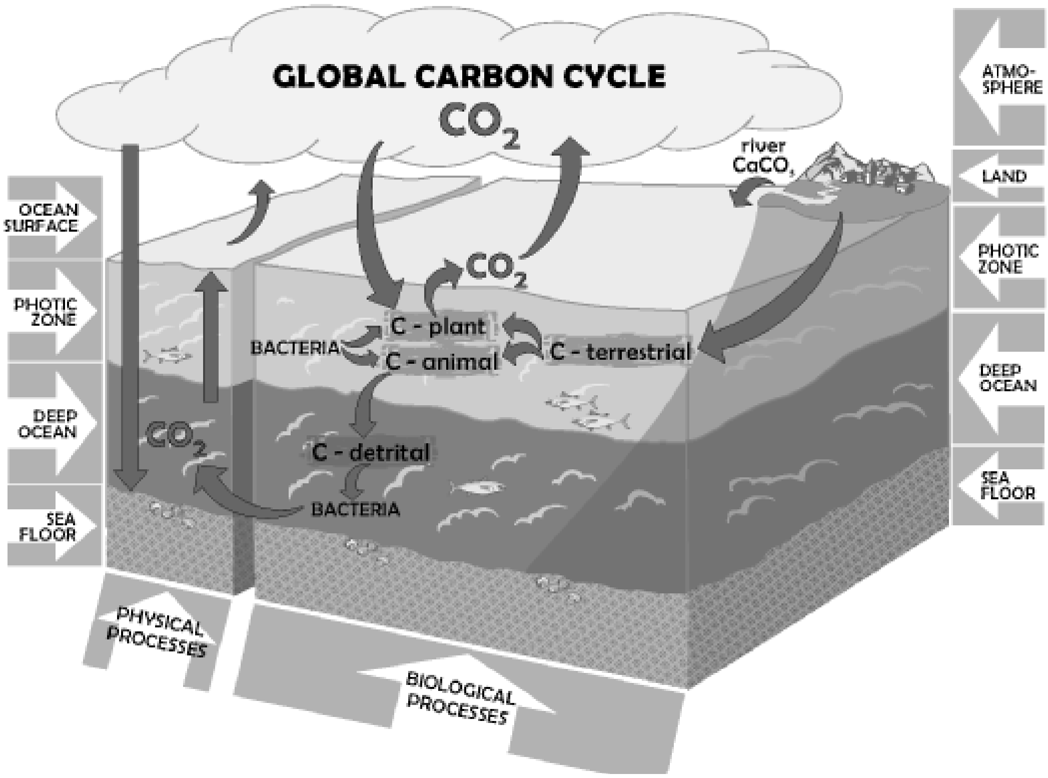

Figure 7.4 Global carbon cycle diagram showing the movement of carbon compounds of the atmosphere, land, marine photic zone, the deep ocean, and the sea floor.

(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 equality of being "high nitrate, low chlorophyll" 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 7.4), 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.

7.4.2.4 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 7.5), 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 7.2.2.3.)

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.

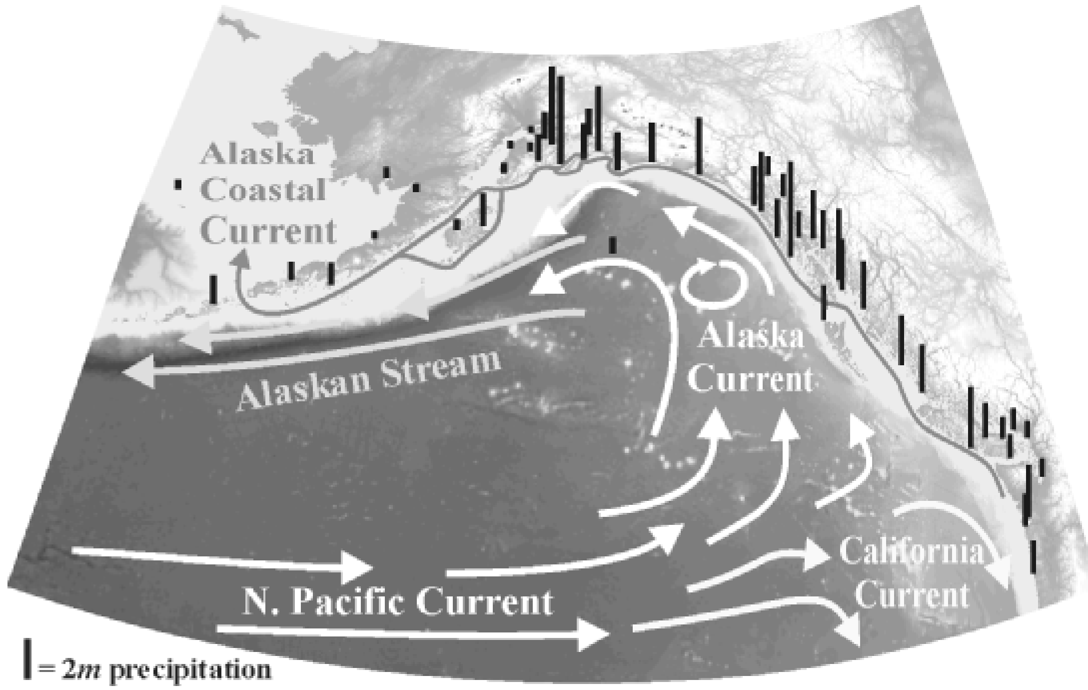

Figure 7.5 Schematic surface circulation fields in the Gulf of Alaska and mean annual precipitation totals from coastal stations (black vertical bars) and for the central gulf (Baumgartner and Reichel 1975).

7.4.3 Multi-decadal and Multi-annual Time Scales

7.4.3.1 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 North Pacific Index (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.

7.4.3.2 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. 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 7.6 and 7.7). 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 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 7.8 and 7.9). In decades of positive PDOs, below-normal sea surface

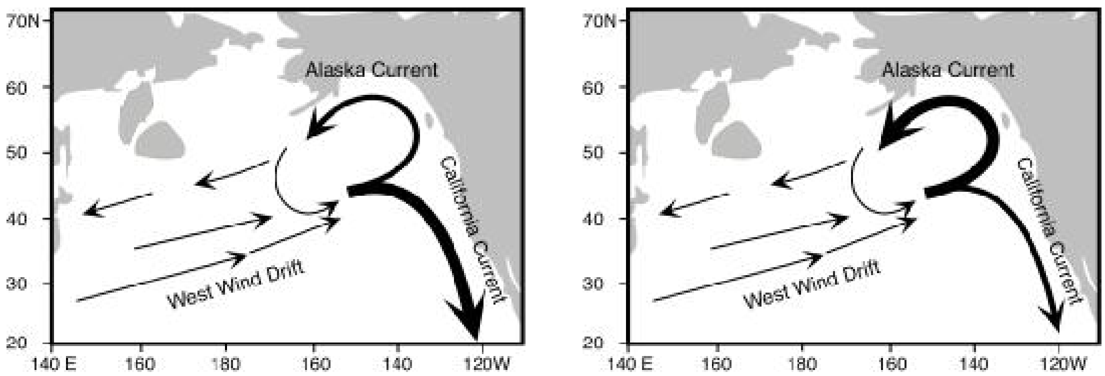

Figure 7.6 Oceanic circulation patterns in the far eastern Pacific Ocean proposed for negative PDO (left) and positive PDO (right) (Hollowed and Wooster 1992).

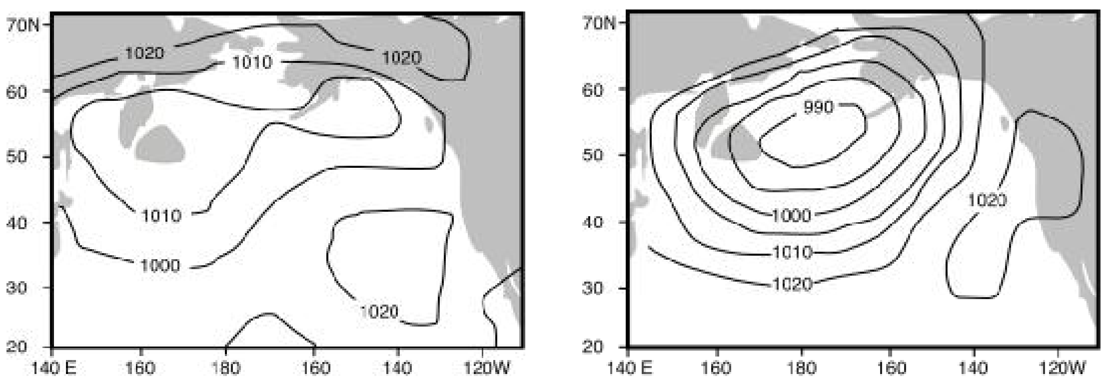

Figure 7.7 Mean sea-level pressure patterns from the winters of 1972 (left) and 1977 (right) (Emery and Hamilton 1985).

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

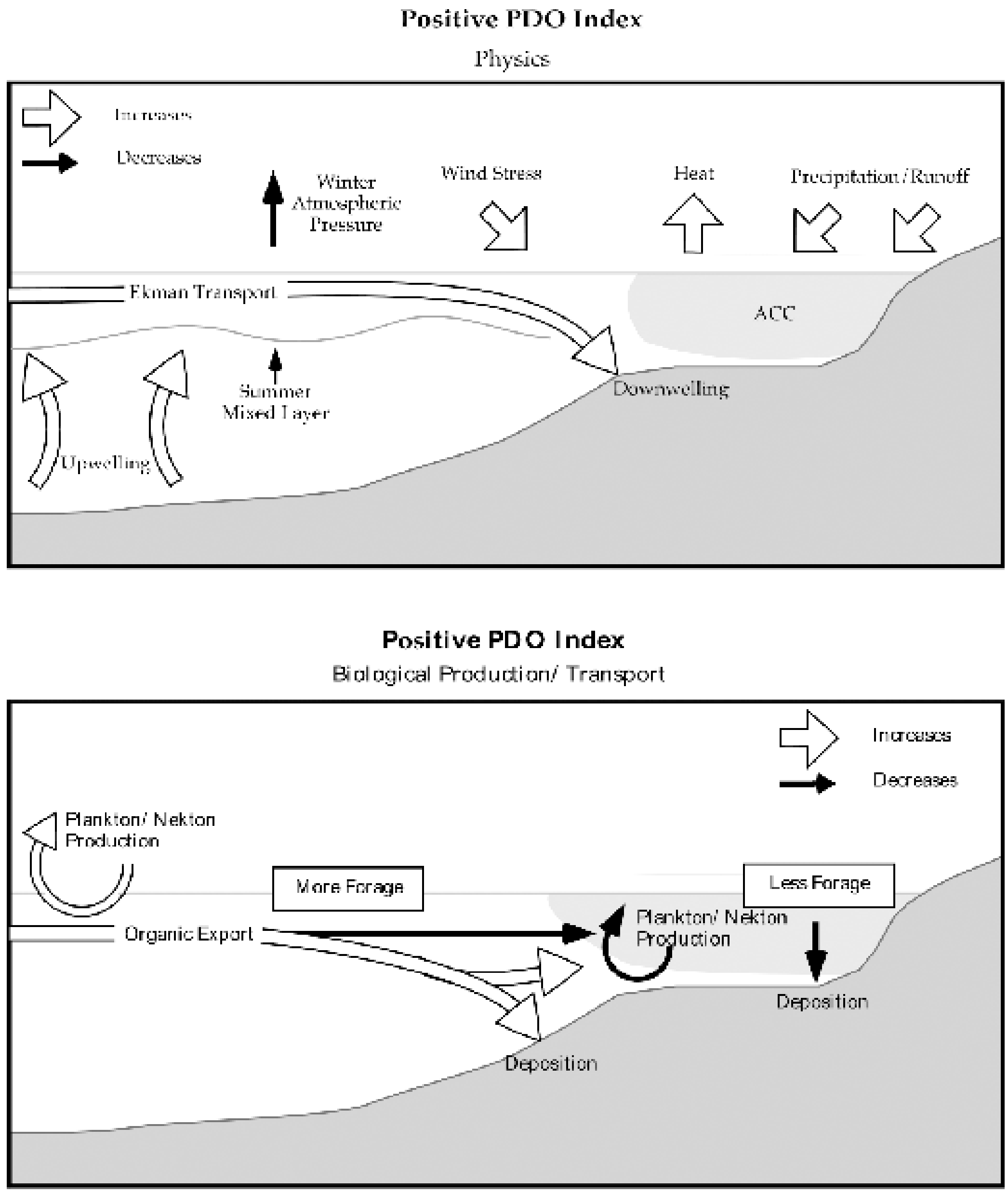

Figure 7.8 Schematic of physical processes during the winter in a positive PDO climatic regime in the Gulf of Alaska from offshore to nearshore areas showing the Alaska Current and the Alaska Coastal Current.

S-shaped waveform with a 50-year period (sinusoidal pentadecadal) (Figure 7.3). His analysis pointed out that rapid transitions from one regime to another could not be fully explained by a single sinusoidal-wavelike effect. The speed with which regime shifts occurred in the twentieth century led Minobe to suggest that the pentadecadal cycle is synchronized or phase locked with another climate variation on a shorter bidecadal time scale (Anderson and Munson 1972).

In addition to periodic and seasonal changes, there is evidence that the Aleutian storm track has shifted to an overall more southerly position during the

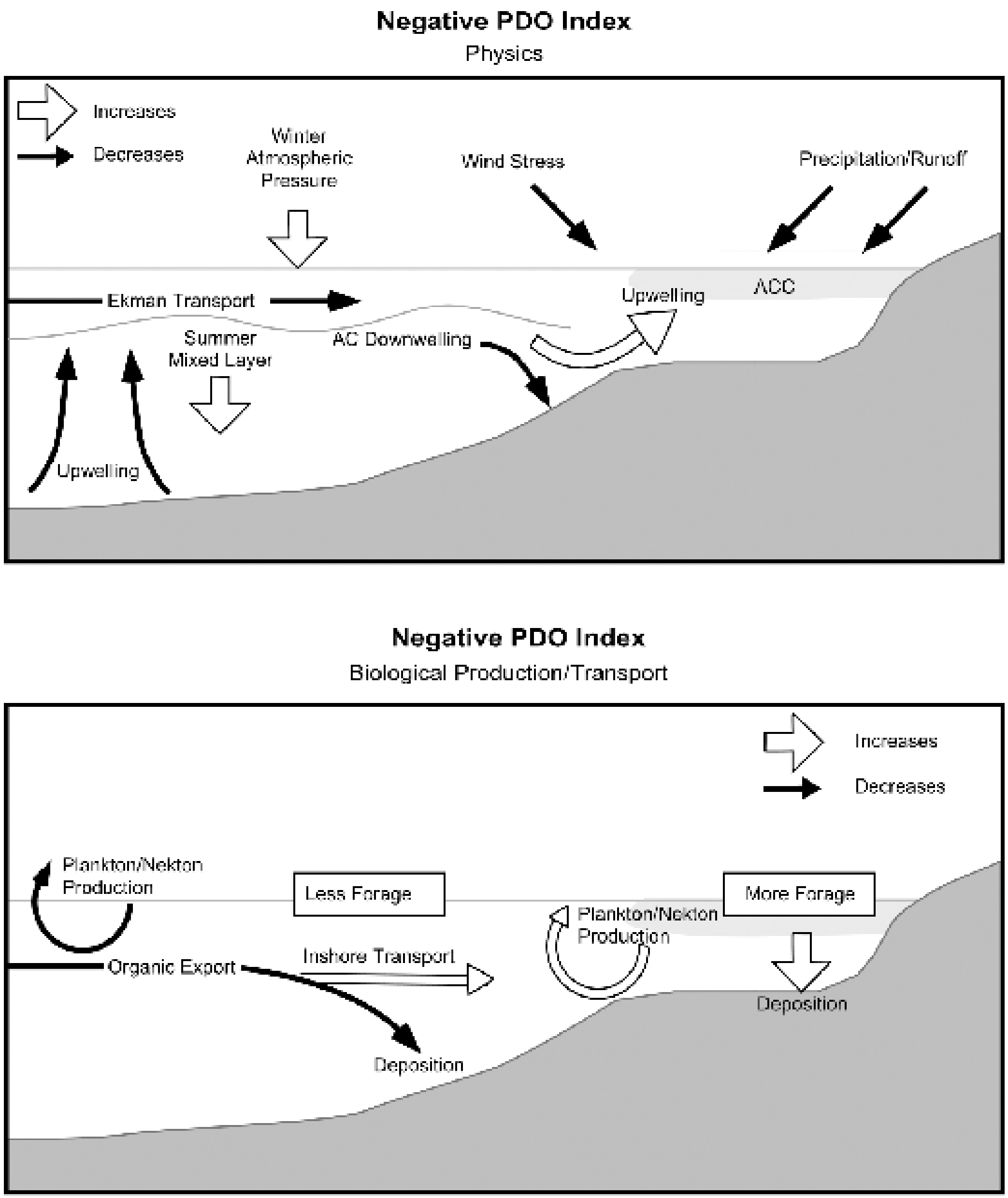

Figure 7.9 Schematic of physical processes during the winter in a negative PDO climatic regime in the Gulf of Alaska from offshore to nearshore areas showing the Alaska Current and the Alaska Coastal Current.

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

7.4.3.3 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 7.3).

7.5 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).

7.6 Physical and Geological Oceanography: Coastal Boundaries and Coastal and Ocean Circulation

7.6.1 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 7.10). It includes a continental shelf area of about 3.7 x 10^5 km^2 (110,000 square nautical miles [Lynde 1986]). The area of the shelf amounts to about 17 percent of the entire Alaskan continental shelf area (2.86 x 10^6 km^2 total) and approximately 12.5percent 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.

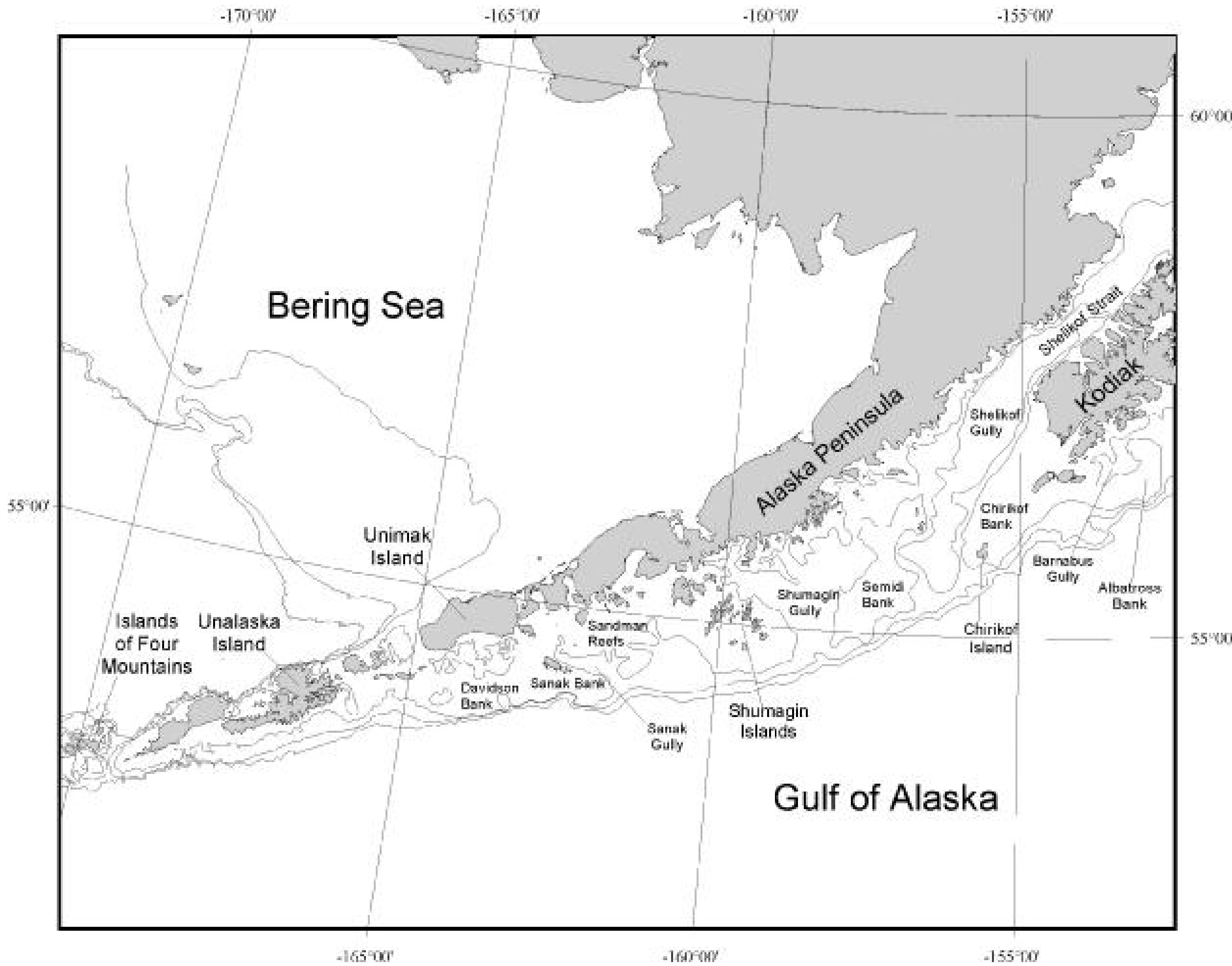

Figure 7.10a Shelf topography of the northern Gulf of Alaska and adjacent waters (Martin 1997).

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 percent 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 7.3) 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.

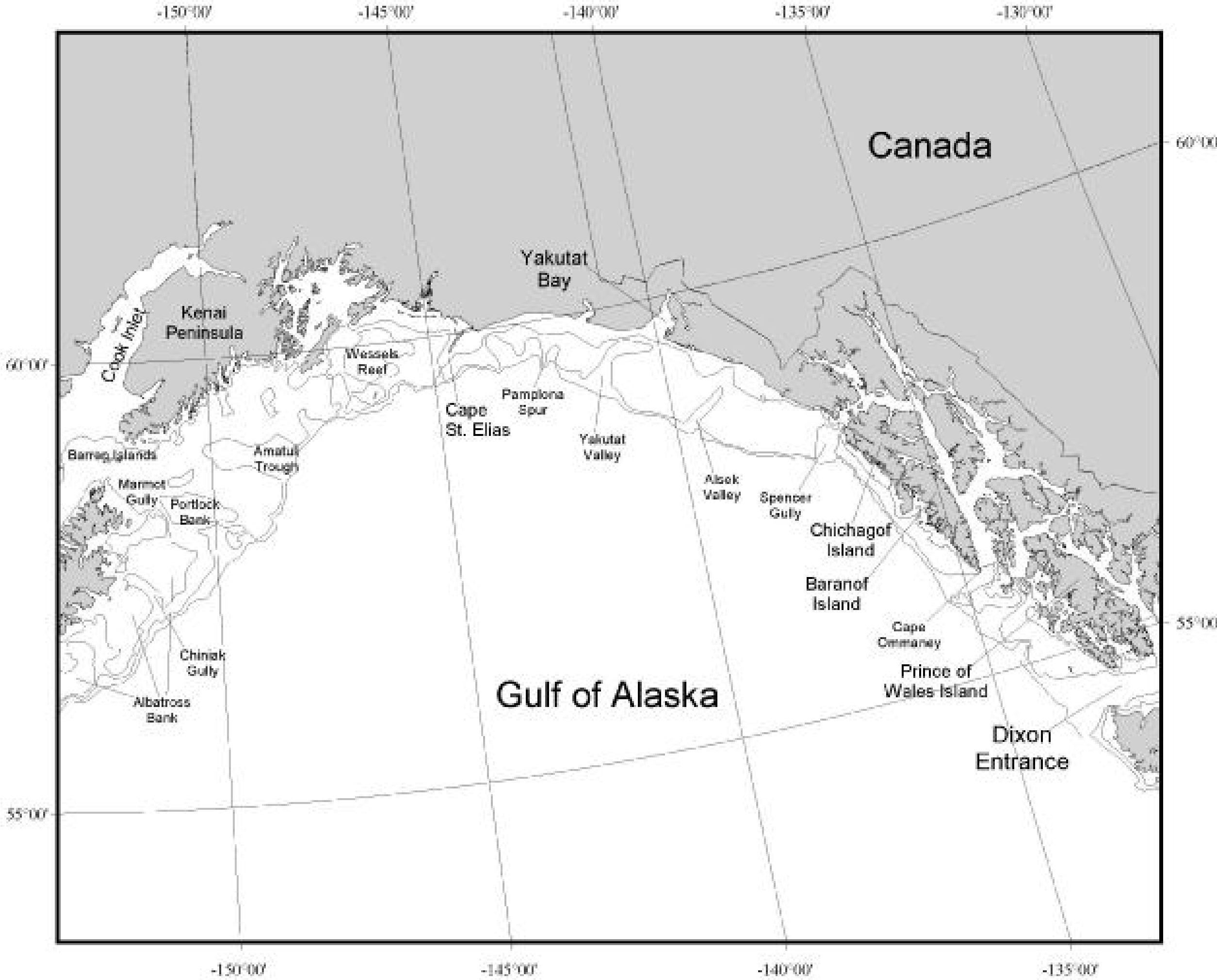

Figure 7.10b Shelf topography of the northern Gulf of Alaska and adjacent waters (Martin 1997).

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 (Figures 7.10a and b). 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 (Ahlnäes 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.

7.6.2 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 7.11. 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.

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

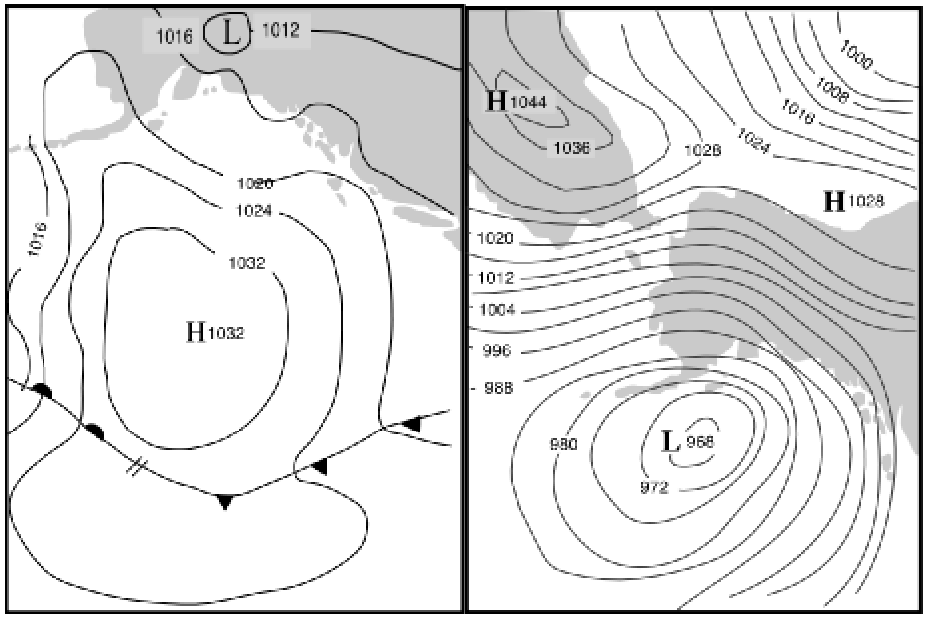

Figure 7.11 Typical summer (left) and winter (right) examples of the Aleutian Low and Siberian High pressure systems. Contours are sea-level pressure in millibars. (Hollowed and Wooster 1987)

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 percent occurs over the northern GOA more than 60 percent of the time (Brower et al. 1988), and cloud cover of less than 25 percent occurs less than 15 percent 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 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 7.12 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 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 7.5 is a composite of long-term average annual precipitation measurements from stations around the GOA. Precipitation rates of 2 to 4 meters per year ($m\text{-}yr^{-1}$) are typical throughout the region, but rates in southeast Alaska and PWS exceed 4 $m\text{-}yr^{-1}$. Except over the Alaska Peninsula in the western GOA, the coastal precipitation rates are much greater than the estimated net precipitation rate of 1 $m\text{-}yr^{-1}$ over the central basin (Baumgartner and Reichel 1975). The coastal estimates are undoubtedly biased because most of the measurements are made at sea level and therefore do not fully capture the influence of altitude on the precipitative flux.

Figure 7.12 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 percent greater than the mean annual Mississippi River discharge, and accounts for nearly 40 percent 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,

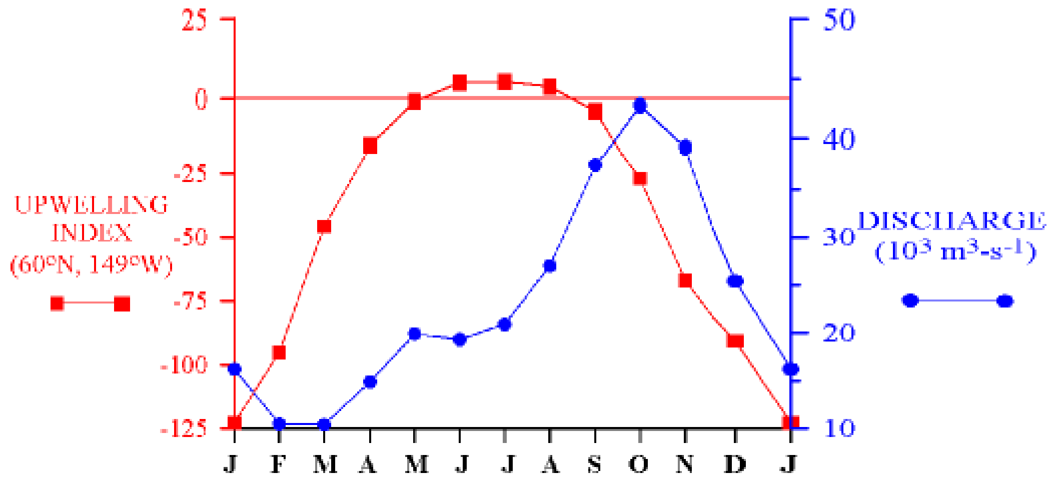

Figure 7.12 Mean monthly upwelling index, 1946 to 1999 (red), and mean monthly coastal discharge, 1930 to 1999 (blue) (Royer 1982, 2000) in the northern GOA. Negative values of the Index imply onshore Ekman transport and coastal downwelling. Discharge is shown in cubic meters per second, a measure of flow.

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 7.12 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 7.5. 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.

7.6.3 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, T.C. 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 7.13). 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

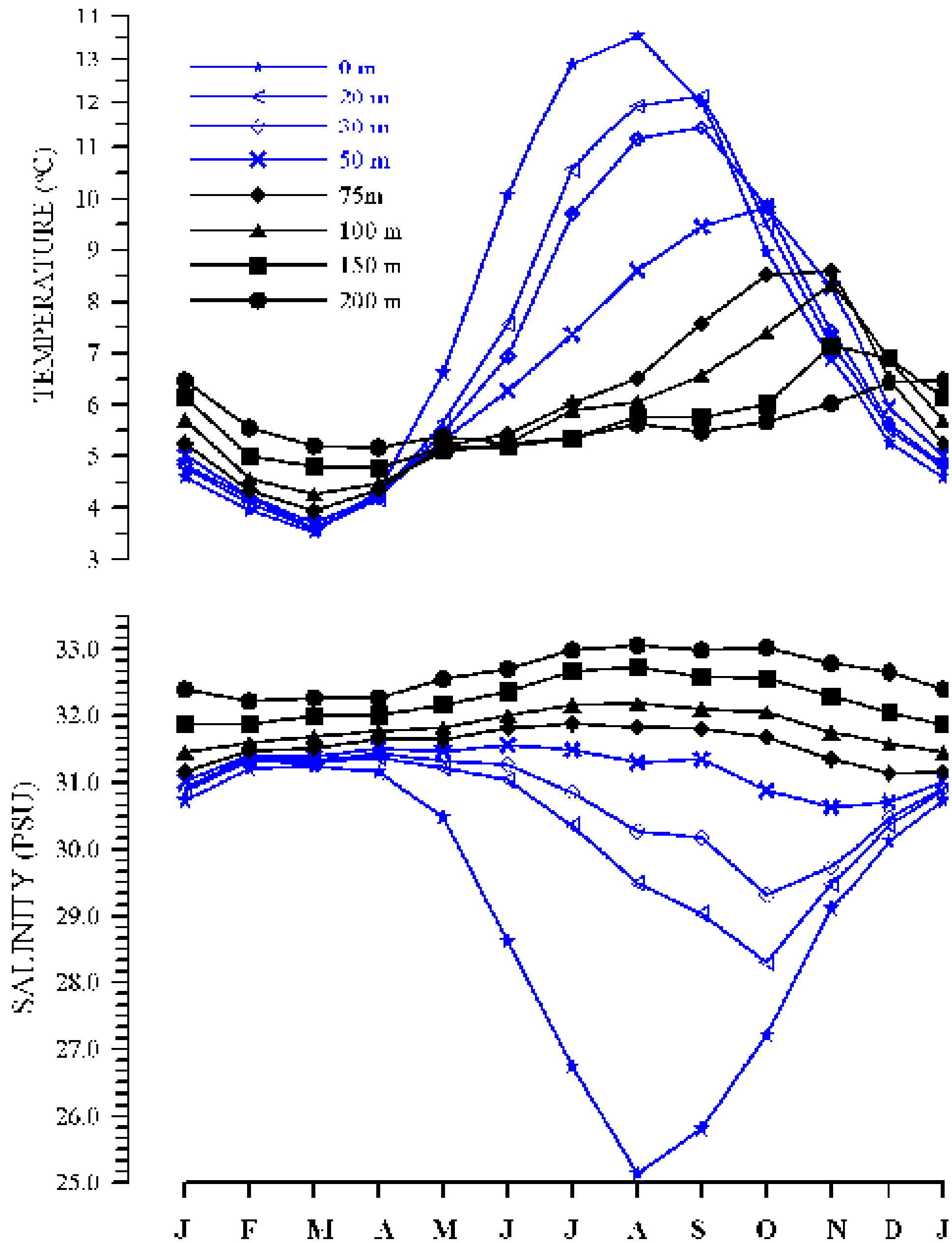

Figure 7.13 The mean annual cycle of temperature (upper) and salinity (lower) at various depths at station GAK1 on the inner shelf of the northern GOA. The monthly estimates are based on data collected from 1970 through 1999. (The figure includes updated information [Xiong and Royer 1984].)

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 150 m depth, the salinity is minimal in March and maximal in late summer-early fall. The phase difference between the near-surface and near-bottom layers reflects the combined influence of winds and coastal discharge. In summer, when downwelling relaxes, salty, nutrient-rich water from offshore invades the inner shelf (Royer 1975). The upper portion of the water column is freshest in summer, when the winds are weak (little mixing) and coastal discharge is increasing. Vertical mixing is strong through the winter and redistributes fresh water, salt, and possibly nutrients throughout the water column.

The effects of the seasonal cycle of wind and buoyancy forcing are also reflected in both the hydrographic properties and the along-shore velocity structure of the shelf. The seasonal transitions in temperature and salinity properties are shown in Figure 7.14, 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.

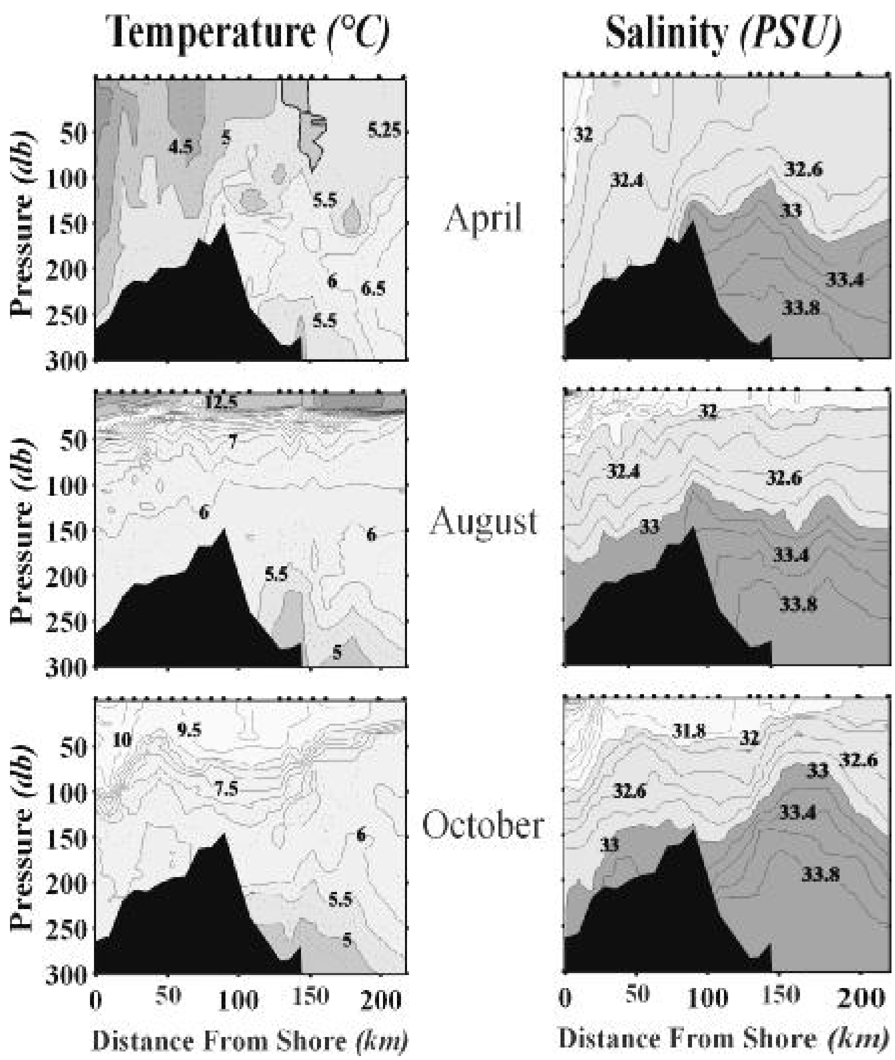

Figure 7.14 Seasonal cross-shore distributions of temperature (left) and salinity (right) along the Seward Line in the northern GOA. The graphs are based on data collected in 1999 as part of the GOA GLOBEC program (Weingartner 2001). The vertical axis is in pressure units (decibars [db]), with 1 db the equivalent of about 1 m.

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 ($m\text{-}d^{-1}$) 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 $cm\text{-}s^{-1}$ seaward of the front and an offshore flow of ~15 $cm\text{-}s^{-1}$ [Johnson et al. 1988] inshore of the front.)

PWS is an important part of the GOA ecosystem providing both habitat to numerous organisms and being a potential sink and source for dissolved and suspended materials carried by shelf waters. The sound has a large central basin of about 60 by 90 km. Depths in the central basin are about 350 m deep. However, maximum depths exceed 750 m in the northwest sound and are typically about 500 m along the western side of the sound. It is surrounded by numerous bays and fjords that provide a diversity of habitats for marine organisms (Schmidt 1977, Niebauer et al. 1994, Gay III, S.M. and Vaughan 2001). The mountains and glaciers that ring PWS comprise its watershed and provide a plentiful supply of freshwater and sediment to the sound through numerous streams and rivers. Flow through this semi-enclosed sea is generally counterclockwise with shelf waters entering through Hinchinbrook Entrance in the east and exiting through Montague Strait in the west. The circulation varies seasonally in accordance with the seasonal cycle of winds and runoff, and it appears that the clockwise circulation might reverse seasonally, or at least occasionally, in summer with surface waters exiting through Hinchinbrook Entrance and entering through Montague Strait (Vaughan et al. 2001). Most of the exchange with the shelf occurs with the ACC as indeed at least a portion if not most of the ACC flows through the lower sound. However, Hinchinbrook Entrance can also communicate directly with the continental slope through Hinchinbrook Canyon, which extends from the entrance southward for more than 100 km to the shelfbreak. Deep water exchange appears to be most prominent in the summer, however, deep water inflow events occur throughout the year (Niebauer et al. 1994, Vaughan et al. 2001). The canyon therefore represents a potential conduit by which slope waters can enter the sound. Because these deep waters are relatively rich in nutrients they could be important to the nutrient budgets of the sound and may provide an advective pathway by which oceanic plankton can be carried into the sound. Reliable transport estimates of mass and property exchanges between the sound and the shelf are not available, although Niebauer et al. (1994) suggest that as much as 40 percent of the sound's volume is exchanged in summer (May – September) and 200 percent of the volume is exchanged in winter (October through April). While these estimates need to be verified, they nevertheless suggest efficient exchange between the shelf and sound and imply that the sound ecosystem is intimately linked to shelf processes. Water property distributions and stratification in the sound are generally similar to those of the ACC on the shelf. However, because of the sheltering effects of land, the sound water column stratifies earlier in spring and persists longer in fall than does the shelf.

The mid-shelf domain covers the region between the ACC and the shelfbreak. Cross-shelf temperature and salinity gradients are weak in all seasons. In general, the strongest horizontal density gradients occur within the bottom 50 m of the water column, probably associated with the inshore location of the shelfbreak front (which does not always have a surface expression). The bottom of the shelfbreak 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 in most months by salinity, 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. It should also vary seasonally strengthening in the winter and weakening in the summer in accordance with the winds. However, both the flow and horizontal density gradients are highly variable because of energetic mesoscale (10 – 50 km) flow features. Potential sources for the mesoscale variability include: (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, for 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 Bogard 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). Although the mid-shelf region is poorly studied and understood compared to other portions of the GOA shelf and slope, it is critically involved in the cross-shelf transport and vertical mixing of nutrients, sediments, organisms, heat, and salt. At the very least it serves as an important link between the inner shelf and the continental slope.

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

1. Separation of the ACC from capes (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 onto the inner shelf is one means by which the slope and basin interior communicates directly with the nearshore, because (as discussed below) this water is drawn from within the permanent halocline (depth horizon over which salinity changes rapidly) of the GOA. The deep summer inflow is a potentially important conduit for nutrients from offshore to onshore. Inflow, however, is not the only means by which nutrient-rich offshore water can supply the shelf. Other mechanisms include flow-up canyons intersecting the shelf break (Klinck 1996, Allen 1996, Allen 2000, Hickey 1997), topographically-induced upwelling (Freeland and Denman 1982), and shelf-break eddies and flow meanders (Bower 1991).

The third domain, consisting of the shelf break and continental slope is influenced by the Alaska Current, which flows along the northeastern and northern GOA, and its transformation west of 150° W, into the southwestward-flowing Alaskan Stream. These currents comprise the poleward limb of the North Pacific Subarctic Gyre and provide the oceanic connection between the GOA shelf and the Pacific Ocean. The Alaska Current is a broad (300 km), sluggish (5 to 15 cm/s) flow with weak horizontal and vertical velocity shears. The Alaskan Stream is a narrow (100 km), swift (100 cm/s) 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 (Sv=Sverdrup=measure of volume) (Reed and Schumacher 1986, Musgrave et al. 1992), and although seasonal transport variations appear small, interannual transport variations may be as great as 30 percent (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 7.14.)

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 (two to three years) and energetic, having typical swirl speeds of 20 to 50 cm/s (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. 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).

7.6.4 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 two to six 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).

7.6.5 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 percent 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 and are barotropic. However, in late summer, tidal velocities in the upper 50 m are about 20 cm/s whereas below 100-m depth they are about 5 cm/s. 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).

7.6.6 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, 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 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), 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).

7.7 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 seven to eight months each year. Although this condition usually moderates during the summer, there is little evidence that wind-forced coastal upwelling is ever well developed. Instead, during the period of relaxed downwelling or sporadic and weak upwelling, a rebound of isopycnal (density boundaries; waters having the same densities) surfaces along the shelf edge permits the run-up of dense slope water onto and across the shelf. This subsurface water, containing elevated concentrations of dissolved nutrients, flows into the deeper coastal basins and fjords (Muench and Heggie 1978, Heggie and Burrell 1981). Presumably the timing and duration of this coastal bottom renewal is related to the nature of the Pacific High pressure dominance in the GOA each summer.

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

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

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

7.8 Biological Oceanography: Plankton and Productivity

7.8.1 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.

7.8.2 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 four to six 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 percent 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 percent of the dry weight, and that dry weight is about 15 percent 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 percent 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.

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 thirty 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 ***Limicina pacifica;*** and larvaceans (***Okiopleura*** 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).

7.8.3 Interannual and Decadal-Scale Variation in Plankton Stocks

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

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

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 percent 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 7.15). 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 (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 7.15) 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.

7.8.4 Factors Effecting Trophic Exchanges Between the Plankton and Larger Consumers

Most would concede that the general theory of trophodynamics articulated by Lindeman (1942) nearly fifty 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.

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

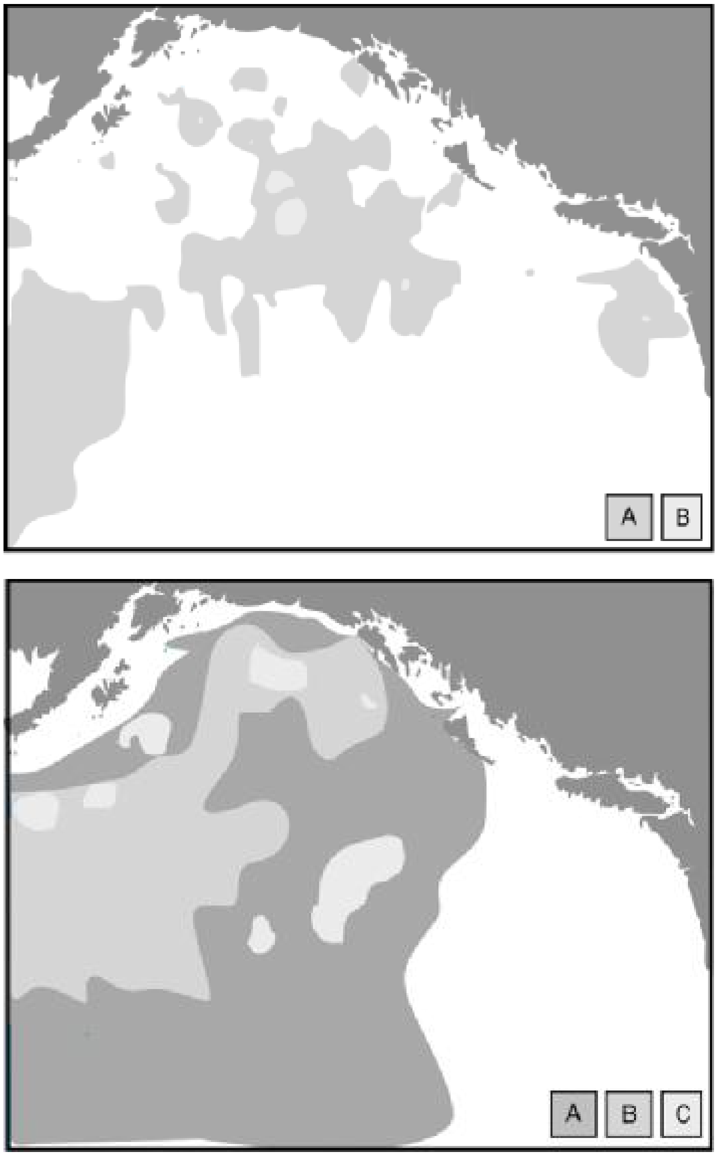

Figure 7.15 Biomass of plankton for the spring and summer period contrasted for a negative PDO period (top) and a positive PDO period (bottom). The shaded boxes present zooplankton biomass as follows: A represents 100 to 200 g/1,000 m^3, B represents 201 to 300 g/m^3, and C represents more than 300 g/m^3. (Brodeur and Ware 1992)

compiled primarily as the result of the Minerals Management Service (MMS)-funded Outer Continental Shelf (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 one 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 two 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 (fifteen to thirty 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 three weeks from year to year in PWS, but that the annual peak in zooplankton always lagged the plants by about twenty-five to thirty 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 percent 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 percent more productive than the outer-shelf environment and 270 percent 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.

7.8.5 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. 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 fifty species within a handful of major taxa comprise 95 percent 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.

7.9 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 thirty 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).

7.9.1 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 forty 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 interference 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,

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

mostly in subtidal areas, but also in intertidal sedimentary environments (Kvitek et al. 1992).

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

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

- 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.

7.9.2 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.

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

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).

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 Partnership for the Interdisciplinary Study of Coastal Oceans (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. In 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, coonstriped 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 gadiids 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.

7.10 Forage Species

7.10.1 Definition

Forage species include a broad suite of species that are commonly consumed by higher trophic level species (fish, seabirds, and marine mammals). Specifc species included in the forage species complex vary 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); and
- 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 research.

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 7.2 summarizes key features of the life history characteristics.

7.10.2 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 percent 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)

Table 7.2 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

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 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).

7.10.3 Assessment Methods and Challenges

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

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

An assessment designed for forage species is needed to develop an accurate evaluation of the distribution and abundance of this important group of species. It is unlikely that a single survey would be adequate for all forage species; therefore, a variety of survey methods should be considered. Potential survey methods for forage species are identified in Table 7.3.

7.10.4 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, although these studies

Table 7.3 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

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).

7.10.4.1 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.

7.10.5 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.

7.10.6 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.

7.11 Seabirds

7.11.1 Overview

The GOA supports huge numbers of resident seabirds: twenty-six species nest around the periphery of the GOA, with an estimated total on the order of eight million birds (Table 7.4). 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 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

Table 7.4 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.*

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 7.4). 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).

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).

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

A strong case also has been made for a broad-scale decline in seabird abundance in the GOA during the past two to three decades beginning before the EVOS. Marine birds counted at sea in summer in PWS apparently declined by some 25 percent in aggregate between 1972 and the early 1990s (Kuletz et al. 1997). Many species contributed to the decline, including loons, cormorants (-95 percent), mergansers, Bonaparte's gulls, glaucous-winged gulls (-69 percent), black-legged kittiwakes (-57percent), arctic terns, pigeon guillemots (-75 percent), marbled and Kittlitz's murrelets (-68 percent), parakeet auklets, tufted puffins, and horned puffins (-65 percent) (Klosiewski and Laing 1994). Other census data further indicated that for the marbled murrelet, at-sea winter abundance declined by more than 50 percent 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 sixteen 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 percent 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 two 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 one 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.

7.11.2 Case Studies

A lot of information has been collected on seabirds in the GOA in the past three decades, although much of the data obtained in the last ten 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 one to more than four 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.

7.11.2.1 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 7.5). 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

Table 7.5 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)

poor productivity and population decline (Gill 1999, Gill and Hatch unpublished data).

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

Glaucous-winged gulls also probably nested in comparatively small numbers on Middleton Island before 1964, although no counts were made in the early years.

By 1973 there were fewer than 1,000 individuals and fewer than 2,000 a decade later. However, in contrast to findings for murres and kittiwakes, the population ballooned to more than 12,000 birds between 1984 and 1993, and now totals about 11,000 (Hatch unpublished data). Predation by gulls on kittiwake and murre eggs and chicks may have contributed to the declines of those species (2001).

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

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 percent 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 percent of the biomass fed to chicks in eleven 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 percent 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).

7.11.2.2 Prince William Sound

Twenty-three kittiwake colonies in PWS were first counted in 1972, but were not counted again until 1984. These and an additional six colonies have been visited nearly each year since (Irons 1996, Irons unpublished data). During this time, long-term increases and decreases have been noted at various colonies, but no obvious geographic pattern to the changes was found. Instead, four colonies have grown to large size, and eleven 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 percent between 1991 and 1993 and increasing by 35 percent 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 7.5). Average productivity differed considerably between colonies with different population trajectories, however (Table 7.4). 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 eleven declining colonies.

7.11.2.3 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 percent and today it is just 25 percent 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 percent of its former abundance. Kittiwake productivity has been poor in most years, averaging just 0.06 chicks per pair (Table 7.5). 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 7.6).

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 percent to 15 percent 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 percent 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 7.5). 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 7.6).

Table 7.6 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)*

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—seven counts between 1975 and 1991 and ten 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 percent (Roseneau unpublished data). Kittiwake productivity at the Barren Islands in the 1990s was as high as at Gull Island (Table 7.5). 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).

7.11.2.4 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 two years in the mid-1970s (about one 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 7.5).

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).

7.11.2.5 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 percent 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 fifteen 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 percent. 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 percent 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 eleven years between then and 1998, the average productivity has been just 0.05 chick per nest (Table 7.5). Accompanying the decline in abundance and collapse of productivity was a delay of nine 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 percent higher by 1998. As for kittiwakes, the mean laying date of murres was about ten 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 7.5).

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.

7.11.3 Conclusions

Seabird populations at colonies in the GOA are very dynamic, with numerous examples of growth and decline during the past three 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 fifteen years and at the Barren Islands and the Semidi Islands during the past ten 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 seventeen 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 seventeen years, notwithstanding apparent oscillations.

7.11.4 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 five-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 fifteen 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 three 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 two 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 percent 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 three 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.

7.12 Fish and Shellfish

7.12.1 Introduction

The GOA is well known for its fish and shellfish because of its long-standing and highly valuable commercial and recreational fisheries. 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. 1994, Purcell et al. 2000, Rooper and Haldorson 2000). 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 7.10, Forage Species, and some of the less common shellfish species are considered in Section 7.9, 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; and
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 G (see survey area map, Figure 7.10).

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.

7.12.2 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 7.7 and 7.8). The bony fish dominate the number of species in the GOA, with less than 10 percent of species being cartilaginous fishes (Petromyzontidae to Acipenseridae, Table 7.7). Species diversity in the fish depends on the type of gear used to sample (Table 7.7). 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 7.7, left two columns) to the species composition in the predominant types of trawl gear surveys (Table 7.7, 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 7.10 in Section 7.6.1). 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. 1999).

Table 7.7 Fish Families and the Approximate Number of Genera and Species Reported from the Gulf of Alaska

Family	Quast and Hall[1] Number of Genera	Quast and Hall[1] Number of Species	Miscellaneous Surveys[2] Number of Genera	Miscellaneous Surveys[2] 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 7.7 Fish Families and the Approximate Number of Genera and Species Reported from the Gulf of Alaska

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

Sources: Hood and Zimmerman 1986 (after Ronholt 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 7.8 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
Zoaricidae	4	Osmeridae	2
Myctophidae	3	Gadidae	2
Rajidae	2	Hexagrammidae	2
Total	**68**		**39**

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

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

Geographic distributions of GOA fish biomass in the NMFS trawl surveys are different from the overall total. In the western GOA, Atka mackeral (Hexagrammid) had the highest biomass in the Shumagin Islands, but this species was not among the twenty 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 twenty 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 twenty 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 7.9 in comparison to Table 7.7).

Table 7.9 Comparison of the Number of Fish Families and Species Found at less than 100 m in Different Regions of the Gulf of Alaska

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

Information summarized from Rogers et al. (1986).
NA = not available

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

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

Both salmon and groundfish populations in the northeastern Pacific appear to vary annually in concert with features of climate, but the responses appear to be different (Francis et al. 1998). Annual groundfish recruitments follow a cycle with a roughly 10-year period that may be related to the ENSO (Hollowed and Wooster 1992), whereas salmon abundance changes sharply at intervals of twenty to twenty-five 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).

7.12.2.1 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, such as 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. 1999). 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).

7.12.2.2 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, Finney et al. 2000).

7.12.2.3 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 twenty years (Bailey et al. 1999). Adult walleye pollock are distributed throughout the GOA at depths above 500 m. A substantial portion (45 percent) 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 1997). 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 1997). 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. 2001).

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 three million mt in 1982 (Witherell 1999). 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 1999). 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. 99). 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).

7.12.2.4 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 two 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 1997).

7.12.2.5 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 1997). 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 7.10). 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 1997).

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 1999). 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.

7.12.3 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 7.9). 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 percent 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 percent), and detritus eaters (33 percent) (Semenov 1965 in Feder, H.M. and S.C. 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).

7.12.3.1 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 1980, 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 fifteen crab stocks in the Bering Sea, Aleutian Islands, and GOA, time trends in seven of fifteen 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 seven of the fifteen 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, G. 1999).

7.12.3.2 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 eight 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 three mt in 1997 to 1998. In the Aleutian Islands, shrimp catches after the 1978 season declined precipitously, and the fishery has not rebounded since.

7.13 Marine Mammals

7.13.1 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 7.10 provides a summary of the general characteristics of twenty marine mammal species that occur regularly in the GEM region, including seven baleen whales, eight toothed whales and porpoises, four 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 7.10 are widely distributed in the North Pacific Ocean, and the animals that inhabit the GEM region represent only part of the total population. Application of modern molecular genetics techniques, however, has provided much new information on population structures (Dizon et al. 1997). Researchers have found that for species such as killer whales (Hoelzel et al. 1998), beluga whales (O'Corry-Crowe and Lowry 1997), (Bickham et al. 1996), harbor seals (Westlake and O'Corry-Crowe 1997), and sea otters (Scribner et al. 1997), genetic exchange among adjacent and sometimes overlapping groups of animals is so low that they need to be managed as separate stocks.

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

§ Mysticete cetaceans—baleen whales;

§ Odontocete cetaceans—toothed whales;

§ Pinnipeds—seals, sea lions, and fur seals; and

§ Mustelids—sea otters.

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

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 percent 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 50º N latitude, but

Table 7.10 Summary of Characteristics of Marine Mammal Species That Occur Regularly in the Gulf of Alaska *Exxon Valdez* Oil Spill 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.

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 one 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 7.10). 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).

7.13.2 Focal Marine Mammal Species for the GEM Program

7.13.2.1 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 fifteen years of age. Females may produce calves until they are about forty, at intervals of two to twelve 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 percent 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 7.10. 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 percent 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, E.L. 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 percent since 1988, with only ten individuals remaining in 2000 (Table 7.11).

Table 7.11 Number of Whales Photographically Identified in Killer Whale Pods in Gulf of Alaska *Exxon Valdez* Oil Spill 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 2000).

[1] *The entire AN20 pod has not been photographed since 1991.*

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 twelve calves have been born in AB pod since then, there is no clear trend toward recovery because an additional ten animals have died. For the AT1 transients, twelve 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 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 four years, the pod numbered thirty-six 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.

7.13.2.2 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/2000_Folder/2000_beluga_whale_tagging.htm, also 1999 and 2001 studies available by substituting year).

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 four to seven years of age and males at seven to nine years. Mature females give birth to calves every two to three years, mostly in late spring or summer. The maximum life span has not been well defined, but is likely to be about forty 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 7.12). 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 percent 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.

Table 7.12 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).

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 twenty whales from a population of 500.

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).

7.13.2.3 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 1971, 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 three to six years of age and most breed annually during June and July (Pitcher and Calkins 1981). Males reach sexual maturity at three to seven years of age and physical maturity by age ten; they establish territories on rookeries during the breeding season, and one male may breed with several females (Thorsteinson and Lensink 1962, Gentry 1971, 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 two 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 ten 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 1971, 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). Seals, sea otters, and birds are also occasionally eaten (Gentry and Johnson 1981, Pitcher and Fay 1982, O'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). 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 percent to 8 percent 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 percent from 109,880 to 18,193 (Crane and Galasso 1999). 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 percent and 87 percent), but it appears that the decline in the eastern GOA began later than in the western GOA and other regions (Sease and Loughlin 1999, Crane and Galasso 1999) (Table 7.13). Counts of pups on rookeries have shown similar declines. Modeling and tagging studies have suggested that the proximate cause of the population decline is probably a reduction in survival of juvenile animals (York 1994, Chumbley et al. 1997). Birth rates are also comparatively low (Calkins and Goodwin 1988), which could be a contributing factor. Population viability analysis suggests that if the decline continues at its current rate some rookeries will go extinct in the next forty to fifty years, and the entire western population could be extinct within 100 to 120 years (York et al. 1996).

Table 7.13 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 (Crane and Galasso 1999).

The multiple factors that have been suggested to affect abundance of the western Steller sea lion population in the past three to four decades (Merrick et al. 1987) are represented by six related hypotheses displayed on a National Marine Fisheries Service web page on December 27, 2001:

Brief Characterization of the Principle Hypotheses Surrounding the Steller Sea Lion Decline
http://www.fakr.noaa.gov/omi/grants/sslri/hypothesis.htm

1. Fisheries Competition

Commercial fisheries potentially cause or contribute to nutritional stress in the western stock of Steller sea lions by reducing either the abundance of prey at scales relevant to foraging sea lions or by disturbing prey patches so as to reduce their availability. In turn, nutritional stress is manifested in the population as increased mortality or lowered reproductive output.

2. Environmental Change

Environmental conditions in areas inhabited by Steller sea lions may have changed since the 1970s in ways that reduced the availability of prey for Steller sea lions and precipitated nutritional stress. The changes may have either reduced the abundance of important prey items or altered their distributions.

3. Predation

Predation of Steller sea lions by killer whales and sharks has increased as a function of a) their increased population size, b) their increased per capita

consumption , or c) remained constant over time, but with increasing effects as the Steller sea lion population has diminished over time.

4. Anthropogenic Effects

One or more sources of anthropogenic activity, including incidental mortality (e.g. entanglement), direct mortality (e.g. shooting), commercial harvesting, subsistence harvesting, and harassment have contributed to the decline in the Steller sea lion population. Such effects would include both those over the past decades since the decline began and those which may be ongoing.

5. Disease

The Steller sea lion population is being reduced by diseases which may result in mortality or reduced reproductive output.

6. Contaminants

Contaminants from either local or distant sources have had detrimental physical impacts on Steller sea lions leading to increased mortality or reduced reproductive output.

Available data permit no definitive evaluation of any of these hypotheses at present. 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, Crane and Galasso 1999). 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 (Crane and Galasso 1999). Major research efforts have been generously funded ($43M FY 01, $40M FY 02, $60M FY 03) by the federal government.

7.13.2.4 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 foorty-nine 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 twenty-seven 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 three to seven 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 three to six 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 percent of the seals shot were retrieved, and 12 percent 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 thirty-six 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 percent per year. From 1988 to 1989, however, there was a 43 percent decline in counts of seals at oiled sites compared to 11 percent 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 7.14). At Tugidak Island (south of Kodiak Island), average molt period counts declined by 85 percent from 1976 to 1988 (Pitcher 1990), followed by a period of stabilization before a population increase of about 5 percent per year during 1994 to 1999 (Small et al. 1999). In eastern and central PWS, the number of seals at twenty-five trend index sites declined by 42 percent 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 percent 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 7.14), suggesting that the decline in that area may have stopped. In the Kodiak trend area, harbor seal counts increased by 5.6 percent per year during 1993 to 1999 (Small et al. 1999).

Table 7.14 Counts of Harbor Seals at Index Sites in the *Exxon Valdez* Oil Spill Gulf of Alaska 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 et al. 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.

7.13.2.5 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 percent 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 percent 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 ten 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 twelve 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 one 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 two, and by age three most females are sexually mature. Where food resources may be limiting population growth, sexual maturation may be delayed to four to five 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 percent to 40 percent, compared to nearly 85 percent 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 percent to nearly 60 percent (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 two years of age is generally high, approaching 90 percent, 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 twenty-two years for females and fifteen 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 percent to 33 percent 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 three hours, separated by periods of rest that also average about three 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 percent 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 percent to 100percent 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 percent at newly occupied sites at Kodiak to 22 percent 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 thirteen 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 7.15), although suitable unoccupied habitat remains in Asia and North America (Bodkin and Kenyon in press).

Table 7.15 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 percent to 59 percent (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 eighty 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.

7.14 Introduction to the Economics of Human Uses and Activities in the Northern Gulf of Alaska

Human uses have likely affected the productivity of GOA marine and surrounding terrestrial environments during the 4,000 or more years of human presence in the GOA region.

Trends since the 1989 ***Exxon Valdez*** oil spill suggest that the pace of change in human-caused effects may have accelerated. The spill itself changed attitudes toward acceptable risks of human-caused disruption, while economic trends have brought about more intense use of some resources and diminishing use of others. Understanding these trends will sharpen strategies for long-term monitoring and extend our understanding of how human uses may affect ecosystem productivity.

In the period before contact with Europeans, Kodiak, Prince William Sound, and most other areas affected by the oil spill were populated by Alutiiq peoples, linguistically related to the Yupik Eskimos of the Bering Sea coast and the Aleut cultures of the western Alaska Peninsula and Aleutian Islands. All of these cultures were “ocean-facing,” deriving most of their livelihood from the sea, with relatively little economic dependence on upland resources (Dumond 1983).

The cultural values and economic systems of these communities appear to have been very stable. The central role of marine mammal and fish resources in the Alutiiq subsistence economies profoundly influenced the social organization of pre-contact societies and shaped their spiritual and cultural values. In the face of environmental variability, rituals and other cultural observances focused on assuring predictable marine resource abundance. Failure of a prime resource such as a salmon run could threaten the extinction of an entire community.

While the Alutiiq had highly developed technologies for exploiting fishery resources with minimum expenditures of time and labor, strongly conservative values and attitudes toward environmental change and resource use tended to limit overharvesting. Property rights to resources such as salmon streams or sea otter hunting areas were vested in clans and villages, who were responsible for stewardship of the resource and its spiritual embodiments (Cooley 1963). Elements of these values remain strong in some GOA communities.

Notwithstanding the high value attributed to environmental stability and sustainability, human activity was a significant factor in pre-contact changes in resource abundance in other parts of the Pacific littoral (Jackson et al. 2001). Human-caused effects might have extended to the salmon resources exploited by the Alutiiq. And certainly sea otters were extirpated from the interior waters of Prince William Sound before the arrival of Europeans in the middle of the 18th century (Lensink 1964, Simenstad et al. 1978).

The hundred years following contact brought an end to the relative cultural and economic stability. European traders and fur hunters possessed weapon technologies and an organizational infrastructure that allowed them to quickly dominate the small, fragmented Alutiiq communities. Europeans also brought upland-facing cultural attitudes that reflected diminished concern for the sustainability and stability of ocean resources. Whatever constraints against overexploitation may have been afforded by the sophisticated system of Alutiiq property rights and clan-based institutional systems, all were quickly brushed aside. For resources that attracted European commercial attention, the results were invariably disastrous.

The sea otter was the first resource to attract commercial attention. Though the trade in pelts was fabulously profitable at the outset, the resource base that made the trade possible quickly shrunk in the face of unremitting harvest pressure to supply Asian and European markets. By the time of the transfer of Alaska to the United States, only remnant populations remained (Rogers 1962).

Improved transportation and food preservation technologies in the late 19th century opened the region's salmon resources to markets thousands to tens of thousands of kilometers distant. Canned salmon production grew from 1.3 million cases in 1900 to a peak of 8.5 million in 1936, and then collapsed from overexploitation to 1.6 million cases in 1959, the year Alaska became a state. Not until the late 1970s did the institutional development of fishery entry limitations make it possible to meet the biological requirements of sustained salmon harvests without dissipating most of the potential economic gains in excess costs.

Despite its long and rich history of human occupation and use, the GOA marine environment remains relatively unsullied, at least in the popular understanding. As is described in section 7.14.1, the closing years of the 20th century saw significant declines in commercial fishing, marine transportation of oil, and logging. Subsistence use of GOA resources partially rebounded after the 1989 oil spill, while tourism and recreational uses of the GOA resources and environment grew.

Many of the benefits of the GOA environment are largely non-market, non-use, existence values with heavy emphasis on the future. Future existence of endangered populations of wild salmon stocks, future protection of charismatic megafauna such as killer whales and sea otters, and the global marine commons are examples (Brown 2000). Contingent valuation studies conducted in 1990 provided an immediate post-spill benchmark of the economic existence value of GOA resources directly affected by the oil spill (NOAA 1993). No follow up work has been done to confirm subsequent changes in GOA existence values. Other economic studies, however, suggest that the public continues to assign high values to the existence of healthy environments, and apply increasingly sophisticated and stringent criteria for evaluating environmental health, particularly in relation to environments viewed as relatively pristine (Whitehead and Hoban 1999). The GEM mission of sustaining a healthy ecosystem and its focus on long-term monitoring have been shaped by the need for a long-term understanding of how human activity shapes the environment, and how human- and non-human-caused environmental change can be distinquished.

7.14.1 Socioeconomic Profile of the Region

The bulk of the land area draining into the spill-affected parts of the GOA is found in five boroughs (a county-level governmental unit unique to Alaska), a portion of a sixth borough, and one unorganized census area. Just under 400,000 people, 63 percent of Alaska's population, live in this physiographic GOA region as of the 2000 census (about 71,000 people in the region directly affected by the oil spill: Prince William Sound, lower Cook Inlet, Kodiak Island, and the Alaska Peninsula). Two to three times that number use the area seasonally for work and recreation. An estimated 700,000 out-of-state tourists visit the region each year (ADCED 2002, Northern Economics Inc. 2002). Although this area is larger in geographic scope than the GEM region, it reflects the scope of the potential human impacts on the GEM region.

The GOA region has grown rapidly throughout the 20th century, but that growth has recently decelerated. During the 1990s, population grew by 19 percent and non-agricultural jobs by 26 percent, the slowest decadal rates since the 1930s (Williams 2000).

Most growth in the 1990s has occurred in three urbanized areas: Anchorage, the bedroom communities of the southern Matanuska and Susitna valleys, and the urbanized west-central Kenai Peninsula around the cities of Kenai and Soldotna. In the remainder of the region, including almost all the areas immediately impacted by the spill, growth has been slower. Table 7.16 shows how boundaries of the overall region and the subregion directly affected by the spill are defined. During the 1990s, population in the directly affected subregion grew by seven percent, less than half as fast as the population of the GOA region as a whole. The 2000 census found 35,470 people residing in the directly affected subregion (U.S. Bureau of the Census 2001).

Migration to and from the GOA region has been highly volatile. High wages and low unemployment in Alaska relative to the Pacific Northwest have generally stimulated net inmigration to the region, while the reverse condition has led to a net population exodus. Over the last half century in Alaska and the Pacific Northwest, economic cycles have tended to be out of phase, amplifying the migratory swings.

Demographic data for the 1989-99 interval and preliminary information for 1999-00 suggest that the 1990s were the first decade since the 1930s in which newcomers to Alaska failed to replace all of those who left. The GOA region is likely to have experienced similar net outmigration over the decade of the 1990s (Williams 2002).

The major reason for the recent net outmigration was the attraction created by the fast-growing economy in the Pacific Northwest and the rest of the nation, and the relatively torpid rate of economic growth in Alaska.

Table 7.16 Representation of Boroughs and Census Areas in Gulf of Alaska and Oil Spill Regions

Borough or Census Area	GOA Economic Region	Oil Spill (GEM) Region
Anchorage Borough	All	None
Aleutians East Borough	All	None
Kenai Peninsula Borough	All	South and southeast portion: Homer, Seldovia, Port Graham, and Seward
Kodiak Island Borough	All	All
Lake and Peninsula Borough	Southern portion only: Chignik, Chignik Lagoon, Chignik Lake, Ivanof Bay and Perryville	Southern portion only: Chignik, Chignik Lagoon, Chignik Lake, Ivanof Bay and Perryville
Matanuska-Sustina Borough	All	None
Valdez-Cordova Census Area	All	Prince William Sound and Cordova census subareas

Over the long term, net migration has been less important to Alaska population growth than the state's chronic excess of births over deaths. Average annual net migration in the twenty years between 1979 and 1999 was +1487 persons, while the average excess of births over deaths during the same period was +8928 (Williams 2000).

This persistent excess has been a consequence of three longstanding features of the state's demographics—fertility rates well above the national averages in all racial groups, an unusually large percentage of residents of child-bearing age, and an unusually small share of the population in the older age groups where natural mortality is highest.

As is described in subsequent sections, commercial fishing, marine transportation of oil, and the wood products industries in the GOA region have all declined in recent years, while tourism and recreation-related industries have grown, as has federal spending. Money transfers to households have also grown, most notably from the state's permanent fund dividend, an annual payment to all residents from earnings on the state's $25-billion oil-money savings account (U.S. Bureau of Economic Analysis 2002). Deepening of local economics through support sector growth has played a role too, with Alaska businesses and households buying more locally and importing less from outside the state. Continuation of these trends would suggest a continuation of slow economic and population growth (Goldsmith 2001).

The fundamentals of Alaska's economy are likely to remain rooted for some time in the state's natural resources, including the indirect effects of oil revenue recycled through state government. As the world's population grows, the demand for access to Alaska's scenic beauty and open spaces of the state is likely to increase as well. Beyond the economic effects of increased tourism, the intangible quality of Alaska as a place of wilderness, beauty and a special way of life will continue to attract migrants to the last frontier, increasing pressures of human uses and activities on the GOA environment.

7.14.1.1 Prince William Sound-Southeast Kenai

The Prince William Sound-Southeast Kenai (PWS-SEK) region is a coastal belt extending from the mouth of the Copper River on the east, in an arc around Prince William Sound, southwest along the GOA coast, and around the southern tip of the Kenai Peninsula to just past Port Graham and Nanwalek. It includes numerous offshore islands. The region is mountainous throughout, and three of its four largest communities are located at the heads of deep fiords. All of the PWS-SEK region is within the Chugach or Kenai mountains, and the region's boundaries are roughly the same as those of the Chugach Regional Native Corporation. Most of its land area is in or adjacent to the Chugach National Forest.

Between 1990 and 2000, the population of the PWS-SEK region grew less than six percent, well below the rates in the GOA region or the state. In 2000, 12,211 people lived in PWS-SEK, eighty percent of whom live in seven communities. The three largest communities—Cordova (population 2,454), greater Seward (3,430), and Valdez (4,036)—are predominantly non-Native, although Valdez and Cordova are home to Alaska Native village corporations and tribes. Of the five other communities, Chenega Bay (86), Port Graham (171), Nanwalek (177), and Tatitlek (107) are Alaska Native villages, and Whittier (182) is mostly non-Native (U.S. Bureau of the Census 2001).

Of the seven communities, only Valdez, Whittier and Seward have highway access to the state's main road system. Whittier and Seward have Alaska Railroad passenger and freight service. Cordova, Valdez, Whittier, Tatitlek, Chenaga Bay, and Seward are served by the Alaska Marine Highway System. Except for Valdez, all of the communities grew during the 1990s, although at rates well below the average of the state or GOA region. The population of Valdez declined by one percent.

The economic base of the seven communities in PWS-SEK is almost entirely resource dependent (Fried and Windisch-Cole 1999a). The Cordova economy is based on commercial fishing, primarily for pink and red salmon. Recent declines in the value of landings have been a hardship to the community and to the Prince William Sound Aquaculture Corporation that operates hatcheries in the sound. Some biologists have expressed concern that the 600 million or more smolt that hatcheries annually release into the sound and adjacent waters have had a deleterious effect on wild salmon (Hilborn 1992).

In recent years formerly important herring fisheries have been closed due to inadequate stocks. However, Cordova has recently benefited from an increase in small-scale tourism, and some cruise ships have visited the port, but the community remains in economic distress.

Valdez, as the terminus of the trans-Alaska pipeline, depends on the oil industry, but did not suffer seriously from the downsizing that occurred in the industry during the 1990s. This is due to additional labor required in Valdez to implement safety and pollution prevention measures adopted in the wake of the 1989 spill. The state's official oil production forecast suggests that crude shipments will roughly maintain their current level over the next decade (see section 7.14.2).

Notwithstanding its dependence on oil, the Valdez economy is more diversified than any other community in PWS. Valdez has used revenue from its large oil-related tax base in ways designed to stimulate economic diversification. The city invested $48 million in cargo and port facilities in an attempt to become the major entry port for cargo headed to the Alaska Interior. The scheme has yielded some success. Other investments in seafood processing have also resulted in additional jobs, but their cost-effectiveness remains uncertain. Although the population of Valdez declined slightly in the 1990s, jobs do not appear to have experienced a similar decline (Alaska Department of Labor 2001).

The major growth industry in Valdez is tourism and recreation. The number of fishing charter boats operating out of the local small boat harbor doubled between 1997 and 1999. Although cruise ship visits have become an important part of the summer economy, cruise ship visitation in 2002 is anticipated to be around twenty-six cruise ships, down from forty-five in 2001 (Valdez Convention and Visitor's Bureau, personal communication). As cruise ship operators redeploy vessels away from foreign waters, the number of visits is expected to increase.

Seward, more than any other community in the GOA region, has transitioned from an economic dependence on fluctuating seafood and timber markets to a visitor and recreation-based economy. Most economic growth since 1990 has been driven by the visitor industry, with employment in trade, services and transportation growing at a 5.9 percent annual rate. The community has capitalized on its road and railroad access to market itself as the major jumping-off point for visits to the Kenai Fjords National Park and Alaska Maritime National Wildlife Refuge. Seward's Alaska SeaLife Center has created another visitor attraction. More than 260,000 cruise ship passengers disembarked at Seward in 2000 (Goldsmith and Martin 2001).

Commercial fishing has trended downward in importance throughout the 1990s, but it remains a significant part of the Seward economy. The nearby state prison and other government facilities, including the headquarters for the Kenai Fjords National Park, are also important year-round employers. Although a major sawmill was opened in 1993, it never became competitive, and has remained closed since 1994.

Although its growing dependence on the seasonal visitor industry has been a concern, in the 1990s Seward developed a diverse and dynamic economy: "Over the last decade, it has successfully exploited its location beyond people's expectations." (Fried and Windisch-Cole 1999b)

Whittier depends on transportation and visitor-related businesses. The other four small communities in the PWS-SWK region augment commercial fishing, logging, aquaculture, and other cash-based activities with subsistence fishing, hunting, and gathering.

7.14.1.2 Western Kenai Peninsula Borough

The western Kenai Peninsula (WKP) region encompasses all the drainages to the northwest of the crest of the Kenai Mountains except those at the southern tip of the peninsula around Port Graham and Nanwalek. In addition, it includes the relatively sparsely populated area on the west side of Cook Inlet.

In terms of its physiography the area faces Cook Inlet (Barnes 1958); its economy has been closely linked since the 1960s with the oil and gas developments in the inlet and on the nearby uplands.

The WKP region is connected to Alaska's main road system, and is only a few hours by car from Anchorage, the state's largest metropolitan area. Homer and Kenai have scheduled air service from Anchorage.

The region grew twenty-three percent in the 1990s, making it second only to the Matanuska-Susitna Borough as the fastest growing area in the GOA region (Williams 2000). In addition to oil and gas, the WKP economy depends on commercial fishing, sport fishing and other outdoor recreation. About 46,500 people live in the WKP region, with over two-thirds living in or near the cities of Kenai and Soldotna. Soldotna is the headquarters of the Kenai Peninsula Borough and the Kenai Borough School District, the fourth and first-largest employers in the borough. Government at all levels accounts for twenty-three percent of the non-agricultural jobs in the borough, slightly less than the twenty-six percent statewide (Fried and Windisch-Cole 1999).

The southern Kenai Peninsula contains Seldovia (286 persons) and Homer (3946). Homer, on the north side of Kachemak Bay, lies at the southern terminus of the state's main road system, and has been popularized in the colorful writings of author Tom Bodett as "the end of the road."

Homer has attracted a significant number of retirees. According to the 2000 census, 10.1 percent of Homer residents are older than 64, the highest percentage of any community in the state. The percentage of over-64 residents in the borough as a whole is 7.3 percent, the highest in the GOA region. The statewide percentage of residents over age 64 is 5.7 percent (Williams 2000).

7.14.1.3 Kodiak Island Borough

The Kodiak Island Borough occupies the Kodiak Archipelago west of the GOA, and a largely uninhabited strip of the Alaska Peninsula coastline across the stormy Shelikof Strait. The borough population in 2000 was 13,913, of which sixty-four percent (8864) lived in the City of Kodiak, the adjacent Coast Guard station, or on the road system nearby. The borough population grew six percent between 1990 and 2000, about one-third as fast as growth in the GOA region as a whole (U.S. Bureau of the Census 2001).

There are six outlying communities, the Alaska Native villages of Port Lions, Ouzinkie, Larsen Bay, Karluk, Old Harbor, and Akhiok, none of which have road connections to each other or the city of Kodiak.

The region's only scheduled jet service is to the Kodiak municipal airport, co-located at the U.S. Coast Guard air station. The Alaska Marine Highway System serves Kodiak and Port Lions. Other communities depend exclusively on air taxis or unscheduled private vessels for access.

The economy of the archipelago depends heavily on commercial fishing and seafood processing, with the borough's population swelling in the fishing season (Alaska Department of Labor 2001). Kodiak is one of the world's major centers of seafood production and has long been among the largest ports in the nation for seafood volume and value of landings.

Village residents largely depend on subsistence hunting and fishing. Kodiak Island also has a growing recreation and tourism economy and is home to a state-owned commercial rocket launch facility that held its first successful launch in 1999. The U.S. Coast Guard Station, with 1,840 permanent residents in 2000, is a major employer.

7.14.1.4 Alaska Peninsula

The Alaska Peninsula is on the western edge of the northern GOA, and encompasses the Aleutians East Borough and the southern part of the Lake and Peninsula Borough. The total population of the region is 3,153. Sand Point, with 952 residents, and King Cove, with 792, are the largest communities (U.S. Bureau of the Census 2001). Aside from government spending, the cash economy of the area depends on the success of the fishing fleets.

Five smaller communities on the south side of the Alaska Peninsula lie within the area directly affected by the ***Exxon Valdez*** oil spill: Chignik, Chignik Lagoon, Chignik Lake, Ivanof Bay, and Perryville. The population of this area is 456, but may double during the fishing season. All five of these communities are in the Lake and Peninsula Borough and served by scheduled air taxi service. Chignik is also served by the Alaska Marine Highway ferries on a seasonal basis.

Sand Point, Chignik, Chignik Lagoon, and King Cove serve as regional salmon fishing centers. In addition to salmon and salmon roe, fish processing plants in Chignik produce herring roe, halibut, cod, and crab. About half the permanent population of these communities is Alaska Native.

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

7.14.1.5 Anchorage / Mat-Su Urban Area

Anchorage, located at the head of Cook Inlet, and the Matanuska-Susitna (Mat-Su) Borough just to the north of Anchorage, constitute the economic, financial and industrial capital of the state. Although outsiders often conceive of Alaska as sparsely populated, the state is also highly urban, and becoming more so. In 2000, fifty-one percent of Alaska's population lived in the Anchorage / Mat-Su metropolitan area, up from forty-eight percent a decade earlier. Between 1990 and 2000, Anchorage / Mat-Su added 53,584 residents, more than the 2000 population of Juneau and Ketchikan combined, the state's third and fourth largest urban areas (U.S. Bureau of the Census 2001). Although Anchorage / Mat-Su is situated outside the oil spill subregion, its geographic proximity suggests that growth there will—as it has in the past—produce environmental impacts in the area directly affected by the oil spill. This is likely to be particularly true where the surface transportation connections already exist, as they do to Seward, Whittier, and Valdez.

No economic development is likely to occur anywhere in the state without links to Anchorage. It serves as headquarters for the state's major financial institutions, its oil companies, major media outlets, largest labor unions, religious organizations, and most of its federal military and civilian government bureaucracy. The Anchorage airport is the major funnel through which most of the state's visitor traffic and a significant share of its seafood harvest pass.

Many Anchorage / Mat-Su residents work in other parts of the state, especially construction workers, oil workers, and fishermen (Fried 2000). These workers provide Anchorage with a direct source of income earned in other parts of the state. With the most diversified economy in the state, Anchorage is better positioned than any other community in the state to maintain growth in the face of economic hardship.

7.15 Economics and Ecological Impacts of Human Use Activities in the Northern Gulf of Alaska

"At first glance, Prince William Sound presents an aspect of pristine and untrammeled wilderness, and this is one of her major delights. Anchored in a secluded cove or ascending a trackless ridge, it is easy to imagine oneself as the first explorer. Yet, a closer examination of the shoreline quickly reveals subtle signs of former habitation. Decayed, sawed off stumps line the shores – witness to former hand-logging operations. The logs were used for cabins, firewood, fishtraps, cannery pilings, mining timbers, railroad ties, fox farm pens and even ship building. If one rummages around the moss, alder and devils club along the shores, virtually every bay reveals the rotted foundations of some old cabin or fox pen. Abandoned, frail human structures do not last long in this damp climate and under such heavy winter snow-loads. And perhaps this is as it should be."

from Cruising Guide to Prince William Sound Alaska, Jim and Nancy Lethcoe

This quote from a book about sailing in Prince William Sound is a fitting introduction to a section on human use activities in the northern GOA. At least a portion of the public has a perception that, prior to the ***Exxon Valdez*** oil spill, the region had little human impact. To the contrary, there has been a succession of different types of human habitation and economic activities in the northern GOA. Many of these activities had a high level of impact on both the environment and other users and residents of the region.

The earliest inhabitants of the region were nomadic Asian explorers crossing the Bering Land Bridge and spreading southward. The dates of first human occupation in Prince William Sound are not known, but radio carbon dating estimates go as far back as 205 AD.

Beginning in the 1700s, the northern GOA was used by a succession of explorers and developers. Russian and English fur traders in the 1700s were followed by development of fish canneries in the late 1880s. The first fox farms were developed in 1894 at Seal Island. Mining activity in the region also developed in the latter part of the 1890s. In 1897, Klondike gold was discovered, opening up the region as a gateway to Alaska's interior. Mining began in the northern GOA in 1896. The communities of Ellamar and Latouche were built to develop copper mines. The Kennicott copper mine was developed around 1905 and resulted in the Valdez to Copper River and Northwestern Railway in 1911.

Mining and fox farming gradually declined, and military activity during World War II added a new type of activity to the region. Whittier remained an active military port until 1960. Commercial fisheries were developed and expanded in the 1950s, 1960s and 1970s. The late 1970s were dominated by development of the trans-Alaska pipeline and the terminal at Valdez. The 1980s and 1990s have shown a large expansion in recreation and tourism.

7.15.1 Commercial Fishing

Commercial fishing is by far the predominant human activity in the northern GOA and is thought at this time to have the potential for the most significant impacts on the GOA ecosystem. Within the GOA, the major commercial fisheries are salmon, Pacific herring, pollock, cod, halibut, and shellfish. Tens of thousands of individuals participate in these fisheries.

The period before the 1989 oil spill was a time of relative prosperity for many commercial fishermen. Since 1989, commercial fishing in the northern GOA has undergone dramatic changes as a result of changes in salmon markets, declining abundance of other fish stocks, institutional changes associated with fishery "rationalization," harvest limitations designed to protect endangered species, and other factors.

Communities within the GEM region have varying levels of dependence on commercial fishing. The communities most dependent on commercial fishing are Cordova, Kodiak (and the outlying six villages within the Kodiak Island Borough), Chignik, Chignik Lagoon, Sand Point and King Cove. Commercial fishing is an important but less dominant economic sector in the road accessible communities of Valdez, Whittier, Seward, and Homer.

7.15.1.1 Salmon

Commercial fishing for pink, sockeye, sockeye, chum, coho and chinook salmon has long been a mainstay of the northern GOA commercial fishing industry. Salmon are harvested by seine, drift gillnet and set gillnet gear. Pink salmon are the dominant species in PWS, contributing over eight percent of total salmon landings by volume and contributing the largest share of ex-vessel value. In Cook Inlet, Kodiak and the Alaska Peninsula, sockeye are by far the dominant species.

PWS exhibits a pattern of odd-even run strength for pink salmon that persists even with the influence of hatchery production. The very low catch levels in 1992 and 1993 were due to closures associated with the ***Exxon Valdez*** oil spill. Harvests since then have increased, but unlike most other Alaska fisheries, are now highly dependent on hatchery returns.

Non-profit hatcheries have operated in Prince William Sound since the mid 1970s. The Prince William Sound Aquaculture Corporation (PWSAC) began operations in 1976 and operates five hatcheries: the W.F. Noerenberg, Armin F. Koernig, Cannery Creek, Main Bay and Gulkana facilities. The Valdez Fisheries Development Association has operated the Solomon Gulch hatchery since 1979 (Kron 1993). Much smaller salmon enhancement programs operate in Cook Inlet and Kodiak.

Returns of both wild and hatchery salmon fluctuate greatly from year to year. During the period 1960-1976, when the pink salmon fishery was supported wholly by wild stocks, the average pink salmon catch in Prince William Sound was 3.3 million fish (Eggers et al. 1991). The pink salmon harvest during this period fluctuated from 0.1 to 7.3 million fish. Since hatchery releases were begun, the average pink salmon catch has been 19.7 million.

In 2001, 76 percent of the total pink salmon return was harvested by PWSAC to cover the costs of hatchery operations. In 2002, the percentage was reduced to fifty-four percent in an attempt to make more of the salmon resource available to commercial fishermen. PWSAC has significant long-term financial obligations, with over $30 million in outstanding state loans.

Salmon prices and market demand for salmon produced in the northern GOA as well as other parts of Alaska are at relatively depressed levels. The primary reason for the market trend has been a huge increase in world production of farmed salmon. Alaska salmon face both price and quality competition from salmon originating in Chile, Norway, Canada and other farmed salmon-producing countries.

7.15.1.2 Herring

Herring are harvested predominantly for sac roe for export to foreign markets. Quotas are established for each discrete stock. Herring fisheries in the region are currently at low levels. In the 2000 season, Prince William Sound and Cook Inlet were both closed due to low abundance. Limited herring fisheries occurred in Kodiak and the Alaska Peninsula.

7.15.1.3 Shellfish

Most of the shellfish fisheries in the northern GOA are closed to commercial fishing due to inadequate stocks. Within PWS, no crab harvests have been permitted for several years, and there is no evidence of recovery. The decline of PWS crab is thought to be associated with the growth of the sea otter population, which preys heavily on shellfish (Trowbridge 1995).

Miscellaneous fisheries for PWS scallops, Cook Inlet scallops and hard shell clams, and Kodiak sea cucumbers and dungeness crab offer limited opportunities for fishermen.

7.15.1.4 Groundfish

GOA groundfish catches have ranged from a low of 135,400 metric tons in 1978 to a high of 352,800 metric tons in 1984. The 2001 groundfish harvest was 181,400 metric tons (NPFMC 2001). Pollock has been the dominant species in the overall catch, followed by Pacific cod and sablefish. Groundfish abundance in the GOA has been relatively stable, rising slowly since the mid 1980s. The estimated long-term annual yield for GOA groundfish is about 450 thousand metric tons. The recent five-year average yield has been about 230 thousand tons per year. The wide disparity between the potential and recent yield is due to fishing restrictions imposed by the North Pacific Fishery Management Council to reduce incidental catches of Pacific halibut. A major portion of the GOA groundfish biomass consists of arrowtooth flounder, with little or no current commercial value. A 1989 National Marine Fisheries Service trawl survey estimated that arrowtooth flounder made up the greatest proportion of total biomass at nearly every site surveyed (NPFMC 2001).

A specific Prince William Sound pollock quota has been established since 1995. The sound's pollock harvest has averaged 1,800 metric tons since 1995. This harvest occurs mostly during the winter months and is processed in Cordova and Seward.

7.15.1.5 Halibut

The Gulf of Alaska is managed by the International Pacific Halibut Commission as Area 3B. The 2001 harvest quote for Area 3B was 16.4 million pounds.

Halibut harvested in the central and western Gulf are delivered to the ports of Cordova, Homer, Seward, Valdez and Whittier. In 2001, 12.2 million pounds of halibut was landed in Homer, making it the number one port in landings among the entire west coast. Most of the halibut landed in Homer is iced, loaded into refrigerator vans and trucked to the Pacific Northwest for distribution to markets.

7.15.1.6 Future Resource Outlook and Issues for Commercial Fisheries

Commercial fisheries in the GEM area have been in a state of dynamic flux for the past several years. Among the ongoing issues affecting commercial fishers are the following:

<u>Environmental and oceanographic conditions</u>. Ocean survival is a key factor in regulating the magnitude of returning salmon and the level of harvest. Since the 1970s, the ocean environment has been favorable off Alaska, and salmon runs increased. However, there are indications that North Pacific circulation patterns may be shifting away from conditions favorable for Alaska salmon production (Mantua et al. 1997). If the warm water regime off Alaska reverses to a cold regime, natural salmon production will decrease throughout Alaska to levels observed in the 1960s. Hatchery production and other salmon enhancement efforts may aid in maintaining harvests if natural production declines, but the outlook remains uncertain. GOA pollock and cod stocks are likely to decrease over the next several years, while most other GOA groundfish remain stable.

A major ecological concern with all types of removals by fishing activities is the sustainability of fish stocks, which could be affected by directed fisheries or as a result of discarded bycatch in other fisheries and high seas interception. This concern drives responsible fishery management. The predominant fishery stocks historically fluctuate because of natural variability and climate cycles, and for that reason, harvest rates are set at sustainable fractions of the available biomass. However, concern still exists that setting harvest rates without a complete understanding of those fluctuations could lead to unintentional overharvest, resulting in population declines that could take years to rebound.

In addition, bycatch may have unintended consequences on non-targeted fish populations. In many fisheries, observers monitor the bycatch. In addition, bycatch is often only a small fraction of the overall mortality. However, bycatch is not monitored in all fisheries, and may be significant in some.

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

A third ecological concern with fishing is the potential for unintentional degradation of habitats and attendant losses of plant and animal species. Sport-fishing activities in watersheds have substantially degraded some riparian habitats in Southcentral Alaska, resulting in lost vegetation, lost fish habitat, and siltation, and necessitating walkways and management restrictions. Various types of marine fishing methods and gear, such as pots and bottom trawls (very large bag-shaped nets), also have the potential for degrading sea-bottom habitat and reducing populations of sedentary species such as corals and seaweeds.

Protection has already been afforded to marine habitats in some sensitive areas by excluding gear types that are thought to be injurious to habitat. For example most state waters are closed to bottom trawling. In the eastern GOA, both state and federal waters are now closed to trawling and dredging in part to protect coral habitats from possible trawling impacts. There are numerous trawl-and-dredge closure areas near Kodiak Island, the Alaska Peninsula, and the Aleutian Islands. But not all areas of the Bering Sea and GOA (especially those that have sandy and sediment bottom types) are vulnerable to trawling impacts. Given the amount of marine habitats already subject to closure, more information on how to define critical marine habitats, a possible role for GEM, is essential to balancing fishing opportunities and protection of habitat.

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

Commercial fishing also has the potential to affect other elements of the marine ecosystem, such as bird and marine mammal populations. Effects result either directly, through entanglement in fishing nets or disturbance to haul-outs and rookeries, or indirectly, through impacts on food supplies. Areas where marine mammals feed and that are adjacent to their haul-out areas have been closed to commercial fishing in parts of the Bering Sea, Aleutian Islands, and GOA. A recent National Marine Fisheries Service (NMFS) Biological Opinion (NMFS 2000) concludes that lack of food is the reason why the endangered Steller sea lion is not recovering from serious declines in the GOA and Bering Sea. On the basis of this opinion, NMFS has severely limited fixed-gear and trawl fishing for several groundfish species, a major food source for the Steller sea lion. However, this opinion has been extremely controversial, and several independent teams of science reviewers have concluded that there is no evidence that sea lions are nutritionally limited and no evidence that fisheries are causing prey depletion.

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

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

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

Resource and Legal Issues. Actions taken under the Endangered Species Act (ESA) as a result of depressed levels of Steller sea lions have created economic hardship for commercial groundfish fishers from several communities, particularly Kodiak, King Cove and Sand Point. The National Marine Fisheries Service developed a biological opinion that pointed to commercial fishing as one of the factors in declining numbers of Steller sea lions. Regulations designed to protect the species by limiting groundfish fishing were put in place in 2002. The status of harbor seals and sea otters is also uncertain, and ESA actions in relation to these species could create additional difficulties for fishers and marine resource-dependent communities.

Regulatory Actions. The North Pacific Fisheries Management Council (NPFMC) is considering a groundfish "rationalization" program for the GOA groundfish fisheries. A similar program covering Bering Sea fisheries established individual fisheries quotas (IFQs), and made other major changes to fisheries management. The fishing interests in the northern GOA will be profoundly affected by the decisions of the NPFMC on these issues.

Since its implementation several years ago, the NPFMC's IFQ share system has spread halibut and sablefish landings over a longer period of time, and as a result, the fresh market has largely displaced frozen production. Road-accessible Homer is now the largest halibut landing port on the west coast, with over 10 million pounds delivered per year. Most of the halibut landed there are placed in iced totes and delivered to processing and distribution companies in the Pacific Northwest via refrigerated van.

Commercial Fishing Summary

Reasons for monitoring: Many commercial fisheries in the northern GOA are at very depressed levels or are currently closed. Interactions with protected species or species that have a subsistence priority may create new problems for commercial fishing in the future. Future activities can have significant ecological impacts.

Type of impacts: Commercial fishing activities create resource conflicts and impact other user groups through gear loss and discard, oil and fuel spills. Resource competition can affect other fish, bird and marine mammal populations. Removal of marine nutrients can affect productivity of watersheds. Fishing gear and techniques may degrade habitat. Hatchery production and salmon farms can have negative environmental effects.

Who is monitoring: ADF&G is the primary agency for monitoring commercial fishing effort and harvests in state waters. The National Marine Fisheries Service has primary responsibility for monitoring fishing effort and harvests in offshore marine waters (three to 200 miles offshore). The International Pacific Halibut Commission has primary responsibility for monitoring effort and harvests for halibut.

Regulatory Authority: The Alaska Board of Fisheries has regulatory authority for fisheries that occur in state waters. The North Pacific Fishery Management Council has regulatory authority for fisheries that occur in offshore marine waters. Recommendations from the NPFMC require action by the Secretary of Commerce to take effect.

7.15.2 Recreation / Tourism

Recreation and tourism are the fastest growing economic activities and human uses in the northern GOA, but incomplete data leave many uncertainties regarding the characteristics of use and rates of growth.

7.15.2.1 Commercial Recreation on Excursion Vessels

Commercial excursion boats operating out of Valdez, Whittier, Seward, Homer and, to a lesser extent, Kodiak provide sightseeing trips for visitors. This group is comprised of several large companies that take most of the passengers, with smaller companies providing services to a much smaller sector of the market. According to a 1990 survey of excursion boat passengers visiting the Kenai Fjords National Park itself, most boat passengers (77 percent) were from other states (72 percent) or other countries (5 percent) (Kenai Fjords National Park 1990). The 5-year data series includes only passengers traveling into Kenai Fjords National Park, and excludes excursion boat passengers that stay within Resurrection Bay. This limited data series is shown in Table 7.17 below.

Table 7.17 Kenai Fjords Excursion Boat Passengers

1996	71,243
1997	67,934
1998	81,538
1999	93,266
2000	86,963
2001	85,047

Source: Kenai Fjords Visitation Report, Mike Tetreau, personal communication.

Excursion boat visitation appears to have declined slightly in 2000 and 2001, but this may reflect a trend toward more Resurrection Bay trips as excursion operators attempted to accommodate the demand for shorter trips typically sought by cruise ship passengers. As limited as the Kenai Fjords' data may be, it is superior to the situation for other areas in the northern GOA, where data is completely lacking.

7.15.2.2 Trends in Sport Fishing Effort

Data on sport fishing effort is also limited. ADF&G data shows the use of private boats for fishing out of Seward and Valdez increased steadily from 1988 through 1995, dropped sharply in 1996, and has increased slowly since that time (ADF&G various years). Because ADF&G changed the way these data were compiled for the years after 1995, they are of only limited usefulness for long-term trend analysis.

Overall sport fishing effort within the northern GOA is centered on the road-accessible areas. Cordova, Seward and Homer are the most popular ports for marine fishing. Whittier and Kodiak are less popular ports for marine fishing. Freshwater angling is concentrated along the road-accessible areas of Cook Inlet and the Susitna River watershed. The number of resident sport anglers in southcentral Alaska has been on a slightly decreasing trend since 1992, but the total number of anglers has increased due to the growth in the numbers of non-resident anglers. Non-resident licenses sold in Alaska increased 46 percent between 1987 and 1997 (see Figure 7.16). The ADF&G has a study underway to investigate the reasons for the declining number of resident anglers (ADF&G various years).

7.15.2.3 Cruise Ships

Cruise ships dock at five ports in the greater GOA region: Anchorage, Homer, Seward, Valdez and Whittier. Seward dominates in cruise ship dockings. Cruise ship patrons typically take passage on either a northbound or southbound run, choosing to fly to or from Anchorage on the reverse leg of their trip. Seward has the important features of proximity to Anchorage as well as access to the Kenai Fjords National Park and the ease of combining a rail or scenic bus ride segment. Seward

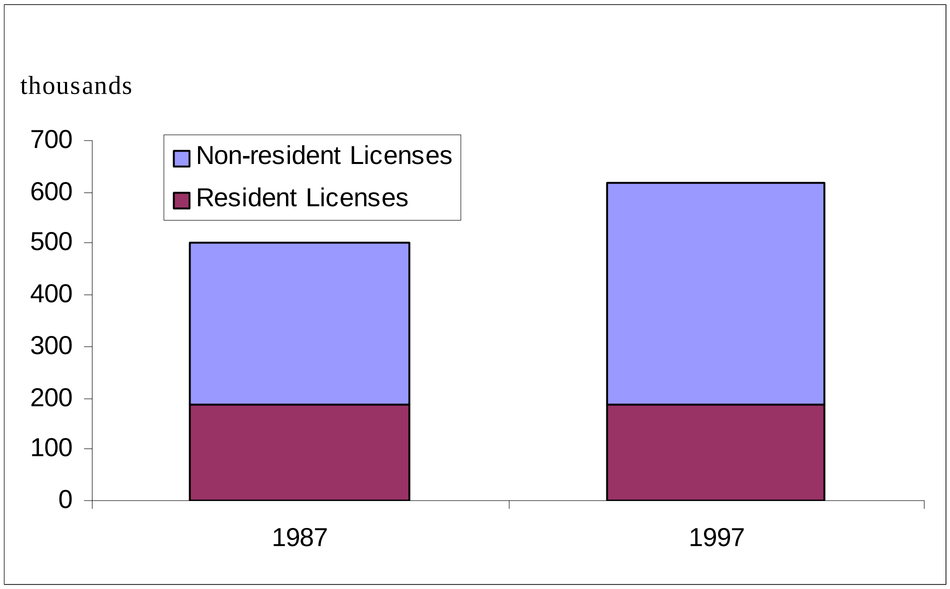

Figure 7.16 Alaska sport fishing licenses: 1987 and 1997

also offers considerable time savings for cruise ships traveling to or from the Pacific Northwest, compared with travel to the Port of Anchorage. Cruise ship docking in Seward can offer passengers a one-week turnaround schedule via return air. The growth of cruise ship use in the oil spill region has been well documented (Figure 7.17).

Cruise ship visitors are non-consumptive users of resources within the northern GOA as they move from port to port, but may become consumptive users when in port. Short-duration sport fishing trips are a popular activity for passengers while in port. Recreation and tourist users, including cruise ship users, can be compatible or incompatible with other uses and groups of users, based on their use characteristics. For example, cruise ship passengers are probably not affected by seeing groups of boaters or kayakers. However, boaters and kayakers may have their experience adversely affected by too many contacts with cruise ships.

Cruise ships often carry more people than populate many Alaska towns. One well known impact of cruise ships is air and water pollution. Cruise ships also affect other user groups by their presence in the northern GOA and, in some areas, by competing with local residents for sport fish harvests. In July 2001, Alaska enacted a law to regulate cruise ship and ferry wastewater discharges in marine waters. The new law sets discharge limits for greywater (sink, shower and galley water) and blackwater (treated sewage) for fecal coliform and suspended solids. It limits discharge to areas at least one mile offshore and requires vessels to be moving at least six knots during discharge. Sampling of discharges is required, and the Alaska Department of Environmental Conservation (ADEC) has independent authority to perform additional sampling. Finally, the new law requires improved

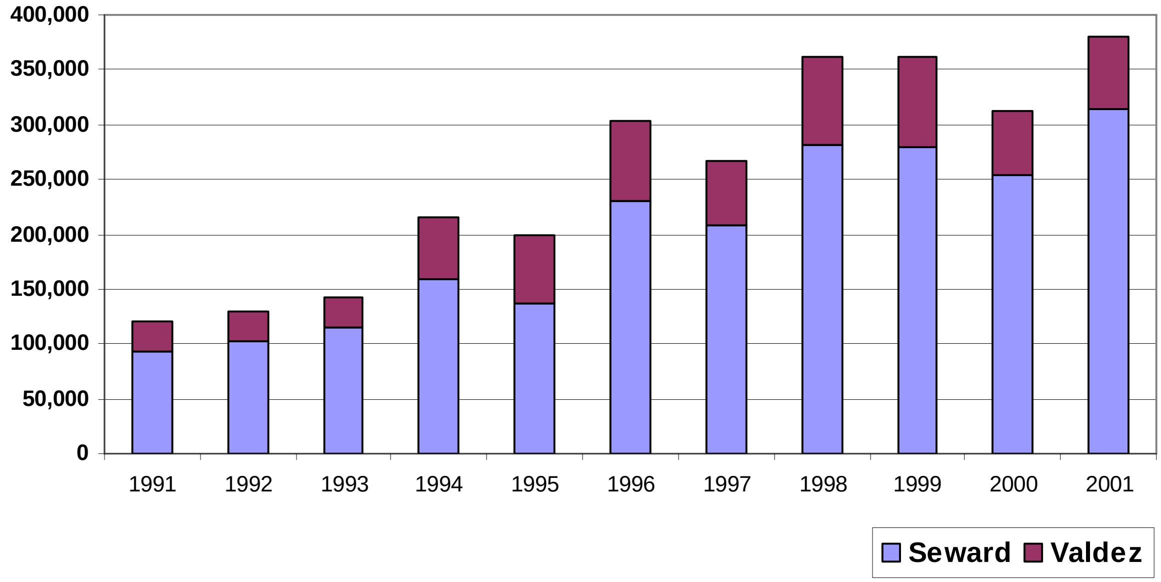

Figure 7.17 Cruise ship visitors to Seward and Valdez 1991 through 2001
Source: Seward Chamber of Commerce and Valdez Convention and Visitors Bureau, 1997-2001. (McDowell Group 1991-1997)

record keeping and reporting of vessel disposal of wastewater, hazardous waste and garbage.

Seward will continue to be the major southcentral Alaska port for cruise ship passengers to embark and disembark. Valdez anticipates a sharp decline in cruise ship passengers in 2002 due to Holland America ending its port calls in that community. The cruise ship visitation in Valdez in 2002 is anticipated to be around twenty-six cruise ships, down from 45 in 2001 (Valdez Convention & Visitors bureau, personal communication).

7.15.2.4 Recreation/Tourism Issues

Sport fishing within the northern GOA has created local environmental damage in some areas by concentrating activity in fragile areas. One area of major concern is the Kenai River, famous for its king and sockeye sport fishing. ADF&G evaluated these impacts along the Kenai River in 1994 (ADF&G 1994) to provide a baseline for future assessments. Sport fishing can also contribute to localized depletion of fish stocks.

Increased hiking and camping on coastal areas and riverbanks can lead to trampling erosion and related impacts on local water quality. The Chugach National Forest is currently completing an analysis of remote recreation carrying capacity in areas around Prince William Sound that may provide information on use impacts and appropriate levels of use. The Alaska Division of Parks completed an analysis of carrying capacity for the Kenai River in 1991 which identified areas of the river where crowding was diminishing user satisfaction for fishing and other recreational experiences (Alaska State Parks 1993).

In October 2001, the North Pacific Fishery Management Council recommended an individual fisheries quota (IFQ) program for commercial charter operators fishing for halibut. Requiring new charter operators to purchase halibut shares to take out sport charters may tend to shift sports fishing effort toward currently non-limited species, such as Pacific cod, ling cod and rockfish, creating localized depletions and potential resource concerns. If commercial halibut charter prices increase as a result of the IFQ program, use of the resource by non-charter private boats may increase in reaction. Impacts on the resource base could be significant.

The growing use of jet skis for recreational use and their potential for disturbing nesting waterfowl has led the Alaska Department of Fish and Game (ADF&G) to ban jet ski use in Kachemak Bay.

Some residents of Prince William Sound communities expressed concern with a potential huge flood of new recreational users to the region as a result of completion of the Whittier tunnel, providing road access to the sound and potential impacts to shorelines, tidelands and nearshore waters, as well as the fish and wildlife populations that rely on these habitats. The tunnel opened on June 7, 2000 and had a total of 88,000 vehicles for the remainder of that year. In 2001, the Whittier tunnel vehicle traffic totaled 85,772 through December 17th (Gordon Burton, personal communication). The initial level of traffic through the Whittier tunnel is much lower than anticipated by the Alaska Department of Transportation and Public Facilities. Local residents speculate that the use tolls imposed after the first year of operation have discouraged users.

Recreation/Tourism Summary

Reasons for monitoring: Immediate impacts of high use levels on habitat as well as localized depletion of fisheries resources. Although recreational users may impact other user groups, areas of conflict are largely unstudied.

Type of impacts: Potential for resource depletion, damage to fragile habitat, disturbance to wildlife on rookeries and haulouts, competition among user groups, water quality degradation from discharges and spills.

Agencies managing for a subsistence priority can create impacts on other user groups using resources within the northern GOA.

Who is monitoring: ADF&G is the primary agency for monitoring sport fishing effort and harvests. The U.S. Forest Service monitors uses within Chugach National Forest. The National Park Service monitors use levels within the Kenai Fjords National Park.

Regulatory Authority: The Alaska Board of Fisheries and Board of Game have regulatory authority over sport fishing and hunting within state lands and waters.

The North Pacific Fishery Management Council has made a recommendation for new regulations dealing with halibut charter vessels.

The U.S. Coast Guard has enforcement authority for vessel operations in marine waters.

7.15.3 Oil and Gas Development

The oil and gas industry is a major economic force in Prince William Sound (PWS) and Cook Inlet. Crude oil from the Alaska North Slope is transported by pipeline to Valdez, where it is loaded onto tankers and shipped to the continental United States, abroad, and to a refinery on Cook Inlet, near Kenai. Whatever their destination, tankers carrying this oil traverse PWS and the GOA on their journey (Fried and Windisch-Cole, 1999).

The number of tanker voyages from the Port of Valdez has declined from 640 in 1995 to 411 in 1999, partly due to a four percent increase in the average load per vessel, but mostly as the result of reduced North Slope production (ADEC 2000).

Annual shipments through PWS peaked at 705 million barrels in 1988 and have declined in every year since. Shipments in 2001 are estimated at 366 million barrels, almost exactly one-half of what they were at the peak. The annual rate of change in shipments has varied from -10 percent in 1998-99, when oil prices were low, to -1 percent last year (2000-01), when prices were high. The state of Alaska's official oil production forecast issued in December 2001 predicts that North Slope production will increase nine percent in 2002, and then remain relatively constant through 2009 (see Figure 7.18). The forecasters acknowledge, however, that unexpected changes in oil prices could shift the trajectory up or down (Alaska Department of Revenue 2001).

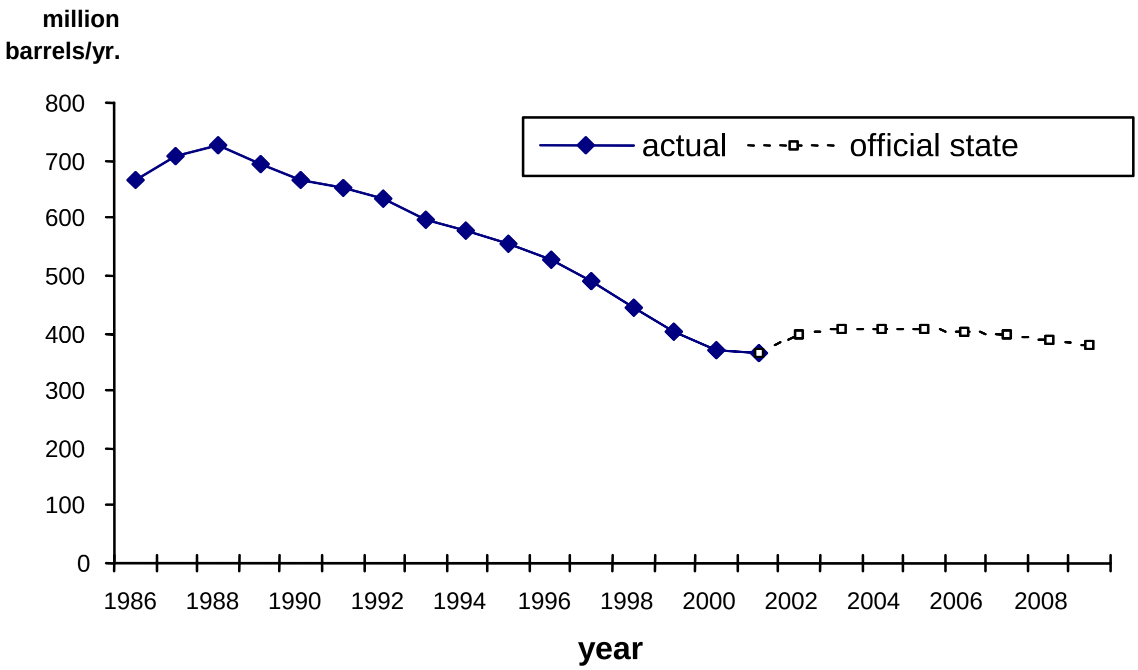

Figure 7.18 PWS oil shipments

Commercialization of North Slope natural gas reserves—estimated at more than 90 trillion cubic feet—could cause PWS tanker traffic to increase. Under one concept, proposed more than 30 years ago and still popular in Alaska, a gas pipeline would be built parallel to the oil line, terminating at a liquefied natural gas (LNG) facility near Valdez. LNG from the plant would be exported in specially built tankships to the Far East, Mexico, or the U.S. West Coast. A similar, but much smaller LNG plant has operated in Cook Inlet since 1966.

A separate gas-to-liquid (GTL) commercialization proposal would transform the gas to methanol liquid or a chemically related product that would be shipped to Valdez in the existing trans-Alaska oil pipeline (Alaska Highway Natural Gas Policy Council 2001).

Three recent studies, sponsored separately by the North Slope gas owners, the state, and an independent energy consulting firm, concluded that the GTL and LNG proposals (including a pipeline project terminating at an LNG plant in northern Cook Inlet) are likely to be less feasible than alternatives in which the gas is shipped by pipeline through Canada to markets in the continental United States (Alaska Highway Natural Gas Policy Council 2001, Purvin & Gertz, Ltd. 2000, Brown 2002). Volumes of gas to be shipped under the various commercialization proposals range up to 2.2 trillion cubic feet per year, equivalent in energy content to roughly 350 million barrels of oil (Purvin & Gertz, Ltd. 2000). In most applications, substitution of gas for oil reduces greenhouse gas emissions by about fifteen percent. No project for commercializing North Slope gas has yet attracted commitments for the $7 billion to $20 billion in investment expected to be required.

Megaprojects do not have an exclusive franchise on potential petroleum developments in the GOA area. The first producing oil wells in Alaska were at Katalla, southeast of Cordova. Small-scale production continued there from 1902, until destruction of the local refinery by fire in 1933. The Chugach Alaska Corporation, owner of much of the Katalla oil and gas acreage, believes that modern technology may make the Katalla oil resource economical to redevelop (Chugach Alaska Corporation 2001).

Modern oil development in Alaska began in 1957 in the Cook Inlet basin, with discovery of oil at the Swanson River field in the Kenai National Wildlife Refuge. In 2001, the basin produced eleven million barrels of oil, about three percent of the volume coming from the North Slope (Alaska Oil and Gas Conservation Commission 2001).

Most of the oil and much of the natural gas produced from the Cook Inlet comes from offshore platforms. Underwater pipelines transport oil and gas to terminals on both sides of Cook Inlet. Much of Cook Inlet oil production is delivered to a local refinery in Nikiski, north of Kenai, for processing.

State forecasters expect oil production from the Cook Inlet basin over the next several years to increase, reaching fifteen million barrels per year in state fiscal year

2003-04. An aggressive state leasing program initiated in 1999, together with planned increases in federal offshore lease offerings, could stimulate additional new production thereafter (Alaska Department of Revenue 2001).

Much of the new exploration in Cook Inlet, however, has been targeted toward natural gas. Cook Inlet gas has provided low cost energy to the Anchorage metropolitan area since 1962, and since the late 1960s has provided energy and feedstock to an LNG plant and a large fertilizer manufacturing facility at Nikiski. The bulk of the region's electricity comes from gas-fired generation.

In recent years Cook Inlet gas sales have ranged close to a quarter trillion cubic feet. The region's utilities and major industrial users believe that additional discoveries or imports from the North Slope will be needed in the next decade to sustain current industrial gas uses and meet the growing demand for utility gas and electric generation (ADNR 2002).

Major concerns about oil and gas development in the northern GOA include the potential for oil spills from vessel traffic, such as the 1987 T/S ***Glacier Bay*** spill in Cook Inlet and the 1989 EVOS. Small chronic spills, pipeline corrosion and subsequent leaks, disposal of drilling wastes and potential impacts on water quality, and the introduction of exotic species from ballast waters are other major concerns. Only six thousand gallons of crude oil were reported spilled in the region from 1998 to 1999 (ADEC 2001).

Oil producers, shippers, and refiners are required to have contingency plans detailing response capabilities and specific response actions in the event of a spill. In addition, the Oil Pollution Act of 1990 authorized regional citizens advisory groups in PWS and Cook Inlet to oversee oil and gas activities. These groups, along with state and federal agencies, maintain oversight of oil industry operations in their respective regions.

Oil and Gas Development Summary

Reasons for monitoring: Increased North Slope development could result in increased tanker traffic and more underwater pipelines. Cook Inlet production is mostly offshore or near the shore and could have impacts on marine system.

Type of impacts: Potential for oil spills from vessel traffic, small chronic spills, pipeline corrosion and subsequent leaks, disposal of drilling wastes, introduction of exotic species in ballast waters.

Who is monitoring: ADEC and the U.S. Coast Guard require oil producers, shippers and refiners to have contingency plans detailing capabilities and planned actions in response to spills. Regional citizens' advisory councils in Prince William Sound and Cook Inlet provide citizen oversight and conduct some monitoring activities.

Regulatory authority: U.S. Coast Guard regulates tanker traffic. U.S. EPA and ADEC are primary agencies regulating activities because of potential impacts on water quality.

7.15.4 Subsistence

Subsistence is an important traditional activity practiced by residents of northern GOA communities to provide food and cultural enrichment. Fifteen predominantly Alaska Native communities in the GEM region, with a total population of about 2,200 people, rely heavily on harvests of subsistence resources such as fish, shellfish, seals, deer, and waterfowl. Subsistence harvests in 1998 varied among communities from 250 to 500 pounds per person, indicating strong dependence on subsistence resources. Subsistence activities also support the culture and traditions of these communities. Many families in other communities also rely on the subsistence resources of the spill area.

In addition to the cultural aspects of subsistence, its economic importance comes from import substitution. Rural residents are able to rely on wild foods rather than food imported into the region. Dependence on subsistence production is typically higher in remote areas and lower near population centers, although there are exceptions to this general trend.

Knowledge of subsistence patterns and consumption largely relies on focused household surveys conducted by the ADF&G's Subsistence Division. The division's analysis and monitoring focuses on subsistence production, consumption, sharing patterns and species of concern. Subsistence studies are typically conducted at irregular intervals, often oriented towards a specific management issues or need, such as the ***Exxon Valdez*** oil spill. The household studies provide a cross-sectional profile of use patterns at a particular time. Due to the focus on oil spill impacts and the availability of funding, several subsistence studies conducted in communities across the oil spill region over the past ten years have provided a wealth of data and information. The declining frequency of subsistence studies suggests that future changes in use patterns within northern GOA communities may not be as well documented.

ADF&G researchers have developed village contacts who provide accurate tracking of subsistence harvests of salmon, seals, sea lions, marine mammals and halibut. It is more difficult for ADF&G to track subsistence harvests of marine invertebrates and marine fish, so there is a much lower level of confidence in the estimated use levels for these species.

In a recent report funded jointly by the Minerals Management Service (MMS) and ADF&G, researchers analyzed subsistence patterns for communities within the area affected by the ***Exxon Valdez*** oil spill (Fall et al. 2001). The communities analyzed were Chenega Bay, Cordova, Tatitlek, Valdez, Kenai, Nanwalek, Port Graham, Seldovia, Akhiok, Karluk, Kodiak City, Larsen Bay, Old Harbor, Ouzinkie, Port Lions, Chignik, Chignik Lagoon, Chignik Lake, Ivanof Bay, and Perryville.

The study tracked wild food harvests measured in pounds per capita before and after the ***Exxon Valdez*** oil spill, producing the following findings:

- Subsistence production averages over 300 pounds per person per year throughout the region. In predominantly Native communities, subsistence production averages 352 pounds annually per person. In Cordova, subsistence production averages 200 pounds per person annually and in Kodiak, it averages 148 pounds per person.
- Subsistence production uses nearly seventeen different types of resources per household.
- The studies show a very high participation rate in subsistence harvests and use, particularly in predominantly Native communities where ninety-nine percent of residents used subsistence resources.
- Subsistence production is often distributed through an extensive network of sharing. In predominantly Native communities, 87.5 percent of households received resources and 78.3 percent of households gave away resources.
- Following the ***Exxon Valdez*** oilspill, there was an immediate decline of over fifty percent in subsistence harvests. Equally important as the decline in production was the reduction in the range of resources used. At first the reduction was due to fear of oil contamination, and later, due to the scarcity of resources.
- The impacts of the oil spill caused a disruption in sharing and teaching of children and a temporary increase in household income associated with spill cleanup activities during the year following the spill.
- In the years from 1990 to the present, there has been a gradual rebound in subsistence production from the EVOS communities. But, communities in Prince William Sound have been slower to rebound than areas outside the sound.
- Since the EVOS, several communities have increased their dependence on fish and reduced their dependence on marine mammals and shellfish.

In addition to ADF&G's Subsistence Division and the Federal Subsistence Board, others monitoring subsistence uses and harvests of certain species include the Alaska Board of Fisheries and the North Pacific Fishery Management Council. The Council recently completed an analysis of impacts relating to subsistence halibut and has recommended new regulations for that species.

The National Marine Fisheries Service (NMFS) follows the status of the beluga whale population and funds operation of the Alaska Beluga Committee. The Committee has attempted to understand beluga whale subsistence harvests through an informal network of contacts. The Cook Inlet Marine Mammal Council, comprised of Cook Inlet beluga whale subsistence hunters, works independently of the Alaska Beluga Committee to focus on beluga whales in Cook Inlet.

The Alaska Native Harbor Seal Commission partners with ADF&G's Division of Subsistence in a harvest assessment project to interview hunters and collect data on the subsistence harvest of seals. This effort is currently funded by the National Marine Fisheries Service. The U.S. Fish & Wildlife Service has a program to monitor the harvests of sea otters. USFWS also monitors waterfowl.

ADF&G's Subsistence Division has been working to coordinate and report on the various monitoring efforts. However, their efforts have been funded through special research funding, such as EVOS. Although another round of surveys is anticipated in 2004, future funding for ADF&G's Subsistence Division to continue coordination of subsistence monitoring as well as periodic household surveys within northern GOA communities is uncertain.

The impact of subsistence harvests on injured resources, particularly marine mammals, has not been determined. In some cases, it may become necessary to address the impact of subsistence on recovery, as was necessary for Cook Inlet beluga whales. ADF&G and NMFS are working cooperatively to combine research efforts on harbor seals. The results of this research program may improve understanding of the status of harbor seals and reasons for population declines within the northern GOA. However, the program will not address the effects of subsistence harvests on this resource.

7.15.4.1 Current and Potential Future Issues, Subsistence

Subsistence activities and production are related to many factors, such as population growth within villages and communities and changes in the abundance and distribution of fish and wildlife resources. The criminal settlement subsistence restoration program, using money from the ***Exxon Valdez*** settlement, has funded thirty-two projects totaling $5.6 million in support of subsistence restoration (Fall et al. 2001). These included fish enhancement projects, development of infrastructure for subsistence activities, cultural education and mariculture. The ***Exxon Valdez*** Trustee Council's Habitat Protection Program has protected over 650,000 acres within the northern GOA through outright purchase of lands or conservation easements. This program ensures that the lands protected will remain part of the productive ecosystem, thus aiding support of the resource base for subsistence production.

Increasing use within Prince William Sound by boaters, fishers, hunters and other recreational users may affect future subsistence opportunities through direct competition or the indirect effects of increased traffic in areas where subsistence harvests occur. In 1995, a consulting firm evaluated the impact of completion of the Whittier tunnel on subsistence uses within six communities: Chenega Bay, Tatitlek, Cordova, Whittier, Hope and Cooper Landing (Stephen R. Braund & Associates 1995).

The study found that subsistence users from the GOA communities identified increased boat traffic within Prince William Sound and the potential increased direct competition for fish and wildlife resources from increased numbers of visitors as their greatest concerns related to the opening of the Whittier tunnel. Although use of the Whittier tunnel has been much lower than forecast, the overall trend in increasing recreation use in the region may create conflicts with subsistence activities.

Recent changes in subsistence regulation and management may affect other user groups, including sport and commercial fishers, hunters and others.

Some future issues may include:

- Definitions of federally-recognized subsistence users could greatly increase the number of subsistence users from outside the GOA region. For example, the Federal Subsistence Board currently plans to allow all recognized subsistence users from anywhere in Alaska to participate in subsistence harvests on the Kenai Peninsula. The Board earlier moved to restrict subsistence salmon fishing within the Copper River watershed to those living in the region.

- The Federal Subsistence Board has received proposals to extend its jurisdiction to include marine waters and species.

- In two decisions in Southeast Alaska, the Federal Subsistence Board has preemptively closed state fisheries in fresh water to make sure that there would be enough fish for subsistence in federal harvest areas. During the 2001 fishing season, the Federal Subsistence Board preemptively closed all the commercial sport, sport and state subsistence fisheries operating within federal waters in both the Kuskokwim and Yukon drainages to ensure that the federal subsistence users would have access to salmon resources.

- In a recent decision, the Federal Subsistence Board increased the limits for subsistence harvests in the Copper River by fish wheels, with no upper limit on king salmon. If the subsistence harvest of king salmon is substantially increased in Copper River fisheries, sport and commercial users could face restrictions.

- The North Pacific Fishery Management Council took final action in April 2002 to define subsistence halibut fishing in Alaska waters. Subsistence management actions include a limit on the number of hooks, a 30-fish annual limit, a system to permit temporary transfer of subsistence rights, and a gear stacking allowance for multiple subsistence fishers on a single vessel.

- The decline of the beluga whale in Cook Inlet provides an example of a resource problem alleged to be caused by subsistence harvests. Under the Marine Mammal Protection Act, state and federal agencies were unable to take any action to address the declining resource until the population reached the point where it could be classified as depleted under the

Endangered Species Act. If the beluga whales fail to recover, many commercial activities within Cook Inlet could face restriction.

Subsistence Summary

Reasons for monitoring: Subsistence uses have not yet recovered and are a priority use under state and federal law.

Type of impacts: Subsistence harvests of recovering species have the potential for causing at least localized depletion of some species.

Agencies managing for a subsistence priority can create impacts on other user groups using resources within the northern GOA.

Who is monitoring: ADF&G is the primary agency for monitoring subsistence uses and harvests.

Regulatory Authority: The U.S. Fish and Wildlife Federal Subsistence Board has regulatory and allocation authority within federal lands in Alaska.

The Alaska Board of Fisheries and Board of Game have regulatory authority over subsistence within state lands and waters.

The North Pacific Fishery Management Council has made a recommendation for new regulations dealing with subsistence halibut.

Federal laws, such as the Marine Mammal Protection Act and the Migratory Bird Treaty Act regulate subsistence uses in both state and federal waters.

7.15.5 Timber and Forest Products

Ancestors of the Alutiiq peoples who occupied most of the GOA area are believed to have migrated into the region from treeless areas to the west and north. In the late 18th century, at the time of the first contacts with Europeans, the Alutiiq made relatively little use of timber resources except for heat (Dumond 1983).

Many small logging and sawmill operations grew up in the 19th century to support local fish processing and mining operations. In the early 20th century, most of the sawlog timber resources of the Prince William Sound area, the Kenai Peninsula and the Kodiak Archipelago came under the control of the U.S. Forest Service. In addition to supporting local fish processing and mining, GOA forests also supplied railroad ties and timber for bridges to the Alaska Railroad and the Copper River & Northwestern Railway.

Throughout most of the 20th century, the timber industry remained small. From 1910 through 1986, total commercial harvests from government land in the GOA region averaged less than four million board feet (MMBF) per year, and never exceeded 12 MMBF per year. As part of a policy to encourage timber-based manufacturing within the national forest and nearby communities, the U.S. Forest

Service largely prohibited the export from Alaska of unprocessed timber (Rogers 1962). Until 1987, there were essentially no forest products exported from the region to anywhere outside Alaska.

That all changed in the 1980s, when regional and village Native corporations, established under the Alaska Native Claims Settlement Act (ANCSA) began receiving lands selected by them in accordance with the act. For the first time in the history of the GOA region, significant timber resources moved under the control of private, profit-seeking corporations. Most of the high-quality timber has since been logged in an effort to monetize the timber assets as rapidly as possible. Annual harvest volumes from the region grew from less than ten MMBF in 1986, to a peak of about 235 MMBF in 1995, and then quickly declined (USDA Forest Service, Chugach National Forest 2000b). Although a major sawmill was opened in Seward in 1993, it never became competitive, and has remained closed since 1994. As allowed under federal law, almost all of the private timber was exported from the state, most being sold abroad as unprocessed logs (Fried and Windisch-Cole, 1999).

Since 1996, a dwindling supply of high-quality timber and a depressed world market for softwood have caused a dramatic decline in harvest from the GOA region. No major timber operations are currently operating in PWS. Some logging continues in the Kodiak Archipelago, and small-scale timber operations are planned for parts of the Kenai Peninsula. Improving market conditions and rising softwood prices could significantly increase the market for significant volumes of currently marginal timber, especially on Afognak Island.

A significant factor affecting forest planning in the GOA area is a major spruce bark beetle infestation. A series of timber sales of beetle-damaged stands on state lands have been proposed (USDA Forest Service and State of Alaska 2000). Harvest from the state's proposed sales would encompass an estimated 115 MMBF over a maximum of five years, but adverse market conditions have caused commercial interest in the offerings to wane, and some recent sales have received no bids. In 2000 the state offered almost 12 MMBF, but the amount cut was less than three MMBF (ADNR 2000).

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

Timber and Forest Products Summary

Reasons for monitoring: Immediate impacts of logging on anadromous fish and riparian habitat. Point source impacts of wood processing facilities on air and water quality. Long-term habitat and water quality degradation from past logging and pollution of uplands and marine sediments.

Type of impacts: Erosion, wide swings in water temperature, loss of habitat, changes in carbon cycle, increased human pressure due to access. Industrial air and water quality impacts from wood processing.

Who is monitoring: USFS on federal land, ADNR on state and private land. ADF&G monitors impacts on economically important sport, commercial and subsistence species. ADEC and EPA monitor effects of bark deposition the on marine environment. EPA and ADEC monitor point source industrial effects on air and water quality.

Regulatory Authority: State and federal laws have established regulatory authority over most aspects of logging and wood processing. Federal laws include the Clean Water Act, the Endangered Species Act, the Wilderness Act, the Federal Land Planning and Management Act, the National Forest Management Act, the Forest and Rangeland Renewable Resources Planning Act and others; state authorities in Alaska Statutes include Title 16 (ADF&G), Title 47 (ADEC), and the Forest Practices Act.

7.15.6 Urbanization and Road Building

Urban areas within the GEM region are likely to continue to grow from natural population growth and from inmigration from smaller communities within Alaska and from outside the state. Increasing urbanization diminishes some basic environmental qualities, even when development is planned and regulated with care. Along with greater numbers and density of residents comes additional air pollution, water pollution, use of lands for solid waste disposal, increased levels of noise, and other effects. Continued expansion of urban areas and increasing density of development of suburban zones inevitably degrade the habitat. Changes in land surfaces can change entire hydrologic systems and cause water pollution problems. Urban growth leads to increasing disposal of human waste. Anchorage, the largest population center in the state, only completes primary treatment for sewage effluent piped into Cook Inlet, although almost all metropolitan communities in the country are required to complete secondary treatment. The City received a 301 Clean Water Act Section (H) waiver to allow primary sewage treatment only, whereas almost all metropolitan communities in the country are required to complete secondary treatment. The inherent turbidity of Cook Inlet water was a significant factor in EPA's grant of the waiver.

Treated waste or street runoff may lead to changes in species composition and productivity of watersheds within the region. A 1998 study of the Kenai River showed a decreased diversity of benthic invertebrates in areas of the river below storm drain outfalls (Litchfield and Milner 1998). What was important in this study was the discovery that even though the benthic invertebrate community was still in place, certain species were missing from the surveyed areas. Based on this study, it appears as if some key indicator species could be used to measure at least some of the effects of storm runoff pollution.

As part of its stormwater discharge permit through ADEC, the Municipality of Anchorage is mapping the impervious surfaces within its area and studying the response of stream macroinvertebrates. Under a U.S. Environmental Protection Agency (EPA) Clean Water Act Section 319 grant from ADEC, the U.S. States Department of Agriculture Cooperative Extension Service is also studying the effects of impervious surfaces. A pilot project is planned for the Anchorage area, and if successful, the methodology may be applied to other areas in the future.

Diminished environmental quality from increased population density is not limited strictly to urban areas. As population density increases in previously rural areas—for example along the Kenai River—there has been a documented loss of environmental quality. In 1994, ADF&G published a study evaluating the cumulative impacts of development and human uses on fish habitat on the Kenai River (Liepitz 1994). Factors diminishing water quality include wetlands loss, point source pollution from outhouses or faulty septic systems, and household spills of oils and other contaminants.

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

The ADEC is responsible for monitoring and regulating state water. However, due to staff and funding limitations, the agency does not attempt to track down and resolve household or small commercial violations. The U.S. Geological Survey operates a National Water Quality Assessment (NAWQA) program tracking water quality and non-point pollution sources in urban watersheds. The goals of the NAWQA Program are to describe current water quality conditions for a large part of the nation's freshwater streams and aquifers; describe how water quality is changing over time; and improve our understanding of the primary natural and human factors affecting water quality (USGS 2001). The Cook Inlet Basin is part of the NAWQA program. The Cook Inlet study will provide increased understanding of water quality in the streams and ground water of the Cook Inlet Basin and identify factors that influence water quality.

Roads are an important factor in habitat damage and water quality degradation. A 2001 study (Western Native Trout Campaign 2001) evaluated the relationship between public roadless lands and existing native trout populations in western states. This report evaluates the diminished status of wild trout and the habitat damage associated with development of road systems. The report concludes that roadless areas are essential to persistence and rebuilding of native salmonid populations.

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

Within the northern GOA, roadbuilding and urbanization are of most concern within the Cook Inlet area. There are no agencies monitoring or evaluating the effects of roads on habitat and water quality within this area.

Urbanization and Road Building Summary

Reasons for monitoring: Direct impacts to fish and wildlife species. Immediate loss of wetlands and water quality.

Type of impacts: Erosion, wide swings in water temperature, erratic water flow and diminished water quality, loss of habitat, changes in carbon cycle, increased human pressure due to access.

Who is monitoring: The Municipality of Anchorage has a wetlands plan but little ongoing involvement. ADF&G and private research groups (such as the Western Native Trout Campaign) study the cumulative effects of roadbuilding and development. The USGS NAWQA program monitors water quality within the Cook Inlet Basin.

Regulatory Authority: ADF&G has Title 16 authority over anadromous fish streams. The ADEC and the U.S. EPA have regulatory authority over water quality. The Army Corps of Engineers has regulatory authority over development on wetlands.

7.15.7 Other Industrial Activity

Large oil spills like the ***Exxon Valdez*** oil spill are rare occurrences. More common are smaller discharges of refined oil products, crude oil and a variety of hazardous substances. These occur frequently in the commercial fishing, petroleum, and timber industries and in a wide variety of commercial establishments such as gas stations and dry cleaners. One of the worst spills near the Kenai River was due to repeated discharges of dry cleaning fluid over many years (ADEC, River Terrace spill 2002).

Under state law, the release of hazardous substances and oil must be reported to the Alaska Department of Environmental Conservation (ADEC). Table 7.18 shows the number of spills by area for the year 2000. In 2000, a total of 604 spills were reported in the GEM region, resulting in a total discharge of 39,744 gallons of refined oil products, crude oil and hazardous substances. Although small spills were reported throughout this region, the largest number of spills (497) and the greatest volume of discharge (24,340 gallons) occurred in Cook Inlet . Most spills (90 percent) involved refined oil products, accounting for about 88 percent of the total volume discharged. Only 3,000 gallons of crude oil were reported spilled in the GEM region during 2000 (ADEC 2002).

Table 7.18 Spills Reported in 2000

	total number of spills	**total gallons spilled**
Cook Inlet:		
hazardous substances	37	5,421
refined oil products	454	18,844
crude oil	6	75
Kodiak:		
hazardous substances	4	161
refined oil products	39	8,767
crude oil	0	0
Prince William Sound:		
hazardous substances	9	53
refined oil products	48	6198
crude oil	7	225

Source: ADEC 2002

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

Other Industrial Activity Summary

Reasons for monitoring: Direct contamination of water quality. Danger of loss of fish and wildlife.

Type of impacts: Erosion, wide swings in water temperature, loss of habitat, changes in carbon cycle, increased human pressure due to access. Industrial air and water quality impacts.

Who is monitoring: The ADEC and U.S. EPA do some limited monitoring.

Regulatory Authority: The ADEC and U.S. EPA have regulatory authority over water quality.

7.15.8 Contaminants and Food Safety

The presence of industrial and agricultural contaminants in aquatic environments has generated worldwide concerns about potential effects on marine organisms and human consumers. The remoteness of the northern GOA from centers of industry and human population does not necessarily offer protection. Industrial and agricultural contaminants can be transported great distances by atmospheric and marine mechanisms, and evidence of persistent organochlorines (DDT), polychlorinated biphenyls (PCBs), dichlorodiphenyldichloroethylene (DDE), other organic pollutants, and heavy metals has been found in the arctic, subarctic, and areas adjacent to the GOA (Crane and Galasso 1999). For example, measurable amounts of organochlorines have been found in precipitation and fishes of the Copper River Delta, a tributary of the GOA that forms the eastern boundary of PWS (Ewald et al. 1998).

In the case of mercury and other metals, such as inorganic arsenic, cadmium, and selenium, low concentrations of the contaminants may be present in the natural environment, with industrial and agricultural sources contributing additional quantities. In many cases there is no known local or regional environmental, industrial or agricultural source of the contaminant.

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

There is also concern about the potential effects of contaminants on people, especially those who consume fish and shellfish, waterfowl, and marine mammals. At higher levels of exposure, many of the chemicals noted above can cause adverse effects in people, such as the suppression of the immune system caused by PCBs.

The state of Alaska does not monitor environmental pollutants in the marine environment or marine organisms on a regular basis, although a small fish-testing program was begun in the summer, 2002. There is no ongoing program for sampling food safety in subsistence resources in coastal communities, although the oil spill provided the opportunity to sample subsistence resources for hydrocarbons in the affected areas from 1989 through 1994. Federal funding for a joint federal-state-Alaska Native initiative has been requested from Congress. The National Oceanic and Atmospheric Administration (NOAA) has annually measured chemicals in mollusks and sediments since 1984, as well as in the livers of bottom-dwelling groundfish and in sediments at the sites of fish capture. The Prince William Sound Regional Citizens' Advisory Council has measured hydrocarbon concentrations and sources within areas of PWS and the GOA. This program focuses on sampling of intertidal mussels and nearby sediments.

Contaminants and Food Safety Summary

Reasons for monitoring: Industrial and agricultural contaminants are concentrated in fish and wildlife species. This can cause mortality in affected fish and wildlife as well as danger to humans consuming contaminated fish and wildlife.

Type of impacts: Persistence within the environment and potentially spreading to fish, wildlife and humans.

Who is monitoring: NOAA monitors chemicals in mollusks, sediments and bottom-dwelling groundfish.

Regulatory Authority: The U.S. EPA has regulatory authority over contaminants in aquatic environments.

7.15.9 Global Warming

Although driven by forces outside the control of Alaska's natural resource managers, global warming is an essential consideration for development and implementation of the GEM program. The earth's climate is predicted to change because human activities, such as the combustion of fossil fuels and increased agriculture, deforestation, landfills, industrial production, and mining, are altering the chemical composition of the atmosphere through the buildup of greenhouse gases. These gases are primarily carbon dioxide, methane, nitrous oxide and chlorofluorocarbons. Their heat-trapping property is undisputed, as is the fact that global temperatures are rising. Observations collected during the last century suggest that the average land surface temperature has risen 0.45° to 0.6° C.

Precipitation has increased by about one percent over the world's continents in the last century, with high-latitude areas tending to see more significant increases in rainfall and rising sea levels. This increase is consistent with observations that indicate the northern GOA sea surface temperature has increased by 0.5° C since 1940, and that precipitation in Alaska (excluding Southeast Alaska) increased eleven percent from 1950 through 1990.

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

A rise in sea level is one of the anticipated changes from global warming, leading to flooding of low-lying property, loss of coastal wetlands, erosion of beaches, saltwater intrusion into fresh water wells and increased costs for maintenance and/or replacement of roads causeways and bridges (USEPA 1998). Among other impacts, an increase in ocean level may have profound impacts on salmon production. The loss of estuarine wetlands from the 1964 earthquake resulted in major losses of pink salmon habitat in Prince William Sound.

Global warming may also have a negative effect on use of water resources throughout Alaska by leading to earlier and more concentrated spring runoff periods. There could be detrimental effects on forests within the northern GOA, for species that are adapted to a cooler temperature regime.

Global Warming Summary

Reasons for monitoring: Danger of losses to fish and wildlife. Salt water intrusion into freshwater supplies.

Type of impacts: Flooding of low-lying property, loss of coastal wetlands, erosion of beaches, salt water intrusion into freshwater wells, increase in public costs for maintenance and replacement of roads and bridges.

Who is monitoring: U.S. EPA .

Regulatory Authority: U.S. EPA has regulatory authority over activities that add to global warming. Many sources are international and not subject to regulation.

7.16 References

ADCED. 2002. Alaska Visitor Statistics Program IV Factsheet.

ADEC. 2000. Strategy document. Alaska's nonpoint source pollution strategy. Juneau, Alaska, Alaska Department of Environmental Conservation.

ADEC. 2001. Spills database. Juneau, Alaska Department of Environmental Conservation.

ADEC, ADNR, ADF&G, and Office of the Governor. 2001. Alaska's clean water actions: protecting our waters. Juneau, Alaska Department of Environmental Conservation.

ADEC, River Terrace spill. 2002.

ADF&G. 1998. Report on the failure of western Alaska salmon runs and the link to ocean and climate changes. Juneau, Alaska, Alaska Department of Fish and Game.

ADF&G. various years. Harvest, catch and participation in Alaska sport fisheries. Fishery data series.

ADNR. 2000. Five-year schedule of timber sales in the Kenai-Kodiak area, FY-01 through FY-05.

ADNR. 2002. Alaska natural gas in-state demand study. Anchorage, Alaska Department of Natural Resources.

Aebischer, N.J., J.C. Coulson, and J.M. Colebrook. 1990. Parallel long-term trends across four marine trophic levels and weather. Nature 347: 753-755.

Ahlnäes, K., T.C. Royer, and T.H. George. 1987. Multipole dipole eddies in the Alaska coastal current detected with Landsat thematic mapper data. Journal of Geophysical Research 92: 13041-13047.

Ainley, D.G. and R.J.E. Broekelheid. 1990. Seabirds of the Farallon Islands. Stanford University Press. Stanford.

Ainley, D.G., W.J. Sydeman, S.A. Hatch, and U.W. Wilson. 1994. Seabird population trends along the west coast of North America: causes and extent of regional concordance. Studies Avian Biology 15: 119-133.

Alaska Department of Labor. 2001. 1999 Alaska employmnet and earnings summary report by census area.

Alaska Department of Revenue. 2001. Juneau, Tax Division, Alaska Department of Revenue.

Alaska Highway Natural Gas Policy Council. 2001. Report to the Governor. Anchorage, Alaska Department of Community and Economic Development.

Alaska Oil and Gas Conservation Commission. 2001. Annual report 2000. Anchorage, Alaska Department of Administration.

Alaska Sea Grant College Program. 1993. Is it food? University of Alaska. Fairbanks.

Alaska State Parks. 1993. The Kenai River carrying capacity study: final report by the Division of Parks and Outdoor Recreation with assistance from the National Parks Service Rivers, Trails and Conservation Assistance Program and Shelby Research Associates.

Allen, M.R., P.A. Stott, J.F.B. Mitchell, R. Schnur, and T.L. Delworth. 2000. Quantifying the uncertainty in forecasts of anthropogenic climate change. Nature 407: 617-620.

Allen, S.E. 1996. Topographically generated, subinertial flows within a finite length canyon. Journal of Physical Oceanography 26: 1608-1632.

Allen, S.E. 2000. On subinertial flow in submarine canyons: effects of geometry. Journal of Geophysical Research 105: 1285-1298.

Alverson, D.L. 1992. A review of commercial fisheries and the Steller sea lion (***Eumetopias jubatus***): the conflict arena. Reviews in Aquatic Sciences 6: 203-256.

Anderson, D.W., F. Gress, K.F. Mais, and P.R. Kelly. 1980. Brown pelicans as anchovy stock indicators and their relationships to commercial fishing. CalCOFI .

Anderson, G.C. and R.E. Munson. 1972. Primary productivity studies using merchant vessels in the North Pacific Ocean. Pages 245-251 in Takenoti, A.Y., editor. Biological oceanography of the northern North Pacific Ocean. Idemitsu Shoten, Tokyo.

Anderson, P.J., J.E. Blackburn, and B.A. Johnson. 1997. Declines of forage species in the Gulf of Alaska, 1972-1995, as an indicator of regime shift. Pages 531-543 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska.

Anderson, P.J. and J.F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series 189: 117-123.

Anthony, J.A. and D.D. Roby. 1997. Variation in lipic content of forage fishes and its effect on energy provisioning rates to seabird nestlings. Pages 725-729 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, Fairbanks, Alaska.

Armstrong, D.A., P.A. Dinnel, J.M. Orensanz, J.L. Armstrong, T.L. McDonald, R.F. Cusimano, R.S. Nemeth, M.L. Landolt, M.L. Skalski, R.F. Lee, and R.J. Huggett. 1995. Status of selected bottom fish and crustacean species in Prince William Sound following the ***Exxon Valdez*** oil spill. Pages 485-547 in Wells, P.G., J.N. Butler, and J.S. Hughes, editors. ***Exxon Valdez*** oil spill: fate and effects in Alaskan waters. American Society for Testing and Materials, Philadelphia.

Bacon, C.E., W.M. Jarman, J.A. Estes, M. Simon, and R.J. Norstrom. 1998. Comparison of organochlorine contaminants among sea otter (***Enhydra***

lutris) populations in California and Alaska. Environmental Toxicology and Chemistry 18: 452-458.

Bailey, E.P. and G.H. Davenport. 1972. Die-off of common murres on the Alaska Peninsula and Unimak Island. Condor 74: 215-219.

Bailey, E.P. and G.W. Kaiser. 1993. Impacts of introduced predators on nesting seabirds in the northeast Pacific. Pages 218-226 in Vermeer, K., K.T. Briggs, K.H. Morgan, and D. Siegel-Causey, editors. The status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service, Ottawa.

Bailey, K.M. 2000. Shifting control of recruitment of walleye pollock ***Theragra chalcogramma*** after a major climatic and ecosystem change. Marine Ecology Progress Series 198: 215-224.

Bailey, K.M., N.A. Bond, and P.J. Stabeno. 1999. Anomalous transport of walleye pollock larvae linked to ocean and atmospheric patterns in May 1996. Fisheries Oceanography 8: 264-273.

Bailey, K.M., A.L. Brown, M.M. Yoklavich, and K.L. Mier. 1996. Interannual variability in growth of larval and juvenile walleye pollock ***Theragra chalcogramma*** in the western Gulf of Alaska, 1983-91. Fisheries Oceanography 6: 137-147.

Bailey, K.M., M.F. Canino, J.M. Napp, S.M. Spring, and A.L. Brown. 1995. Contrasting years of prey levels, feeding conditions and mortality of larval walleye pollock ***Theragra chalcogramma*** in the western Gulf of Alaska. Marine Ecology Progress Series 119: 11-23.

Bailey, K.M., S.A. Macklin, R.K. Reed, R.D. Brodeur, W.J. Ingraham, J.F. Piatt, M. Shima, R.C. Francis, P.J. Anderson, T.C. Royer, A.B. Hollowed, D.A. Somerton, and W.S. Wooster. 1995. ENSO events in the northern Gulf of Alaska, and effects on selected marine fisheries. California Cooperative Oceanic Fisheries Investigations Reports (CalCOFI) 36: 78-96.

Bailey, K.M., Quinn II, T.J., P. Bentzen, and W.S. Grant. 1999. Population structure and dynamics of walleye pollock, ***Theragra chalcogramma***. Advances in Marine Biology 37: 179-255.

Baird, P.A. and P.J. Gould. 1986. The breeding biology and feeding ecology of marine birds in the Gulf of Alaska. Pages 121-503 MMS / NOAA OCSEAP Final Report 45.

Baird, P.H. 1990. Influence of abiotic factors and prey distribution on diet and reproductive success of three seabird species in Alaska. Ornis Scandinavica 21: 224-235.

Bakus, G.J. 1978. Benthic ecology in the Gulf of Alaska. Energy / Environment '78. Society of Petroleum Industry Biologists, Los Angeles, California 169-192.

Ballachey, B.E., J.L. Bodkin, and A.R. DeGange. 1994. An overview of sea otter studies. Pages 47-59 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego.

Banse, K. 1982. Cell volumes, maximal growth rates of unicellular algae and ciliates, and the role of ciliates in the marine pelagial. Limnology and Oceanography 27: 1059-1071.

Barnes, F.F. 1958. Cook Inlet Susitna Lowland. National Park Service, U.S.D.o.t.I. Landscapes of Alaska. Berkeley and Los Angeles, University of California Press.

Barrett-Lennard, L.G., G.M. Ellis, C.O. Matkin, and J.K.B. Ford. in press. A propensity for isolationism: genetic analysis of social segregation within and between sympatric killer whale ecotypes.

Barrett-Lennard, L.G., K. Heise, E. Saulitis, G. Ellis, and C. Matkin. 1995. The impact of killer whale predation on Steller sea lion populations in British Columbia and Alaska. Unpublished Report. Vancouver, North Pacific Universities Marine Mammal Research Consortium.

Baumgartner, A. and E. Reichel. 1975. The world water balance. Elsevier. New York.

Baur, D.C., M.J. Bean, and M.L. Gosliner. 1999. The laws governing marine mammal conservation in the United States. Pages 48-86 in Twiss, J.R. Jr. and R.R. Reeves, editors. Conservation and management of marine mammals. Smithsonian University Press, Washington, D.C.

Beamish, R.J., K.D. Leask, O.A. Ianov, A.A. Balanov, A.M. Orlov, and B. Sinclair. 1999. The ecology, distribution, and abundance of mid-water fishes of the Subarctic Pacific gyres. Progress in Oceanography 43: 399-442.

Beamish, R.J., D.J. Noakes, G.A. McFarlane, L. Klyashtorin, V.V. Ivanov, and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 56: 516-526.

Beissinger, S.R. 1995. Population trends of the marbled murrelet projected from demographic analyses. Pages 385-393 in Ralph, C.J., G.L. Hunt Jr., M.G. Raphael, and J.F. Piatt, editors. Ecology and conservation of the marbled murrelet. Pacific Southwest Research Station, U.S.D.A Forest Service, Berkeley.

Ben-David, M., R.T. Bowyer, L.K. Duffy, D.D. Roby, and D.M. Schell. 1998b. Social behavior and ecosystem processes: river otter latrines and nutrient dynamics of terrestrial vegetation. Ecology 79: 2567-2571.

Ben-David, M., R.W. Flynn, and D.M. Schell. 1997b. Annual and seasonal changes in diets of martens: evidence from stable isotope analysis. Oecologia 280-291.

Ben-David, M., T.A. Hanley, D.R. Klein, and D.M. Schell. 1997a. Seasonal changes in diets of coastal and riverine mink: the role of spawning Pacific salmon. Canadian Journal of Zoology 803-811.

Ben-David, M., T.A. Hanley, and D.M. Schell. 1998a. Fertilization of terrestrial vegetation by spawning Pacific salmon: the role of flooding and predator activity. Oikos 47-55.

Berger, A., J. Imbrie, J. Hays, G. Kukla, and B. Saltzman. 1984. Milankovitch and climate. Reidel. Boston.

Bickham, J.W., T.R. Loughlin, J.K. Wickliffe, and V.N. Burkanov. 1998a. Genetic variation in the mitochondrial DNA of Steller sea lions: haplotype diversity and endemism in the Kuril Islands. Biosphere Conservation 1: 107-117.

Bickham, J.W., J.C. Patton, and T.R. Loughlin. 1996. High variability for control-region sequences in a marine mammal: implications for conservation and biogeography of Steller sea lions (***Eumetopias jubatus***). Journal of Mammalogy 77: 95-108.

Bigg, M.A., G.E. Ellis, J.K.B. Ford, and K.C. Balcomb. 1987. Killer whales: a study of their identification, genealogy, and natural history in British Columbia and Washington State. Phantom Press. Nanaimo.

Bilby, R.E., B.R. Fransen, and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 164-173.

Blackburn, J.E. and P.J. Anderson. 1997. Pacific sand lance growth, seasonal availability, movements, catch variability, and food in the Kodiak - Cook inlet area of Alaska. Pages 409-426 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska, Fairbanks.

Bodkin, J.L., A.M. Burdin, and D.A. Ryzanov. 2000. Age and sex specific mortality and population structure in sea otters. Marine Mammal Science 16: 201-219.

Bodkin, J.L. and R. Jameson. 1991. Patterns of seabird and marine mammal carcass deposition along the central California coast, 1980-1986. Canadian Journal of Zoology 69: 1149-1155.

Bodkin, J.L. and K.W. Kenyon. in press. Sea otters. in Feldham. G.A. and B. Thompson, editors. Wild mammals of North America. Johns Hopkins University Press.

Bodkin, J.L., D. Mulcahy, and C.J. Lensink. 1993. Age specific reproduction in the sea otter (Enhydra lutris); an analysis of reproductive tracts. Canadian Journal of Zoology 71: 1811-1815.

Bodkin, J.L. and M.S. Udevitz. 1994. An intersection model for estimating sea otter mortality along the Kenai Peninsula. Pages 81-95 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego.

Bodkin, J.L. and M.S. Udevitz. 1999. An aerial survey method to estimate sea otter abundance. Pages 13-29 in Garner, G.W., S.C. Amstrup, J.L. Laake, B.F.J. Manly, L.L. McDonald, and D.G. Robertson, editors. Marine mammal survey and assessment methods. Balkema Press, Netherlands.

Boersma, P.D. and M.J. Groom. 1993. Conservation of storm petrels in the North Pacific. Pages 112-121 in Vermeer, K., K.T. Briggs, and D. Siegel-Causey, editors. Status and ecology of temperate North Pacific seabirds. Canadian Wildlife Service, Ottawa.

Bogard, S.J., P.J. Stabeno, and J.D. Schumacher. 1994. A census of mesoscale eddies in Shelikof Strait, Alaska during 1989. Journal of Geophysical Research 99: 18243-18254.

Booth, B.C. 1988. Size classes and major taxonomic groups of phytoplankton at two locations in the Subarctic Pacific Ocean in May and August, 1984. Marine Biology 97: 275-286.

Booth, B.C., J. Lewin, and J.R. Postel. 1993. Temporal variation in the structure of autotrophic and heterotrophic communities in the subarctic Pacific. Progress in Oceanography 32: 57-99.

Bower, A. 1991. A simple kinematic mechanism for mixing fluid parcels across a meandering jet. Journal of Physical Oceanography 21: 173-180.

Boyd, P.W., A.J. Watson, C.S. Law, E.R. Abraham, T. Trull, R. Murdoch, D.C.E. Bakker, A.R. Bowie, K.O. Buesseler, H. Chang, M. Charette, P. Croot, K. Downing, R. Frew, M. Gall, M. Hadfield, J. Hall, M. Harvey, G. Jameson, J. LaRoche, M. Liddicoat, R. Ling, M.T. Maldonado, R.M. McKay, S. Nodder, S. Pickmere, R. Pridmore, S. Rintoul, K. Safi, P. Sutton, R. Strzepek, K. Tanneberger, S. Turner, A. Waite, and J. Zeldis. 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. Nature 407: 695-702.

Braddock, J.F., J.E. Lindstrom, T.R. Yeager, B.T. Rasley, and E.J. Brown. 1996. Patterns of microbial activity in oiled and unoiled sediments in Prince William Sound. American Fisheries Society Symposium 18: 94-108.

Braham, H.W. and M.E. Dahlheim. 1982. Killer whales in Alaska documented in the Platforms of Opportunity Program. Report to the International Whale Commission 32: 643-646.

Breiwick, J.W. 1999. Gray whale abundance estimates, 1967/68-1997/98: ***ROI, RY, and K.*** Page 62 in Rugh, D.J., M.M. Muto, S.E. Moore, and D.P. DeMaster, editors. Status review of the Eastern North Pacific stock of gray whales. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Brodeur, R.D., G.W. Boehlert, E. Casillas, M.B. Eldridge, J.H. Helle, W.T. Peterson, W.R. Heard, S.T. Lindley, and M.H. Schiewe. 2000. A coordinated research plan for estuarine and ocean research on Pacific salmon. Fisheries 25: 7-16.

Brodeur, R.D., B.W. Frost, S.R. Hare, R.C. Francis, and Ingraham Jr., W.J. 1996. Interannual variations in zooplankton biomass in the Gulf of Alaska and covariation with California current zooplankton biomass. California Cooperative Oceanic Fisheries Investigations Reports (CalCOFI) 80-100.

Brodeur, R.D. and D.M. Ware. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fisheries Oceanography 1: 32-38.

Brodeur, R.D. and D.M. Ware. 1995. Interdecadal variability in distribution and catch rates of epipelagic nekton in the Northeast Pacific Ocean. Pages 329-356 in Beamish, R.J., editor. Climate change and northern fish populations. Canadian Special Publication of Fisheries and Aquatic Sciences.

Broecker, W.S. 1982. Glacial to interglacial changes in ocean chemistry. Progress in Oceanography 11: 151-197.

Brower Jr., W.A., R.G. Baldwin, Williams Jr., C.N., J.L. Wise, and L.D. Leslie. 1988. Climate atlas of the outer continental shelf waters and coastal regions of Alaska. Volume I, Gulf of Alaska. Asheville, NC, National Climatic Data Center.

Brown, E. 2000. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Brown, G. 2000. Renewable natural resources management and use without markets. Journal of Economic Literature 38.

Brown, J. 2002. Remarks to the Resource Development Council for Alaska. Alaska Support Industry Alliance and Anchorage Chamber of Commerce, June 28, 2002, Anchorage, Alaska.

Brown Gladden, J.G., M.M. Ferguson, M.K. Freisen, and J.W. Clayton. 1999. Population structure of North American beluga whales (***Delphinapterus leucas***) based on nuclear DNA microsatellite variation and contrasted with the population structure revealed by mitochondrial DNA variation. Molecular Ecology 8: 347-363.

Burger, A.E. and J.F. Piatt. 1990. Flexible time budgets in breeding common murres: buffers against variable prey abundance. Studies Avian Biology 14: 71-83.

Burrell, D.C. 1986. Interaction between silled fjords and coastal regions. Pages 187-220 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Burton, G. 2001. personal communication. Alaska Department of Transportation and Public Facilities.

Byrd, G.V., D.E. Dragoo, and D.B. Irons. 1998. Breeding status and population trends of seabirds in Alaska in 1997. U.S. Fish and Wildlife Service. Homer.

Byrd, G.V., D.E. Dragoo, and D.B. Irons. 1999. Breeding status and population trends of seabirds in Alaska in 1998. Homer, U.S. Fish and Wildlife Service.

Cairns, D.K. 1987. Seabirds as indicators of marine food supplies. Biological Oceanography 5: 261-271.

Calambokidis, J., G.H. Steiger, J.M. Straley, T. Quinn, L.M. Herman, S. Cerchio, R. Salden, M. Yamaguchi, F. Sato, J.R. Urban, J. Jacobson, O. Von Zeigesar, K.C. Balcomb, C.M. Gabriele, M.E. Dahlheim, N. Higashi, S. Uchida, J.K.B. Ford, Y. Miyamura, P. Ladrón de Guevara, S.A. Mizroch, L. Schlender, and K. Rasmussen. 1997. Abundance and population structure of humpback whales in the North Pacific basin. Southwest Fisheries Science Center. LaJolla.

Caley, K.J., M.H. Carr, M.A. Hixon, T.P. Hughes, J.P. Jones, and B.A. Menge. 1996. Recruitment and the local dynamics of open marine populations. Annual Review of Ecology and Systematics 27: 477-500.

Calkins, D. 1986. Marine mammals. Pages 527-558 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Calkins, D.G. 1978. Feeding behavior and major prey species of the sea otter, Enhydra lutris, in Montague Strait, Prince William Sound, Alaska. Fishery Bulletin 76: 125-131.

Calkins, D.G. 1984. Susitna hydroelectric project phase II annual report: big game studies. Vol. IX, belukha whale. Alaska Department of Fish and Game. Anchorage.

Calkins, D.G. 1986. Sea lion investigations in southern Alaska. Page 23 Final report to the National Marine Fisheries Service, Alaska region. Alaska Department of Fish and Game, Anchorage.

Calkins, D.G. 1998. Prey of Steller sea lions in the Bering Sea. Biosphere Conservation 1: 33-44.

Calkins, D.G. and E. Goodwin. 1988. Investigation of the declining sea lion population in the Gulf of Alaska. Unpublished Report. Alaska Department of Fish and Game. Anchorage.

Calkins, D.G. and K.W. Pitcher. 1982. Population assessment, ecology and trophic relationships of Steller sea lions in the Gulf of Alaska. Pages 447-546 in Environmental assessment of the Alaskan continental shelf. U.S. Department of Commerce and U.S. Department of the Interior.

Calvin, N.I. and R.J. Ellis. 1978. Quantitative and qualitative observations on Laminaria digitata and other subtidal kelps of southern Kodiak Island, Alaska. Marine Biology 47: 331-336.

Canino, M.F., K.M. Bailey, and L.S. Incze. 1991. Temporal and geographic differences in feeding and nutritional condition of walleye pollock larvae ***Theragra chalcogramma*** in Shelikof Strait, Gulf of Alaska. Marine Ecology Progress Series 79: 27-35.

Carlson, P.R., T.R. Burns, B.F. Molnia, and W.C. Schwab. 1982. Submarine valleys in the northeast Gulf of Alaska: characteristics and probable origin. Marine Geology 47: 217-242.

Carroll, M.L. and R.C. Highsmith. 1996. Role of catastrophic disturbance in mediating Nucella-Mytilus interactions in the Alaskan rocky intertidal. Marine Ecology Progress Series 138: 125-133.

Carscadden, J. and B.S. Nakashima. 1997. Abundance and changes in distribution, biology and behavior of capelin in response to cooler waters of the 1990s. Pages 457-468 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska, Fairbanks.

Chapman, D.C. 2000. A numerical study of the adjustment of a narrow stratified current over a sloping bottom. Journal of Physical Oceanography 30: 2927-2940.

Chapman, D.C. and S.J. Lentz. 1994. Trapping of a coastal density front by the bottom boundary layer. Journal of Physical Oceanography 24: 1464-1479.

Childers, A. 2000. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Chisholm, S.W. 2000. Stirring times in the Southern Ocean. Nature 407: 685-687.

Chugach Alaska Corporation. 2001.

Chumbley, K., J. Sease, M. Strick, and R. Towell. 1997. Field studies of Steller sea lions (***Eumetopias jubatus***) at Marmot Island, Alaska 1979 through 1994.

Cianelli, L. and R. Brodeur. 1997. Bioenergetics estimation of juvenile pollock food consumption in the Gulf of Alaska. Pages 71-76 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska, Fairbanks.

Clark, W.G., S.R. Hare, A.M. Parma, J. Sullivan, and R.J. Trumble. Decadal changes in growth and recruitment of Pacific halibut (Hippoglossus stenolepis). draft.

Coats, D.A., E. Imamura, A.K. Fukuyama, J.R. Skalski, S. Kimura, and J. Steinbeck. 1999. Monitoring of biological recovery of Prince William Sound intertidal sites impacted by the ***Exxon Valdez*** oil spill: 1997 biological monitoring survey. Seattle, NOAA. NOAA Technical Memorandum NOS OR&R I. NOAA Hazardous Materials Response Division, Seattle, WA.

Connell, J.H. 1972. Community interactions on marine rocky intertidal shores. Annual Review of Ecology and Systematics 3: 169-192.

Cooley, R.A. 1963. Politics and conservation: the decline of the Alaska salmon. Harper & Row. New York.

Cooney, R.T. 1983. Some thoughts on the Alaska Coastal Current as a feeding habitat for juvenile salmon. Pages 256-268 in Pearcy, W.G., editor. The influence of ocean conditions on the production of salmonids in the North Pacific. Sea Grant College Program, Oregon State University.

Cooney, R.T. 1986. The seasonal occurrence of ***Neocalanus cristatus***, ***Neocalanus plumchrus***, and ***Eucalanus bungii*** over the shelf of the northern Gulf of Alaska. Continental Shelf Research 5: 541-553.

Cooney, R.T. 1988. Distribution and ecology of zooplankton in the Gulf of Alaska. Bulletin of the Ocean Research Institute of Tokyo 26: 27-41.

Cooney, R.T. 1989. Acoustic evidence for the vertical partitioning of biomass in the epipelagic zone of the Gulf of Alaska. Deep-Sea Research 36: 1177-1189.

Cooney, R.T. 1993. A theoretical evaluation of the carrying capacity of Prince William Sound, Alaska, for juvenile Pacific salmon. Fisheries Research 18: 77-87.

Cooney, R.T. unpublished. Institute of Marine Science, University of Alaska, Fairbanks, Alaska.

Cooney, R.T., J.R. Allen, M.A. Bishop, D.L. Eslinger, T. Kline, B.L. Norcross, C.P. McRoy, J. Milton, E.V. Patrick, A.J. Paul, D. Salmon, D. Scheel, G.L. Thomas, S.L. Vaughan, and T.M. Willette. 2001. Ecosystem control of pink salmon (***Onchorhynchus gorbuscha***) and Pacific herring (***Clupea pallasi***) populations in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1): 1-13.

Cooney, R.T. and K.O. Coyle. 1982. Trophic implications of cross-shelf copepod distributions in the southeastern Bering Sea. Marine Biology 70: 187-196.

Cooney, R.T., K.O. Coyle, E. Stockmar, and C. Stark. 2001. Seasonality in surface-layer net zooplankton communities in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1): 97-109.

Costa, D.P. 1982. Energy, nitrogen and electrolyte flux and sea-water drinking in the sea otter, Enhydra lutris. Physiological Zoology 55: 34-44.

Coyle, K.O. 1997. Distribution of large calanoid copepods in relation to physical oceanographic conditions and foraging auklets in the western Aleutian islands. University of Alaska,Fairbanks.

Crane, K. and J.L. Galasso. 1999. Arctic environmental atlas. Washington, D.C. U.S. Naval Research Laboratory, Office of Naval Research.

Crawford, W.R. 1984. Energy flux and generation of diurnal shelf waves along Vancouver Island. Journal of Physical Oceanography 14: 1600-1607.

Crawford, W.R., J.Y. Cherniawsky, F.A. Whitney, and M.G.G. Foreman. 1999. Eddies in the Gulf of Alaska and Alaska Stream. EOS, Transactions of the American Geophysical Union 80.

Crawford, W.R. and R.E. Thomson. 1984. Diurnal period shelf waves along Vancouver Island: a comparison of observations with theoretical models. Journal of Physical Oceanography 14: 1629-1646.

Cronin, M.A., J. Bodkin, B. Ballachey, J. Estes, and J.C. Patton. 1996. Mitochondrial-DNA variation among subspecies and populations of sea otters (Enhydra lutris). Journal of Mammalogy 72: 546-557.

Cummins, P.F. and L.-Y. Oey. 2000. Simulation of barotropic and baroclinic tides off northern British Columbia. Journal of Physical Oceanography 27: 762-781.

Dagg, M. 1993. Grazing by the copepod community does not control phytoplankton production in the open subarctic Pacific Ocean. Progress in Oceanography 32: 163-184.

Dagg, M.J. and Walser Jr., E.W. 1987. Ingestion, gut passage, and egestion by the copepod Neocalanus plumchrus in the laboratory and in the Subarctic Pacific Ocean. Limnology and Oceanography 32: 178-188.

Dahlheim, M.E. and C.O. Matkin. 1994. Assessment of injuries to Prince William Sound killer whales. Pages 163-171 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego.

Danielson, S. 2000. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Dayton, P.K. 1971. Competition, disturbance, and community organization: the provision and subsequent utilization of space in a rocky intertidal community. Ecological Monographs 41: 351-389.

Dayton, P.K. 1975. Experimental studies of algal canopy interactions in a sea-otter dominated kelp community at Amchitka Island, Alaska. Fisheries Bulletin U.S. 73: 230-237.

Dayton, P.K., S.F. Thrush, M.T. Agardy, and R.J. Hoffman. 1995. Environmental effects of marine fishing. Aquatic Conservation of Marine and Freshwater Ecosystems 5: 205-232.

Dean, T.A., J.L. Bodkin, S.C. Jewett, D.H. Monson, and D. Jung. 2000. Changes in sea urchins and kelp following a reduction in sea otter density as a result of the ***Exxon Valdez*** oil spill. Marine Ecology Progress Series 199: 281-291.

Dean, T.A., S.C. Jewett, D.R. Laur, and R.O. Smith. 1996b. Injury to epibenthic invertebrates resulting from the ***Exxon Valdez*** oil spill. American Fisheries Society Symposium 18: 424-439.

Dean, T.A., M.S. Stekoll, S.C. Jewett, R.O. Smith, and J.E. Hose. 1998. Eelgrass (Zostera marina L.) in Prince William Sound, Alaska: effects of the ***Exxon Valdez*** oil spill. Marine Pollution Bulletin 36: 201-210.

Dean, T.A., M.S. Stekoll, and R.O. Smith. 1996a. Kelps and oil: the effects of the ***Exxon Valdez*** oil spill on subtidal algae. American Fisheries Society Symposium 18: 412-423.

DeGange, A.R., A.M. Doroff, and D.H. Monson. 1994. Experimental recovery of sea otter carcasses at Kodiak Island, Alaska, following the ***Exxon Valdez*** oil spill. Marine Mammal Science 10: 492-496.

DeGange, A.R. and G.A. Sanger. 1986. Marine birds. Pages 479-526 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Denman, K.L., H.J. Freeland, and D.L. Mackas. 1989. Comparison of time scales for biomass transfer up the marine food web and coastal transport processes. Canadian Special Publication of Fisheries and Aquatic Sciences 108: 255-264.

Denny, M.W. 1988. Biology and mechanics of the wave-swept environment. Princeton University Press. Princeton.

Dethier, M.N. and D.O. Duggins. 1988. Variations in strong interactions in the intertidal zone along a geographic gradient: a Washington-Alaska comparison. Marine Ecology Progress Series 50: 97-105.

Divoky, G.J. 1998. Factors affecting the growth of a black guillemot colony in northern Alaska. University of Alaska. Fairbanks.

Dizon, A.E., S.J. Chivers, and W.F. Perrin. 1997. Molecular genetics of marine mammals. The Society for Marine Mammalogy Spec. Publ. No. 3: 388.

Dodimead, A.J., F. Favorite, and T. Hirano. 1963. Salmon of the North Pacific Ocean. Part II. Review of oceanography of the subarctic Pacific region. International North Pacific Fisheries Commission Bulletin 13: 1-195.

Doroff, A.M. and J.L. Bodkin. 1994. Sea otter foraging behavior and hydrocarbon levels in prey. Pages 193-208 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego.

Doroff, A.M. and A.R. DeGange. 1994. Sea otter, Enhydra lutris, prey composition and foraging success in the northern Kodiak Archipelago. Fishery Bulletin 92: 704-710.

Driskell, W.B., A.K. Fukuyama, J.P. Houghton, D.C. Lees, A.J. Mearns, and G. Shigenaka. 1996. Recovery of Prince William Sound intertidal infauna from ***Exxon Valdez*** oiling and shoreline treatments, 1989 through 1992. American Fisheries Society Symposium 18: 362-378.

Duggins, D.O., C.A. Simenstad, and J.A. Estes. 1989. Magnification of secondary production by kelp detritus in coastal marine ecosystems. Science 245: 170-173.

Dumond, D.E. 1983. Alaska and the northeast coast. in Jennings, J.D., editor. Ancient North Americans. W.H. Freeman and Company, New York.

Ebeling, A.W. and D.R. Laur. 1998. Fish populations in kelp forests without sea otters: effects of severe storm damage and destructive sea urchin grazing. Pages 169-191 in VanBlaricom, G.R. and J.A. Estes, editors. The community ecology of sea otters. Springer Verlag, Berlin.

Ebert, T.A. and D.C. Lees. 1996. Growth and loss of tagged individuals of the predatory snail Nucella lamellosa in areas within the influence of the ***Exxon Valdez*** oil spill in Prince William Sound. American Fisheries Society Symposium 18: 349-361.

Edie, A.G. 1977. Distribution and movements of Steller sea lion cows (***Eumetopias jubata***) on a pupping colony. University of British Columbia,Vancouver.

Egbert, G.D. and R.D. Ray. 2000. Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data. Nature 405: 775-778.

Eggers, D.M., L.R. Peltz, B.G. Bue, and T.M. Willette. 1991. Trends in abundance of hatchery and wild stocks of pink salmon in Cook Inlet, Prince William Sound, and Kodiak, Alaska. ***in*** Proceedings of the international symposium on interactions between wild and enhanced salmon. Nanaimo, British Columbia.

Emery, W.J. and K. Hamilton. 1985. Atmospheric forcing of interannual variability in the northeast Pacific Ocean: connections with El Niño. Journal of Geophysical Research 90: 857-868.

Enfield, D. 1997. Multi-scale climate variabillity: besides ENSO, what else?, in a colloquim on El Niño-Southern Oscillation (ENSO): atmospheric, oceanic, societal, environmental and policy perspectives. July 20-August 1, 1997, Boulder, Colorado.

Erickson, D., E. Pikitich, P. Suuronen, E. Lehtonen, C. Bublitz, C. Klinkert, and C. Mitchell. 1999. Selectivity and mortality of walleye pollock escaping from the codend and intermediate (extension) selection of a pelagic trawl. Final Report. Anchorage.

Erikson, D.E. 1995. Surveys of murre colony attendance in the northern Gulf of Alaska following the ***Exxon Valdez*** oil spill. Pages 780-819 in Wells, P.G., J.N. Butler, and J.S. Hughes, editors. ***Exxon Valdez*** oil spill: fate and effects in Alaskan waters. American Society for Testing and Materials, Philadelphia.

Eslinger, D., R.T. Cooney, C.P. McRoy, A. Ward, T. Kline, E.P. Simpson, J. Wang, and J.P. Allen. 2001. Plankton dynamics: observed and modeled responses to physical factors in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1): 81-96.

Estes, J.A. 1999. Response to Garshelis and Johnson. Science 283: 175.

Estes, J.A., C.E. Bacon, W.M. Jarman, R.J. Norstrom, R.G. Anthony, and A.K. Miles. 1997. Organochlorines in sea otters and bald eagles from the Aleutian Archipelago. Marine Pollution Bulletin 34: 486-490.

Estes, J.A. and J.L. Bodkin. in press. Marine otters. in Perrin, W.F., B. Wursig, H.G.M. Thewissen, and C.R. Crumly, editors. Encyclopedia of marine mammals. Academic Press.

Estes, J.A. and D.O. Duggins. 1995. Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. Ecological Monographs 65: 75-100.

Estes, J.A. and C. Harrold. 1988. Sea otters, sea urchins, and kelp beds: some questions of scale. Pages 116-142 in VanBlaricom, G.R. and J.A. Estes, editors. The community ecology of sea otters. Springer Verlag, Berlin.

Estes, J.A., R.J. Jameson, and E.B. Rhode. 1982. Activity and prey selection in the sea otter: influence of population status on community structure. American Naturalist 120: 242-258.

Estes, J.A. and J.F. Palmisano. 1974. Sea otters: their role in structuring nearshore communities. Science 185: 1058-1060.

Estes, J.A., M.T. Tinker, T.M. Williams, and D.F. Doak. 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282: 473-476.

EVOSTC. 2000. Gulf Ecosystem Monitoring: a sentinel monitoring program for the conservation of the natural resources of the northern Gulf of Alaska, GEM science program NRC review draft. Anchorage, Alaska, ***Exxon Valdez*** Oil Spill Trustee Council.

Fall, J., R. Miraglia, W. Simeone, C.J. Utermohle, and R.J. Wolfe. 2001. Long term consequences of the ***Exxon Valdez*** oil spill for coastal communities of Southcentral Alaska. OCS Study, MMS 2001-032, Technical Report No. 163.

Farmer, D.M. and J.D. Smith. 1980. Generation of lee waves over the sill in Knight Inlet, in fjord oceanography. Pages 259-270 in Freelan, H.J., D.M. Farmer, and C.D. Levings, editors. NATO conference on fjord oceanography, Victoria, B.C., 1979. Plenum Press, New York.

Favorite, F. 1974. Flow into the Bering Sea through Aleutian Island passes. Pages 3-38 in Hood, D.W. and E.J. Kelley, editors. Oceanography of the Bering Sea with emphasis on renewable resources: proceeding of an international symposium. Institute of Marine Science, University of Alaska, Fairbanks.

Favorite, F., A.J. Dodimead, and K. Nasu. 1976. Oceanography of the subarctic Pacific region, 1960-71. International North Pacific Fisheries Commission Bulletin No. 33, 1-187.

Feder, H.M. and A. Blanchard. 1998. The deep benthos of Prince William Sound, Alaska, 16 months after the ***Exxon Valdez*** oil spill. Marine Pollution Bulletin 36: 118-130.

Feder, H.M. and S.C. Jewett. 1986. The subtidal benthos. Pages 347-398 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Feder, H.M. and G.E. Kaiser. 1980. Intertidal biology. in Colonell, J.M., editor. Port Valdez, Alaska: environmental studies 1976-1979. Institute of Marine Sciences, University of Alaska, Fairbanks.

Feder, H.M., A.S. Naidu, and A.J. Paul. 1990. Trace-element and biotic changes following a simulated oil-spill on a mudflat in Port Valdez, Alaska. Marine Pollution Bulletin 21: 131-137.

Feder, H.M. and A.J. Paul. 1974. Age, growth and size-weight relationships of the soft-shell clam, ***Mya arenaria***, in Prince William Sound, Alaska. Pages 45-52 Proceedings national shellfisheries association. University of Alaska, Fairbanks.

Feder, H.M. and A.J. Paul. 1980. Food of the king crab, ***paralithodes camtschatica*** and the dungeness crab, ***cancer magister*** in Cook Inlet, Alaska. Pages 240-246 Proceedings of the national shellfisheries association. University of Alaska, Fairbanks.

Feder, H.M. and A.J. Paul. 1980. Seasonal trends in meiofaunal abundance on two beaches in Port Valdez, Alaska. Syesis 13: 27-36.

Ferrero, R.C., D.P. DeMaster, P.S. Hill, M. Muto, and A.L. Lopez. 2000. Alaska marine mammal stock assessments, 2000. U.S. Department of Commerce. Seattle.

Ferrero, R.C., S.E. Moore, and R.C. Hobbs. in press. Development of beluga, Delphinapterus leucas, capture and satellite tagging protocol in Cook Inlet, Alaska. Marine Fisheries Review, Special Issue.

Finney, B.P. 1998. Long-term variability of Alaska sockeye salmon abundance determined by analysis of sediment cores. North Pacific Anadromous Fish Commission Bulletin 388-395.

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

Flather, R.A. 1988. A numerical investigation of tides and diurnal-period continental shelf waves along Vancouver Island. Journal of Physical Oceanography 18: 115-139.

Ford, J.K.B. 1991. Vocal traditions among resident killer whales (***Orcinus orca***) in coastal waters of British Columbia. Canadian Journal of Zoology 69: 1454-1483.

Ford, J.K.B., G. Ellis, and K.C. Balcomb. 1994. Killer whales: the natural history and genealogy of ***Orcinus orca*** in British Columbia and Washington state. University of British Columbia Press and University of Washington Press. Vancouver and Seattle.

Ford, J.K.B., G.M. Ellis, L.G. Barrett-Lennard, A.B. Morton, and K.C. Balcomb III. 1998. Dietary specialization in two sympatric populations of killer whales (***Orcinus orca***) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76: 1456-1471.

Foreman, M.G.G., W.R. Crawford, J.Y. Cherniawsky, R.F. Henry, and M.R. Tarbotton. 2000. A high-resolution assimilating tidal model for the northeast Pacific Ocean. Journal of Geophysical Research 105: 28629-28651.

Foreman, M.G.G. and R.E. Thomson. 1997. Three-dimensional model simulations of tides and buoyancy currents along the west coast of Vancouver Island. Journal of Physical Oceanography 27: 1300-1325.

Forney, K.A., J. Barlow, M.M. Muto, M. Lowry, J. Baker, G. Cameron, J. Mobley, C. Stinchcomb, and J.V. Caretta. 2000. U. S. Pacific marine mammal stock assessments: 2000. U. S. Department of Commerce.

Foster, M.S. 1990. Organization of macroalgal assemblages in the Northeast Pacific: the assumption of homogeneity and the illusion of generality. Hydrobiologia 192: 21-33.

Foster, M.S. and D.R. Schiel. 1988. Kelp communities and sea otters: keystone species or just another brick in the wall. Pages 92-108 in VanBlaricom, G.R. and J.A. Estes, editors. The community ecology of sea otters. Springer Verlag, Berlin.

Foy, R.J. and A.J. Paul. 1999. Winter feeding and changes in somatic energy content for age 0 Pacific herring in Prince William Sound, Alaska. Transactions of the American Fisheries Society 128: 1193-1200.

Francis, R.C. and S.R. Hare. 1994. Decadal-scale regime shifts in the large marine ecosystems of the north-east Pacific: a case for historical science. Fisheries Oceanography 3: 279-291.

Francis, R.C., S.R. Hare, A.B. Hollowed, and W.S. Wooster. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the northeast Pacific. Fisheries Oceanography 7: 1-21.

Freeland, H.J. and K.L. Denman. 1982. A topographically controlled upwelling center off southern Vancouver Island. Journal of Marine Research 40: 1069-1093.

Freeland, H.J., K.L. Denman, C.S. Wong, F. Whitney, and R. Jacques. 1997. Evidence of change in the winter mixed layer in the northeast Pacific Ocean. Deep-Sea Research 44: 2117-2129.

Freeland, H.J. and D.M. Farmer. 1980. Circulation and energetics of a deep, strongly stratified inlet. Canadian Journal of Aquatic Science 37: 1398-1410.

Fried, N. 2000. The Matanuska-Susitna Borough. Alaska Department of Labor and Workforce Development, Alaska Economic Trends 20.

Fried, N. and B. Windisch-Cole. 1999a. Prince William Sound. Alaska Department of Labor and Workforce Development, Alaska Economic Trends 19.

Fried, N. and B. Windisch-Cole. 1999b. The Kenai Peninsula. Alaska Department of Labor and Workforce Development, Alaska Economic Trends.

Fritz, L.W., R.C. Ferrero, and R.J. Berg. 1995. The threatened status of Steller sea lions, Eumetopias jubatus, under the Endangered Species Act: effects on Alaska groundfish fisheries management. Marine Fisheries Review 57: 14-27.

Frost, B.W. 1983. Interannual variation of zooplankton standing stock in the open Gulf of Alaska. Pages 146-157 in Wooster, W.S., editor. From year to year: interannual variability of the environment and fisheries of the Gulf of Alaska and eastern Bering Sea. Washington Sea Grant Program, University of Washington, Seattle.

Frost, B.W. 1991. The role of grazing in nutrient rich areas of the open sea. Limnology and Oceanography 36: 1616-1630.

Frost, B.W. 1993. A modeling study of processes regulating plankton standing stock and production in the open subarctic Pacific Ocean. Progress in Oceanography 32: 17-56.

Frost, K., L. Lowry, and J. Ver Hoef. unpublished. Alaska Department of Fish and Game and University of Fairbanks School of Fisheries and Ocean Science, Fairbanks, Alaska.

Frost, K.J. and L.F. Lowry. 1986. Sizes of walleye pollock, Theragra chalcogramma, consumed by marine mammmals in the Bering Sea. Fishery Bulletin 84: 192-197.

Frost, K.J. and L.F. Lowry. 1990. Distribution, abundance, and movements of beluga whales, ***Delphinapterus leucas***, in coastal waters of western Alaska. Advances in research on the beluga whale, ***Delphinapterus leucas***. Pages 39-57 in Smith, T.G., D.J. St. Aubin, and J.R. Geraci, editors. Canadian Bulletin of Fisheries and Aquatic Sciences. Canadian Bulletin of Fisheries and Aquatic Sciences, Ottawa.

Frost, K.J. and L.F. Lowry. 1994. Habitat use, behavior, and monitoring of harbor seals in Prince William Sound, Alaska, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 93046). Alaska Department of Fish and Game, Wildlife Conservation Division. Fairbanks.

Frost, K.J., L.F. Lowry, E.H. Sinclair, J. ver Hoef, and D.C. McAllister. 1994. Impacts on distribution, abundance, and productivity of harbor seals. Pages 97-118 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego, California.

Frost, K.J., L.F. Lowry, J. Small, and S.J. Iverson. 1996. Monitoring, habitat use, and trophic interactions of harbor seals in Prince William Sound, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 95064). Alaska Department of Fish and Game, Division of Wildlife Conservation. Fairbanks.

Frost, K.J., L.F. Lowry, and J. Ver Hoef. 1995. Habitat use, behavior, and monitoring of harbor seals in Prince William Sound, Alaska, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 94064 and 94320F). Alaska Department of Fish and Game, Wildlife Conservation Division. Anchorage.

Frost, K.J., L.F. Lowry, and J.M. Ver Hoef. 1998. Monitoring, habitat use and trophic interactions of harbor seals in Prince William Sound. ***Exxon Valdez*** Oil Spill Restoration Office. Anchorage.

Frost, K.J., L.F. Lowry, and J.M. Ver Hoef. 1999. Monitoring the trend of harbor seals in Prince William Sound, Alaska, after the ***Exxon Valdez*** oil spill. Marine Mammal Science 15: 494-506.

Frost, K.J., L.F. Lowry, J.M. Ver Hoef, and S.J. Iverson. 1997. Monitoring, habitat use, and trophic interactions of harbor seals in Prince William Sound, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 96064). Alaska Department of Fish and Game, Division of Wildlife Conservation. Fairbanks.

Frost, K.J., L.F. Lowry, J.M. Ver Hoef, S.J. Iverson, and T. Gotthardt. 1998. Monitoring, habitat use, and trophic interactions of harbor seals in Prince William Sound, Alaska, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 97064). Alaska Department of Fish and Game, Division of Wildlife Conservation. Fairbanks.

Frost, K.J., C.A. Manen, and T.L. Wade. 1994. Petroleum hydrocarbons in tissues of harbor seals from Prince William Sound and the Gulf of Alaska. Pages 331-358 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego.

Frost, K.J., M.A. Simpkins, and L.F. Lowry. 2001. Diving behavior of non-pup harbor seals in Prince William Sound, Alaska. Marine Mammal Science 17

Fukuyama, A.K., G. Shigenaka, and R.Z. Hoff. 2000. Effects of residual Exxon Valdez oil on intertidal Protothaca staminea: mortality, growth, and bioaccumulation of hydrocarbons in transplanted clams. Marine Pollution Bulletin 40: 1042-1050.

Fulton, J.D. 1983. Seasonal and annual variations of net zooplankton at Ocean Station "P", 1956-1980. Canadian Data Report of Fisheries and Aquatic Sciences 374: 65.

Funk, F. 2000. Abundance, biology, and historical trends of Pacific herring, ***Clupea pallasi***, in Alaskan waters. REX workshop: trends in herring populations and trophodynamics. PICES.

Furness, R.W. and D.N.C. Nettleship. 1991. Seabirds as monitors of changing marine environments. Proceedings of the International Ornithological Congress 20: 2237-2280.

Gaines, S.D. and J. Roughgarden. 1987. Fish and offshore kelp forests affect recruitment to intertidal barnacle populations. Science 235: 479-481.

Ganopolski, A. and S. Rahmstorf. 2001. Rapid changes of glacial climate simulated in a coupled climate model. Nature 409: 153-158.

Gargett, A. 1997. Optimal stability window: A mechanism underlying decadal fluctuations in north Pacific salmon stocks. Fisheries Oceanography 109-117.

Garrett, C.J.R. and J.W. Loder. 1981. Dynamical aspects of shallow sea fronts. Philosophical Transactions of the Royal Society of London A302: 563-581.

Garshelis, D.L. 1997. Sea otter mortality estimated from carcasses collected after the ***Exxon Valdez*** oil spill. Conservation Biology 11: 905-916.

Garshelis, D.L., J.A. Garshelis, and A.T. Kimker. 1986. Sea otter time budgets and prey relationships in Alaska. Journal of Wildlife Management 50: 637-647.

Garshelis, D.L., A.M. Johnson, and J.A. Garshelis. 1984. Social organization of sea otters in Prince William Sound, Alaska. Canadian Journal of Zoology 62: 2648-2658.

Gawarkiewicz, G. 1991. Linear stability models of shelfbreak fronts. Journal of Physical Oceanography 21: 471-488.

Gawarkiewicz, G. and D.C. Chapman. 1992. The role of stratification in the formation and maintenance of shelf-break fronts. Journal of Physical Oceanography 22: 753-772.

Gay III, S.M. and S.L. Vaughan. 2001. Seasonal hydrography and tidal currents of bays and fjords in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1): 159-193.

Gentry, R.L. 1971. Social behavior of the Steller sea lion. University of California,Santa Cruz.

Gentry, R.L. and J.H. Johnson. 1981. Predation by sea lions on northern fur seal neonates. 45: 423-430.

Gilfillan, E.S., D.S. Page, E.J. Harner, and P.D. Boehm. 1995a. Shoreline ecology program for Prince William Sound, Alaska, following the ***Exxon Valdez*** oil spill: part 3 - biology. Pages 398-443 in Wells, P.G., J.N. Butler, and J.S. Hughes, editors. ***Exxon Valdez*** oil spill: fate and effects in Alaskan waters. American Society for Testing and Materials, Philadelphia.

Gilfillan, E.S., T.H. Suchanek, P.D. Boehm, E.J. Harner, D.S. Page, and N.A. Sloan. 1996b. Shoreline impacts in the Gulf of Alaska region following the ***Exxon Valdez*** oil spill. Pages 444-487 in Wells, P.G., J.N. Butler, and J.S. Hughes, editors. ***Exxon Valdez*** oil spill: fate and effects in Alaskan waters. American Society for Testing and Materials, Philadelphia.

Gill, V. and S. Hatch. unpublished data. U.S. Geological Survey, Anchorage, Alaska.

Gill, V.A. 1999. Breeding performance of black-legged kittiwakes (***Rissa tridactyla***) in relation to food availability: a controlled feeding experiment. Anchorage, University of Alaska.

Gisiner, R.C. 1985. Male territorial and reproductive behavior in the Steller sea lion, ***Eumetopias jubatus***. University of California,Santa Cruz.

Goldsmith, S. 2001. Economic projections: Alaska and the Southern Railbelt 2000-2025. Prepared by the Institute of Social and Economic Research for Chugach Electric Association.

Goering, J.J., W.E. Shiels, and C.J. Patton. 1973. Primary production. Pages 253-279 in Hood, D.W., W.E. Shiels, and E.J. Kelley, editors. Evironmental studies of Port Valdez. Institute of Marine Science, University of Alaska, Fairbanks.

Goldsmith, S. and S. Martin. 2001. ANILCA and the Seward economy for the Alaska State Office, National Audubon Society. Anchorage, Institute of Social and Economic Research, University of Alaska.

Groot, C. and L. Margolis. 1991. Pacific salmon life histories. University of British Columbia Press. Vancouver.

Haldorson, L. 2001. personal communication. Fisheries Division, School of Fisheries and Ocean Sciences, University of Alaska, Juneau, Alaska.

Hampton, M.A., P.R. Carlson, and H.J. Lee. 1986. Geomorphology, sediment and sedimentary processes. Pages 93-143 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Hansen, D.J. and J.D. Hubbard. 1999. Distribution of Cook Inlet beluga whales (***Delphinapterus leucas***) in winter. U.S.Department of the Interior, Minerals Management Service. Anchorage.

Hare, S.R. and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47: 103-146.

Hare, S.R., N.J. Mantua, and R.C. Francis. 1999. Inverse production regimes: Alaska and west coast Pacific salmon. Fisheries 24: 6-14.

Hart, J.L. 1973. Pacific fishes of Canada. Bulletin of the Fisheries Research Board of Canada 180: 740.

Hatch, S. 2001. personal communication. U.S. Geological Survery, Anchorage, Alaska.

Hatch, S. unpublished data. U.S. Geological Survery, Anchorage, Alaska.

Hatch, S. and V. Gill. unpublished data. U.S. Geological Survey, Anchorage, Alaska.

Hatch, S.A. 1984. Nestling diet and feeding rates of rhinoceros auklets in Alaska. Pages 106-115 in Nettleship, D.N., G.A. Sanger, and P.F. Springer, editors. Marine birds: their feeding ecology and commercial fisheries relationships. Canadian Wildlife Service, Ottawa.

Hatch, S.A. 1993. Ecology and population status of northern fulmars (***Fulmarus glacialis***) of the North Pacific. Pages 82-92 in Vermeer, K., K.T. Briggs, K.H. Morgan, and D. Siegel-Causey, editors. Status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service, Ottawa.

Hatch, S.A., G.V. Byrd, D.B. Irons, and G.L. Hunt. 1993. Status and ecology of kittiwakes (***Rissa tridactyla*** and ***R. brevirostris***) in the North Pacific. Pages 140-153 in Vermeer, K., K.T. Briggs, K.H. Morgan, and D. Siegel-Causey, editors. The status, ecology and conservation of marine birds of the North Pacific. Canadian Wildlife Service, Special Publication, Ottawa.

Hatch, S.A. and M.A. Hatch. 1983. Populations and habitat use of marine birds in the Semidi Islands. Murrelet 64: 39-46.

Hatch, S.A. and M.A. Hatch. 1989. Attendance patterns of murres at breeding sites: implications for monitoring. Journal of Wildlife Management 53: 483-493.

Hatch, S.A. and G.A. Sanger. 1992. Puffins as samplers of juvenile pollock and other forage fish in the Gulf of Alaska. Marine Ecology Progress Series 80: 1-14.

Hay, D.E., J. Boutillier, M. Joyce, and G. Langford. 1997. The eulachon (***Thaleichthys pacificus***) as an indicator species in the North Pacific. Pages 509-530 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska, Fairbanks.

Hayes, D.L. and K.J. Kuletz. 1997. Decline of pigeon guillemot populations in Prince William Sound, Alaska, and apparent changes in distribution and abundance of their prey. Pages 699-702 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, Fairbanks.

Hays, J.D., J. Imbrie, and N.J. Skackleton. 1976. Variations in the Earth's orbit: pacemaker of the ice ages. Science 194: 1121-1132.

Hazard, K. 1988. Beluga whale, ***Delphinapterus leucas***. Pages 195-235 in Lentfer, J.W., editor. Selected marine mammals of Alaska: species accounts with research and management recommendations. U.S. Marine Mammal Commission, Washington, D.C.

Heggie, D.T. and D.C. Burrell. 1981. Deepwater renewals and oxygen consumption in an Alaskan fjord. Estuarine, Coastal and Shelf Science 13: 83-99.

Heinrich, A.K. 1962. The life history of plankton animals and seasonal cycles of plankton communities in the oceans. Journal du Conseil Conseil International pour l'Exploration de la Mer 27: 15-24.

Heyning, J.E. and M.E. Dahlheim. 1988. ***Orcinus orca***. Mammalian Species 304: 1-9.

Hickey, B.M. 1997. The response of a steep-sided narrow canyon to strong wind forcing. Journal of Physical Oceanography 27: 697-726.

Highsmith, R.C., T.L. Rucker, M.S. Stekoll, S.M. Saupe, M.R. Lindeberg, R.N. Jenne, and W.P. Erickson. 1996. Impact of the ***Exxon Valdez*** oil spill on intertidal biota. American Fisheries Society Symposium 18: 212-237.

Highsmith, R.C., M.S. Stekoll, W.E. Barber, L. Deysher, L. McDonald, D. Strickland, and W.P. Erickson. 1994. Comprehensive assessment of coastal habitat, ***Exxon Valdez*** oil spill state/federal natural resource damage assessment final report (Coastal Habitat Study Number 1A). Fairbanks, School of Fisheries and Ocean Sciences, University of Alaska. Coastal Habitat Study Number 1A.

Hilborn, R. 1992. Hatcheries as future of salmon in Northwest. Fisheries. 17:5

Hobbs, R. 2000. personal communication. National Marine Fisheries Service, National Marine Mammal Laboratory, Seattle, Washington.

Hobbs, R.C., D.J. Rugh, and D.P. DeMaster. in press. Abundance of beluga whales in Cook Inlet, Alaska, 1994-1998. Marine Fisheries Review.

Hoelzel, A.R., M.E. Dahlheim, and S.J. Stern. 1998. Low genetic variation among killer whales (Orcinus orca) in the Eastern Northern Pacific, and genetic differentiation between foraging specialists. Journal of Heredity 89.

Hollowed, A.B. and W.S. Wooster. 1992. Variability of winter ocean conditions and strong year classes of northeast Pacific groundfish. Pages 433-444 ICES marine science symposium.

Hollowed, A.B. and W.S. Wooster. 1995. Decadal-scale variations in the eastern subarctic Pacific: II. Response of northeast Pacific fish stocks. Pages 373-385 in Beamish, R.J., editor. Climate change and northern fish populations. National Research Council of Canada, Ottawa.

Hood, D.W. and S.T. Zimmerman. 1986. The Gulf of Alaska, physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Washington, D.C.

Hoover-Miller, A., K.R. Parker, and J.J. Burns. 2000. A reassessment of the impact of the ***Exxon Valdez*** oil spill on harbor seals (***Phoca vitulina richardsi***) in Prince William Sound, Alaska. Marine Mammal Science 17: 111-135.

Hoover-Miller, A.A. 1994. Harbor seal (Phoca vitulina) biology and management in Alaska. Washington, D.C.

Hostettler, F.D., R.J. Rosenbauer, and K.A. Kvenholden. 2000. Reply: response to comment by Bence et al. Organic Geochemistry 31: 939-943.

Houghton, J.P., A.K. Fukuyama, D.C. Lees, Teas III, H., H.L. Cumberland, P.M. Harper, T.A. Ebert, and W.B. Driskell. 1993. Evaluation of the 1991 condition of Prince William Sound shorelines following the ***Exxon Valdez*** oil spill and subsequent shoreline treatment: Volume II, 1991 biological monitoring survey. Seattle, NOAA, Hazardous Materials Response and Assessment Division.

Houghton, J.P., D.C. Lees, W.B. Driskell, and S.C. Lindstrom. 1996a. Evaluation of the condition of Prince William Sound shorelines following the Exxon Valdez oil spill and subsequent shoreline treatment: Volume I, 1994 biological monitoring survey. Seattle, NOAA, Hazardous Materials Response and Assessment Division. NOAA Technical Memorandum NOS ORCA 91.

Houghton, J.P., D.C. Lees, W.B. Driskell, S.C. Lindstrom, and A.J. Mearns. 1996b. Recovery of Prince William Sound epibiota from Exxon Valdez oiling and shoreline treatments, 1989 through 1992. American Fisheries Society Symposium 18: 379-411.

Houghton, R.W., Olson, and Celone. 1986. Observation of an anticyclonic eddy near the continental shelf break south of New England. Journal of Physical Oceanography 16: 60-71.

Hunt Jr., G.L., C.L. Baduini, R.D. Brodeur, K.O. Coyle, N.B. Kachel, J.M. Napp, S.A. Salo, J.D. Schumacher, P.J. Stabeno, D.A. Stockwell, T. Whitledge, and S. Zeeman. 1999. The Bering Sea in 1998: a second consecutive year of weather forced anomalies. EOS, Transactions of the American Geophysical Union 89: 561-566.

Hunt Jr., G.L., B. Burgesson, and G.A. Sanger. 1981. Feeding ecology of seabirds of the eastern Bering Sea. Pages 629-648 in Hood, D.W. and J.A. Calder, editors. The eastern Bering Sea shelf: oceanography and resources. National Oceanic and Atmospheric Administration, Juneau.

Incze, L.S., A.W. Kendall, Schumacher Jr., J.D., and R.K. Reed. 1989. Interactions of a mesoscale patch of larval fish (***Theragra chalcogramma***) with the Alaska Coastal Current. Continental Shelf Research 9: 269-284.

Incze, L.S., D.W. Siefert, and J.M. Napp. 1997. Mesozooplankton of Shelikof Strait, Alaska: abundance and community composition. Continental Shelf Research 17: 287-305.

Irons, D. unpublished data. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Irons, D.B. 1992. Aspects of foraging behavior and reproductive biology of the black-legged kittiwake. University of California,Irvine.

Irons, D.B. 1996. Size and productivity of black-legged kittiwake colonies in Prince William Sound before and after the ***Exxon Valdez*** oil spill. Pages 738-747 in Rice, S.D., R.B. Spies, D.A. Wolf, and B.A. Wright, editors. Proceedings of the ***Exxon Valdez*** oil spill symposium.

Irons, D.B., S.J. Kendall, W.P. Erickson, L.L. McDonald, and B.K. Lance. 2000. Nine years of ***Exxon Valdez*** oil spill: effects on marine birds in Prince William Sound, Alaska. The Condor 102: 723-737.

Iverson, S.J., K.J. Frost, and L.F. Lowry. 1997. Fatty acids signatures reveal fine scale structure of foraging distribution of harbor seals and their prey in Prince William Sound, Alaska. Marine Ecology Progress Series 151: 255-271.

Jackson, J.B., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629-638.

Jacob, K.H. 1986. Seismicity, tectonics, and geohazards of the Gulf of Alaska regions. Pages 145-186 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska

Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Jameson, R.J. 1989. Movements, home ranges, and territories of male sea otters off central California. Marine Mammal Science 5: 159-172.

Jameson, R.J. and A.M. Johnson. 1993. Reproductive characteristics of female sea otters. Marine Mammal Science 9: 156-167.

Jewett, S.C., T.A. Dean, R.O. Smith, and A. Blanchard. 1999. ***Exxon Valdez*** oil spill: impacts and recovery in the soft-bottom benthic community in and adjacent to eelgrass beds. Marine Ecology Progress Series 185: 59-83.

Jewett, S.C. and H.M. Feder. 1982. Food and feeding habits of the king crab ***Paralithodes camtschatica*** near Kodiak Island, Alaska. Marine Biology 66: 243-250.

Jewett, S.C. and H.M. Feder. 1983. Food of the tanner crab Chionoecetes bairdi near Kodiak Island, Alaska. Journal of Crustacean Biology 3: 196-207.

Johnson, W.R., T.C. Royer, and J.L. Luick. 1988. On the seasonal variability of the Alaska Coastal Current. Journal of Geophysical Research 12423-12437.

Jones, M.L., S.L. Swartz, and S. Leatherwood. 1984. The gray whale ***Eschrichius robustus***. Academic Press. London.

Joyce, T., Bishop, and Brown. 1992. Observations of offshore shelf water transport induced by a warm core ring. Deep-Sea Research 39: 97-113.

Kajimura, H. and T.R. Loughlin. 1988. Marine mammals in the oceanic food web of the eastern subarctic Pacific. Bulletin of the Ocean Research Institute of Tokyo 26: 187-223.

Kannan, K., K.S. Guruge, N.J. Thomas, S. Tanabe, and J.P. Giesy. 1998. Butyltin residues in southern sea otters (Enhydra lutris nereis) found dead along California coastal waters. Environmental Science and Technology 32: 1169-1175.

Kastelein, R.A., N. Vaughan, and P.R. Wiepkema. 1990. The food consumption of Steller sea lions (***Eumetopias jubatus***). Aquatic Mammals 15: 137-144.

Kawamura, A. 1988. Characteristics of the zooplankton biomass distribution in the standard Norpac net catches in the North Pacific region. Bulletin of Plankton Society of Japan 35: 175-177.

Kenai Fjords National Park. 1990. Visitor services project, report no. 30.

Kendall, A.W., R.I. Perry, and S. Kim. 1996. Fisheries oceanography of walleye pollock in Shelikof Strait, Alaska. Fisheries Oceanography 5: 203.

Kenyon, K.W. 1969. The sea otter in the eastern Pacific Ocean. North American Fauna 68: 352.

Kenyon, K.W. 1982. Sea otter, Enhydra lutris. Pages 704-410 in Chapman, J.A. and G.A. Feldhamer, editors. Wild mammals of North America. The Johns Hopkins University Press, Baltimore.

Kenyon, K.W. and D.W. Rice. 1961. Abundance and distribution of the Steller sea lion. Journal of Mammalogy 42: 223-234.

Kirsch, J., G.L. Thomas, and R.T. Cooney. 2000. Acoustic estimates of zooplankton distributions in Prince William Sound, spring, 1996. Fisheries Research 47: 245-260.

Kitaysky, A.S., J.C. Wingfield, and J.F. Piatt. 1999. Dynamics of food availability, body condition and physiological stress response in breeding kittiwakes. Functional Ecology 13: 577-584.

Klein, W.H. 1957. Principal tracks and mean frequencies of cyclones and anti-cyclones in the northern hemisphere. Washington, D.C., U.S. Weather Bureau, U.S. Government Printing Office. Research Paper Number 40.

Klinck, J.M. 1996. Circulation near submarine canyons: a modeling study. Journal of Geophysical Research 101: 1211-1223.

Kline Jr., T.C. 1999a. Temporal and spatial variability of ^{13}C/^{12}C and ^{15}N/^{14}N in pelagic biota of Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 56 (Suppl. 1): 94-117.

Kline, T.C., J.J. Goering, O.A. Mathisen, P.H. Poe, and P.L. Parker. 1990. Recycling of elements transported upstream by runs of Pacific salmon: I. • ^{15}N and • ^{13}C evidience in Sashin Creek, Southeastern, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 47: 136-144.

Kline, T.C., J.J. Goering, O.A. Mathisen, P.H. Poe, P.L. Parker, and R.S. Scalan. 1993. Recycling of elements transported upstream by runs of Pacific salmon: II. • ^{15}N and • ^{13}C evidence in the Kvichak River watershed, Bristol Bay, Southwestern, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 50: 2350-2365.

Klinkhart, E.G. 1966. The beluga whale in Alaska. Alaska Department of Fish and Game. Federal Aid in Wildlife Restoration Project Report Volume VII.

Klosiewski, S.P. and K.K. Laing. 1994. Marine bird populations of Prince William Sound, Alaska, before and after the ***Exxon Valdez*** oil spill. Anchorage, U.S. Fish and Wildlife Service.

Koblinsky, C.J., P.P. Niiler, and Schmitz Jr., W.J. 1989. Observations of wind-forced deep ocean currents in the North Pacific. Journal of Geophysical Research 94: 10773-10790.

Kron, T. 1993. Prince William Sound enhancement programs and considerations relative to wild stocks. Alaska Department of Fish and Game.

Kruse, G.H., F.C. Funk, H.J. Geiger, K.R. Mabry, H.M. Savikko, and S.M. Siddeek. 2000. Overview of state-managed marine fisheries in the Central and Western Gulf of Alaska, Aleutian Islands, and Southeastern Bering Sea, with reference to Steller Sea Lions. Juneau, Alaska Department of Fish and Game. Regional Information Report 5J00-10.

Kuletz, K.J., D.B. Irons, B.A. Agler, and J.F. Piatt. 1997. Long-term changes in diets of populations of piscivorus birds and mammals in Prince William Sound, Alaska. Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Fairbanks, Alaska Sea Grant College Program, University of Alaska Fairbanks.

Kvitek, R.G., C.E. Bowlby, and M. Staedler. 1993. Diet and foraging behavior of sea otters in southeast Alaska. Marine Mammal Science 9: 168-181.

Kvitek, R.G. and J.S. Oliver. 1988. Sea otter foraging habits and effects on prey populations and communities in soft-bottom environments. Pages 22-47 in VanBlaricom, G.R. and J.A. Estes, editors. The community ecology of sea otters. Springer Verlag, Berlin.

Kvitek, R.G. and J.S. Oliver. 1992. Influence of sea otters on soft-bottom prey communities in Southeast Alaska. Marine Ecology Progress Series 82: 103-113.

Kvitek, R.G., J.S. Oliver, A.R. DeGange, and B.S. Anderson. 1992. Changes in Alaskan soft-bottom prey communities along a gradient in sea otter predation. Ecology 73: 413-428.

Lagerloef, G. 1983. Topographically controlled flow around a deep trough transecting the shelf off Kodiak Island, Alaska. Journal of Physical Oceanography 13: 139-146.

Laidre, K., K.E.W. Shelden, B.A. Mahoney, and D.J. Rugh. in press. Distribution of beluga whales and survey effort in the Gulf of Alaska. Marine Fisheries Review.

Lambeck, K. 1980. The Earth's variable rotation: geophysical causes and consequences. Cambridge University Press. London.

Larkin, G.A. and P.A. Slaney. 1997. Implications of trends in marine-derived nutrient influx to south coastal British Columbia salmonid production. Fisheries 16-24.

Lawrence, J.M. 1975. On the relationship between marine plants and sea urchins. Oceanography and Marine Biology Annual Review 13: 213-286.

Leatherwood, S., C.O. Matkin, J.D. Hall, and G.M. Ellis. 1990. Killer whales, ***Ornicus orca***, photo-identified in Prince William Sound, Alaska 1976-1987. Canadian Field-Naturalist 104: 32-371.

LeBrasseur, R.J. 1965. Biomass atlas of net-zooplankton in the Northeastern Pacific Ocean, 1956-1964. Manuscript Report Series (Oceanography and Limnological) .

Leigh, Jr.E.G., R.T. Paine, J.F. Quinn, and T.H. Suchanek. 1987. Wave energy and intertidal productivity. Proceedings of the National Academy of Sciences USA 84: 1314-1318.

Lensink, C. 1964. Distribution and status of sea otters in Alaska. Purdue University,West Lafayette, Indiana.

Lensink, C.J. 1962. The history and status of sea otters in Alaska. Purdue University,Indiana.

Lentfer, J. 1988. Selected marine mammals of Alaska. Washington, D.C.

Lethcoe, J. and Lethcoe, N. 1985. Cruising guide to Prince William Sound, Alaska. Volume II: eastern part Prince William Sound.

Lewis, J.P. 1996. Harbor seal investigations in Alaska. Juneau, National Marine Fisheries Service. Annual Report Award Number NA57FX0367.

Liepitz, G.S. 1994. An assessment of the cumulative impacts of development and human uses on fish habitat on the Kenai River. Alaska Department of Fish and Game. Technical Report No. 94-6.

Lindberg, D.R., J.A. Estes, and K.I. Warheit. 1998. Human influences on trophic cascades along rocky shores. Ecological Applications 8: 880-890.

Lindeman, R.L. 1942. The trophodynamic aspect of ecology. Ecology 23: 399-418.

Litchfield, V. and A. Milner. 1998. Kenai River bioassessment: effects of storm drain outfall on the benthic invertebrate community. Alaska Department of Fish and Game. Report No. 2A98-26.

Livingstone, D. and T.C. Royer. 1980. Observed surface winds at Middleton Island, Gulf of Alaska and their influence on ocean circulation. Journal of Physical Oceanography 10: 753-764.

Loeb, V., V. Siegel, O. Holm-Hansen, R. Hewitt, W. Fraser, W. Trivelpiece, and S. Trivelpiece. 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. Nature 387: 897-900.

Longhurst, A.L. 1976. Vertical migration. Pages 116-137 in Cushing, D.H. and J.J. Walsh, editors. The ecology of the seas. W. B. Sanders Co., Philadelphia.

Loughlin, T.R. 1981. Home range and territoriality of sea otters near Monterey, California. Journal of Wildlife Management 44: 576-582.

Loughlin, T.R. 1997. Using the phylogeographic method to identify Steller sea lion stocks. Pages 159-171 in Dizon, A.E., S.J. Chivers, and W.F. Perrin, editors. Molecular genetics of marine mammals. Society for Marine Mammalogy Special Publication 3.

Loughlin, T.R. 1998. The Steller sea lion: a declining species. Biosphere Conservation 1: 91-98.

Loughlin, T.R., A.S. Perlov, and V.A. Vladimirov. 1992. Range-wide survey and estimation of total number of Steller sea lions in 1989. Marine Mammal Science 8: 220-239.

Loughlin, T.R., D.J. Rugh, and C.H. Fiscus. 1984. Northern sea lion distribution and abundance: 1956-80. Journal of Wildlife Management 48: 729-740.

Lowry, L. and K. Frost. unpublished. Alaska Department of Fish and Game and University of Alaska School of Fisheries and Ocean Science, Fairbanks, Alaska.

Lowry, L. and K. Frost. unpublished data. Alaska Department of Fish and Game and University of Alaska School of Fisheries and Ocean Science, Fairbanks, Alaska.

Lowry, L.F. and K.J. Frost. unpublished. Alaska Beluga Whale Committee surveys of beluga whales in Bristol Bay, Alaska, 1993-1994. Paper SC/51/SM__ presented to the IWC Scientific Committee, May, 1999.

Lowry, L.F., K.J. Frost, R. Davis, R.S. Suydam, and D.P. DeMaster. 1994. Movements and behavior of satellite-tagged spotted seals (Phoca largha) in the Bering and Chukchi Seas. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Lowry, L.F., K.J. Frost, and T.R. Loughlin. 1989. Importance of walleye pollock in the diets of marine mammals in the Gulf of Alaska and Bering Sea, and implications for fishery management. Pages 701-726 in Proceedings of the international symposium on the biology and management of walleye pollock, November 14-16, 1988 Anchorage, Alaska. University of Alaska Sea Grant Program, Fairbanks.

Lowry, L.F., K.J. Frost, J.M. Ver Hoef, and R.A. DeLong. 2001. Movements of satellite-tagged non-pup harbor seals in Prince William Sound, Alaska. Marine Mammal Science 17

Lubchenco, J. and S.D. Gaines. 1981. A unified approach to marine plant-herbivore interactions. I. Populations and communities. Annual Review of Ecology and Systematics 12: 405-437.

Luick, J.L., T.C. Royer, and W.P. Johnson . 1987. Coastal atmospheric forcing in the northern Gulf of Alaska. Journal of Geophysical Research 92: 3841-3848.

Lynch-Stieglitz, J., W.B. Curry, and N. Slowey. 1999. Weaker gulf stream in the Florida Straits during the last glacial maximum. Nature 402: 644-648.

Lynde, M.V. 1986. The historical annotated landing (HAL) database: documentation of annual harvest of groundfish from the northeast Pacific and eastern Bering Sea from 1956-1980.

Mackas, D.L. and B.W. Frost. 1993. Distributions and seasonal/interannual variations in the phytoplankton and zooplankton biomass. PICES Scientific Report 1: 51-56.

Mackas, D.L., R. Goldblatt, and A.G. Lewis. 1998. Interdecadal variation in developmental timing of ***Neocalanus plumchrus*** populations at Ocean Station P in the subarctic North Pacific. Canadian Journal of Fisheries and Aquatic Sciences 55: 1878-1893.

Mackas, D.L., H. Sefton, C.B. Miller, and A. Raich. 1993. Vertical habitat partitioning by large calanoid copepods in the oceanic subarctic Pacific during spring. Progress in Oceanography 32: 259-294.

Macklin, S.A., G.M. Lackmann, and J. Gray. 1988. Offshore directed winds in the vicinity of Prince William Sound, Alaska. Monthly Weather Review 116: 1289-1301.

Mahoney, B.A. and K.E.W. Shelden. in press. The native subsistence harvest of beluga whales, Delphinapterus leucas, in Cook Inlet, Alaska. Marine Fisheries Review, Special Issue.

Malloy, R.J. and G.F. Merrill. 1972. Vertical crustal movement on the sea floor. The great Alaska earthquake of 1964, vol. 6: oceanography and coastal engineering. Washington, D.C., National Research Council, National Academy of Sciences.

Mangel, J., L.M. Talbot, G.K. Meffe, M.T. Agardy, D.L. Alverson, J. Barlow, D.B. Botkin, G. Budowski, T. Clark, J. Cooke, R.H. Crozier, P.K. Dayton, D.L. Elder, C.W. Fowler, S. Funtwicz, J. Giske, R.J. Hofman, S.J. Holt, S.R. Kellert, L.A. Kimbal, D. Ludwig, K. Magnusson, Malayang III, C., C. Mann, E.A. Norse, S.P. Nothridge, W.F. Perrin, C. Perrings, R. Peterman, G.B. Rabb, H.A. Regier, J.E. Reynolds, K. Sherman, M.P. Sissenwine, T.D. Smith, A. Starfield, R.J. Taylor, M.F. Tillman, C. Toft, J. Twiss, R. John, J. Wilen, and T.P. Young. 1996. Principles for the conservation of wild living resources. Ecological Applications 6: 338-362.

Mann, K.H. and J.R.N. Lazier. 1996. Dynamics of marine ecosystems, biological-physical interactions in the oceans, 2nd ed. Blackwell Science, Inc. Cambridge.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78: 1069-1079.

Mantyla and Reid. 1983. Abyssal characteristics of the world ocean waters. Deep-Sea Research 30: 805-833.

Marchland, C., Y. Simrad, and Y. Gratton. 1999. Concentration of capelin (***Mallotus villosus***) in tidal upwelling fronts at the head of the Laurentian Channel in the St. Lawrence estuary. Canadian Journal of Fisheries and Aquatic Sciences 56: 1832-1848.

Martin, J.H. 1990. Glacial-interglacial CO_2 change: the iron hypothesis. Paleoceanography 5: 1-13.

Martin, J.H. 1991. Iron, Leibig's law, and the greenhouse. Oceanography 4: 52-55.

Martin, J.H. and R.M. Gordon. 1988. Northeast Pacific iron distributions in relation to primary productivity. Deep-Sea Research 35: 177-196.

Martin, M.H. 1997. Data report: 1996 Gulf of Alaska bottom trawl survey. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Mathisen, O.A. 1972. Biogenic enrichment of sockeye salmon lakes and stock productivity. Verhandlungen der Internationalen Vereinigung für Theoretische and Angewandte Limnologie 18: 1089-1095.

Matkin, C. 2000. personal communication. North Gulf Oceanic Society, Homer, Alaska National Oceanic and Atmospheric Administration, Juneau, Alaska.

Matkin, C.O. unpublished data. North Gulf Oceanic Society, Homer, Alaska.

Matkin, C.O., G. Ellis, L. Barrett-Lennard, H. Jurk, and E. Saulitis. 2000. Photographic and acousic monitoring of killer whales in Prince William Sound and Kenai Fjords, Alaska. Homer, North Gulf Oceanic Society. Restoration Project Annual Report 99012.

Matkin, C.O., G. Ellis, L. Barrett-Lennard, H. Jurk, D. Sheel, and E. Saulitis. 1999. Comprehensive killer whale investigation restoration project 98012 annual report . North Gulf Oceanic Society. Homer.

Matkin, C.O., G.M. Ellis, M.E. Dahlheim, and J. Zeh. 1994. Status of killer whales in Prince William Sound, 1985-1992. Pages 141-162 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, San Diego.

Matkin, C.O., D.R. Matkin, G.M. Ellis, E. Saulitis, and D. McSweeney. 1997. Movements of resident killer whales in southeastern Alaska and Prince William Sound, Alaska. Marine Mammal Science 13: 469-475.

Matkin, C.O. and E.L. Saulitis. 1994. Killer whale (Orcinus orca) biology and management in Alaska.

Matkin, C.O., D. Scheel, G. Ellis, L. Barrett-Lennard, H. Jurk, and E. Saulitis. 1998. Comprehensive killer whale investigation, ***Exxon Valdez*** oil spill restoration project annual report (Restoration Project 97012). North Gulf Oceanic Society. Homer.

McAllister, C.D. 1969. Aspects of estimating zooplankton production from phytoplankton production. Journal of Fisheries Research Board of Canada 26: 199-220.

The McDowell Group. 1999. The economic impacts of the cruise ship industry in Anchorage.

McElroy, M.P. 1983. Marine biological controls on atmospheric CO_2 and climate. Nature 302: 328-329.

McRoy, C.P. 1970. Standing stocks and other features of eelgrass (Zostera marina) populations on the coast of Alaska. Journal of the Fisheries Research Board of Canada 27: 1811-1821.

McRoy, C.P. and J.J. Goering. 1974. Coastal ecosystems of Alaska. Pages 124-145 in Odum, H.T., B.J. Copeland, and E.H. McMahan, editors. Coastal ecological systems of the United States, vol. 3. The Conservation Foundation, Washington, D.C.

Mearns, A.J. 1996. ***Exxon Valdez*** shoreline treatment and operations: implications for response, assessment, monitoring, and research**.** American Fisheries Society Symposium 18: 309-328.

Megrey, B.A., A.B. Hollowed, S.R. Hare, S.A. Macklin, and P.J. Stabeno. 1996. Contributions of FOCI research to forecasts of year-class strength of walleye pollock in Shelikof Strait, Alaska. Fisheries Oceanography 5(Suppl. 1): 1989-203.

Meier, M.F. 1984. Contribution of small glaciers in global sea level. Science 226: 1481-1421.

Melsom. A., S.D. Meyers, H.E. Hurlburt, E.J. Metzger, and J.J. O'Brien. 1999. El Niño induced eddies in the Gulf of Alaska, Earth interact.

Mendenhall, V.M. 1997. Preliminary report on the 1997 Alaska seabird die-off. Anchorage, U.S. Fish and Wildlife Service.

Menge, B.A. 1995. Indirect effects in marine rocky intertidal interaction webs: patterns and importance. Ecological Monographs 65: 21-74.

Menge, B.A., E.L. Berlow, C.A. Blanchette, S.A. Navarette, and S.B. Yamada. 1994. The keystone species concept: variation in interaction strength in a rocky intertidal habitat. Ecological Monographs 249: 249-287.

Menge, B.A. and E.D. Sutherland. 1987. Community regulation: variation in disturbance, competition, and predation in relation to gradients of environmental stress and recruitment. American Naturalist 130: 730-757.

Merrick, R.L. and D.G. Calkins. 1996. Importance of juvenile walleye pollock, ***Theragra chalcogramma***, in the diet of Gulf of Alaska Steller sea lions, ***Eumetopias jubatus***. Pages 153-166 in Brodeur, R.D., P.A. Livingston, T.R. Loughlin, and A.B. Hollowed, editors. Ecology of juvenile walleye pollock, ***Theragra chalcogramma***. National Marine Fisheries Service, Seattle.

Merrick, R.L., M.K. Chumbley, and G.V. Byrd. 1997. Diet diversity of Steller sea lions (***Eumetopias jubatus***) and their population decline in Alaska: a potential relationship. Canadian Journal of Zoology 54: 1342-1348.

Merrick, R.L. and T.R. Loughlin. 1997. Foraging behavior of adult female and young-of-the-year Steller sea lions in Alaskan waters. Canadian Journal of Zoology 75: 776-786.

Merrick, R.L., T.R. Loughlin, and D.G. Calkins. 1987. Decline in abundance of the northern sea lion, Eumetopias jubatus, in Alaska, 1956-86. Fishery Bulletin 85: 351-365.

Meyers, S.D. and S. Basu. 1999. Eddies in the eastern Gulf of Alaska from TOPEX/POSEIDON altimetry. Journal of Geophysical Research 104: 13333-13343.

Miller, C.B. 1988. ***Neocalanus flemingeri***, a new species of Calanidae (Copepoda:Calanoida) from the Subarctic Pacific Ocean, with a comparative redescription of ***Neocalanus plumchrus*** (Marukawa) 1921. Progress in Oceanography 20: 223-274.

Miller, C.B. 1993. Pelagic production processes in the subarctic Pacific. Progress in Oceanography 32: 1-15.

Miller, C.B. and M.J. Clemons. 1988. Revised life history analysis of the large grazing copepods in the Subarctic Pacific Ocean. Progress in Oceanography 20: 293-313.

Miller, C.B., B.W. Frost, B. Booth, P.A. Wheeler, M.R. Landry, and N. Welschmeyer. 1991a. Ecological processes in the Subarctic Pacific: iron limitation cannot be the whole story. Oceanography 4: 71-78.

Miller, C.B., B.W. Frost, P.A. Wheeler, M.R. Landry, N. Welschmeyer, and T.M. Powell. 1991b. Ecological dynamics in the subarctic Pacific, possibly iron limited system. Limnology and Oceanography 36: 1600-1615.

Miller, C.B. and R.D. Nielsen. 1988. Development and growth of large calanid copepods in the Subarctic Pacific, May 1984. Progress in Oceanography 20: 275-292.

Minobe, S. 1997. A 50-70 year climatic oscillation over the North Pacific and North America. Geophysical Research Letters 24: 683-686.

Minobe, S. 1999. Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: role in climatic regime shifts. Geophysical Research Letters 26: 855-858.

Molnia, B.F. 1981. Distribution of continental shelf surface sedimentary units between Yakutat and Cross Sound, northeastern Gulf of Alaska . Journal of the Alaska Geological Society 1: 60-65.

Monson, D.H. and A.R. DeGange. 1995. Reproduction, preweaning survival, and survival of adult sea otters at Kodiak Island, Alaska. Canadian Journal of Zoology 73: 1161-1169.

Monson, D.H., D.F. Doak, B.E. Ballachey, A.M. Johnson, and J.L. Bodkin. 2000. Long-term impacts of the Exxon Valdez oil spill on sea otters, assessed through age-dependent mortality patterns. Pages 6562-6567 Proceedings of the National Academy of Sciences.

Monson, D.H., J.A. Estes, J.L. Bodkin, and D.B. Siniff. 2000. Life history plasticity and population regulation in sea otters. Oikos 90: 457-468.

Montevecchi, W.A. and R.A. Myers. 1996. Dietary changes of seabirds indicate shifts in pelagic food webs. Sarsia 80: 313-322.

Moore, S.E., K.E.W. Shelden, L.K. Litzky, B.A. Mahone, and D.J. Rugh. in press. Beluga, Delphinapterus leucas, habitat associations in Cook Inlet, Alaska. Marine Fisheries Review, Special Issue.

Muench, R.D. and D.T. Heggie. 1978. Deep water exchange in Alaskan subarctic fjords. Pages 239-267 in Kjerfve, B., editor. Estuarine transport processes. B. Baruch Institute for Marine Biology and Coastal Research, University of South Carolina Press, Columbia.

Muench, R.D., H.O. Mofjeld, and R.L. Charnell. 1978. Oceanographic conditions in lower Cook Inlet: spring and summer 1973. Journal of Geophysical Research 83: 5090-5098.

Mueter, F.J. and B.L. Norcross. 1999. Linking community structure of small demersal fishes around Kodiak Island, Alaska, to environmental variables. Marine Ecology Progress Series 190: 37-51.

Mueter, F.J. and B.L. Norcross. 2000. Species composition and abundance of juvenile groundfish around Steller Sea Lion ***Eumetopias jubantus*** rookeries in the Gulf of Alaska. Alaska Fishery Research Bulletin. Alaska, State of Alaska, Department of Fish and Game.

Murphy, E.C., A.M. Springer, D.G. Roseneau, and B.A. Cooper. 1991. High annual variability in reproductive success of kittiwakes (***Rissa tridactyla***) at a colony in western Alaska. Journal of Animal Ecology 60: 515-534.

Musgrave, D., T. Weingartner, and T.C. Royer. 1992. Circulation and hydrography in the northwestern Gulf of Alaska. Deep-Sea Research 39: 1499-1519.

Myers, K.W., R.V. Walker, H.R. Carlson, and J.H. Helle. 2000. Synthesis and review of U.S. research on the physical and biological factors affecting ocean production of salmon. Pages 1-9 in Helle, J.H., Y. Ishida, D. Noakes, and V. Radchenko, editors. Recent changes in ocean production of Pacific salmon. North Pacific Anadromous Fish Commission Bulletin , Vancouver.

Mysak, L., R.D. Muench, and J.D. Schumacher. 1981. Baroclinic instability in a downstream varying channel: Shelikof Strait, Alaska. Journal of Physical Oceanography 11: 950-969.

Nagasawa, K. 2000. Winter zooplankton biomass in the Subarctic North Pacific, with a discussion on the overwintering survival strategy of Pacific Salmon (***Oncorphynchus*** spp.). Pages 21-32 in Helle, J.H., Y. Ishido, D. Noakes, and V. Radchenko, editors. Recent changes in ocean production of Pacific salmon. North Pacific Anadromous Fish Commission Bulletin , Vancouver.

Nakata, H., K. Kannan, L. Jing, N.J. Thomas, S. Tanabe, and J.P. Giesey. 1998. Accumulation pattern of organochlorine pesticides and polychlorinated biphenyls in southern sea otters (***Enhydra lutris nereis***) found stranded along coastal California, USA. Environmental Pollution 103: 45-53.

Napp, J.M., L.S. Incze, P.B. Ortner, D.L. Siefert, and L. Britt. 1996. The plankton on Shelikof Strait, Alaska: standing stock, production, mecoscale variability and their relevance to larval fish survival. Fisheries Oceanography 5: 19-35.

Niebauer, H.J., J. Roberts, and T.C. Royer. 1981. Shelf break circulation in the northern Gulf of Alaska. Journal of Geophysical Research 86: 13041-13047.

Niebauer, H.J., T.C. Royer, and T.J. Weingartner. 1994. Circulation of Prince William Sound, Alaska. Journal of Geophysical Research 99: 14113-14126.

NMFS. 2000. Endangered Species Act--Section 7 consultation, biological opinion and incidental take statement. Silver Spring, MD, NMFS Office of Protected Resources.

NMFS. 2001. Alaska groundfish fisheries draft programmatic supplemental environmental impact statement. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Region.

NMML. unpublished data. Cetacean Assessment and Ecology.

NOAA. 1993. Report of the NOAA panel on contingent valuation. Federal Register 58: 10.

Norcross, B.L. 1998. Volume I, Final Report. Defining habitats for juvenile groundfishes in southcentral Alaska with emphasis on flatfishes. Fairbanks, University of Alaska, Coastal Marine Institute.

Norcross, B.L., E.D. Brown, R.J. Foy, M. Frandsen, S.M. Gay, M. Jin, J. Kirsch, T.C. Kline, D.M. Mason, C.N.K. Mooers, E.V. Patrick, A.J. Paul, K.D.E. Stokesbury, S.J. Thorton, S.L. Vaughan, and J. Wang. 1999. Life history and ecology of juvenile Pacific herring in Prince William Sound, Alaska. Fisheries Oceanography

Northern Economics Inc. 2002. Alaska visitor's expenditures and options fall/winter 2000-01 prepared for Alaska Department of Community and Economic Development.

NPFMC. 2000. Stock assessment and fishery evaluation report for groundfish resources of the Gulf of Alaska. Anchorage, Alaska, North Pacific Fisheries Management Council.

NRC. 1971. The great Alaska earthquake of 1964. National Academy Press. Washington, D.C.

NRC. 1996. The Bering Sea ecosystem. National Academy Press. Washington, D.C.

Nysewander, D.R. and J.L. Trapp. 1984. Widespread mortality of adult seabirds in Alaska, August-September 1983. Anchorage, U.S. Fish and Wildlife Service.

O'Clair, C. and S.T. Zimmerman. 1986. Biogeography and ecology of the intertidal and shallow subtidal communities. Pages 305-346 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

O'Corry-Crowe, G.M., A.E. Dizon, R.S. Suydam, and L.F. Lowry. in press. Molecular genetic studies of population structure and movement patterns in a migratory species: the beluga whale (***Delphinapterus leucas***) in the western Nearctic. in Pfeiffer, C.J., editor. Molecular and cell biology of marine mammals. Krieger, Florida.

O'Corry-Crowe, G.M. and L.F. Lowry. 1997. Genetic ecology and management concerns for the beluga whale (***Delphinapterus leucas***). Pages 249-274 in Dizon, A.E., S.J. Chivers, and W.F. Perrin, editors. Molecular genetics of marine mammals.

O'Corry-Crowe, G.M., R.S. Suydam, A. Rosenberg, K.J. Frost, and A.E. Dizon. 1997. Phlylogeography, population structure and dispersal patterns of the beluga whale ***Delphinus leucas*** in the western Nearctic revealed by mitochondrial DNA. Molecular Ecology 6: 955-970.

O'Daniel, D. and J.C. Schneeweis. 1992. Steller sea lion, ***Eumetopias jubatus***, predation on glaucous-winged gulls, Larus glaucescens. Canadian Field-Naturalist 106: 268.

Oakley, K.L. and K.J. Kuletz. 1996. Population, reproduction, and foraging of pigeon guillemots at Naked Island, Alaska, before and after the ***Exxon Valdez*** oil spill. Pages 759-769 American Fisheries Society Symposium.

Okey, T.A. and D. Pauly. 1999. Trophic mass balance model of Alaska's Prince William Sound ecosystem, for the post-spill period 1994-1996. EVOS restoration project 98330-1annual report. The Fisheries Centre, University of British Columbia. Vancouver.

Okkonen, S. 2001. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Okkonen, S.R. 1992. The shedding of an anticyclonic eddy from the Alaskan Steam as observed by the GEOSAT altimeter. Geophysical Research Letters 19: 2397-2400.

Olesiuk, P.F., M.A. Bigg, G.M. Ellis, S.J. Crockford, and R.J. Wigen. 1990. An assessment of the feeding habits of harbour seals (***Phoca vitulina***) in the Strait of Georgia, British Columbia, based on scat analysis. Canadian Technical Report of Fisheries and Aquatic Sciences 1730.

Omori, M. 1969. Weight and chemical composition of some important oceanic zooplankton in the North Pacific Ocean. Marine Biology 3: 4-10.

Orensanz, J.M.L., J. Armstrong, D. Armstrong, and R. Hilborn. 1998. Crustacean resources are vulnerable to serial depletion - the mutifaceted decline of crab and shrimp fisheries in the Greater Gulf of Alaska. Reviews in Fish Biology and Fisheries 8: 117-176.

Orr, R.T. and T.C. Poulter. 1967. Some observations on reproduction, growth, and social behavior in the Steller sea lion. Proceedings of the California Academy of Sciences 35: 193-226.

Ostrand, W.D., K.O. Coyle, G.S. Drew, J.M. Maniscalco, and D.B. Irons. 1998. Selection of forage-fish schools by murrelets and tufted puffins in Prince William Sound, Alaska. The Condor 100: 286-297.

Overland, J.E. 1990. Prediction of vessel icing at near-freezing sea surface temperatures. Weather and Forecasting 5: 62-77.

Page, D.S., E.S. Gilfillan, P.D. Boehm, and E.J. Horner. 1995. Shoreline ecology program for Prince William Sound, Alaska, following the ***Exxon Valdez*** oil spill: Part 1 - study design and methods . Pages 263-295 in Wells, P.G., J.N. Butler, and J.S. Hughes, editors. ***Exxon Valdez*** oil spill: fate and effects in Alaskan waters. American Society for Testing and Materials, Philadelphia.

Paine, R.T. 1966. Food web complexity and species diversity. American Naturalist 100: 65-75.

Paine, R.T., J.L. Ruesink, A. Sun, E.L. Soulanille, M.J. Wonham, C.D.G. Harley, D.R. Brumbaugh, and D.L. Secord. 1996. Trouble on oiled waters: lessons from the ***Exxon Valdez*** oil spill. Annual Review of Ecology and Systematics 27: 197-235.

Paine, R.T., J.T. Wootton, and P.D. Boersma. 1990. Direct and indirect effects of Peregrine Falcon predation on seabird abundance. Auk 107: 1-9.

Parker, K.S., T.C. Royer, and R.B. Deriso. 1995. High-latitude climate forcing and tidal mixing by the 18.6-year lunar nodal cycle and low-frequency recruitment trends in Pacific halibut (Hippoglosus stenolepis), in climate change and northern fish populations . Pages 447-458 Beamish, editor. Canadian Special Publication of Fisheries and Aquatic Sciences.

Parsons, T.R. 1986. Ecological relations. Pages 561-570 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Parsons, T.R. and C.M. Lalli. 1988. Comparative oceanic ecology of the plankton communities of the Subarctic Atlantic and Pacific Oceans. Oceanography and Marine Biology Annual Review 26: 317-359.

Parsons, T.R., M. Takahashi, and B. Hargrave. 1984. Biological oceanographic processes, 3rd ed. Pergamon Press. New York.

Paul, A.J. and Paul. J.M. 1999. First-year energy storage patterns of Pacific herring and walleye pollock: insight into competitor strategies. Pages 117-127 in Ecosystem approaches for fisheries management. Sea Grant College Program, University of Alaska , Fairbanks.

Paul, A.J., J.M. Paul, and R.L. Smith. 1998. Seasonal changes in whole-body energy content and estimated consumption rates of age 0 walleye pollock from Prince William Sound, Alaska. Estuarine, Coastal and Shelf Science 47: 251-259.

Paul, A.J. and R. Smith. 1993. Seasonal changes in somatic energy content of yellowfin sole ***Pleuronectes asper*** Pallas 1814. Journal of Fish Biology 43: 131-138.

Peixoto, J.P. and A.H. Oort. 1992. Physics of climate. American Institute of Physics. New York.

Perry, S.L., D.P. DeMaster, and G.K. Silber. 1999. The great whales: history and status of six species listed as endangered under the U.S. Endangered Species Act of 1973. Marine Fisheries Review 61: 1-74.

Peterson, C.H. 1991. Intertidal zonation of marine invertebrates in sand and mud. American Scientist 79: 236-249.

Peterson, C.H. 2000. The web of ecosystem interconnections to shoreline habitats as revealed by the ***Exxon Valdez*** oil spill perturbation: a synthesis of acute direct vs indirect and chronic effects. Advances in Marine Biology

Peterson, C.H. 2001. The ***Exxon Valdez*** oil spill in Alaska: acute, indirect and chronic effects on the ecosystem. Advances in Marine Biology 39: 1-103.

Peterson, C.H., Kennicutt II, M.C., R.H. Green, P. Montagna, Harper Jr., D.E., E.N. Powell, and P.F. Rosigno. 1996. Ecological consequences of environmental perturbations associated with offshore hydrocarbon production: a perspective on long-term exposures in the Gulf of Mexico. Canadian Journal of Fisheries and Aquatic Sciences 53: 2637-2654.

Piatt, J. personal communication. U.S. Geological Survey, Anchorage, Alaska.

Piatt, J.F. unpublished data. U.S. Geological Survey, Anchorage, Alaska.

Piatt, J.F. and P. Anderson. 1996. Response of common murres to the ***Exxon Valdez*** oil spill and long-term changes in the Gulf of Alaska marine ecosystem. Pages 720-737 in Rice, S.D., R.B. Spies, D.A. Wolf, and B.A. Wright, editors. Proceedings of the ***Exxon Valdez*** oil spill symposium. Bethesda.

Piatt, J.F. and R.G. Ford. 1993. Distribution and abundance of marbled murrelets in Alaska. Condor 95: 662-669.

Piatt, J.F. and R.G. Ford. 1996. How many birds were killed by the ***Exxon Valdez*** oil spill? Pages 712-719 in Rice, S.D., R.B. Spies, D.A. Wolfe, and B.A. Wright, editors. Proceedings of the ***Exxon Valdez*** oil spill symposium. Bethesda.

Piatt, J.F. and D.N. Nettleship. 1985. Diving depths of four alcids. Auk 102: 293-297.

Piatt, J.F. and T.I. van Pelt. 1993. A wreck of common murres (***Uria aalge***) in the northern Gulf of Alaska during February and March of 1993. Anchorage, U.S. Fish and Wildlife Service.

Pickart, R.S. 2000. Bottom boundary layer structure and detachment in the shelfbreak jet of the Middle Atlantic Bight. Journal of Physical Oceanography 30: 2668-2686.

Piorkowski, R.J. 1995. Ecological effects of spawning salmon on several southcentral Alaskan streams. University of Alaska,Fairbanks.

Pitcher, K.W. 1980. Food of the harbor seal, ***Phoca vitulina richardsi***, in the Gulf of Alaska. Fishery Bulletin 78: 544-549.

Pitcher, K.W. 1981. Prey of the Steller sea lion, Eumetopias jubatus, in the Gulf of Alaska. Fishery Bulletin 79: 467-472.

Pitcher, K.W. 1984. The harbor seal (***Phoca vitulina richardsi***). Pages 65-70 in Burns, J.J., K.J. Frost, and L.F. Lowry, editors. Marine mammals species accounts. Alaska Department of Fish and Game.

Pitcher, K.W. 1989. Harbor seal trend count surveys in southern Alaska, 1988. U.S. Marine Mammal Commission. Washington, D.C.

Pitcher, K.W. 1990. Major decline in the number of harbor seals, Phoca vitulina richardsi, on Tugidak Island, Gulf of Alaska. Marine Mammal Science 6: 121-134.

Pitcher, K.W. and D.G. Calkins. 1981. Reproductive biology of Steller sea lions in the Gulf of Alaska. Journal of Mammalogy 62: 599-605.

Pitcher, K.W. and F.H. Fay. 1982. Feeding by Steller sea lions on harbor seals. Murrelet 63: 70-71.

Pitcher, K.W. and D.C. McAllister. 1981. Movements and haul out behavior of radio-tagged harbor seals, ***Phoca vitulina***. Canadian Field-Naturalist 95: 292-297.

Plafker, G. 1972. Tectonics. Pages 47-122 in The great Alaska earthquake of 1964, Vol. 6: oceanography and coastal engineering. National Research Council, National Academy of Sciences, Washington, D.C.

Plakhotnik, A.F. 1964. Hydrological description of the Gulf of Alaska. Page 289 in Moiseev, P.A., editor. Soviet fisheries investigations in the Northeast Pacific, part II.

Polovina, J.J., G.T. Mitchum, and G.T. Evans. 1995. Decadal and basin-scale variation in mixed layer depth and impact on biological production in the Central and North Pacific, 1960-88. Deep Sea Research 42: 1701-1716.

Power, M.E., D. Tilman, J.A. Estes, B.A. Menge, W.J. Bond, L.S. Mills, G. Daily, J.C. Castilla, J. Lubchenco, and R.T. Paine. 1996. Challenges in the quest for keystones. Bioscience 46: 609-620.

Prichard, A.K. 1997. Evaluation of pigeon guillemots as bioindicators of nearshore ecosystem health. University of Alaska,Fairbanks.

Purcell, J.E. and M.V. Sturdevant. 2001. Prey selection an dietary overlap among zooplantivorous jellyfish and juvenile fishes in Prince William Sound, Alaska . Marine Ecology Progress Series 210: 67-83.

Purvin & Gertz, Ltd. 2000. Alaskan gas development strategies. Purvin & Gertz, Ltd. Calgary.

Quast, J.C. and E.L. Hall. 1972. List of fishes of Alaska and adjacent waters with a guide to some of the literature.

Rafaelli, D. and S. Hawkins. 1996. Intertidal ecology. Chapman and Hall. London.

Ramp. 1986. The interaction of warm core rings with the shelf water and the shelf/slope front south of New England. University of Rhode Island.

Rausch, R. 1958. The occurrence and distribution of birds on Middleton Island, Alaska. Condor 60: 227-242.

Reeburgh, W.S. and G.W. Kipphut. 1986. Chemical distributions and signals in the Gulf of Alaska, its coastal margins and estuaries. Pages 77-91 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Reed, R.K. and J.D. Schumacher. 1986. Physical oceanography. Pages 57-75 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Reid, J.L. 1981. On the mid-depth circulation of the world ocean. Pages 70-111 in Warren, B.A. and C. Wunsch, editors. Evolution of physical oceanography scientific surveys in honor of Henry Stommel. MIT press, Cambridge.

Reid Jr., J.L. 1965. Intermediate waters of the Pacific Ocean. The Johns Hopkins Oceanographic Studies.

Reid, K. and J.P. Croxall. 2001. Environmental response of upper trophic-level predators reveals a system change in an Antarctic marine ecosystem. Proceedings of the Royal Society of London B Biological Sciences 268: 377-384.

Reynolds Jr., J.E. and S.A. Rommel. 1999. Biology of marine mammals. Smithsonian University Press. Washington, D.C.

Rhoads, D.C. and D.K. Young. 1970. The influence of deposit-feeding organisms on sediment stability and community trophic structure. Journal of Marine Research 28: 150-178.

Richardson, R.W. 1936. Winter air-mass convergence over the North Pacific. Monthly Weather Review 64: 199-203.

Ricketts, E.F. and J. Calvin. 1968. Between pacific tides, 4th ed. Stanford University Press. Stanford.

Riedman, M.L. and J.A. Estes. 1990. The sea otter (***Enhydra lutris***): behavior, ecology and natural history. U.S. Fish and Wildlife Service.

Riedman, M.L., J.A. Estes, M.M. Staedler, A.A. Giles, and D.R. Carlson. 1994. Breeding patterns and reproductive success of California sea otters. Journal of Wildlife Management 58: 391-399.

Robards, M., J.F. Piatt, A. Kettle, and A. Abookire. 1999. Temporal and geographic variation in fish populations in nearshore and shelf areas of lower Cook Inlet. Fishery Bulletin.

Roden, G. 1970. Aspects of the mid-Pacific transition zone. Journal of Geophysical Research 75: 1097-1109.

Rogers, D.E., B.J. Rogers, and R.J. Rosenthal. 1986. The nearshore fishes. Pages 399-415 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Ocean Assessments Division, National Oceanic and Atmospheric Administration, Department of Commerce, Washington, D.C.

Rogers, G. 1962. The future of Alaska: the economic consequences of statehood. Johns Hopkins Press. Baltimore.

Rogers, I.H., I.K. Birtwell, and G.M. Kurzynski. 1990. The Pacific eulachon (***Thaleichthys pacificus***) as a pollution indicator organism in the Fraser River estuary, Vancouver, British Columbia. The Science of the Total Environment 97/98: 713-727.

Rogers, J.C. 1981. The North Pacific oscillation. Journal of Climatology 1: 39-57.

Ronholt, L.L., H.H. Shippen, and E.S. Brown. 1978. Demersal fish and shellfish resources of the Gulf of Alaska from Cape Spencer to Unimak Pass 1948-1976: a historical view. Vol. I. Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators 2 (Biological Studies) 1-304.

Rosen, D.A.S. and A.W. Trites. 2000. Pollock and the decline of Steller sea lions: testing the junk-food hypothesis. Canadian Journal of Zoology 78: 1243-1250.

Rosenberg, D.H. 1972. A review of the oceanography and renewable resources of the Northern Gulf of Alaska. Sea Grant Report 73-3. Fairbanks, Institute of Marine Science, University of Alaska. IMS Report R72-23.

Roseneau, D.G. unpublished data. U.S. Fish and Wildlife Service, Homer, Alaska.

Rosenkranz, G. 1999. Statistical modeling of tanner crab recruitment. University of Alaska,Fairbanks.

Rotterman, L.M. and T. Simon-Jackson. 1988. Sea otter. Pages 237-275 in Lentfer, J.W., editor. Selected marine mammals of Alaska. U.S. Marine Mammal Commission, Washington, D.C.

Royer, T. 2000. personal communication. Center for Coastal Phyiscal Oceanography, Old Dominion University, Norfolk, Virginia.

Royer, T.C. 1975. Seasonal variations of waters in the northern Gulf of Alaska. Deep-Sea Research 22: 403-416.

Royer, T.C. 1981a. Baroclinic transport in the Gulf of Alaska. Part I. Seasonal variations of the Alaska current. Journal of Marine Research 39: 239-250.

Royer, T.C. 1981b. Baroclinic transport in the Gulf of Alaska. Part II. A freshwater-driven coastal current. Journal of Marine Research 39: 251-266.

Royer, T.C. 1982. Coastal freshwater discharge in the northeast Pacific. Journal of Geophysical Research 87: 2017-2021.

Royer, T.C. 1993. High-latitude oceanic variability associated with the 18.6 year nodal tide. Journal of Geophysical Research 98: 4639-4644.

Royer, T.C. 1998. Coastal processes in the northern North Pacific. Pages 395-414 in Robinson, A.R. and K.H. Brink, editors. The sea. John Wiley and Sons, New York.

Royer, T.C., D.V. Hansen, and D.J. Pashinski. 1979. Coastal flow in the northern Gulf of Alaska as observed by dynamic topography and satellite-tracked drogued drift buoys. Journal of Physical Oceanography 9: 785-801.

Rugh, D.J., K.E.W. Shelden, and B.A. Mahoney. in press. Distribution of beluga whales in Cook Inlet, Alaska, during June and July, 1993-1998. Marine Fisheries Review.

Rutherford, S. and S. D'Hondt. 2000. Early onset and tropical forcing of 100,000-year Pleistocene glacial cycles. Nature 408: 72-75.

SAI. 1980. Environmental assessment of the Alaskan Continental Shelf. Northeast Gulf of Alaska interim synthesis report. Boulder, Science Applications, Inc.

SAI. 1980a. Environmental assessment of the Alaskan Continental Shelf. Kodiak interim synthesis report - 1980. Boulder, Science Applications, Inc.

SAI. 1980b. Environmental assessment of the Alaskan Continental Shelf. Northeast Gulf of Alaska interim synthesis report. Boulder, Science Applications, Inc.

Sambrotto, R.N. and C.J. Lorenzen. 1986. Phytoplankton and primary production. Pages 249-282 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Sandegren, F.E. 1970. Breeding and maternal behavior of the Steller sea lion (***Eumetopias jubata***) in Alaska. University of Alaska,Fairbanks.

Sanger, G.A. 1987. Trophic levels and trophic relationships of seabirds in the Gulf of Alaska. Pages 229-257 in Croxall. J.P., editor. Seabirds feeding ecology and role in marine ecosystems.

Saulitis, E.L. 1993. The vocalizations and behavior of the "AT"-group of killer whales (***Orcinus orca***) in Prince William Sound, Alaska. University of Alaska,Fairbanks.

Schiel, D.R. and M.S. Foster. 1986. The structure of subtidal algal stands in temperate waters. Oceanography and Marine Biology Annual Review 24: 265-307.

Schlitz, R. submitted. The interaction of shelf water with warm core rings. Journal of Geophysical Research

Schmidt, G.M. 1977. The exchange of water between Prince William Sound and the Gulf of Alaska. University of Alaska,Fairbanks.

Schneider, D. and Hunt Jr., G.L. 1982. A comparison of seabird diets and foraging distribution around the Pribilof Islands, Alaska. Pages 86-95 in Nettleship, D.N., G.A. Sanger, and P.F. Springer, editors. Marine birds: their feeding ecology and commercial fisheries relationships. Minister of Supply and Services, Canada.

Schumacher, J.D. and Kendall Jr., A.W. 1991. Some interactions between young walleye pollock and their environment in the western Gulf of Alaska. La Jolla, California Cooperative Oceanic Fisheries Investigations.

Schumacher, J.D., C.A. Pearson, and R.K. Reed. 1982. An exchange of water between the Gulf of Alaska and the Bering Sea through Unimak Pass. Journal of Geophysical Research 87: 5785-5795.

Schumacher, J.D. and T. Royer. 1993. Review of the physics of the subarctic gyre. PICES Scientific Report No. 1:37-40.

Schumacher, J.D., P.J. Stabeno, and S.J. Bogard. 1993. Characteristics of an eddy over the continental shelf: Shelikof Strait, Alaska. Journal of Geophysical Research 98: 8395-8404.

Schumacher, J.D., P.J. Stabeno, and A.T. Roach. 1990. Volume transport in the Alaska Coastal Current. Continental Shelf Research 9: 1071-1083.

Scribner, K.T., J. Bodkin, B. Ballachey, S.R. Fain, M.A. Cronin, and M. Sanchez. 1997. Population genetic studies of the sea otter (Enhydra lutris): a review and interpretation of available data. Pages 197-208 in Dizon, A.E., S.J. Chivers, and W.F. Perrin, editors. Molecular genetics of marine mammals. Society for Marine Mammalogy, Lawrence.

Seaman, G.A., K.J. Frost, and L.F. Lowry. 1985. Investigations of belukha whales in coastal waters of western and northern Alaska. Part I. Distribution, abundance and movements. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Sease, J.L. 1992. Status review, harbor seals (***Phoca vitulina***) in Alaska. National Marine Fisheries Service .

Sease, J.L. and T.R. Loughlin. 1999. Aerial and land-based surveys of Steller sea lions (***Eumetopias jubatus***) in Alaska, June and July 1997 and 1998.

Seiser, P.E. 2000. Mechanism of impact and potential recovery of pigeon guillemots (***Cepphus columba***) after the Exxon Valdez oil spill. Fairbanks, University of Alaska.

Sergeant, D.E. and P.F. Brodie. 1969. Body size in white whales, ***Delphinapterus leucas***. Journal of the Fisheries Research Board of Canada 26: 2561-2580.

Shaughnessy, P.D. and F.H. Fay. 1977. A review of the taxonomy and nomenclature of North Pacific harbour seals. Journal of Zoology (London) 182: 385-419.

Shigenaka, G., D.A. Coates, A.K. Fukuyama, and P.D. Roberts. 1999. Effects and trends in littleneck clams (***Protothaca staminea***) impacted by the ***Exxon Valdez*** oil spill. Proceedings of the 1999 international oil spill conference, Seattle. American Petroleum Institute, Washington, D.C.

Sigman, D.M. and E.A. Boyle. 2000. Glacial/interglacial variations in atmospheric carbon dioxide. Nature 407: 859-869.

Simenstad, C.A., J.A. Estes, and K.W. Kenyon. 1978. Aleuts, sea otters, and alternate stable state communities. 200: 403-411.

Siniff, D.B. and K. Ralls. 1991. Reproduction, survival and tag loss in California sea otters. Marine Mammal Science 7: 7:211-229.

Siniff, D.B., T.D. Williams, A.M. Johnson, and D.L. Garshelis. 1982. Experiments on the response of sea otters, Enhydra lutris, to oil. Biological Conservation 23: 261-272.

Small, R. 2001. personal communication. Alaska Department of Fish and Game, Juneau, Alaska.

Small, R.J. 1998. Harbor seal investigations in Alaska. Juneau, Alaska, National Marine Fisheries Service. Annual Report Award Number NA57FX0367.

Small, R.J., K. Hastings, and L.A. Jemison. 1999. Harbor seal investigations in Alaska. Juneau, Alaska, National Marine Fisheries Service. Annual Report Award Number NA87FX0300.

Small, R.J. and G.W. Pendleton. 2001. Harbor seal population trends in the Ketchikan, Sitka, and Kodiak areas of Alaska, 1983-1999. Marine Mammal Science

Small, R.J., G.W. Pendleton, and K.M. Wynne. 1997. Harbor seal population trends in the Ketchikan, Sitka, and Kodiak Island areas of Alaska. Pages 7-32 in Annual report: harbor seal investigations in Alaska. Alaska Department of Fish and Game, Anchorage.

Smith, D.R., S. Niemeyer, J.A. Estes, and A.R. Flegal. 1990. Stable lead isotopes evidence of anthropogenic contamination in Alaskan sea otters. Environmental Science and Technology 24: 1517-1521.

Smith, T.G., D.J. St. Aubin, and M.O. Hammill. 1992. Rubbing behaviour of belugas, ***Delphinapterus leucas***, in a high arctic estuary. Canadian Journal of Zoology 70: 2405-2409.

Snarski, D. 1971. Kittiwake ecology, Tuxedni National Wildlife Refuge. Alaska Cooperative Wildlife Research Unit, quarterly report. Fairbanks, University of Alaska.

Sobolevsky, Y.I., T.G. Sokolovshaya, A.A. Balanov, and I.A. Senchenko. 1996. Distribution and trophic relationships of abundant mesopelagic fishes of the Bering Sea. Pages 159-167 in Mathisen, O.A. and K.O. Coyle, editors. Ecology of the Bering Sea: a review of Russian literature. Alaska Sea Grant College Program, Fairbanks.

Sogard, S.M. and B.L. Olla. in press. Endurance of simulated winter conditions by age-0 walleye pollock (Theragra chalcogramma): effects of body size, water temperature and energy stores. Journal of Fish Biology

Sousa, W.P. 1979. Experimental investigations of disturbance and ecological succession in a rocky intertidal community. Ecological Monographs 49: 227-254.

Southward, A.J. and E.C. Southward. 1978. Recolonization of rocky shores in Cornwall after the use of toxic dispersants to clean up the Torrey Canyon spill. Journal of the Fisheries Research Board of Canada 35: 682-706.

Spraker, T.R., L.F. Lowry, and K.J. Frost. 1994. Gross necropsy and histopathological lesions found in harbor seals. Pages 281-312 in Loughlin, T.R., editor. Marine mammals and the ***Exxon Valdez***. Academic Press, Inc., San Diego.

Springer, A.M. 1991. Seabird relationships to food webs and the environment: examples from the North Pacific Ocean. Pages 39-48 in Montevecchi, W.A. and A.J. Gaston, editors. Studies of high-latitude seabirds. 1. Behavioral, energetic, and oceanographic aspects of seabird feeding ecology. Canadian Wildlife Service, Ottawa.

Springer, A.M. 1998. Is it all climate change? Why marine bird and mammal populations fluctuate in the North Pacific? Pages 109-119 in Holloway, G., P. Muller, and D. Henderson, editors. Biotic impacts of extratropical climate variability in the Pacific: proceedings'Aha Huliko'a Hawaiian winter workshop. University of Hawaii, Hawaii.

Springer, A.M., A.Y. Kondratyev, H. Ogi, Y.V. Shibaev, and G.B. Van Vliet. 1993. Status, ecology, and conservation of ***Synthliboramphus*** murrelets and auklets. Pages 187-201 in Vermeer, K., K.T. Briggs, K.H. Morgan, and D. Siegel-Causey, editors. The status, ecology, and conservation of marine birds of the North Pacific. Canadian Wildlife Service, Ottawa.

Springer, A.M., C.P. McRoy, and M.V. Flint. 1996. The Bering Sea Green Belt: shelf edge processes and ecosystem production. Fisheries Oceanography 5: 205-223.

Springer, A.M., J.F. Piatt, and G. Van Vliet. 1996. Sea birds as proxies of marine habitats and food webs in the western Aleutian arc. Fisheries Oceanography 5: 45-55.

Springer, A.M. and S.G. Speckman. 1997. A forage fish is what? Summary of the symposium. Pages 773-805 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska, Fairbanks.

St. Aubin, D.J., T.G. Smith, and J.R. Geraci. 1990. Seasonal epidermal molt in beluga whales, ***Delphinapterus leucas***. Canadian Journal of Zoology 68: 359-367.

Stabeno, P.J., R.K. Reed, and J.D. Schumacher. 1995. The Alaska coastal current: continuity of transport and forcing. Journal of Geophysical Research 100: 2477-2485.

Stephen R. Braund & Associates. 1995. Whittier access project subsistence technical report. Prepared for HDR Engineeringas part of the Whittier access project, environmental impact statement.

Stewart, B.S. 1997. Ontogeny of differential migration and sexual segregation in northern elephant seals. Journal of Mammalogy 78: 1101-1116.

Stockmar, E.J. 1994. Diel and seasonal variability of macrozooplankton and micronekton in the near-surface of the Gulf of Alaska. University of Alaska,Fairbanks.

Stockwell, D. 2000. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Stommel, H. and A.B. Arons. 1960a. On the abyssal circulation of the world ocean - I. Stationary planetary flow patterns on a sphere. Deep-Sea Research 6: 140-154.

Stommel, H. and A.B. Arons. 1960b. On the abyssal circulation of the world ocean - II. An idealized model of the circulation pattern and amplitude in oceanic basins. Deep-Sea Research 6: 217-233.

Sturdevant, M.V., A.C. Wertheimer, and J.L. Lum. 1996. Diets of juvenile pink and chum salmon in oiled and non-oiled nearshore habitats in Prince William Sound, 1989 and 1990. American Fisheries Society Symposium 18: 578-592.

Suchanek, T.H. 1985. Mussels and their role in structuring rocky shore communities. Pages 70-89 in Moore, P.G. and R. Seed, editors. Ecology of rocky coasts: Chapter VI. Hodder and Stoughton Educational Press, Kent.

Sugimoto, T. 1993. Subarctic gyre: gross structure and decadal scale variations in basin scale climate and oceanic conditions. PICES Scientific Report No. 1:35-37.

Sugimoto, T. and K. Tadokoro. 1997. Interannual-interdecadal variations in zooplankton biomass, chlorophyll concentration, and physical environment of the subarctic Pacific and Bering Sea. Fisheries Oceanography 6: 74-92.

Sundberg, K., L. Deysher, and L. McDonald. 1996. Intertidal and supratidal site selection using a geographical information system. American Fisheries Society Symposium 18: 167-176.

Suryan, R.M., D.B. Irons, and J. Benson. 2000. Prey switching and variable foraging strategies of black-legged kittiwake and the effect on reproductive success. Condor 102: 374-384.

Szepanski, M.M., M. Ben-David, and V. Van Ballenberghe. 1999. Assessment of anadromous salmon resources in the diet of the Alexander Archipelago wolf using stable isotope analysis. Oecologia 120: 327-335.

Tabata, S. 1982. The anticyclonic, baroclinic eddy of Sitka, Alaska, in the Northeast Pacific Ocean. Journal of Physical Oceanography 12: 1260-1282.

Taylor, C., L.K. Duffy, R.T. Bowyer, and G.M. Blundell. 2000. Profiles of fecal porphyrins in river otters following the ***Exxon Valdez*** oil spill. Marine Pollution Bulletin 40: 1132-1138.

Tetreau, M. 2001. personal communication. Kenai Fjords National Park Service, Seward, Alaska.

Thompson, R.O.R.Y. and T.J. Golding. 1981. Tidally induced upwelling by the Great Barrier Reef. Journal of Geophysical Research 86: 6517-6521.

Thomson, R.E. 1972. On the Alaskan Stream. Journal of Physical Oceanography 2: 363-371.

Thomson, R.E., Hickey, and LeBlond. 1989. The Vancouver Island Coastal Current: fisheries barrier and conduit. Pages 265-296 in Beamish , R.J. and G.A. McFarlane, editors. Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Canadian Special Publication of Fisheries and Aquatic Sciences.

Thomson, R.E., P.H. LeBlond, and W.J. Emery. 1990. Analysis of deep-drogued satellite-tracked drifter measurements in the Northeast Pacific Ocean. Atmosphere-Ocean 28: 409-443.

Thomson, R.E. and E. Wolanski. 1984. Tidal period upwelling with Raine Island Entrance Great Barrier Reef. Journal of Marine Research 42: 787-808.

Thorsteinson, F.V. and C.J. Lensink. 1962. Biological observations of Steller sea lions taken during an experimental harvest. Journal of Wildlife Management 26: 353-359.

Trenberth, K.E. and J.W. Hurrell. 1994. Decadal atmospheric-ocean variations in the Pacific. Climate Dynamics 9: 303-319.

Trenberth, K.E. and D.A. Paolino. 1980. The Northern Hemisphere sea-level pressure data set: trends, errors, and discontinuities. Monthly Weather Review 108: 855-872.

Trillmich, F. and K. Ono. 1991. Pinnipeds and El Niño: responses to environmental stress. Springer Verlag. Berlin.

Trites, A.W. 1990. Thermal budgets and climate spaces: the impact of weather on the survival of Galapagos (***Arctocephalus galapagoensis Heller***) and northern fur seal pups (***Callorhinus ursinus L.***). Functional Ecology 4: 753-768.

Trowbridge, C. 1995. Prince William Sound management area 1994 shellfish annual management report. Anchorage, Alaska, Alaska Department of Fish and Game.

Tully, J.P. and F.G. Barber. 1960. An estuarine analogy in the sub-arctic Pacific Ocean. Journal of Fisheries Research Board of Canada 17: 91-112.

Tyler, A.V. and G.H. Kruse. 1996. Conceptual modeling of brood strength of red king crabs in the Bristol Bay region of the Bering Sea. High latitude crabs: biology, management, and economics. Alaska Sea Grant College Program, University of Alaska. Alaska Sea Grant College Program, AK-SG-96-02.

Tyler, A.V. and G.H. Kruse. 1997. Modeling workshop on year-class strength of Tanner crab, ***Chionoecetes bairdi***. Juneau, Alaska Department of Fish and Game. Regional Information Report No. 5J97-02.

U.S. Bureau of Economic Analysis. 2002. CA1-3: personal income summary estimates, Alaska, 1969-1999. U.S. Department of Commerce.

U.S. Bureau of the Census. 2001. Profiles of general demographic characteristics, 2000 census of population and housing: Alaska.

Underwood, A.J. and E.J. Denley. 1984. Paradigms, explanations and generalizations in models for the structure of intertidal communities on rocky shores. Pages 151-180 in Simberloff, D. and et al., editors. Ecological communities: conceptual issues and the evidence. Princeton University Press, Princeton.

USDA Forest Service and State of Alaska. 2000. Forest health management report forest insect and disease conditions in Alaska 1999. U.S. Department of Agriculture, Forest Service, Alaska Region and Alaska Department of Natural Resources, Division of Forestry. R10-TP-82, February 2000a.

USDA Forest Service, Chugach National Forest. 2000b. Chugach National Forest, proposed revised land management plan and environmental impact statement. U.S. Forest Service.

USEPA. 1998. Climate change and Alaska.

USFWS. unpublished data. U.S. Fish and Wildlife Service, Anchorage, Alaska.

USGS. unpublished data. Anchorage, Alaska.

USGS. 2000. National Water Quality Assessment Program. http://AK.water.usgus.gov/Projects/NAWQA

Valdez Chamber of Commerce. 2001. personal communication. Valdez, Alaska.

Valdez Convention & Visitors Bureau. 2001. personal communication. Valdez, Alaska.

Valiela, I. 1995. Marine ecological processes, Second ed. Springer-Verlag. New York.

Van Pelt, T.I., J.F. Piatt, B.K. Lance, and D.D. Roby. 1997. Proximate composition and energy density of some North Pacific forage fishes. Comparative Biochemistry and Physiology A118: 1393-1398.

Van Scoy, K.A., D.B. Olson, and R.A. Fine. 1991. Ventilation of North Pacific intermediate water: the role of the Alaskan gyre. Journal of Geophysical Research 96: 16801-16810.

van Tamelen, P.G., M.S. Stekoll, and L. Deysher. 1997. Recovery processes of the brown alga, ***Fucus gardneri*** (Silva), following the ***Exxon Valdez*** oil spill: settlement and recruitment. Marine Ecology Progress Series 160: 265-277.

VanBlaricom, G.R. 1987. Regulation of mussel population structure in Prince William Sound, Alaska. National Geographic Research 3: 501-510.

VanBlaricom., G.R. 1988. Effects of foraging by sea otters on mussel-dominated intertidal communities. Pages 48-91 in VanBlaricom, G.R. and J.A. Estes, editors. The community ecology of sea otters. Springer Verlag, Berlin.

Vastano, A.C., L.S. Incze, and J.D. Schumacher. 1992. Environmental and larval pollock observations in Shelikof Strait, Alaska. Fisheries Oceanography 1: 20-31.

Vaughan, S.L., C.N.K. Moores, and Gay III, S.M. 2001. Physical variability in Prince William Sound during the SEA study (1994-1998). Fisheries Oceanography 10 (Suppl. 1): 58-80.

Vermeer, K., S.G. Sealy, and G.A. Sanger. 1987. Feeding ecology of Alcidae in the eastern North Pacific Ocean. Pages 189-227 in Croxall, J.P., editor. Seabirds: feeding ecology and role in marine ecosystems. Cambridge University Press, Cambridge.

Vermeer, K. and S.J. Westrheim. 1984. Fish changes in diets of nestling rhinoceros auklets and their implications. Pages 96-105 in Nettleship, D.N., G.A. Sanger, and P.F. Springer, editors. Marine birds: their feeding ecology and commercial fisheries relationships. Canadian Wildlife Service, Ottawa.

von Huene, R.W., Shor Jr., G.G., and R.J. Malloy. 1972. Offshore tectonic features in the affected region. Pages 266-289 in The great Alaska earthquake of 1964, Vol. 6: oceanography and coastal engineering. National Research Council, National Academy of Sciences, Washington, D.C.

von Ziegesar, O., G. Ellis, C.O. Matkin, and B. Goodwin. 1986. Repeated sightings of identifiable killer whales (***Orcinus orca***) in Prince William Sound, Alaska, 1977-1983. Cetus 6: 9-13.

Wang, J. 1992. Interaction of an eddy with the continental slope. WHOI-92-40.

Ward, A.E. 1997. A temporal study of the phytoplankton spring bloom in Prince William Sound, Alaska. University of Alaska, Fairbanks.

Ware, D.M. 1991. Climate, predators and prey: behavior of a linked oscillating system. Pages 279-291 in Kawasaki, T., S. Tanaka, Y. Toba, and A. Tanaguchi, editors. Long-term variability of pelagic fish populations and their environments. Pergamon Press, Tokyo.

Warren, B.A. 1983. Why is no deep water formed in the North Pacific? Journal of Marine Research 41: 327-347.

Warren, B.A. and W.B. Owens. 1985. Some preliminary results concerning deep northern-boundary in the North Pacific. Progress in Oceanography 14: 537-551.

Warwick, R.M. 1993. Environmental impact studies in marine communities: pragmatical considerations. Australian Journal of Ecology 18: 63-80.

Warwick, R.M. and K.R. Clarke. 1993. Comparing the severity of disturbance: a meta-analysis of marine macrobenthic community data. Marine Ecology Progress Series 92: 221-231.

Weingartner, T. 2000. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.
Notes: University's GLOBEC project.

Weingartner, T. 2001. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Welch, D. 2001. personal communication. Canada Department of Fisheries, Pacific Biological Station.

Welch, D.W., B.R. Ward, B.D. Smith, and P. Eveson. 1998. Influence of the 1990 ocean climate shift on British Columbia steelhead (***O. mykiss***) and coho (***O. kisutch***) populations. in Holloway, G., P. Muller, and D. Henderson, editors. Biotic impacts of extratropical climate variability in the Pacific: proceedings 'Aha Huliko'a Hawaiian winter workshop. University of Hawaii, Honolulu.

Welschmeyer, N.A., S. Strom, R. Goerjcke, G. DiTullio, L. Belvin, and W. Petersen. 1993. Primary production in the subarctic Pacific Ocean: project SUPER. Progress in Oceanography 32: 101-135.

Wendell, F.E., R.A. Hardy, and J.A. Ames. 1986. An assessment of the accidental take of sea otters, Enhydra lutris, in gill and trammel nets. Marine Resources Technical Report 54. California Department of Fish and Game, Long Beach.

Western Native Trout Campaign. 2001. Imperiled western trout and the importance of roadless areas.

Westlake, R.L. and G. O'Corry-Crowe. 1997. Genetic investigation of Alaskan harbor seal stock stricture using mtDNA. Pages 205-234 Annual report: harbor seal investigations in Alaska. Alaska Department of Fish and Game, Anchorage.

Wheeler, P.A. and S.A. Kokkinakis. 1990. Ammonium recycling limits nitrate use in the oceanic Subarctic Pacific. Limnology and Oceanography 35: 1267-1278.

Whitehead, J.C. and T.J. Hoban. 1999. Testing for temporal reliability in contingent valuation with time for changes in factors affecting demand. Land Economics 75.

Whitledge, T. 2000. personal communication. Institute of Marine Sciences, School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, Alaska.

Whitney, F.A., C.S. Wong, and P.W. Boyd. 1998. Interannual variability in nitrate supply to surface waters of the northeast Pacific Ocean. Marine Ecology Progress Series 170: 15-23.

Whittaker, L.M. and L.H. Horn. 1982. Atlas of Northern Hemisphere extratropical cyclonicactivity, 1958-1977. Madison, Department of Meteorology, University of Wisconsin.

Willette, M., M. Sturdevant, and S. Jewett. 1997. Prey resource partitioning among several species of forage fishes in Prince William Sound, Alaska. Pages 11-29 in Forage fishes in marine ecosystems: proceedings of the international symposium on the role of forage fishes in marine ecosystems. Alaska Sea Grant College Program, University of Alaska, Fairbanks.

Willette, T.M., R.T. Cooney, and K. Hyer. 1999. Predator foraging-mode shifts affecting mortality of juvenile fishes during the subarctic spring bloom. Canadian Journal of Fisheries and Aquatic Sciences 56: 364-376.

Willette, T.M., R.T. Cooney, V. Patrick, D.M. Mason, G.L. Thomas, and D. Scheel. 2001. Ecological processes influencing mortalities of juvenile pink salmon (***Oncorhynchus gorbascha***) in Prince William Sound, Alaska. Fisheries Oceanography 10 (Suppl. 1): 14-42.

Williams, G.J. 2000. Juneau, Alaska, Alaska Department of Labor.

Williams, G.J. 2002. Juneau, Alaska.

Willis, J.M., W.G. Pearcy, and N.V. Parin. 1988. Zoogeography of midwater fishes in the subarctic Pacific. Pages 79-142 in Nemoto, T. and W.G. Pearcy, editors. The biology of the subarctic Pacific. Tokyo.

Willmott, A.J. and L.A. Mysak. 1980. Atmospherically forced eddies in the northeast Pacific. Journal of Physical Oceanography 10: 1769-1791.

Wilson, D.E., M.A. Bogan, Brownell Jr., R.L., A.M. Burdin, and M.K. Maminov. 1991. Geographic variation in sea otters, Enhydra lutris. Journal of Mammalogy 72: 22-36.

Wilson, J.G. and J.E. Overland. 1986. Meteorology. Pages 31-54 in Hood, D.W. and S.T. Zimmerman, editors. The Gulf of Alaska physical environment and biological resources. Alaska Office, Ocean Assessments Division, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

Winston, J. 1955. Physical aspects of rapid cyclogenesis in the Gulf of Alaska. Tellus 7: 481-500.

Wipfli, M.S., J. Hudson, and J. Caouette. 1998. Influence of salmon carcasses on stream productivity: response of biofilm and benthic macroinvertebrates in southeastern Alaska, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 66: 1503-1511.

Wipfli, M.S., J.P. Hudson, D.T. Chaloner, and J.P. Caouette. 1999. Influence of salmon spawner densities on steam productivity in Southeast Alaska. Canadian Journal of Fisheries and Aquatic Sciences 56: 1600-1611.

Witherell, D. 1999. Status and trends of principal groundfish and shellfish stocks in the Alaska exclusive economic zone, 1999. Anchorage, North Pacific Fishery Management Council.

Witherell, D. and N. Kimball. 2000. Status and trends of principal groundfish and shellfish stocks in the Alaska EEZ, 2000. Anchorage, North Pacific Fishery Management Council.

Wolfe, R.J. and L.B. Hutchinson-Scarbrough. 1999. The subsistence harvest of harbor seal and sea lion by Alaska Natives in 1998. Alaska Department of Fish and Game. Juneau.

Wootton, J.T. 1994. The nature and consequences of indirect effects in ecological communities. Annual Review of Ecology and Systematics 25: 443-466.

Xie, L. and W.W. Hsieh. 1995. The global distribution of wind-induced upwelling. Fisheries Oceanography 4: 52-67.

Xiong, Q. and T.C. Royer. 1984. Coastal temperature and salinity observations in the northern Gulf of Alaska, 1970-1982. Journal of Geophysical Research 8061-8068.

Yankovsky, A.E. and D.C. Chapman. 1997. A simple theory for the fate of buoyant coastal discharges. Journal of Physical Oceanography 27: 1386-1401.

Yeardley Jr., R.B. 2000. Use of forage fish for regional streams wildlife risk assessment: relative bioaccumulation of contaminants. Environmental Monitoring and Assessments 65: 559-585.

York, A.E. 1994. The population dynamics of northern sea lions, 1975-1985. Marine Mammal Science 10: 38-51.

York, A.E., R.L. Merrick, and T.R. Loughlin. 1996. An analysis of the Steller sea lion metapopulation in Alaska. Pages 259-292 in McCullough, D.R., editor. Metapopulations and wildlife conservation. Island Press, Washington, DC.

Zador, S.G. and J.F. Piatt. 1999. Time-budgets of common murres at a declining and increasing colony in Alaska. Condor 101: 149-152.

Zheng, J. and G.H. Kruse. 2000. Recruitment patterns of Alaskan crabs and relationships to decadal shifts in climate and physical oceanography. ICES Journal of Marine Science 57: 438-451.

8. MODELING

In This Chapter

- Ø A Survey of North Pacific Models Relevant to GEM
- Ø Goals and Purposes of Gathering and Analyzing Data with Models
- Ø Use of a Hierarchical Strategy in Decision-making
- Ø Modeling Strategies and Methods

8.1 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.

8.2 Survey of Modeling

8.2.1 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 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 (U.S. GOOS Steering Committee 2000).

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 coordination 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. (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).

8.2.2 Core Variables for Modeling

Table 8.1 shows spatial domains, currencies, inputs, and outputs for several of the most relevant North Pacific models.

Table 8.1 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 $carbon/m^3$

Table 8.1 Model Spatial Domains, Currencies, Inputs, and Outputs

Model Name/ Model Region	Model Spatial Domain	Inputs	Outputs/Currency
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.
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 (50ºN 145ºW), Bering Sea (57.5ºN 175ºW), and Station A7 off the east of Hokkaido island, Japan (41.3ºN 145.3ºW)	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		

Source: Table 2 in Appendix E prepared by Kerim Aydin.

Units of Measure: Boreal Migration and Consumption Model, Eastern Bering Sea, Global Ocean Ecosystem Dynamics, Gulf of Alaska, kilometer, kilo calorie, meter, mixed layer depth, millimolar, Multispecies Virtual Population Analysis, North Pacific Ecosystem Model for Understanding Regional Oceanography, North Pacific Fisheries Management Council, nutrient-phytoplankton-zooplankton, Ocean Surface Current Simulations, metric ton, days of year

8.3 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, 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 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 GOA ecosystems. 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 to:

§ Inform, communicate, and provide common problem definition;

§ Identify key variables and relationships;

§ Set priorities;

§ Improve and develop experimental designs to attain monitoring objectives; and

§ Improve decision-making and risk assessment.

8.4 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 3, 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 8.1, 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

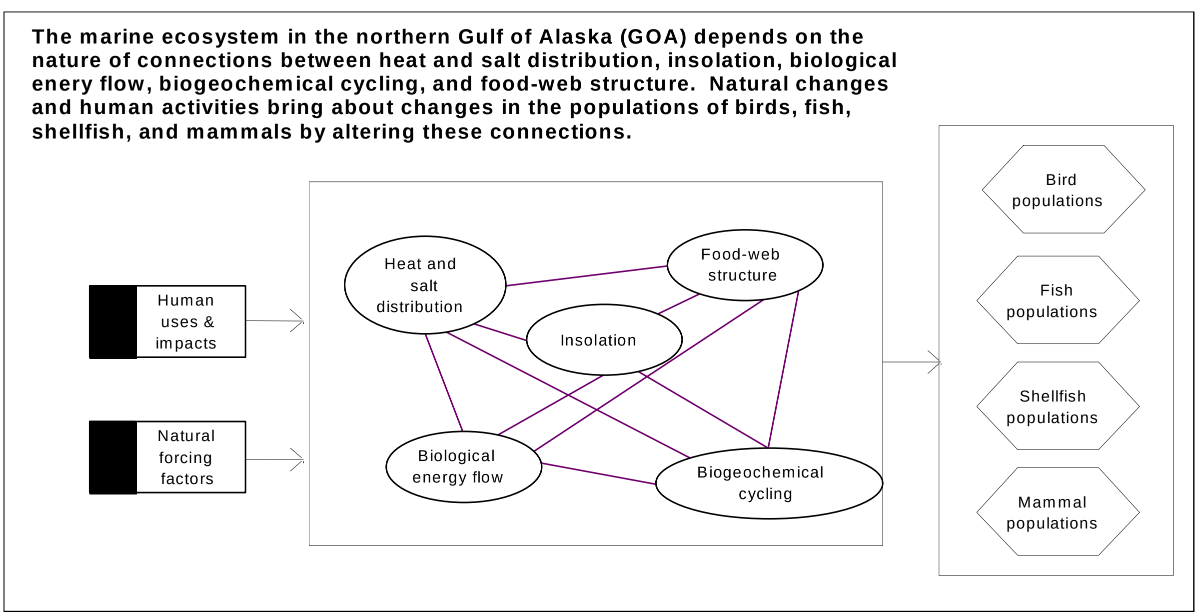

Figure 8.1 Influence diagram illustrating GEM conceptual foundation.

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 8.2. The analytical relationships between the monitored variables of Figure 8.2 and the conceptual foundation represented by Figure 8.1, are developed and investigated with statistical and analytical tools, called models.

The ultimate goal of GLOBEC's Northeast Pacific modeling appears to be a suite of computer models that represents an entire conceptual foundation. The way this is framed in programs like GLOBEC, the North Pacific Marine Science Organization (called PICES), and Global Ocean Observing System (GOOS) (see Section 8.2 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.

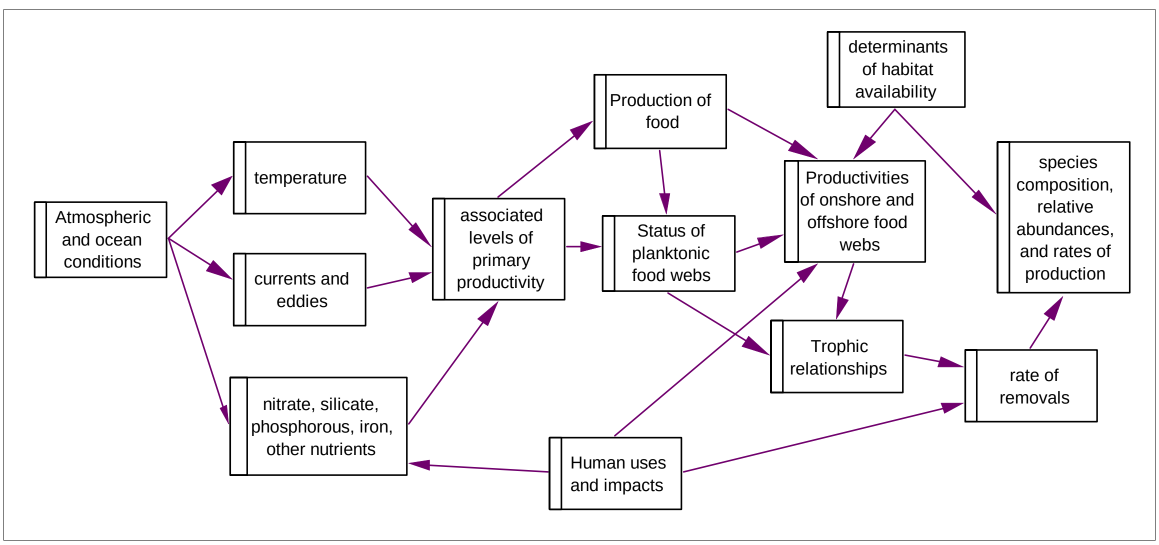

Figure 8.2. Linkages among system attributes that the conceptual foundation identified as "essential" to monitor.

A feasible way to proceed from what can be done now is through an iterative process framed by the conceptual foundation (Figure 8.3). 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.

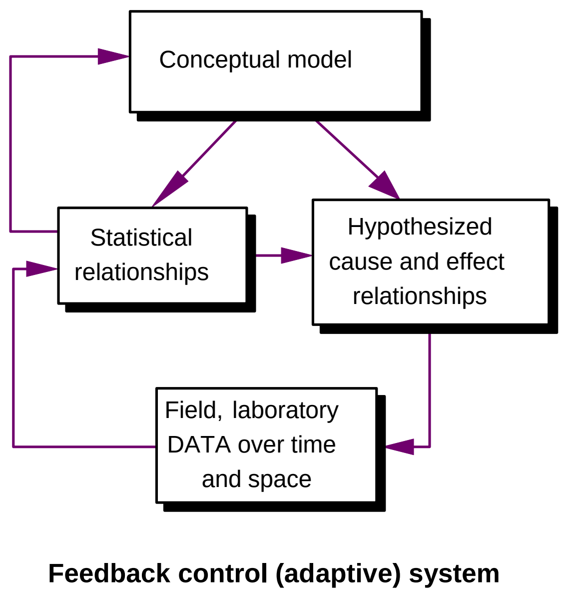

Figure 8.3 Feedback control system linking the conceptual foundation, monitoring, and modeling efforts.

8.5 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 tools and strategies (Chapter 3) and mission goals (Chapter 1). 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 research 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 8.2 identifies preliminary objectives and attributes derived from this idealized model that could be used to evaluate modeling strategies.

Table 8.2 Potential Objectives and Attributes for Use in Evaluation of Modeling Strategies

Objective or Attribute	Supported by models that help…
Relevance to questions and hypotheses of the GEM Program	Identify 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

8.6 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 8.2 of this chapter.

The relationship between monitoring, modeling, 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 the National Oceanic and Atmospheric Administration (Seattle), which summarizes North Pacific models of the Alaska Fisheries Science Center and others (see Section 8.3, Table 8.1, and North Pacific models in Appendix E). 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.

8.6.1 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.

8.6.2 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).

8.6.3 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.

8.6.4 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 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 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).

8.7 Evaluating Model Proposals

Model proposals should, of course, be evaluated within a decision-structured framework such as that outlined above and detailed in Table 8.2. Proposals must also demonstrate a high probability of actually producing what they propose to produce andmeeting 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.

8.8 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 2), 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.

8.9 References

Botkin, D. B., Peterson, D. L., and Calhoun, J. M. 2000. The scientific basis for validation monitoring of salmon for conservation and restoration plans. University of Washington, Olympic Natural Resources Center. Forks.

Burgman, M. A., Ferson, S., and Akcakaya, H. R. 1993. Risk assessment in conservation biology. Chapman and Hall. United Kingdom.

Caddy, J. F. 1995. Comment - fisheries management science: a plea for conceptual change. Canadian Journal of Fisheries and Aquatic Sciences 52: 2057-2058.

Carpenter, S. R., Cottingham, K. L., and Stow, C. A. 1994. Fitting predator-prey models to time series with observation errors. Ecology 75: 1254-1264.

Fahrig, L. 1991. Simulation methods for developing general landscape-level hypotheses of single-species dynamics. Pages 417-442 in M. G. Turner and R. H. Gardner, editors. Quantitative methods in landscape ecology: the analysis and interpretation of landscape heterogeneity. Springer-Verlag, New York.

Gargett, A. E., Li, M., and Brown, R. 2001. Testing mechanistic explanations of observed correlations between environmental factors and marine fisheries. Canadian Journal of Fisheries and Aquatic Sciences 58: 208-219.

Glickman, T. S. and Gough, M. 1990. Readings in risk. resources for the future. Washington D.C.

Hilborn, R. 1997. Statistical hypothesis testing an decision theory in fisheries science. Fisheries 22: 19-20.

Hilborn, R. and Mangel, M. 1997. The ecological detective: confronting models with data. Princeton University Press. Princeton.

Holling, C. S. 1978. Adaptive environmental assessment and management. John Wiley and Sons. Chichester.

Holling, C. S. and Clark, W. C. 1975. Notes towards a science of ecological management. Pages 247-251 in W. H. van Dobben and R. H. Lowe-McConnell, editors. First international congress of ecology. Dr W. Junk B.V. Publishers, The Hague, Netherlands.

Intergovernmental Oceanographic Commission. 2000. Strategic design plan for the coastal component of the Global Ocean Observing System (GOOS). Paris, UNESCO.

Jackson, D. A., Peres-Neto, P. R., and Olden, J. D. 2001. What controls who is where in freshwater fish communities - the roles of biotic, abiotic, and spatial factors. Canadian Journal of Fisheries and Aquatic Sciences 58: 157-170.

Keeney, R. 1992. Value-focused thinking. Harvard University Press. London.

Law, A. M. and Kelton, W. D. 1991. Simulation modeling and analysis. McGraw-Hill. New York.

Ludwig, D. 1999. Is it meaningful to estimate a probability of extinction? Ecology 80: 298-310.

Marmorek, D. R., Anderson, J. J., Bashan, L., Bouillon, D., Cooney, T., Derison, R., Dygert, P., Garrett, L., Giorgi, A., Langness, O. P., Lee, D., McConnaha, C., Parnell, I., Paulsen, C. M., Peters, S., Petrosky, C. E., Pinney, C., Schaller, H. A., Toole, C., Weber, E., Wilson, P., and Zabel, R. W. 1996. Plan for analyzing and testing hypotheses (PATH): final report on retrospective analyses for fiscal year 1996. Vancouver, ESSA Technologies.

Meir, E. and Fagan, W. F. 2000. Will observation error and biases ruin the use of simple extinction models? Conservation Biology 14: 148-154.

Meyer, J. S., Ingersll, C. G., McDonald, L. L., and Boyce, M. S. 1986. Estimating uncertainty in population growth rates: jackknife vs. bootstrap techniques. Ecology 67: 1156-1166.

Mode, C. J. and Jacobson, M. E. 1987a. On estimating critical population size for an endangered species in the presence of environmental stochasticity. Mathematical BioSciences 85: 185-209.

Mode, C. J. a. M. E. J. 1. 1987b. A study of the impact of environmental stochasticity on extinction probabilities by Monte Carlo integration. Mathematical BioSciences 83: 105-125.

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

Oosterhout, G. 1998. PasRAS: a stochastic simulation of chinook and sockeye life histories. Eagle Point, Decision Matrix, Inc.

Oosterhout, G. R. 1996. An evolutionary simulation of the tragedy of the commons. Systems Science. Portland State University,Portland.

Pace, M. L. 2001. Prediction and the aquatic sciences. Canadian Journal of Fisheries and Aquatic Sciences 58: 63-72.

Perry, R. I., Yoo, S., and Terazaki, M. 1997. MODEL task team report, workshop on conceptual/theoretical studies and model development. Sidney, British Columbia, North Pacific Marine Science Organization (PICES).

Pickett, S. T. A., Kolasa, J., and Jones, C. G. 1994. Ecological understanding. Academic Press. San Diego.

Punt, A. E. and Hilborn, R. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries 7: 35-63.

Ralls, K. and Taylor, B. L. 2000. Introduction to special section: better policy and management decisions through explicit analysis of uncertainty: new approaches from marine conservation. Conservation Biology 14: 1240-1242.

Ruckelshaus, M., Hartway, C., and Jareuva, P. 1997. Assessing the data requirements of spatially explicit dispersal models. Conservation Biology 11: 1298-1306.

Schnute, J. T. and Richards, L. J. 2001. Use and abuse of fishery models. Canadian Journal of Fisheries and Aquatic Sciences 58: 10-17.

U.S. GOOS Steering Committee. 2000. A position paper of the U.S. GOOS Steering Committee. Toward a national, cost-effective approach to predicting the future of our coastal environment. http://www-ocean.tamu.edu/GOOS/publications/position.html.

von Winterfeldt, D. and Edwards, W. 1986. Decision analysis and behavioral research. Cambridge University Press. Cambridge.

Vose, D. 2000. Risk analysis: a quantitative guide. John Wiley and Sons. Chichester.

Zacharias, M. A. and Roff, J. C. 2000. A hierarchical ecological approach to conserving marine biodiversity. Conservation Biology 14: 1327-1334.

9. DATA MANAGEMENT AND INFORMATION TRANSFER

In This Chapter

- Ø The Role of Data Management
- Ø Characterizing the Data within GEM
- Ø Characterizing the GEM User Community
- Ø The Structure of the GEM Data System

9.1 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, administrative support, 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 the Coastal Committee of the Global Ocean Observing System, C-GOOS (GOOS 2000) as shown in Figure 9.1.

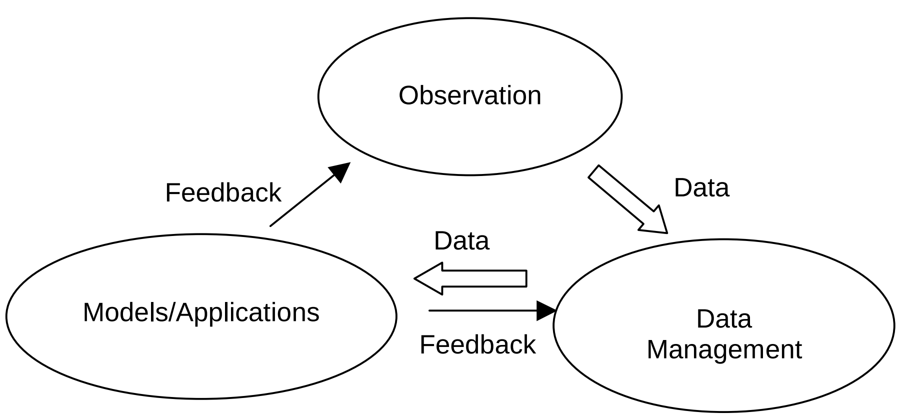

Figure 9.1 GOOS model of data management

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. Initial efforts by projects or groups that collected or archived data provided relatively simple access through the use of navigational 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. Newer systems include more sophisticated search options based on selection of spatial and temporal attributes. 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 their 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. National Aeronautics and Space Administration (NASA) has funded some projects with a demand-oriented focus (The Federation of Earth Science Information Partners NASA Research Announcement), 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 will need to be continuously surveyed 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. The immediate objective of data management and information transfer is to insure that the data collected by projects under GEM are well documented, safely stored, and accessible to the public within a reasonable period of time after collection. An ongoing objective of data management and information transfer in the GEM Program is to achieve to the extent possible the documentation, storage and public access for past data acquired with EVOS funds under Natural Resource Damage Assessment and Restoration. GEM will establish coordination among parties as soon as possible by such means as file transfer protocol (ftp) sites, Web sites, and e-mail lists.

For data acquired with GEM funds, GEM will define and enforce appropriate data and metadata standards. GEM data management staff will ensure that projects are designed so that data and samples are collected in a manner that will yield accuracy and precision sufficient for the objectives of each field program and sufficient for those comparisons and syntheses among programs that can be anticipated. It is fundamental to any research program that high-quality data be collected. While the primary responsibility for this always belongs to the principal investigator, GEM data management staff will provide guidance, coordination and monitoring, particularly for situations where the level and type of data management appropriate for an individual project may not be the same as that required by an interdisciplinary program of large geographic and temporal extent. To provide the opportunity for comparison with historical data, measurement techniques will be consistent with techniques used to collect the existing data unless there is significant scientific justification for change. When new techniques are adopted, methods for relating the new data to existing data will be developed.

It is just as important that appropriate metadata ("data about data") be created and made available in order to search, identify and retrieve data sets in the GEM data archive. Under no circumstances will a data file, data set, data layer, or database be accepted by or made available via the GEM archive without appropriate supporting metadata. Metadata usually include, but may not be limited to, location, time, units, accuracy, precision, method of measurement, method of sensor calibration and sensor calibration data, analyst or operator, and data processing methods. The metadata format will be compliant with the Federal Geographic Data Committee (FGDC) standards.

The Federal Ocean Data Policy requires that appropriate ocean data and related information collected under federal funding be submitted to and archived by designated national data centers, such as the National Ocean Data Center (NODC). Such an archive will be used in addition to the GEM data archive. The GEM data management component may not in itself support a "24 hours a day-7 day a week-365 day a year," always on and open system, but could support these types of operations as a partner. The GEM Program will continue to maintain metadata and a data search interface to locate and access GEM data that is maintained by the GEM data archive and other data archives in use.

The long-term end point for GEM data management and information transfer is a system that manages the rapid and efficient flow of data and information based on core monitoring projects to end users, and that facilitates the flow of data and information between and among GEM partners and the user community. A partnership system of data distribution will be designed to make information products readily available to partners and other user groups. The ultimate goal will be an end-to-end system, in which a monitoring network provides data to models and other applications that provide services to a variety of end users, including the ongoing GEM synthesis, research, and modeling.

In the long term 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 be 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 metadata and continue to provide custom data products and services to a set of targeted users.

9.2 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 metadata and processing that are associated with the chemical and biologic data from the bottle sample will be nearly identical, as will the processing and metadata 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
- Metadata: The content, format, or both of the metadata

9.2.1 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 make 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 metadata describe the collection and or processing location and sometimes the conditions. These data are often in a database management system or a spreadsheet, which forces a level of consistency that allows automated processing upon retrieval. Examples of observational data sets from the GEM habitat types (see Chapter 4) include:

Watersheds

- 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

Offshore

- Lab results for chemical and biological oceanography
- Species counts for zooplankton
- Bird and mammal surveys

9.2.2 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 metadata include instrument details and conditions, and the data formats are standard enough to allow customized processing during retrieval. Examples from the GEM habitat types include:

Watersheds

- Physical and hydrologic variables

Intertidal and Subtidal

- Physical oceanographic variables

Alaska Coastal Current

- Lidar measurements
- Hydroacoustic plankton or nekton surveys
- Fluorescence measurements

Offshore

- Physical oceanography
- Hydroacoustic plankton or nekton surveys
- Fluorescence measurements

9.2.3 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 metadata need to describe the classification and version of the model and may need to include relevant input parameters. The metadata 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.

9.2.4 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 metadata 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.

9.2.5 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 metadata 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:

Watersheds

§ 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

Offshore

- Ocean color imagery from SeaWiFS
- MODIS ocean products

9.2.6 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.

9.3 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, to administration of projects, reports and data. 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 types: watersheds, intertidal and subtidal, ACC, and the Offshore.

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, file 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.

5. GEM programmatic/administrative support will encompass programmatic assistance from original proposal submission to final report publication. Development of administrative systems will allow for timelier and well monitored data submission, and provide linkages between data and information only available in the final reports. In addition, data management will support continuing gap analysis through a continuously

updated database of current and historical information-gathering projects in the GOA and adjacent areas.

9.3.1 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 metadata and data relating to Cook Inlet and other areas of Alaska;
- Systems such as GLIMPSE/Webglimpse (http://lternet.edu/data/), EMAP (http://www.epa.gov/emap/), 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 metadata 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 metadata 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 metadata 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 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.

9.3.2 GEM Administrative Support

Managing the projects funded by and associated with GEM requires a project-oriented database (see Chapter 5). 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 metadata 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.

9.4 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 9.2).

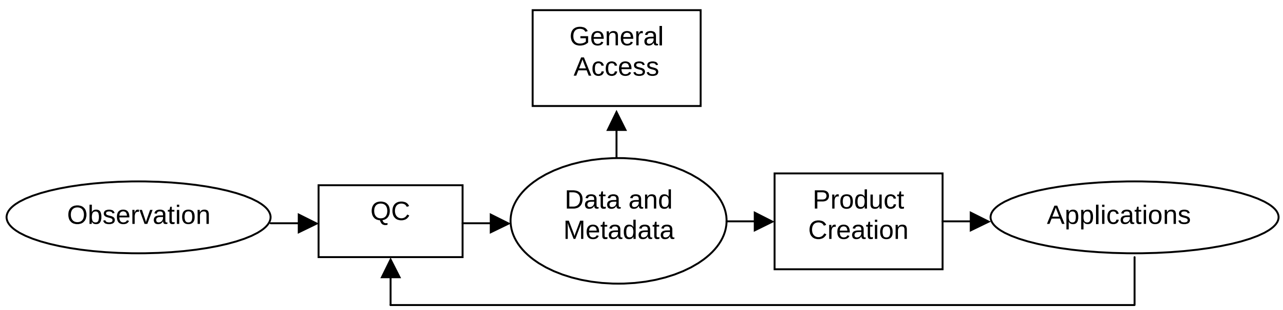

Figure 9.2 The GEM data system

9.4.1 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 metadata (and to some degree the data) and quality assurance of the data and the metadata. Quality control will ensure that the metadata 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 metadata.

9.4.2 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 "open source" 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.

9.4.3 Metadata Support

The core of the data system will be metadata and a data-storage component. The metadata 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 database of metadata. The QC routines will ensure that the metadata 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 metadata.

The metadata maintained by the GEM Program will also support access to remote GEM archives that are maintained by individual researchers and their supporting organizations. The GEM Program will also evaluate whether to ingest metadata 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.

The metadata maintained by the GEM Program could also be available for searching by other data clearinghouse programs. In such a situation, the GEM metadata would be a information node for that clearinghouse. The GEM Program will identify and work with such programs to ensure that the GEM data is available to a wide and varied audience through a variety of search mechanisms.

Most search and download systems include some level of metadata support. The GEM Program will evaluate the use of these existing systems, including the structure of the metadata. Because the population and use of the metadata will be the central activity of the GEM data system, any existing system will need to be modified before it is used by GEM.

9.4.4 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 metadata 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, optical media or a storage area network 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 metadata 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.

9.5 References

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