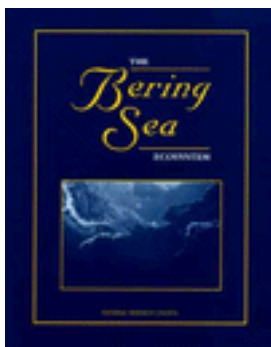


## The Bering Sea Ecosystem



Committee on the Bering Sea Ecosystem, National Research Council

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# The Bering Sea Ecosystem

Committee on the Bering Sea Ecosystem  
Polar Research Board  
Commission on Geosciences, Environment, and Resources  
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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## Preface

The plentiful fish and game of the Bering Sea have supported the lives and livelihood of people on both the Asian and the North American continents since prehistoric times. The Bering Sea is a subarctic, semi-enclosed northern extension of the North Pacific Ocean; its southern boundary is marked by the Aleutian Islands and its northern boundary by Bering Strait. Its wide variety of fish, shellfish, birds, and mammals both in coastal areas and offshore provided an incentive for small population centers to be established in what is now Russia and the United States. As the world's demand for furs and whale oil grew in the eighteenth and nineteenth centuries, exploitation of the Bering Sea's bountiful living resources began on a commercial scale. During the twentieth century, international markets turned to the Bering Sea for its seafood resources. Legal protections for marine mammals were developed in recent decades, and the taking of them declined significantly. Today, approximately 25 species of fish, crustaceans, and mollusks of the Bering Sea are considered important commercially.

Despite the protection for marine mammals, birds, and fish resources afforded by laws of the United States and Russia, and joint treaties between these two nations, some species of the Bering Sea and adjacent regions have undergone large and sometimes sudden population fluctuations. For example, Steller sea lions have declined by 50 to 80 percent and northern fur seal pups on the Pribilof Islands (the major Bering Sea rookeries) declined by 50 percent between the 1950s and 1980s. In parts of the Gulf of Alaska, harbor seal numbers have dropped by as much as 90 percent since the 1970s. Populations of seabirds such as common murre, thick-billed murre, and red-legged and black-legged kittiwakes have also declined significantly in some areas such as the Pribilof Islands and the eastern Aleutians. These changes have raised concerns about how living resources in the area have been and should be managed. Although many suggestions have been put forward as to the factors responsible for these wildlife population fluctuations, there have been no definitive answers.

Concerned about the future of the Bering Sea ecosystem, the U.S. Department of State asked the National Research Council (NRC) to study the available scientific and technical information on the Bering Sea ecosystem, focusing, in particular, on environmental factors that influence natural variability in populations of marine mammals, seabirds, and fish. The U.S.

Coast Guard joined in supporting this project because of its role in scientific research, rescue, and law enforcement in U.S. waters, particularly the Bering Sea. To respond to the charge, the National Research Council's Polar Research Board established the Committee on the Bering Sea Ecosystem.

The charge to the study committee was to review and evaluate the following:

- Environmental factors and ecological relationships that control the Bering Sea ecosystem, including atmospheric and ocean circulation patterns, biological production pathways, and energy transfer within the food web.
- The life history, distribution, and population dynamics of commercially important species, with special emphasis on species that migrate through international waters or into the United States or Russian exclusive economic zones; and the probable causes and effects of their population fluctuations.
- Estimates of historical population dynamics of marine mammals, seabirds, and commercially important species of the Bering Sea, their interrelationships, their current status, and the factors contributing to their population fluctuations.
- The historical records of the commercial fisheries of the Bering Sea.
- The relationship between the biological resources of the Bering Sea and (a) subsistence cultures and economies of indigenous peoples, (b) commercial fisheries and other users, and (c) the assemblage of organisms that constitute the biological component of the Bering Sea ecosystem.

To execute this charge, the committee met five times to gather information and deliberate on issues. We read many reports, published papers, and other documents. At its meetings in Anchorage and Seattle, the committee was briefed by the National Marine Fisheries Service, environmental organizations, the U.S. North Pacific fishing industry, Native American organizations, the Japanese Ministry of Fisheries, the U.S. Coast Guard, the North Pacific Fishery Management Council, the Russian Academy of Sciences, the Smithsonian Institution, and other organizations and individuals. The committee is most grateful to these people and organizations (see [Appendix B](#)).

The committee members approached their task with many varying views but with open minds. None of us foresaw the conclusions we reached and unanimously agreed to, and we all learned a great deal from each other and from this study. I am pleased that our conclusions agree with some aspects of U.S. arctic policy as reflected in recent policy statements, in particular the importance of sustainable resource management and economic development, the need to strengthen institutional cooperation among arctic nations, the importance of an integrated research program, and the importance of involving indigenous peoples in decisions concerning them. My experience on this committee in particular brought home to me the need to develop ways to overcome the difficulties of meaningfully bridging the deep differences between indigenous and western cultures.

This report is the result of the committee's hard work and deliberations and the PRB staff's valuable support. Thanks are due to both for the tremendous effort they put forth to

bring this work to conclusion. The diversity of backgrounds and intellectual focus brought to the issue at hand made this an enjoyable and edifying experience as well.

Finally, I wish to thank two outstanding individuals who have helped make my task much easier. Kelly Norsingle took care of most of the logistics, facilitation, and report preparation, and—more importantly—she was always there with an effervescent and helping attitude to the task at hand. To me, she defines the term "service excellence." And last but certainly not least, David Policansky has not only supported my efforts to make this report a quality one, he has patiently and persistently guided me along the path of this long and difficult journey.

Robert C. Francis, *Chair*,  
Committee on the Bering Sea Ecosystem

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## Executive Summary

The Bering Sea, a semi-enclosed northern extension of the North Pacific Ocean, contains a tremendous variety of biological resources, including at least 450 species of fish, crustaceans, and mollusks; 50 species of seabirds; and 25 species of marine mammals. The plentiful fish and game of the Bering Sea have supported the lives and livelihoods of people on both the Asian and the North American continents since prehistoric times. As the world's demand for furs and whale oil grew in the eighteenth and nineteenth centuries, exploitation of the Bering Sea's bountiful living resources began on a commercial scale. During the twentieth century, international markets turned to the Bering Sea for its seafood resources. Today, approximately 25 species of fish, crustaceans, and mollusks of the Bering Sea are considered important commercially.

Despite a variety of recent protections for marine mammals, birds, and fish resources afforded by laws of the United States and Russia and a number of international agreements, some species of the Bering Sea and adjacent regions have undergone large and sometimes sudden population fluctuations. For example, Steller sea lions have declined by 50 to 80 percent, and northern fur seal pups on the Pribilof Islands (the major Bering Sea rookeries) declined by 50 percent between the 1950s and 1980s. In parts of the Gulf of Alaska, harbor seal populations have dropped by as much as 90 percent since the 1970s. Populations of seabirds such as common murre, thick-billed murre, and red-legged and black-legged kittiwakes have also declined significantly in some areas such as the Pribilof Islands and the eastern Aleutians. Large changes in the abundance of a number of shellfish and fish populations over the past 30 years—including some large increases—have occurred as well.

As a result of concerns about how living resources in the Bering Sea have been and should be managed, the National Research Council (NRC) was asked to assess the current scientific understanding of the Bering Sea. The NRC appointed the Committee on the Bering Sea Ecosystem to study the population dynamics and changes in the marine mammals, birds, and commercially important species in the ecosystem and the probable causes of the changes; gaps in knowledge and the research needs to fill the gaps, including opportunities for interagency and



international cooperation; and as appropriate, alternative management strategies and institutional arrangements.<sup>1</sup> The committee concludes that a combination of environmental changes and human exploitation of Bering Sea resources is the most likely explanation of recent changes in the Bering Sea ecosystem.

### CHANGES IN THE BERING SEA ECOSYSTEM

Both natural environmental fluctuations and human activities have caused biological changes in the Bering Sea ecosystem. Fish populations and other components of the ecosystem appear to react to many different environmental variables in the atmosphere and ocean. Overall, the committee concludes that climate-driven variability in the Bering Sea ecosystem is significant, occurs at many different time scales, and appears to affect many ecosystem components. It appears that climate has caused relatively rapid shifts in the organization of this marine ecosystem—most recently in the late 1970s—and that changes over periods of decades may have larger effects than those over yearly periods.

Human-induced change in the ecosystem is also significant. Fishing and hunting of marine mammals by Aleuts and Eskimos have occurred for hundreds of years at least; intensive exploitation of Bering Sea marine resources by the United States, Russia, Japan, and other nations began in the eighteenth century and increased in the nineteenth and twentieth centuries. Exploitation by indigenous peoples affected the abundance and community structures of marine resources, especially close to shore, and, coupled with natural fluctuations, led to occasional food shortages. The more extensive exploitation of the region's resources by Russia, the United States, Japan, and European nations that began in the eighteenth century led to more severe local food shortages and even starvation among the indigenous peoples.

Intensive exploitation of Bering Sea resources continued until the expansion of exclusive economic zones in the 1970s, when overall exploitation rates in U.S. waters began to decline. Intense fishing continued in international waters (e.g., the "donut hole"), but in recent years that has been reduced or eliminated as well. Information on exploitation rates in the western Bering Sea since the dissolution of the Soviet Union in 1991 is very unreliable, but anecdotal information suggests that exploitation rates are unsustainably high, especially near shore.

Large-scale, intensive exploitation of whales occurred during the 1950s, 1960s, and early 1970s in many parts of the Bering Sea and Gulf of Alaska. During this period, trawl fisheries severely reduced populations of eastern Bering Sea shelf flatfishes and slope rockfishes. Eastern Bering Sea pollock abundance increased in the late 1960s, perhaps as a result of an increase in the amount of food made available by the reduction in whales and other fishes, and the trawl fisheries switched their primary focus to pollock, where it has remained to the present.

As a result of environmental changes and human exploitation of the ecosystem, the eastern Bering Sea fish assemblage probably became pollock-dominated in the late 1960s and

<sup>1</sup> A detailed description of the committee's statement of task is in [Chapter 1](#).

early 1970s, and a similar shift probably occurred in the western Bering Sea as well. In addition, both eastern Bering Sea king crab and herring were reduced significantly, perhaps by fishing, in the 1960s and early 1970s. King crab populations and their fisheries increased in the early 1970s, and then collapsed again in the early 1980s. Several eastern Bering Sea finfish populations grew rapidly in the late 1970s and early 1980s while one flatfish species and a number of forage species appear to have declined significantly.

Superimposed on all of this are the changes in Bering Sea and Gulf of Alaska seabird and mammal populations. Fluctuations in seabird populations vary across the region, apparently depending on local environmental and ecological conditions. The pinnipeds (seals, sea lions, and walruses) present a different picture, with more uniform changes. Juvenile and adult female fur seals declined in the Pribilof Islands from the mid-1970s to the early 1980s and then subsequently stabilized. Harbor seals in the Gulf of Alaska declined rapidly in the late 1970s and have remained low. The trend in the number of Steller sea lions is uncertain before the 1970s, but declines were first noted in the eastern Aleutians in the early 1970s and then continued in the central and western Aleutians and western Gulf of Alaska during the 1980s. These declines appear to be related to a lack of adequate food, with juveniles probably affected most severely.

### CAUSE AND EFFECT IN THE BERING SEA: THE CASCADE HYPOTHESIS

The most likely explanation of events over the past few decades in the Bering Sea ecosystem is that a combination of changes in the physical environment acted in concert with human exploitation of predators (whales, other fish) to cause pollock to dominate the ecosystem. The increase of adult pollock and other predatory fishes in the past 20 years might also be responsible for keeping the forage fishes relatively scarce. As a result, some forage fishes that have higher nutritional value than pollock became less available to some marine mammals and birds, leading to their decline. This food shortage might have been exacerbated by fishing for pollock that was concentrated in space and time, which might have removed them from some areas for long enough to cause difficulties to marine mammals and birds, especially juveniles.

Although the committee concludes that such a "cascade hypothesis" is the most likely explanation of events over the past 50 years, other explanations of these changes might develop as research progresses. There is no evidence that any human activity other than fishing and whaling has had any significant effect on the Bering Sea ecosystem, although more evidence concerning the effects of various pollutants would be of interest.

This scenario does not lead to the conclusion that overfishing of pollock over the past 25 years—often blamed for some of the changes in the Bering Sea—is directly (or even indirectly) responsible for recent declines of mammals and birds. As a result, it is unlikely that reduction of the total rate of exploitation of pollock would halt or reverse the declines in the short-term. It is more likely, although by no means certain, that marine mammals and birds have been affected by the distribution in space and time of fishing effort on pollock, and thus that they would be helped by a broader distribution of fishing effort in space and time, especially in areas where they are known to feed.

It is also hard to predict the effects of protecting other marine mammals. It seems extremely unlikely that the productivity of the Bering Sea ecosystem can sustain current rates of human exploitation as well as the large populations of all marine mammal and bird species that existed before human exploitation—especially modern exploitation—began. Over the long-term, fishing competes to some degree with at least some top-level predators. Therefore, if the goal of management is to have as many top-level predators as possible (not a common management goal), then it seems that ultimately fishing will have to be reduced. Note that "fishing" includes subsistence, recreational, and various kinds of commercial fishing, all of whose effects need to be dealt with.

Finally, it will be difficult for human management to cause a large, complex marine ecosystem to achieve and maintain a desirable balance. Some of the changes that have occurred might be irreversible over normal human time frames (100 years or less). This difficulty emphasizes the need for an adaptive approach to management and the need for good, long-term data on physical and biological phenomena.

### DIFFICULTIES IN OBTAINING INFORMATION

In reviewing data on the Bering Sea, the committee found that data sets are not catalogued in any one place and that there is no way of knowing what organization has what research holdings. Therefore, the committee concludes that a directory of databases relevant to the Bering Sea is needed. Another difficulty was the lack of good information from the former Soviet Union. As a result, the committee concludes that a data rescue and archiving project should be initiated immediately to preserve physical and biological information on the Bering Sea currently residing in the former Soviet Union, as well as information on resource use and conservation.

Many efforts are now underway nationally and internationally to examine the values and usefulness of the traditional knowledge of the region's indigenous peoples. Incorporating their approaches could be of value in furthering our understanding of the history of changes in the region, although the committee concludes that research is needed on how to integrate traditional knowledge into the body of scientific knowledge on the Bering Sea. The above considerations led the committee to the following recommendations.

### RECOMMENDATIONS

#### Research Recommendations

- **Adopt a broader ecosystem perspective for both scientific research and management of Bering Sea resources.**
- **Adopt an adaptive or experimental approach to management actions concerning the Bering Sea ecosystem.**

- **Conduct research on the structure of the Bering Sea ecosystem, including the nature and causes of the dynamics of pollock populations in the northeastern Pacific and Bering Sea over the past 50 years.**

Understanding this broad question can be approached by studying a number of specific questions, including:  
Is the cascade hypothesis a plausible scenario for ecosystem dynamics?

What are the short- and long-term effects of commercial fishing on the structure and dynamics of the Bering Sea ecosystem?

What are the roles of top-down and bottom-up forcing in the Bering Sea ecosystem?

What are the relationships between juvenile pollock and other forage species in the ecosystem?

What is the role of ice in structuring the Bering Sea ecosystem?

What are the periodicities of ecosystem changes?

How do lower trophic levels of the ecosystem interact?

What are the structure and functioning of the "green belt"?

- **Conduct research on how well the management and institutions of the Bering Sea are structured to address problems and provide appropriate management solutions.**

### **Management and Institutional Recommendations**

The committee identified four basic problems that need to be solved to achieve proper management of the Bering Sea ecosystem: the lack of knowledge and inherent limitations on understanding and predictability, incomplete specification of management objectives, lack of appropriate domestic institutional structures through which to make and implement coordinated management decisions on either side of the Bering Sea, and the limited ability to coordinate domestic management with users and management agencies of other nations. The committee recommends the following steps to address these problems:

- **Improve the coordination of the many institutional structures that make management decisions concerning resource use in the Bering Sea.**
- **Coordinate the philosophy and objectives of laws dealing with management in the Bering Sea ecosystem.**
- **Improve processes and institutions to coordinate the implementation of major federal acts relating to resource use in the ecosystem, and federal-state and international management.**
- **Develop a research program to increase understanding of the Bering Sea ecosystem (keeping international issues and cooperation in mind), to fulfill the research needs identified by the committee to help future policy makers solve both short-term management and longer-term ecological problems.**

### **Recommendation to Reverse Declines in Marine Mammals and Birds**

The concentrated fishing for pollock in some places at specific times probably reduces the availability of food for marine mammals and birds, especially juveniles. Thus one step that might help improve the food supply for and reverse declines in marine mammals and birds would be to distribute fishing over wider areas and over longer periods. This management strategy is unlikely to have any adverse effects. Note that this is a call for broadening the distribution of fishing, not a recommendation to increase total catches; in fact, some areas should probably be closed to fishing to protect specific fish, bird, and mammal populations. This leads to the recommendation below. As with all management actions, this strategy should be followed on an adaptive basis.

- **Broaden the distribution of fishing effort in space and time, especially for pollock.**

### **THE FUTURE**

The Bering Sea ecosystem, like all ecosystems, has been affected by natural fluctuations since time immemorial. Like most ecosystems, it has been affected by human activities since prehistory, but especially within the past 200 years as commercial exploitation developed. Thus, the recent changes that we see today should not be thought of as perturbations of a "pristine" ecosystem, but as part of a pattern of change affected by a complex array of natural and human influences.

The complexity of the influences on the ecosystem makes understanding and management difficult, but some things are clear. First, environmental change will continue to occur in the future. Second, significant human exploitation of a single species can affect not only that species but many other species as well. In other words, there are connections among ecosystem components. Finally, the total productivity of the ecosystem has a limit, which means that human use of living resources will affect the ecosystem to some degree. Those three conclusions imply that unexpected events will continue in the future and that they will be larger as living resources are more heavily exploited. It also follows that actions with respect to single species will have complex consequences that will be hard to predict. Simply changing exploitation rates on a single species—pollock, for example—is unlikely to have easily predictable effects on other ecosystem components—marine mammals, for example.

To operate successfully within this complex system, management strategies must be developed based on long-term data on physical and biological phenomena and must be adapted as we learn more about the structure and functioning of the ecosystem. A better understanding of institutional and socioeconomic factors will also be needed. Finding a balance between human uses of the region's many resources and maintaining other desired aspects of the ecosystem, such as high productivity of marine mammals or a particular composition of fish communities, will be an ongoing challenge.

# 1

## Introduction

The Bering Sea, a semi-enclosed northern extension of the North Pacific Ocean (Figure 2.2), contains a tremendous variety of biological resources, including many species of marine mammals, seabirds, fish, and shellfish. The Bering Sea ecosystem includes more than 450 species of fish, crustaceans, and mollusks (about 25 of which are commercially important), more than 50 species of seabirds, and at least 25 species of marine mammals. The magnitude and nature of biological productivity in the Bering Sea ecosystem have led to extensive use of these animals by human societies. Indigenous peoples of the region have long used animals from the Bering Sea as sources of food, clothing, and energy, as well as for a variety of cultural purposes. In addition, a number of fish, shellfish, and marine mammal species have been used extensively by the United States and other nations for commercial purposes. Over the past several decades, some species of fish, shellfish, marine mammals, and seabirds in the Bering Sea and adjacent regions have undergone large and sometimes sudden population fluctuations. These changes have raised concern about how living resources in the area have been and should be managed.

Animals from the Bering Sea have been used by the indigenous peoples on both sides of the Bering Sea as a subsistence resource for thousands of years. Fish, shellfish, marine mammals, and seabirds from the Bering Sea have been used as a source of food by local residents along the extensive U.S. and Russian coasts. Marine mammals and seabirds have also been used for fuel (blubber) and as raw materials for clothing, tools, and other objects (skins, bones, ivory, feathers). The animals of the Bering Sea ecosystem also play an important role in the cultural and religious traditions of many indigenous peoples.

Over the last 200 years, the United States, Russia, Canada, and Japan, and in recent decades Poland, Korea, Taiwan, and China, have also exploited these biological resources through commercial whaling, sealing, and fishing. Most prominently exploited have been fur seals, whales, sea otters, salmon, crab, and groundfishes (flatfish, rockfish, Pacific cod, walleye pollock, and Atka mackerel). Although marine mammals are no longer exploited commercially in the Bering Sea, the fish and shellfish taken amount to between 2 and 5 percent of the world's fishery production, and 56 percent of U.S. fishery production (U.S. Department of Commerce, 1994).



Except for salmon, which have supported a commercial fishery since the turn of the century, large-scale commercial exploitation of the fish and shellfish of the Bering Sea began about 1950. In the early years of fishery development, stocks were aggressively fished. By the late 1960s, a number of rockfish, flatfish, and crab stocks had been significantly reduced by fishing (Fritz et al., in press; NPFMC, 1993; Wooster, 1992). Over the same period—from the 1950s through the early 1970s—the substantial populations of large baleen whales and toothed whales of the Bering Sea, Aleutian Islands, and Gulf of Alaska were nearly eliminated (NMFS, 1991b).

Partly in response to the threat of overfishing, in 1976 the U.S. Congress passed the Fisheries Conservation and Management Act, which extended U.S. jurisdiction in coastal waters out to 200 miles (approximately 320 km) from the U.S. coast. The intent of the act was to regulate the intensity of fishing, to ensure long-term sustainability of the fish stocks, and within the constraints imposed by that goal, to maximize fishery yields. This act does not provide for protection of species that range beyond the 200-mile limit, the most noteworthy of which are salmon and walleye pollock. Salmon fisheries in international waters are regulated by international agreements, whereas pollock fisheries have not been until recently.

### THE PROBLEM

Recent declines in populations of some piscivorous (fish-eating) marine mammals and seabirds in the Bering Sea and adjacent areas have raised concerns and triggered actions mandated by the United States Endangered Species Act (ESA) and the Marine Mammal Protection Act. Steller sea lions have declined by 50 to 80 percent and have been listed as threatened in the area under the Endangered Species Act over the past 15 to 20 years (NMFS, 1992). The production of northern fur seal pups on the Pribilof Islands (the location of the major Bering Sea rookeries) declined by 50 percent between the 1950s and the 1980s, and the stock was listed as depleted under the Marine Mammal Protection Act (NMFS, 1993a). In some areas along the north-central Gulf of Alaska, harbor seal numbers have dropped by as much as 90 percent since the 1970s (Pitcher, 1990). Bering Sea populations of common murre, thick-billed murre, and red- and black-legged kittiwakes have also declined significantly in the Pribilof Islands (Byrd, 1989a).

There are disagreements about the causes and the significance of the declines. The declines might be due to overfishing of the species on which these marine mammals and seabirds depend (principally walleye pollock) or to food web relationships mediated by pollock (Springer, 1992). Other believe that the declines are due to other factors, including climate-induced changes in the physical and biological environment of the North Pacific and Bering Sea, entanglement of the declining species in marine debris (including abandoned and discarded fishing nets), shooting by fishermen, pollution, and disease (Alverson, 1992).

## THIS STUDY

Because of the questions raised about a number of recent changes in biological components of the Bering Sea ecosystem, the U.S. Department of State requested that the National Research Council form a committee to study the available scientific and technical information on the Bering Sea ecosystem, focusing in particular on factors that influence variability in populations of marine mammals, seabirds, and fish. The U.S. Coast Guard joined in financial support because of its role in research, rescue, and law enforcement in polar waters, particularly the Bering Sea. This report was prepared to assess (1) current scientific understanding of the Bering Sea ecosystem; (2) gaps in knowledge and the research needs to fill the gaps, including opportunities for interagency and international cooperation; and, as appropriate, (3) possible management alternatives or institutional arrangements. The committee was asked to consider the following topics:

- Environmental factors and ecological relationships that control the Bering Sea ecosystem, including atmospheric and ocean circulation patterns, biological production pathways, and energy transfer within the food webs of the region.
- The life history, distribution, and population dynamics of commercially important species, with special emphasis on species that migrate through international waters or into the United States or Russian exclusive economic zones; and the probable causes and effects of their population fluctuations.
- Estimates of historical population dynamics of marine mammals, seabirds, and commercially important species of the Bering Sea; and their interrelationships, their current status, and the factors contributing to their population fluctuations.
- The historical records of the commercial fisheries of the Bering Sea.
- The relationship between the biological resources of the Bering Sea and (a) subsistence cultures and economies of indigenous peoples, (b) commercial fisheries and other users, and (c) the assemblage of organisms that constitute the biological component of the Bering Sea ecosystem.

To set the stage for addressing these issues, [Chapter 2](#) presents a general conceptual framework for understanding marine ecosystems. [Chapter 3](#) then describes the geological, physical, chemical, and lower trophic level biological attributes of the Bering Sea ecosystem, and it addresses both the current state of the system and how it has changed over time. [Chapter 4](#) summarizes available data on the invertebrate, fish, bird, and marine mammal species of the Bering Sea region, including their life cycles, species distribution, and population variability, if known. [Chapter 5](#) describes the history of Bering Sea fisheries (for fishes and marine mammals) and their management, including a discussion of coastal communities, cultures, and economics.

[Chapter 6](#) summarizes the most serious problems and issues affecting the Bering Sea ecosystem and proposes a hypothesis that is consistent with available data on species abundance and variability. In a conceptual framework consistent with earlier parts of the report, [Chapter 7](#) then addresses the implications of these data and hypotheses for management policy and institutional arrangements governing the Bering Sea ecosystem. The most pressing gaps in



knowledge and research needs and the committee's conclusions and recommendations are presented in [Chapter 8](#).

## 2

# Marine Ecosystems: A Conceptual Framework

Before attempting to define the Bering Sea ecosystem and its analogs, it is useful to examine the nature of oceanic ecosystems from a conceptual point of view. The approach taken here is not the standard "ecosystem ecology," but rather a practical hybrid combining dynamics (from population biology), a multispecies perspective (from community ecology), and an acknowledged role for the effects of physical environmental fluctuations (an ecosystem perspective). What we attempt to do is transmit to the reader a sense of an "ecosystem perspective" for management—a context that recognizes the interactions among biotic and abiotic elements of ecosystems and their effects on human institutions.

This chapter provides a conceptual framework for oceanic ecosystems with a particular focus on the Bering Sea and introduces three conceptual questions that are important to later discussions.

- Are there fundamental differences between oceanic and terrestrial ecosystems and if so, what are they?
- How does one determine the relationship between natural and anthropogenic forcing in an ecosystem context?
- How does one assess the "condition" of an ecosystem?

The chapter then discusses ecosystem management and explores whether it can be seen as a solution to perceived problems in the Bering Sea. Finally, it describes the Bering Sea ecosystem and its analogs.

## CONCEPTUAL FRAMEWORK

### Ecosystems and the Concept of Order

Understanding an ecosystem first requires some justifiable delineation of what constitutes the ecosystem. The complete description of biotic and abiotic variables that interact to define a functional ecological system represents a tremendous challenge. Ecologists recognize that

global interdependencies operate among atmospheric, hydrospheric, and lithospheric processes, such that no absolute independence exists for any given ecosystem defined at a subglobal scale. Yet ecosystems are operationally defined and meaningfully studied on more manageable scales—smaller than the entire planet (Steele, 1974).

Such delineations of ecosystems are made in practice by setting explicit geographic bounds around some subset of nature. For example, Sherman and Alexander (1986) identified several separate large marine ecosystems (LMEs) as appropriate units for analysis and management in the marine environment. These delineations of ecosystems are based on distinct hydrographic boundaries, bottom topography, and trophic dependencies of interacting populations. Such abstractions of nature not only are necessary to allow feasible study of community and ecosystem processes but also acknowledge that the earth's biota is spatially partitioned into meaningful groups of interacting species. Nevertheless, despite success at setting spatial bounds to ecosystems that may correspond well to biogeographic, habitat, and hydrographic distinctions, it is still important to recognize and analyze those processes that cross the boundaries.

The necessary practice of setting bounds to an ecosystem before it can be meaningfully studied and analyzed is actually just the first step in the process of abstraction, averaging, and pooling that must be done to simplify the ecosystem for effective study of organizing processes (Levin, 1992). The complexity of any natural ecosystem is just too great to allow even its complete description, let alone meaningful analysis of its individually recognizable components. Decisions about which variables to pool or average and over what scales in time and space are critical to the success of efforts to understand the dynamics of ecosystems and the causes of underlying patterns. These decisions are informed and guided by the results of conceptual and mathematical models, which should be constructed and iteratively modified in collaboration with empirical observations and experiments (Kareiva and Anderson, 1988). Unlike many other aspects of ecology, modeling is a necessary part of ecosystem study in that it identifies those areas of most sensitivity and critical importance for improved measurement and the time and space scales needed for those critical measurements. In addition, the models sharpen our understanding of nature by making processes explicit and by allowing some degree of prediction, which cannot be achieved through description of patterns alone. Interestingly, the simplest models without elaborate reductionist detail are often the most reliable predictors of ecosystem pattern (Ludwig and Walters, 1985).

Mathematical modeling of the effects of interactions between species on the dynamics of species populations has a long history in ecological research. Some of the earliest work was done by Lotka (1925) and Volterra (1931) on predator-prey interactions and by Gause (1934) on effects of competitors. These approaches were later expanded by May (1973), Caswell (1978), Yodzis (1988), and others to encompass more complete communities of interacting species.

Perhaps the major cross-cutting challenge to scientists interested in evaluating ecological patterns is the integration of the multiple spatial and temporal scales involved (Levin, 1992). There is no single "correct" scale at which to view ecosystems. Processes that occur at one scale have impacts observable on other scales. Patchiness on virtually all scales is a

characteristic of ecosystems that complicates their complete description and poses an implicit challenge to ecologists to explain these patterns (Denman and Powell, 1984). Our snapshot views of temporally dynamic ecological systems represent one of the most serious limitations to proper understanding of causes of ecosystem dynamics. The evolutionary history and the more immediate past in ecological time are important contributors to the patterns observed in nature. Yet the historical memories present in any ecosystem are difficult or impossible to extract in the short time horizons of both management institutions and scientific study plans. Because of the significance of processes on multiple spatial and temporal scales to the generation of ecological pattern, and especially the unknown contributions of historical events, scientists studying ecosystems are always faced with incomplete and imperfect information. As a result, ecosystem processes reside in what Magnuson (1990) called "the invisible present," hidden from view or understanding because they occur slowly or because effects lag years behind causes.

Pomeroy et al. (1988) elaborated on this theme and emphasized the concept of scale as being critical to the understanding of ecosystems.

One feature of the biosphere that clearly emerges from ecological studies is the range of scales of space and time over which events occur. Each kind of event may have a characteristic time or half-time, ranging from nanoseconds for intracellular processes...to millions of years for the evolution of continents and ocean basins and their contained ecosystems. We are really dealing with a continuum, of functional response over a range of time scales, and it is often necessary to think about a substantial part of that range in order to properly describe and understand ecological processes.

Central to conventional ecosystem theory is the concept that structure (the way process distributes itself in space) results from differences in process rates. Thus, according to this theory, ecosystems are structured according to the relationships between processes occurring at different time and space scales. Although organisms as taxonomic entities are not the essential "stuff" of ecosystems, their populations, as variable conduits, clearly define the fundamental nature of ecosystem dynamics. It is the populations of species that participate in creating or modifying energy fluxes that, as a result, occur at different rates in space and time. What we are talking about here is ecology in four dimensions. An ecosystem cannot be defined or conceived of without clear reference to time. In the words of Allen and Hoekstra (1992), "...complex behavior will arise when very different rates are pressed together in the formulation of a population equation...complexity arises from the interaction of differently scaled processes..."

The ecosystem is thus a hierarchical system that responds differently over a range of time and space scales. Lower-level components (those operating at short time scales) respond significantly to disturbances at higher levels. However, higher levels "see" only the averaged or integrated responses of lower-level components. This does not mean that everything in an ecosystem occurs in a top-down fashion. O'Neill et al. (1986) pointed out that in hierarchical organizations, lower-level behaviors are essential to the functioning and persistence of higher-

level structure, although, because of their slower rates, they are unable to affect the behavior of the higher level.

Apollonio (1994) brought hierarchy theory into the realm of marine fisheries. He distinguished between long- and short-lived species in terms of their ecosystem-organizing capacities as follows: "[Long-lived] species, because of their biological attributes, have a role in structuring or shaping their systems...That is to say, their presence induces predictability into the system. And, by inference, their reduction or removal reduces internal control mechanisms and increases variability and unpredictability."

The point that Apollonio (1994) was making here is that, according to hierarchy theory, ecosystems are structured in part by the natural frequencies of their component parts. "Structuring" tends to occur as a function of these cycle times or natural frequencies. The implication is that ecosystems that are dominated at the top by long-lived species tend to be more "structured" and predictable than those that are not.

It is interesting to chronicle the history of fishing in the Bering Sea in the second half of the twentieth century with respect to these concepts. Whales and seals were harvested first; then rockfish such as Pacific Ocean perch; then herring, crab, and yellowfin sole; and then pollock. The interesting thing is the apparent succession in the targets of harvest from long-lived to short-lived species. Because the exploitation history affects the organization of a marine ecosystem, it should be taken into account in attempting to develop ecosystem management policy.

### **Cascading Trophic Interactions in Ecosystems**

Development of the science necessary to support ecosystem management probably will require a new synthesis of previously separate approaches to the study of ecology—a melding of relevant aspects of population ecology, community ecology, and traditional ecosystem ecology. The goal is to be able to predict, understand, and interpret changes in populations of component species of an ecosystem, especially those that have value to human society. Such understanding must be based in large part on knowledge of the interaction of those important populations with other species in the ecosystem. Such questions are the essence of community ecology, and the experimental work done on trophic cascades by Paine (1980) in marine intertidal systems, the research done to evaluate the indirect effects of removal of sea otters from subtidal communities (Estes and Palmisano, 1974; Simenstad et al., 1978), and the experimental manipulations by Carpenter and colleagues (e.g., Carpenter et al., 1985; Carpenter and Kitchell, 1988) in lakes represent the best examples of how community ecology must be involved to develop appreciation of processes controlling dynamics of individual species.

Parsons (1992) presented examples from the Atlantic, Pacific, and Antarctic oceans where the removals of marine predators by fisheries have had various cascading short- and long-term effects on ecosystems (e.g., the effects of the harvest of antarctic blue whales on changes in abundance of other krill-eating and krill-dependent species and the inverse relationship between the abundance of planktivorous right whales and the abundance of planktivorous sand lance in the Gulf of Maine). These reports tend to substantiate the existence and importance of top-down effects in structuring marine ecosystems. In addition, they demonstrate that these effects can occur at a number of different time scales.

### The Effects of Climate on Structuring Marine Ecosystems

Several marine ecosystem scientists have written that the nonlinear and seemingly unpredictable nature of marine ecosystems is a manifestation of the capacity for self-organization (Allen, 1985; Mann, 1988). The classical example of this kind of behavior is the so-called Russell Cycle of the western English Channel (Figure 2.1) (Mann, 1988; Mann and Lazier, 1991). In essence, the Russell Cycle involved a major flip in the 1930s in the western English Channel from one fairly stable configuration of organisms to another quite different mix of species; then the system reversed itself in the late 1960s. These flips seem to have been induced by changes in climate associated with the North Atlantic Oscillation. The essence of this theory is contained in Allen's (1985) interpretation of the work of Ilya Prigogine (see, for example, Nicolis and Prigogine, 1977; Prigogine, 1980) on chemical systems. Nicolis and Prigogine consider ecosystems to be thermodynamically open dissipative systems. Natural systems are open, usually have strong inputs and outputs, and have strong internal coupling between elements. Although they may appear to be stable (dynamic stability), they are in fact accompanied by incessant fluxes of energy and materials and are maintained far from equilibrium. Prigogine coined the term *dissipative* for structures that are formed in response to the fluxes themselves. They are formed within the system and obtain the energy for their formation from the dissipation of energy flowing through the system. In fact, the flow of substances through the system can cause tension in the organization of the system, similar to the tension that occurs between tectonic plates prior to an earthquake. In this way, systems can flip from one state to another, causing quite drastic alterations in system structure, and yet the alterations in system structure may be triggered by changes in system fluxes that are themselves relatively small. In the words of Margalef (1986), the impetus for these changes in system fluxes can come from climate-induced energy "kicks" which tend to disrupt or decouple a number of ecological relationships within the ecosystem.

#### Summary

Marine ecosystems are complex structures in which significant (re-)ordering occurs in both top-down and bottom-up directions. The key aspects are the roles of rates (e.g., natural frequencies) and time (e.g., cascading trophic interactions and infrequent but often rapid changes in physical forcing due to climate change). In addition, most of the marine fisheries ecosystems with which we are presently concerned have very substantial pieces missing; i.e., major components with which the current fish community evolved and interacted are no longer there in any significant numbers (Apollonio, 1993). Some populations, such as large whales, have been harvested to the point of extinction. Others, such as marine fish, have both been reduced in absolute abundance and had their population structure altered by the significant truncation of their age structure. Because of its reactive nature, fisheries science has seldom if ever considered a marine community before exploitation and frequently does so only after heavy exploitation. This combination of factors has significant effects on the Bering Sea ecosystem.

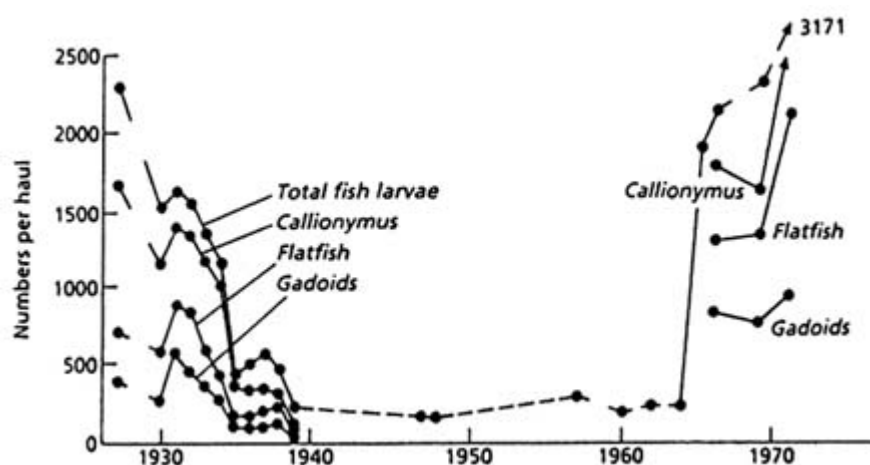


Figure 2.1 The Russell Cycle of the western English Channel (Mann and Lazier, 1991).

### OCEANIC AND TERRESTRIAL ECOSYSTEMS

In thinking about the Bering Sea ecosystem, it is important to recognize that extrapolation from terrestrial to marine, and especially to oceanic, ecosystems can be misleading. In particular, marine and terrestrial ecosystems differ markedly in their functional responses to environmental change (Steele, 1985, 1991). Important differences include the following:

- Random environmental forcing of terrestrial ecosystems shows constant variance per unit frequency out to about 50 years, while that of oceanic ecosystems shows increasing variance with decreasing frequency from hours to millennia. Thus, terrestrial ecosystems for periods up to 50 years are inherently more predictable than oceanic ecosystems.
- On time scales of years to decades, oceanic systems are more closely coupled to variations in their physical environment than are terrestrial systems.
- Unlike many terrestrial ecosystems, natural fluctuations in oceanic ecosystems between states of high and low abundance are usually related to long-term climate trends, rather than to internal dynamics.
- Since the amplitude of environmental variability is much smaller in the ocean than on land, marine organisms have less robust internal processes to handle variability at the short periods commensurate with their life spans. Marine populations have different ways of dealing with short-term variance and also respond differently at longer time scales.
- Except at the benthic or coastal boundaries, components of oceanic ecosystems



are subject to circulation and mixing, which affect their dispersal, migrations, and aggregations. In particular, there is a close interaction between reproductive processes and particular patterns of ocean currents and mixing.

- Because most organisms in oceanic ecosystems tend to move or to be moved extensively in three dimensions that include the water column, and they move between trophic levels as they develop, oceanic ecosystems are much less well defined than terrestrial ecosystems and at a given location tend to be more changeable than those on land.

As a consequence of these differences, Steele (1991) concluded that it is inappropriate to apply terrestrial perspectives to marine communities, especially in the context of management or conservation. In particular, he noted:

Large switches in open sea marine communities can last several decades. While these changes can have major economic consequences, they cannot be considered as ecological disasters or even as being deleterious in any way within the marine systems. Such switches have occurred without human involvement, for example before heavy fishing was a factor, but they may be increased in frequency or amplitude by human actions.

However, this is not to suggest that fishing cannot significantly affect the composition of marine fish communities. Events on Georges Bank off New England and Nova Scotia provide a rather convincing example of the effects of intensive exploitation on the composition of fish assemblages. Most of the important groundfish species on Georges Bank have been seriously overfished, and the high fishing effort continued well into the 1990s, despite declines in the catch per unit effort (NOAA [National Oceanic and Atmospheric Administration], 1993). In addition, dogfish and skates increased in numbers and biomass while groundfish and flounders declined; in 1963, dogfish and skates were only about 25 percent by weight of the fish surveyed, while in recent years they have increased to 75 percent (NOAA, 1993).

### ENVIRONMENTAL AND ANTHROPOGENIC EFFECTS

Oceanic ecosystems are affected by environmental change as well as by human activities such as fishing. The oceanic environment changes over a broad range of time scales. In considering large systems, of particular interest are periods of years to many decades; changes over such long periods are usually referred to as climate changes.

The surface layers of the ocean (to 100 m or so) are the principal habitat for organisms in most oceanic ecosystems. Changes in atmospheric circulation and the exchange of energy between the atmosphere and the sea surface cause horizontal flow, vertical mixing, and variation in temperature and salinity of the surface layer. Temperature also serves as an index of more fundamental change in ocean conditions, apart from its direct effects.

The direct effects of climate changes in near-surface temperature (and to a lesser extent, salinity) are principally on distributions of organisms. Thus, prolonged warming of the surface



layer can be associated with invasions of warmth-preferring organisms and reductions in abundance or relocation of the system's usual residents (see, for example, Wooster and Fluharty, 1985). In some cases, regime shifts can occur. For example, after the collapse of the Peruvian anchovy population in 1973, the continuing warm conditions allowed a sardine-mackerel community to establish itself for a number of years (Pauly et al., 1989).

Distributions are also affected by changes in horizontal flow, as are locations of frontal and more diffuse transitional zones between ecological provinces. For example, the Russell Cycle could be interpreted as a decadal-scale relocation of the transition zone between temperate and boreal provinces. Locations and intensities of zones of convergence and divergence are also affected, the latter being related to the supply of nutrients to the euphotic zone. Thus, environmental change can lead to changes in phytoplankton species composition and the primary productivity underlying the ecosystem.

Although the mechanisms have not been well clarified, the effects of environmental change on recruitment have been established (see, for example, Hollowed et al., 1987). A study group of the International Council for the Exploration of the Sea (ICES) (anonymous, 1992) concluded that most fluctuations in fish populations seem to be driven by recruitment rather than by exploitation, with the major fluctuations in recruitment (and subsequently in biomass) being more successfully linked to physical oceanography than to the biological consequences of fish catches. Nonetheless, many marine and anadromous fish populations have been substantially reduced by fishing (e.g., NRC [National Research Council], 1994a; NMFS, 1992). In fact, as discussed in more detail below, it is plausible that anthropogenic removals from the northeast Pacific, Bering Sea, and Aleutians in the 1950s and 1960s could have caused a rapid increase in pollock populations, which, in turn, could have caused the current declines in sea lion and bird populations of the region.

Particular sets of environmental conditions appear to favor the production of strong year classes, and different species have different environmental preferences. Thus, over periods of several years, the mix of species in an ecosystem can be altered by environmental change (Hollowed and Wooster, 1994). This effect is, of course, in addition to that caused by removal of selected species by fisheries.

It is often alleged that overfishing is a major cause of ecosystem damage. Certainly large-scale fishing operations reduce populations of target and incidentally caught species and thus affect predators, prey, and competitors of these species. These effects are commonly seen as evidence of overfishing. For example, Goni et al. (1993) stated, "After several decades of intense fishing in the Eastern Bering Sea, the Aleutian Islands, and the Gulf of Alaska, a number of fish stocks have been overfished, with signs of depletion and ecosystem disturbance apparent in associated marine populations."

Although the meaning of the term is ambiguous, *overfishing* in the context of fishery management is generally defined as "a [fishing] rate in excess of sustainability" (Rosenberg et al., 1993). In 1992, 95 stocks were managed under federal fishery management plans and had approved definitions of overfishing under the Magnuson Fishery Conservation Act Management Act. Of these, 68 stocks (72 percent) were defined as overfished on the basis of fishing rate without reference to stock abundance. A related term, *overutilization*, is applied when more fishing effort than is necessary is used to achieve long-term potential yield (NMFS, 1992).

While from an economic point of view such overutilization is certainly inefficient, it would not necessarily appear to threaten the continued viability of overutilized stocks.

From a biological point of view, *species overfishing* can be defined as a level of exploitation that jeopardizes the ability of a stock to replace itself. Ultimately, this concept of overfishing implies the threat of species extinction, or at least reduction below a minimum viable population. Although this is unlikely outcome with respect to oceanic finfish, it could apply in the case of marine mammals, as it did, for example, to the Steller sea cow, which became extinct through exploitation by humans.

It is often difficult to tell whether declines in commercial fish populations are due to fishing, environmental changes, or both. Species with relatively short life spans, such as sardines, anchovies, and herrings, are well known to experience large fluctuations in abundance. Populations of such species can decline rapidly even in the absence of fisheries and, under favorable environmental conditions, can quickly recover to high abundance despite very low stock levels caused by either heavy fishing or natural variation (Baumgartner et al., 1992). The ICES study group (anonymous, 1992) concluded that "the collapse of the North Sea herring in 1976–1978 has been linked to overharvesting. However, the recruitment failure which followed can be explained by anomalies in North Sea circulation affecting recruitment processes, as well as by depressed spawning biomass. Whatever the cause, the stock rebounded strongly less than half a decade later."

It can be argued that species overfishing has also occurred when the rate of recovery from low levels has been significantly slowed. This is a problem particularly for the case of stocks with relatively long replacement times. A classic example is Pacific Ocean perch, which was reduced to very low abundance in the northeastern Pacific Ocean by heavy fishing and is only slowly recovering. In this instance, the reproductive potential survived the heavy harvest, as evidenced by the recent increase in population, but it seems clear that the fishery could have been managed to produce more fish at a steadier rate than actually happened.

For a definition of species overfishing to be based on rebuilding, it is necessary to know how a rate compares with rebuilding in the absence of fishing. Applying the definition would be difficult because of interspecies differences in replacement times, frequency of strong year classes, and response of recruitment to biomass reduction and to environmental change.

In most cases where overfishing and mismanagement have been blamed for declines of nontarget species, as for the pollock fishery and Steller sea lions in the eastern North Pacific, the effects (alleged or actual) have been indirect, and *ecosystem* (or *ecological*) overfishing might be the appropriate term for such effects. Reduction of one component of an ecosystem by fishing can have consequences for other components, especially for predators, competitors, and prey of the target species. Predictability of these consequences is poor for several reasons, including the nonlinear and poorly understood relationships among the components and the accompanying effects of natural variability forced by environmental change.

This discussion suggests that many cases of alleged overfishing, although serious from an economic or social point of view, do not necessarily present any threat to the continued existence or replacement of a target species (with the exception of marine mammals). Ecosystem overfishing, on the other hand, can also have a variety of serious effects, but it is difficult to demonstrate because the effects of significant removals need not to be direct and are not always consistent with intuition.

## THE CONDITION OF AN ECOSYSTEM

It has been charged that the Bering Sea ecosystem has been damaged by human activity. This charge is based on (1) the greatly increased level of human activity, especially commercial fishing, since the 1960s, and (2) unexpected and unexplained changes in important components of the ecosystem (e.g., some pinnipeds and seabirds). Indeed, human removals from certain populations have been large (e.g., more than a million tons [t] of pollock per year), with likely effects on other species (predators, competitors, prey) and probable changes in the proportions of various species components of the ecosystem. Regarding unexplained populations changes, some declines appear to have been unprecedented, but some other species have increased, and the relative importance of alternative causes of these changes (e.g., fishing versus environmental change) has not been determined.

Doubtless the Bering Sea ecosystem has changed and has been changing throughout its existence. Before the eighteenth century, the changes must have resulted mainly from environmental forcing and internal restructuring. Human activity since the late eighteenth century eliminated one species (Steller sea cows) and greatly reduced other populations (e.g., some whales and fur seals). Commercial fisheries for finfish and crustaceans increased enormously from the middle of the twentieth century. The charge of ecosystem damage has been most often applied during the last few decades, to the large pollock fishery, and to the declines of Steller sea lions, harbor seals, and certain seabirds.

What criteria are appropriate to determine the condition of an oceanic ecosystem? Change is certain, and the desirability of a specific change is a value judgment reflecting human, not ecosystem, preference. Reversibility is said to be a desirable attribute, but irreversible changes can occur in ecosystems free of human influence (e.g., extinctions). The rapidity of change is not necessarily diagnostic (crashes can occur in populations in the absence of human activity), nor is surprise, which can reflect misunderstanding of ecosystem behavior as much as the nature of the ecosystem itself. Similarly, the rate of response to external forcing may be a function of species composition—a whale-dominated ecosystem probably would have response times different from those of one dominated by pollock.

The most useful diagnostic may be comparison of the observed rates of change of selected ecosystem components with those expected to occur. Expectation may be based on historical records from that system or changes observed in analogous systems. Apart from this, there appear to be few, if any, objective criteria that can be used to determine if an oceanic ecosystem has been adversely affected by humans.

## ECOSYSTEM MANAGEMENT

Ecosystem management in the marine environment lags substantially behind the record of terrestrial progress both in conceptual development and in application. Management in the oceans is still typified by a focus on maximizing yields or economic profits from individual resources without an understanding of the ecosystem processes required to sustain those resources. This substantial disparity between the goals of management in marine and terrestrial environments may be due to our lack of perception of some of the fundamental differences

between marine and terrestrial ecosystems mentioned earlier or due to other conceptual problems such as (1) gross undersampling of the marine environment and consequent poverty of information on its biological diversity; (2) widespread ignorance of the functional dynamics of marine (especially pelagic) ecosystems; (3) the openness and interconnectedness of marine ecosystems on a scale that exceeds greatly the bounds of any management authority; and (4) a perception that intense exploitation of marine resources has sufficient economic and social value to outweigh any risk of damage to future ecosystem services or any alternative management goal of ecosystem integrity. Only in shallow coastal habitats dominated by sessile organisms emergent from the substrate (coral reefs, seagrass beds, marshes) is ecosystem management practiced to a degree that approaches management of terrestrial lands. For example, the Great Barrier Reef Marine Park Authority in Australia created an effective zoning and management scheme to protect and manage the ecosystem services of the Great Barrier Reef (Kelleher and Kenchington, 1992).

The management of natural resources, including especially timber resources and marine fish stocks, has been undergoing a major change during the past decade (Sherman, 1991). The traditional management of natural resources has been based on formulations of the dynamics of the individual species in question. In fisheries, single-species models, especially those of Ricker (1958) and Beverton and Holt (1957), have been instrumental in determining management decisions with an intent of achieving optimal sustainable yields of the fish stocks in question. This approach has been recently modified to reflect the realization that species do not exist in isolation, independent of other species in the ecosystem. The National Marine Fisheries Service has developed and employed multispecies models and has expressed commitment to the principles of *ecosystem management*.

Although ecosystem management is widely perceived as the goal of modern fishery management, it is not clearly defined in an operational sense. Ecosystem management usually refers to either attempts to manage human activities to achieve specific ecosystem characteristics or products, or attempts to keep the whole ecosystem in mind when managing (or harvesting) particular components. The latter is usually easier to put into practice than the former (NRC, 1995). A committee of the Ecological Society of America recently described ecosystem management (Ecological Society of America, in press). The unanimous judgment of that committee was that ecosystem management does not imply any specific management goal, such as preserving biodiversity or promoting one value basis for a resource over any other, but rather that ecosystem management simply reflects a formal acknowledgment that species populations are nested within an ecosystem such that interdependencies among ecosystem components must be identified and included to achieve any specified management goal. However ecosystem management is defined, establishing preference among incompatible management outcomes requires negotiation among stakeholders, who may have conflicting values and priorities.

The management goal of sustaining ecosystem composition, structure, and functioning implies that human actions can be mandated to produce desired consequences. But practical implementation of ecosystem management as defined above is difficult and may be impossible in marine ecosystems, for several reasons:

- Control over human activities is inadequate.

- Many key ecosystem elements are not monitored or harvested commercially, and the cost of monitoring them is often considered unacceptable.
- Within any oceanic ecosystem, the interactions among organisms and between them and the abiotic environment are poorly understood and difficult to quantify and are likely to remain that way for the foreseeable future.
- Because the interactions are nonlinear and the systems are inherently dynamic and complex, their predictability is inherently limited.

Inasmuch as needed understanding of cause and effect is generally unavailable, protection of the ecosystem requires management to be risk-averse. Conservatism is also necessary because the desired control of human activities often cannot be fully achieved. The conservative approach can be relaxed if management is experimental or adaptive. For these approaches to be successful, tight control, comprehensive monitoring, and quick response by management to changes in forcing both human or environmental and ecosystem reaction are essential.

Another key element to the concept of ecosystem management is a point made by Norton (1992): human cultures and institutions change much faster and, generally, at a smaller spatial scale than the ecological systems they are related to. As Norton pointed out, *resource management* generally operates on an annual cycle, whereas *environmental management*, governed by constraints necessary to protect the self-organizing and self-regulatory resource system, must operate on much longer time scales.

Marine ecosystems are influenced by actions taken by a wide spectrum of management agencies. Coastal estuaries, bays, and oceans to a distance of three miles offshore in the United States fall within the purview of individual states. States take responsibility for management of fisheries resources within this coastal fringe, although regional management councils play an increasing role in integrating state programs on migratory stocks shared among several states. The National Marine Fisheries Service of the National Oceanic and Atmospheric Administration has responsibility for management of fishery resources from 3 to 200 miles offshore. Similarly, states can manage the exploitation of minerals, including oil and gas, within 3 miles of the coast, whereas the federal (Department of the Interior) Minerals Management Service makes management decisions for the 3 to 200 mile zone. Various federal laws mandate federal agency review of state land use management to protect certain marine habitats, notably marshes and submerged aquatic vegetation (seagrasses, etc.) and to protect endangered and threatened species. State environmental management authorities influence the integrity of coastal marine ecosystems by permitting discharges of nutrients, oxygen-consuming materials, and other chemicals into rivers that flow to the seacoast. These same authorities regulate emissions of greenhouse gases, which threaten the ecological integrity of all marine ecosystems via changes in global climate. States also have responsibility for regulation of land development so as to prevent erosion of soils and enhancement of turbidity of coastal marine waters and sediment deposition on the seafloor.

Marine ecosystems include some of the best and some of the least understood of all the world's ecosystems. The processes that organize ecosystems on intertidal and shallow subtidal rocky shores are particularly well understood. The intertidal zone has been subjected to intense observation and a wealth of imaginative experimental manipulations, revealing much about the functional basis of these ecosystems (e.g., Connell, 1972; Paine, 1980). On the other hand,



marine pelagic and deeper sea-bottom communities and ecosystems are rarely studied as functional ecosystems. Experimentation is difficult and sometimes impossible in these environments. Only a small minority of the ecological players are described and ecosystem dynamics are typically unstudied. At the federal level, the National Marine Fisheries Service has made a commitment to development of ecosystem-management by choosing practices that preserve the health and sustainability of marine ecosystems (NMFS, 1991). However, management of marine fisheries in the context of the broader ecosystem is rare. A widespread international movement exists to urge management of marine resources as ecosystem units (LMEs) (Sherman, 1993). This approach represents ecosystem management of marine resources, but it is difficult to implement without better understanding of the processes that control function and structure of these ecosystems. One of the best ways to improve our understanding of process in these systems is to use management as perturbation experiment and thereby practice adaptive management of these systems. This approach holds great promise for advancing both our process understanding and our management.

The LME approach recognizes the wide spatial scales over which most marine ecosystems extend. Nevertheless, these scales differ for different species and the management of even a single LME challenges existing management structures. Many natural marine ecosystems extend into international waters, where complex treaty agreements may be required for their effective management as ecosystems. Many LMEs have important component species with life stages that depend on coastal habitats and thus respond to management decisions made at the level of the state (within the United States). Where pollution from terrestrial runoff is degrading an LME, the range of management authorities that require coordination is even greater. Ecosystem management as applied to pelagic marine ecosystems demands a fundamental change in our management institutions and integration among them.

Transition from commodity to ecosystem management in the sea also will require public involvement to be successful. There is now abundant evidence that humans have changed and degraded many marine ecosystems by many means (Norse, 1993). Overexploitation has caused extinctions and dramatic reductions in populations of many of the larger marine animals, especially whales and other marine mammals, sea turtles, and seabirds. Intentional and accidental introductions of exotic species through importation for aquaculture, release of ballast waters, and other mechanisms have changed many marine ecosystems (Carlton and Geller, 1993). Eutrophication of coastal estuaries and bays has affected ecosystem structure and functioning. Habitat alteration through fishing practices such as trawling, dredging, and dynamiting is widespread in coastal habitats (e.g., Riemann and Hoffmann 1991). The influence of fishing both on targeted species and on species incidentally caught has altered the composition and functioning of many marine ecosystems (Norse, 1993; NRC, 1994a).

Despite the substantial and compelling list of human alterations of natural marine ecosystems, the economic and social importance of fisheries resources may continue to drive marine resource management in its traditional commodity-based mode. Social and economic pressures contribute strongly to marine fisheries management. Skepticism over the argument that present exploitation schemes threaten long-term sustainability provides a selective force for setting short-term goals of maximizing yields. Several fisheries scientists argue that these social and economic pressures for short-term gain have resulted already in gross overexploitation of many of the world's fisheries resources (Ludwig et al., 1993). This view is not shared by

everyone responsible for managing the fisheries, and there may be resistance to changing the current practice of marine fisheries management to one based on maintaining ecosystem structure and functioning. Fundamental conflicts between the usual goals of maximizing yields in marine fisheries management and the goals of the Endangered Species Act, Marine Mammal Protection Act, and National Environmental Policy Act remain unresolved even at the federal level in the National Marine Fisheries Service, as illustrated by the present groundfish management by the North Pacific Fishery Management Council, which does not explicitly orient management to provide additional food resources for the threatened Steller sea lion or for other declining marine mammals and seabirds in the Bering Sea and Gulf of Alaska ecosystems (NPFMC, 1993). At the state level, ecosystem management is even less contemplated and almost never practiced. Public opinion must play a vital role in resolving these conflicts and in setting limits to the application of ecosystem management in the seas.

### THE BERING SEA ECOSYSTEM AND ITS ANALOGS

The Bering Sea ecosystem is not unique among oceanic ecosystems in its response to environmental and anthropogenic forcing. Most such systems in temperate and higher latitudes have experienced similar decadal-scale environmental fluctuations, along with continued, usually increasing, fishing pressure, accompanied by significant changes in the abundance of commercially important and other fish populations. In most cases, the systems include marine mammals as top predators. Indeed, the distribution of pinnipeds overlaps that of most commercially important fish stocks. This is perhaps not surprising as pinnipeds often feed directly on these stocks or share prey consumed by these fish stocks.

Oceanic ecosystems with substantial fisheries and pinniped populations are of particular interest. The most similar system is that of the eastern Gulf of Alaska, where Steller sea lion populations are stable or increasing off both southeast Alaska and British Columbia. Otariids (sea lions and fur seals) also occur in eastern boundary current systems (off California, Peru-Chile, and southwestern Africa), as well as off the Kuril Islands and Japan. In these and other regions of high oceanic productivity, other seal species (phocids) are found. Two seasonally ice-covered seas are similar to the Bering Sea in many ways. The Okhotsk Sea has both Steller sea lions and northern fur seals and the same phocid species as the Bering Sea. The Barents Sea, although having no otariids, has most of the same phocid species.

The effects on other species in the ecosystem of reductions in key species abundances by fishing have rarely been established. In particular, the indirect effects of fishing on pinniped and seabird populations have been poorly documented. Some information on the co-existence of pinnipeds and fisheries is available from Peru and South Africa.

Off Peru, the fur seal population was driven to low abundance by commercial exploitation and despite restrictions, some killing of this species and the local sea lion continues. Anchovy has been an important component of the diets of both species. Studies on the fur seal suggest that the diet reflects the availability and abundance of prey, so that when anchovy is scarce, a wider range of prey is taken, as occurred after the collapse of the anchovy population in the early 1970s. According to Majluf and Reyes (1989), "Recovery of these marine mammal populations to their former levels is...unlikely, since the biomass of anchoveta necessary to

maintain large numbers of sea mammals is no longer available." Nonetheless, even with continuing exploitation mortality, the biomass of pinnipeds in the Peru Current region increased by a factor of three from 1955–65 to 1975–85 (Muck, 1989).

The South African fur seal is the only species of seal breeding on the coasts of South Africa and Namibia, mostly on the west coast, where the fishing grounds are particularly rich (David, 1989). Since the beginning of the century there has been heavy exploitation, which reached its zenith in 1983 (when the 10-year average harvest was 75,000 pups), after which the industry collapsed, largely for political reasons. The species feeds principally on fishes (74 percent) and squids (17 percent). The quantities consumed are comparable with those caught by humans and by predatory pelagic fish; seals probably account for 5 to 10 percent of the total biomass of vertebrates and cephalopods removed by humans and other predators (Crawford et al., 1992). Yet in the presence of heavy fishing and continuing exploitation mortality, the fur seal population has increased throughout the century, by 1987 exceeding 1 million animals (David, 1989).

Another relevant analog may be the North Sea, where heavy fishing for gadoids and other species has occurred throughout most of this century. While there are fewer species of pinnipeds (in this case, phocids), and their populations are smaller in the North Sea than in the Bering Sea, pinnipeds are important predators of gadoids in both regions (Perez and Loughlin, 1986). While Bering Sea fur seals and sea lions have declined during the last several decades, in the North Sea, grey seal populations have been stable or increased. The same is true of common seals up to and following the sharp decline caused by the phocine distemper virus in 1988 (anonymous, 1992).

These observations, incomplete as they are, suggest that comparative studies of analogous oceanic ecosystems, in part because of their differences in biologies, fisheries, and environmental conditions, could add to the understanding of events in the Bering Sea ecosystem.

### DELINEATION OF THE BERING SEA ECOSYSTEM

Any definition of the principal ecosystem of concern is likely to be equivocal. The offshore boundaries of the system(s) are nebulous, may differ for different trophic levels, and may shift with time as environmental changes occur.

Sherman and Alexander (1986) proposed that logical units for research and management related to marine living resources are LMEs, which they defined as extensive areas of ocean space of at least 200,000 km<sup>2</sup>, characterized by distinct hydrographic regimes, submarine topography, productivity, and trophically dependent populations. It is relatively easy to think in these terms when the LME is clearly bounded (e.g., in an enclosed sea) or has characteristic boundaries and features that are relatively repeatable (e.g., eastern boundary coastal upwelling ecosystems). The situation is less clear in the Bering Sea, for which three relevant LMEs have been identified (Sherman, 1993): the eastern Bering Sea, the western Bering Sea, and the adjacent Gulf of Alaska. In this scheme, the Bering Sea is divided by the shelf break and, in the north, by the international boundary; the "Gulf of Alaska" extends offshore for 200 miles and south to the Straits of Juan de Fuca. These domains appear to reflect political more than ecological realities. A more natural division of the Bering Sea is that of Hela and Laevastu



(1962), who identified Kamchatka-Kurile Water, West Bering Gyral, Alaska Coastal Water, Alaska Gyral, and Northwest American Coastal Water.

For convenience, this report considers four domains of the Bering Sea: (1) the continental shelf and slope, east and west, (2) the Aleutian Basin, (3) the Aleutian Islands, and (4) the adjacent Gulf of Alaska (Figure 2.2). The boundaries of these domains are basically physiographic and represent generalized ecological boundaries. The principal exchanges of water take place through Bering Strait into the Chukchi Sea, and in the western Bering Sea where the Kamchatka Current flows south into the Oyashio mixing region; this water is supplied by diffuse flow through the Aleutians. Atmospheric systems that control surface ocean conditions in the region, such as the Aleutian Low, extend well beyond these domains and are influenced by events at much greater distances, such as El Niño Southern Oscillation events in the equatorial Pacific.

The more mobile organisms at higher trophic levels can move among these domains. For example, in the eastern Bering Sea, fish such as salmon and halibut, birds, and mammals move back and forth into the northern Gulf of Alaska. The co-location of a population of animals with an ecological domain varies with time, with life history stages and their migrations, and with environmental conditions. Furthermore, the distributions of populations of interest are rarely identical with those of their prey, competitors, and predators. Both walleye pollock and Steller sea lions are important components of the ecosystems of concern, but the ecosystems they inhabit are not identical, although they overlap substantially, with the extent of overlap varying over time.

Thus, the boundaries of the several ecological domains of interest to this study tend to be ill defined and changeable. This limitation must be kept in mind as we attempt to trace the ecosystem consequences of changes in one or another species component, whatever the causes of these changes.

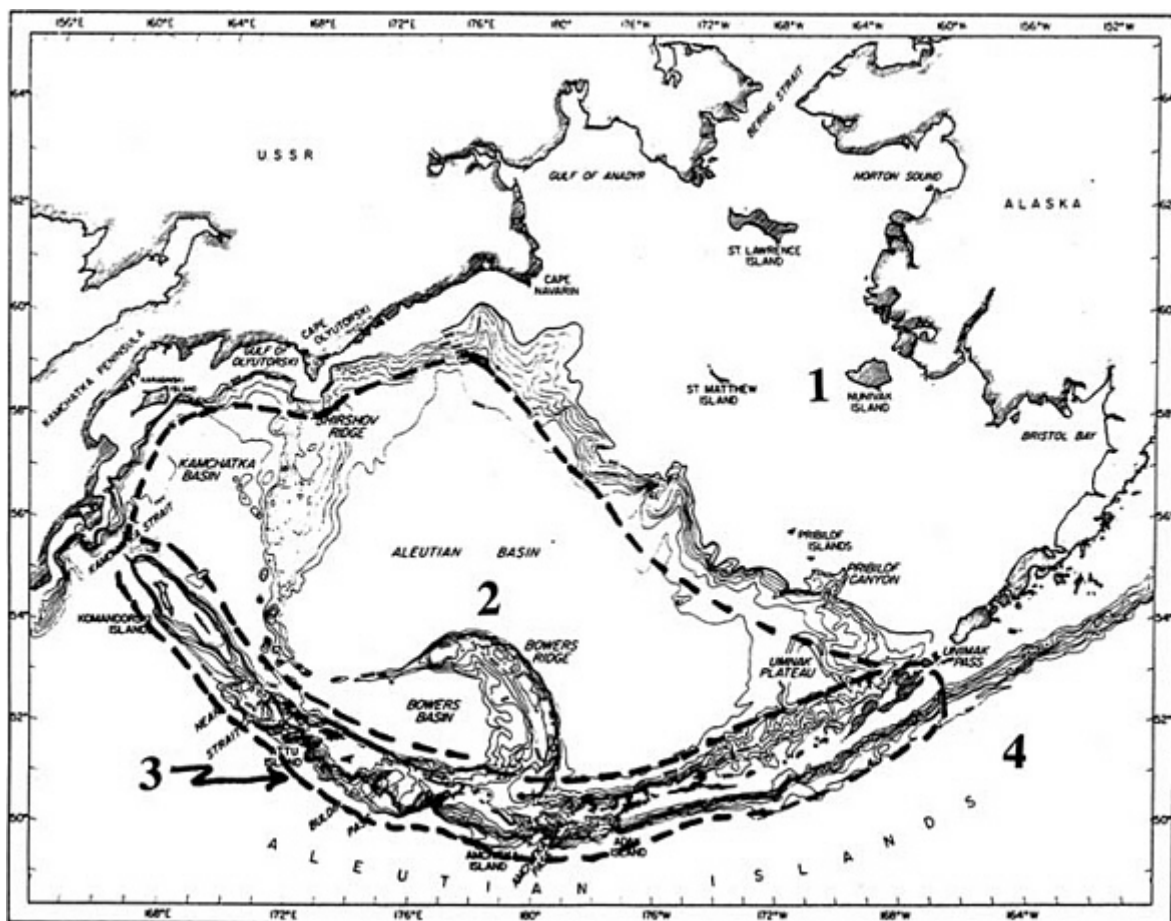


Figure 2.2 Four domains of the Bering Sea: (1) continental shelf and slope, (2) Aleutian Basin, (3) Aleutian Islands, and (4) the northern Gulf of Alaska.

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### 3

## The Bering Sea Ecosystem: Geology, Physics, Chemistry, and Biology of Lower Trophic Levels

### MARINE GEOLOGY

The Bering Sea is framed by the Seward and Chukchi peninsulas on the north, by the Kamchatka Peninsula on the southeast, and a 1,900 km long ridge and island chain that comprise the Aleutians to the south and southwest (Figure 3.1). Geographically, the Bering Sea lies between 52° and 66° north latitude, and 162° east and 157° west longitude. The narrow, 85 km long passage of the Bering Strait connects the Bering Sea on the north to the Chukchi Sea and the Arctic Ocean. This subarctic Bering Sea lies in the northern part of the Pacific Basin. It exchanges water with the Arctic Ocean (through Bering Strait) and with the Pacific Ocean, into the Bering Sea from the Gulf of Alaska through the Aleutian Islands and into the northwest Pacific Ocean through Kamchatka Strait. The Bering Sea covers almost 3 million km<sup>2</sup> and is unusual in having an extremely wide continental shelf, ranging from 500 km wide in the southeast region to over 800 km wide in the north. The Bering seafloor is partitioned into a series of sedimentary basins, the principal of which are (1) the Aleutian Basin, just north of the Shirshov Ridge, Bowers Bank, and Aleutian Islands; (2) Komandorsky (Commander) Basin, adjacent to the Komandorsky Islands, Kamchatka Peninsula, and Shirshov Ridge; (3) Bowers Basin, enclosed by the arm of Bowers Bank; (4) Anadyr Basin, encompassing the Gulf of Anadyr; (5) Chirikov Basin, adjacent to the Chukotka Peninsula and Bering Strait; (6) Norton Basin, between Alaska's Seward Peninsula and Yukon-Kuskokwim delta; (7) Bristol Basin, between the Alaska Peninsula and mainland, and (8) the Beringian Shelf, which encompasses the remainder of the continental shelf from Chukotka Peninsula, St. Lawrence Island, and Alaska mainland southwestward to the extensive submarine canyon system described below (Hood and Kelley, 1974; Sharma, 1977).

The Bering Sea region shelf is unusual from the global perspective in being extremely smooth and generally featureless (Figure 3.2), with the exception of three large and some small islands. Its gradient is among the gentlest in the world (0.24 m/km), with bathymetry less than 200 m deep and a very steep continental margin (Sharma, 1977). This continental shelf is incised by seven of the largest submarine canyons in the world. From north to south, they are Navarin sky, Pervenets, St. Matthew, Middle, Zhemchug, Pribilof, and Bering canyons. The abyssal Aleutian Basin, which lies at depths of between 2,800 and 3,600 m, constitutes the southwest portion of the Bering Sea and is adjacent to the Aleutian Islands, Komandorsky Islands, and Kamchatka Peninsula. Two submerged mountain chains, the Bowers and Shirshov

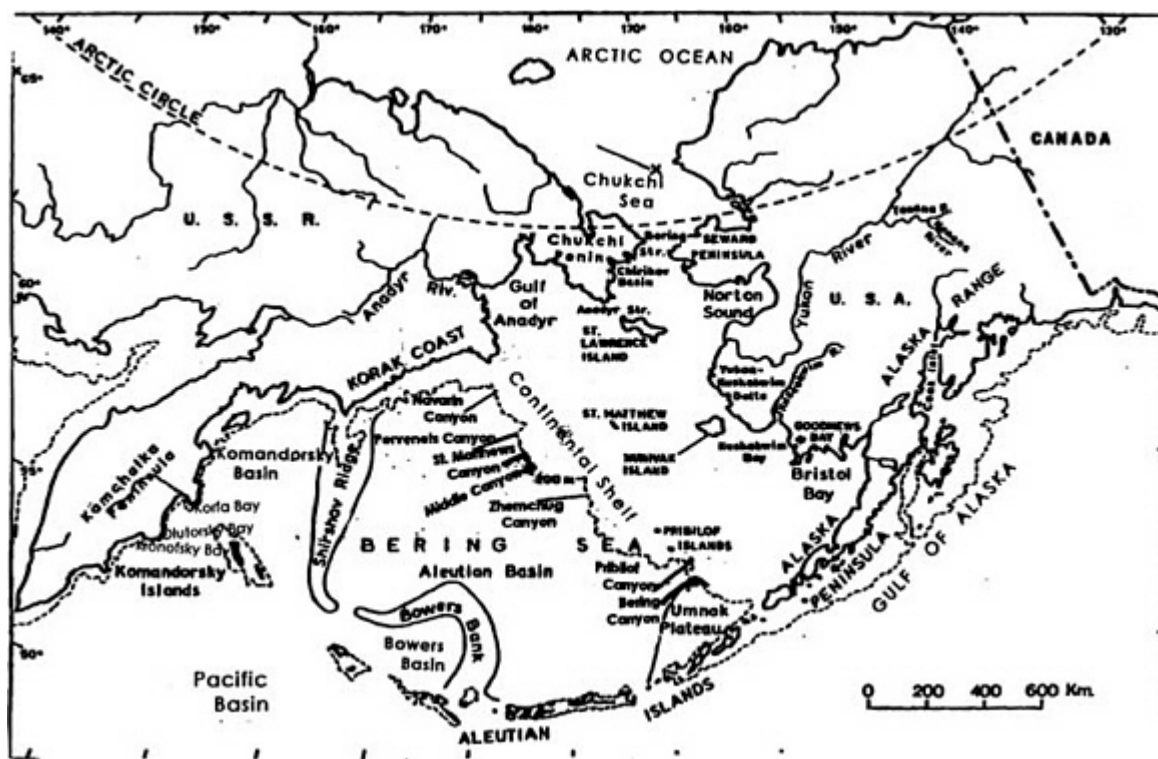


Figure 3.1 Physiographic features of the Bering Sea seafloor (adapted from Hood and Kelley, 1974).

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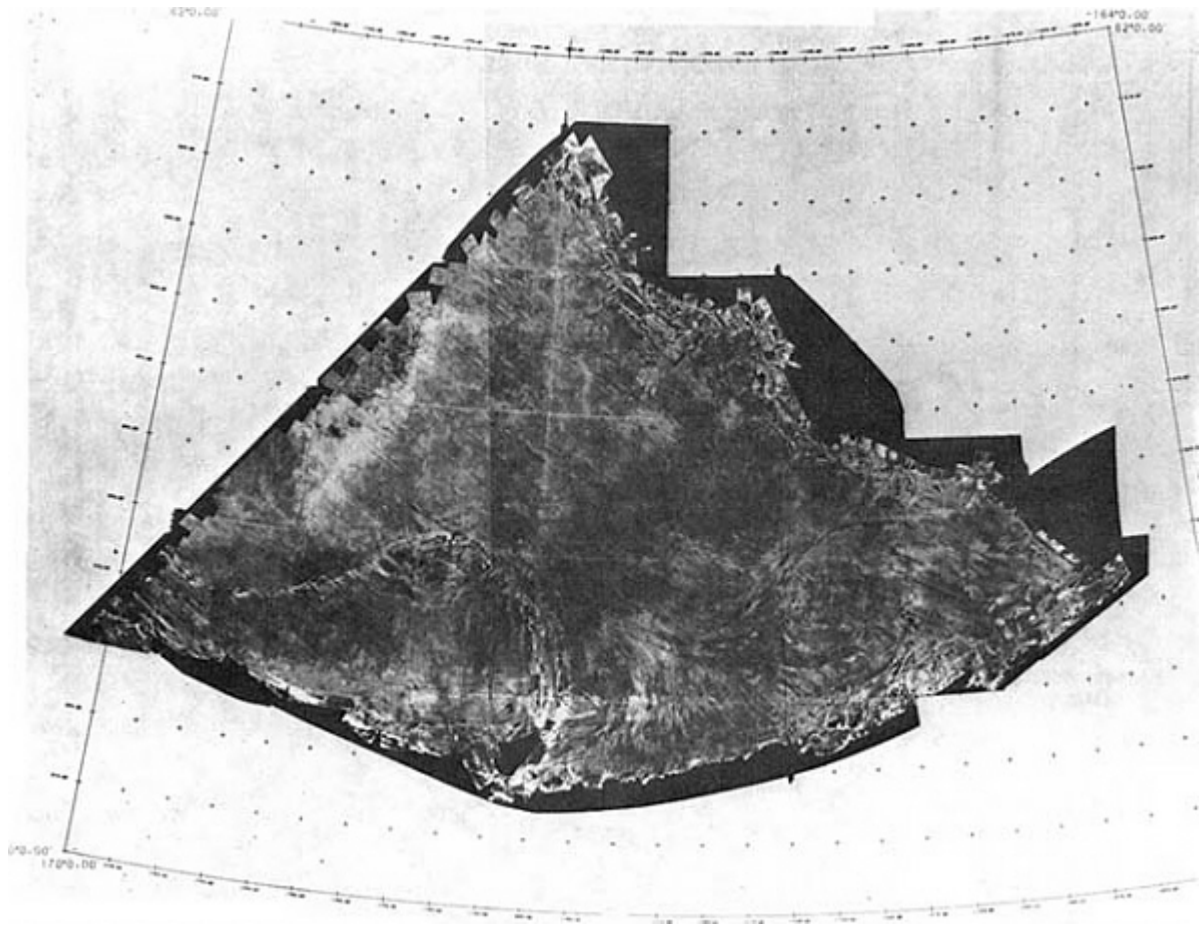


Figure 3.2 A side-scan sonar image of the Bering Sea seafloor (EEZ-SCAN Scientific Staff, Atlas of the U.S. Economic Zone, Bering Sea, U.S. Geological Survey miscellaneous investigations series 1-2053 1991).

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ridges, divide this basin into the separate Aleutian, Bowers, and Komandorsky basins (Cooper et al, 1987a).

The Bering Sea became separated from the rest of the Pacific Basin through evolution of the Aleutian Island arc during the Eocene. This arc of islands with active volcanoes was established at the current site of continental drift and collision, where the northward-moving Pacific is subducted beneath the North American Plate. Preceding the formation of this island arc, the Beringian margin was the site of plate subduction, with fault block basins forming to the southwest in response to tectonic forces. The rocks found in the Alaska-Bering Sea-Siberia region appear to have moved several thousand kilometers northward during the Mesozoic era and were accreted in their approximate current locations by the Paleocene epoch. Bedrock geology of the offshore areas of the Bering Sea is not well known; only a few rock samples have been collected or drilled, leaving seismic reflection geophysical data to provide basic information. The Aleutian Basin is believed to be underlain by Mesozoic oceanic crust, and has been a center for sediment deposition of between 2 and 9 km since formation of the Aleutian Island arc. Deposition in smaller basins, such as the Bowers and Komandorsky, consists of a thinner sedimentary section of between 1 and 3 km. Bedrock underlying the Beringian Shelf is comprised primarily of Paleozoic, Mesozoic, and Cenozoic sedimentary rocks, and Tertiary and older volcanic rocks. Formation of the submarine canyon system of the Beringian margin occurred in Cenozoic glacial periods during low stands of sea level (Carlson and Karl, 1988).

For more detailed discussions of the geologic evolution and history of the Bering Sea region, see Bogdanov and Neprochnov (1984), Carlson and Karl (1988), Churkin (1972), Cooper et al. (1991, 1987a, 1987b), Dundo and Lopatin (1989), Grantz et al. (1970a, 1970b), Hood and Kelley (1972), Lisitsyn (1966), Marlow et al. (1976), Scholl et al. 1966, 1968, 1978), and Sharma (1977).

### Sediments

The configuration of the Bering Sea continental shelf, margin, and abyssal basins, in association with weather patterns of the region, influences the basal physical oceanographic conditions present in the Bering Sea. Circulation models indicate that tides and the Bering Slope Current flow to the northwest paralleling the continental slope, although they are complicated by countercurrents and eddies developed near the canyons (Kinder et al., 1975). The breadth and size of the continental shelf contribute to the huge storm waves of the Bering, which are capable of moving sediment at outer shelf and slope depths. Principal unconsolidated seafloor sediments are gravels, sands, silts and clays derived from previous glacial action, river erosion and deposition, and ice rafting. Again, the shelf is very flat, except for a few basins and banks, with transitory swales and ridges, channels, and depressions. Sediments of the partially enclosed bays, such as Bristol Bay, Norton Sound, and Chirikov Basin, and areas adjacent to islands of the shelf have more sands and gravels than clays, but clays and silts predominate on the deeper shelf.

Accumulations of organic materials in shallow sediments of Norton Sound, Chirikov Basin, and elsewhere in the northern Bering Sea have undergone chemical transformation into natural gases. Gases ranging from methane to carbon dioxide have been found to seep into the

water column at a variety of seafloor locations either derived from circular blowout pits or along faults. It has been postulated that the gas has a proclivity for release during storms when shallow sediments are disturbed by wave-action. These sites can be extensive: 7,000 km<sup>2</sup> in Norton Sound alone are underlain by areas of potential shallow gas pockets (Larsen et al., 1980). The effects of gas seepage on marine life in the Bering Sea, positive or negative, are unknown at this time.

Sediments deposited annually in the Bering Sea are derived primarily from the Yukon River (88 to 100 million metric t), with lesser amounts from the Kuskokwim (4 million t) (Sharma, 1977) and the Russian coast. Plumes of sediment from the rivers draining the Russian and Alaskan coasts are easily seen in satellite photography, and these plumes concentrate suspended sediment load near the coastal regions. Sharma (1977) details the mechanisms of ice rafting of sediment: fine sediments are apparently incorporated during ice formation from suspended sediment in water and resuspension of bottom sediment by storm waves in shallow water; ice-rafted clay, silt, and biogenic materials drop into the water column after the winter months along the receding ice edge margin—amounts have not been quantified. Bottom sediments derived from the Alaskan mainland rivers and coastal erosion are deposited on the seafloor and then swept by northward currents toward the Bering Strait. Sediments from the Russian coast deposited on the Bering Shelf are swept northward and eastward toward the Bering Strait as well. Materials derived from the Aleutian Islands and Kamchatka Peninsula are mostly deposited into the abyssal basins. [Figure 3.3](#) shows sediment distribution on the northern Bering Sea shelf.

### Coastal Geography

Geography of the coastal areas bordering the Bering Sea is strongly influenced by the geologic forces that shaped and are shaping the region: the relentless erosional forces of the Bering itself and the subarctic climatic conditions. *Alaska Regional Profiles* (undated) contains detailed maps and descriptions of the coastal regions of Alaska, while *Landscape Atlas of the USSR* (Plummer et al., 1971) profiles aspects of the Russian coast. The local topography and resultant water, surface materials, and vegetation affect the presence of local and regional biota.

The southern border of the study region is bounded by the Aleutian Islands, a chain of volcanic islands, many of which are still active, driven by tectonic forces. The islands extend more than 1,100 miles (1,770 km) and consist of more than 50 islands, in five groups, separating the Bering Sea from the northern Pacific Ocean. The Aleutian and Shumagin islands are low mountains with steep to moderate slopes and rolling topography. Plateaus and uplands occur in some places in the chain. Elevations of the islands range from sea level to nearly 5,000 feet (1,524 m). A good number have wave-derived terraces up to 600 feet (183 m) above sea level, and are bordered by lower sea cliffs from previous sea level stands. Generally broad and flat intertidal platforms derived from glacial period sea level changes surround some islands. Those islands with peaks higher than 3,000 feet (914 m) were heavily glaciated and include fjords extending up to 2,000 feet (610 m) into the sea. Frequent lakes occur in ice-derived basins on islands showing signs of glaciation, while streams move water in high-gradient descent



to the ocean. Where volcanoes have erupted in the recent past, the presence of ash, cinders, or lava has either killed local vegetation or provided a poor substrate that is resistant to revegetation for a number of years.

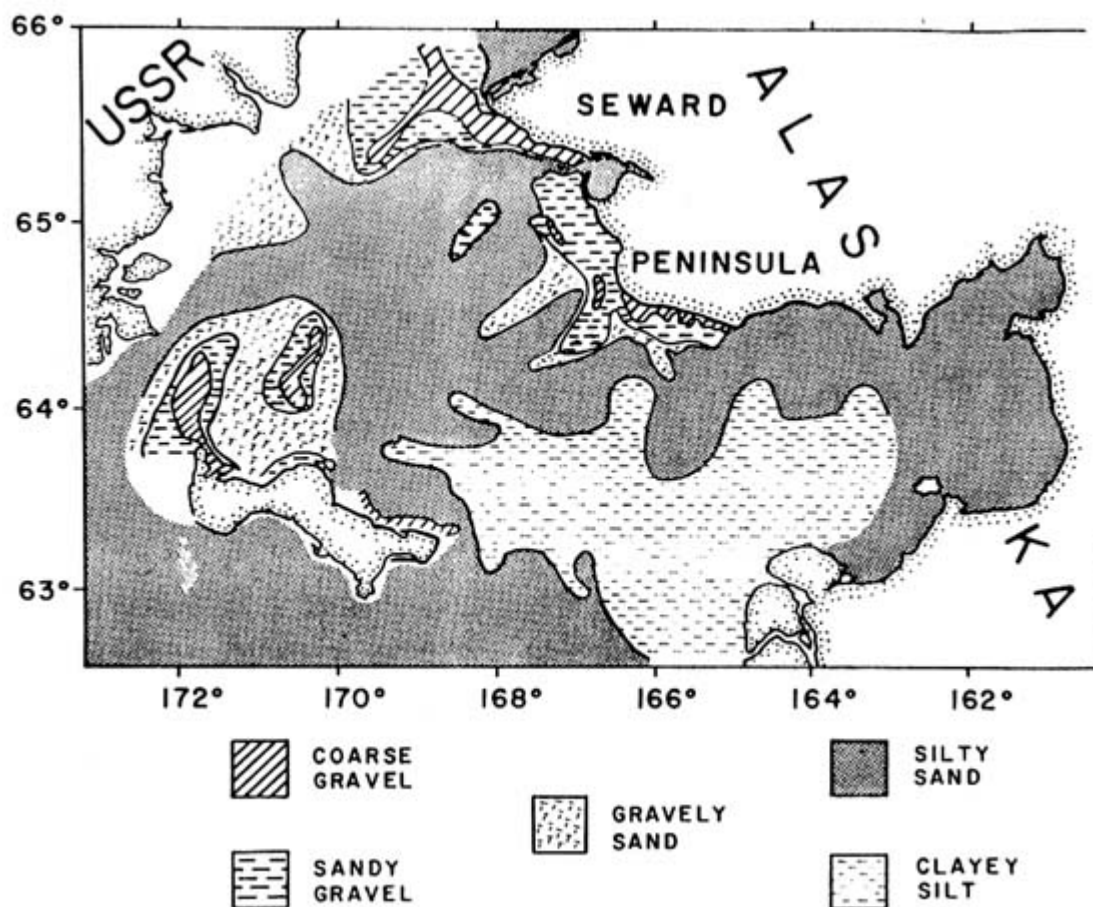


Figure 3.3 Sediment distributions of the Bering seafloor based on data from Sharma (1977) and Hood and Kelley (1974).

The Pribilof Islands are five small islands in the Bering Sea that lie 200 miles (322 km) north of the Aleutian island Unalaska. St. George, one of two populated islands in the group, has hills and ridges with steep cliffs rising up to 900 feet (274 m), whereas St. Paul has a rolling plateau with some extinct volcanic peaks. The islands of St. Matthew, Pinnacle, and Hall are located in the Bering Sea north of the Pribilofs and approximately 220 miles (324 km) west of mainland Alaska. These islands have volcanic ridges separated by valleys; highest elevations of approximately 1,500 feet (458 m) are associated with volcanic cones. Shorelines of these islands are mostly quite steep, and St. Matthew has some lagoons and freshwater lakes.

Islands of the Bristol Bay area of Alaska have extensive glacial outwash and morrainal deposits at the base of volcanic islands at their cores. These sediments are bisected by streams and small lakes, and include beaches with sand dunes. Other parts of the southwestern Alaska coast have unconsolidated gravel, sand, silt, and clay of glacial origin. Lowland deltas and

coastal plains have formed in the material, with extensive beaches, spits, and offshore bars, dunes, and islands.

Permafrost—permanently frozen ground, remaining frozen at least one winter to the next—is found throughout much of Alaska and the Russian Far East, with depths of less than 1 m up to 610 m (2,000 feet) or more bordering the Arctic Ocean. In general, permafrost is mostly absent in the Aleutians and Alaska Peninsula, discontinuous in the area south of the Kuskokwim River (60° north latitude), and continuous to the north along the coast. Similar depths have been reported in Russia, with the southern permafrost limit found in the south-central Kamchatka Peninsula, then stretching north to the Bering Strait; the highest content of ice is found in the deposits of the northern coastal plains and islands of Novosibirsk, where ice may constitute 10 to 15 percent of the soil at depths up to 10 m (30 feet). Permafrost limits rooting depth of plants. Where an active layer that thaws in summer and refreezes in winter may be present in the permafrost, the melting results in small pools of standing water conducive to marsh and tundra development and accumulation of peat deposits. Certain kinds of features are formed in permafrost environments that border the Bering Sea coast including polygonal ground, stone nets, thaw lakes, and beaded drainage (Ferrians et al., 1969). Small areas of high brush, spruce-hardwood forest, and spruce-poplar forest occur only along drainages of the major and some medium sized rivers that drain toward the sea (the Kuskokwim and Yukon, for example). High brush may be found along the largest of the Aleutians in southerly-facing mountain slopes primarily bordering the Pacific Ocean.

The southwestern part of Alaska is one of the most seismically active areas of North America and the world. Over the last 100 years, nine Alaskan earthquakes have been recorded with magnitude of 8 or greater on the Richter scale, with a large number of additional earthquakes registering 7 or more. The results of these earthquakes include faulting, cliff collapse, landslides and slumping, changes in water drainage patterns, tsunamis with their resultant wave-based erosion and destruction, underwater slumps, and increased water turbidity (Eckel, 1970). The most recent destructive earthquake in the region (magnitude 7.5) struck the Kamchatka Peninsula in June 1995.

Volcanoes and volcanic ranges border nearly the entire Bering Sea coast. Nearly 30 active volcanoes are found in the southwestern part of Alaska, almost all of which have been active since 1760 (Alaska Geographic, 1976). Kamchatka has 127 volcanic cones, of which approximately 15 are active (National Geographic, 1994). Volcanic eruptions result in earthquakes, magma and ash flows into coastal and marine areas, land and water temperature induced changes, changes in local and regional substrates, and increased ocean turbidity in the vicinity and downwind of volcanic ash or magma eruptions. The impacts on local and regional flora and fauna include die-offs from smothering or heat effects, and migration due to changed ecological conditions. In addition, the mountain ranges formed by the volcanoes, especially those along the Russian coast, intercept the landward flow of air from the Pacific, causing localized high precipitation zones.

The Yukon delta consists of tidal flats and lowlands with lakes, ponds, and tundra, and also some highlands, such as the Cape Romanzoff Bluffs. The river deltas of the Yukon and Kuskokwim are significant because they provide a major nesting area for waterfowl, including geese, ducks, and swans. Raptors are not common in tundra habitats, but they are found in cliff areas near rivers and the Bering Sea. The cliffs, such as those at Nunivak, also provide suitable

habitat for seabird rookeries (for kittiwakes, murres, puffins, and gulls). Passerines are less abundant on the deltas than shorebirds, and leave by mid-September. The beaches, sea cliffs, tundra, and willow-lined water courses bring in many smaller birds, including Old World species. The extensive beach environments, ranging from rocky to muddy, attract intertidal fauna that are food sources for large populations of birds and marine mammals. Sandy beaches are particularly important for harbor seals, whereas Steller sea lions are found along the rocky coast. Fur seals prefer the coasts of the Pribilofs. Sea otters inhabit the shallow waters along the islands, where offshore reefs and kelp beds provide safety and food.

Erosion of beaches and coastal marches generally occurs at a slow rate across southwestern Alaska. However, storms can severely affect local or regional areas through storm surges and waves, as undercutting of cliffs and bluffs by waves results in collapse and cliff retreat. The fallen materials become available for redistribution in the sea or down current along the coasts.

## PHYSICAL OCEANOGRAPHIC STRUCTURE

### Physical Characteristics and Bathymetry of the Northern North Pacific and Bering Sea

The circulation of the northern North Pacific and Bering Sea, seen in a global context, serves to transport heat and freshwater poleward. It also replenishes the nutrients in the surface layers to support biological productivity. Changes in this transport system affect heat, salt, and food supply for the Bering Sea ecosystem.

#### The Basins

The northeast Pacific Ocean contains the Gulf of Alaska, a feature bounded on the northern and eastern sides with a moderately wide (100 km) shelf. It has relatively free communication to the south and west. Water depths are in excess of 4,000 m; the deepest feature is the Aleutian Trench, in close proximity to the Aleutian Island arc (Figure 3.4). The Aleutian-Komandorsky Island arc forms a semipermeable boundary between the Gulf of Alaska and the Bering Sea. The ability for water exchange between the North Pacific and Bering Sea depends on the water depth in the passes. Since there are no deep passes east of 180° W, deep water exchange is restricted to the western side of this boundary.

#### Gulf of Alaska Circulation

Deep ocean circulation for the Gulf of Alaska consists of a large (1,000 km) cyclonic (counterclockwise) gyre that advects warm water northward along the British Columbia coast and southeast Alaska. In its northward flow off the British Columbia shelf break, the current

is wide and unorganized (Tabata, 1982). As it is diverted westward at the apex of the gulf, it forms a western boundary current and becomes a much more coherent flow. The currents have speeds of 25 to 75 cm s<sup>-1</sup> and transports on the order of 10 to 30 Sverdrups (Sv) (1 Sv = 1 million m<sup>3</sup> s<sup>-1</sup>) (Dodimead et al., 1963). The current continues southwestward along the shelf break in the western Gulf of Alaska, closely following topography, until it reaches a longitude of about 180° W. Here, it tends to continue on a zonal, or sometimes a southwestward, trajectory (Thomson, 1972).

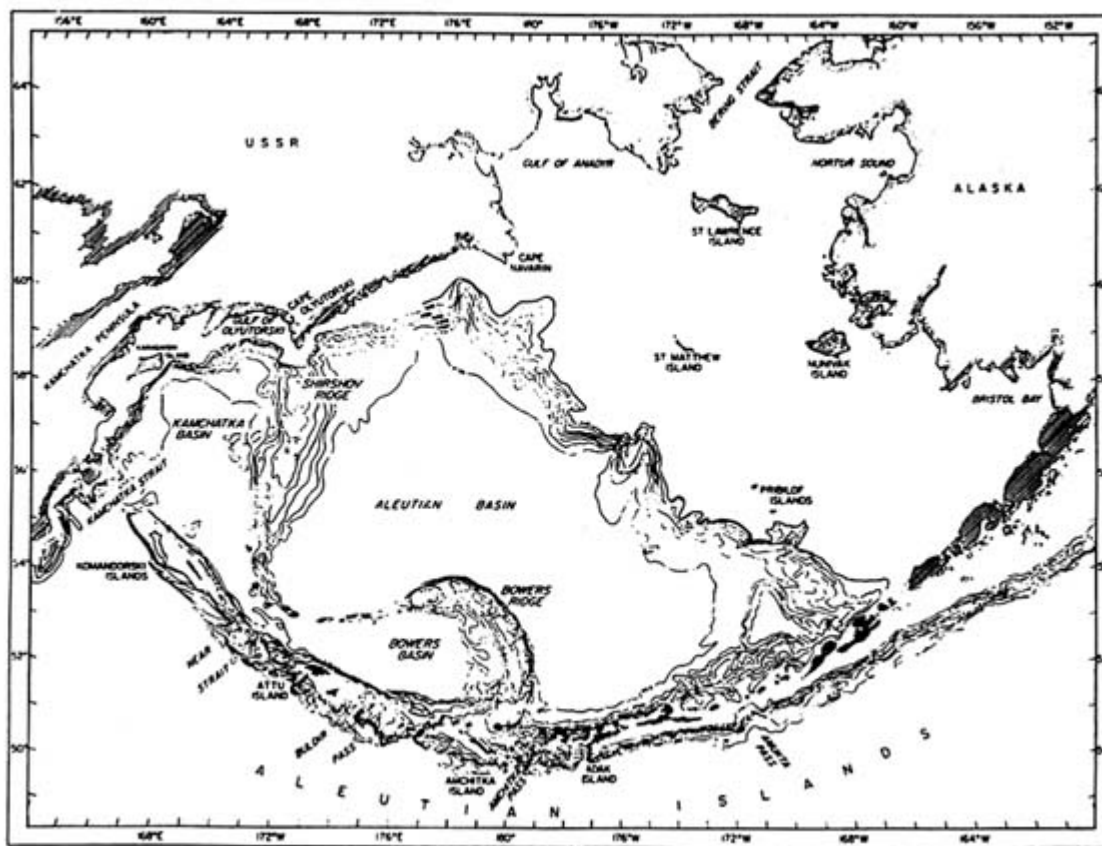


Figure 3.4 Bathymetric map of the Bering Sea (Sayles et al., 1979)

The northern North Pacific is the terminus for the world oceans deep circulation. Deep water formed in other high-latitude regions of the North Atlantic and Southern Ocean reaches the Gulf of Alaska after traveling for centuries. Gulf of Alaska deep waters are therefore some of the oldest waters in the world's ocean and have very high nutrient concentrations. Unlike most other high-latitude regions, the North Pacific is not a site for the formation of deep water. The reason for this absence of deep water is the relatively low density surface water that is created by high rates of precipitation and runoff in the region. The northeast Pacific has been thought of as analogous to an estuary (Tully and Barber, 1960), with the halocline and accompanying pycnocline serving as a cap on the ocean in the North Pacific and Bering Sea.

The deep ocean circulation is accompanied by a very active coastal circulation. High rates of precipitation over the Gulf of Alaska and coastal freshwater discharge around the

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perimeter create a low-salinity surface layer that contributes to a cyclonic flow over the shelf, especially adjacent to the coast (Reed and Schumacher, 1986). On average, more than  $23,000 \text{ m}^3 \text{ s}^{-1}$  of terrestrial freshwater discharge enters the coastal region, creating a buoyancy-influenced alongshore flow in the Gulf of Alaska that is constrained along the coast by the cyclonic (downwelling) wind system. Current speeds in excess of  $175 \text{ cm s}^{-1}$  have been reported for this flow called the Alaska Coastal Current (Royer, 1982). The width of this current is generally less than 20 km. It flows westward in the northern Gulf of Alaska and along the Aleutian Island arc to Unimak Pass, where a portion of it enters the Bering Sea (Figure 3.5). This coastal flow continues around the Bering Sea in a cyclonic sense, until it flows through Bering Strait into the Arctic Ocean.

The exchange of water between the North Pacific Ocean and Bering Sea through the passes in the island arc is quite uncertain. Best estimates are that there is an outflow through Kamchatka Pass (21.0 Sv) (Arsen'ev, 1967) and inflow through Near Strait (14.4 Sv), with smaller inflows through Kiska, Buldir, and Semichi passes (West Aleutian group) of 0.7 Sv and inflows through the Central Aleutian group (Tanaga and Amchitka passes) of about 4.4 Sv. There is also a net inflow below 3,000 m through Kamchatka Strait. New observational results on inflow into the Bering Sea show that flow through Amukta Pass is larger than previously expected (-1 Sv). This inflow is comparable to the flow measured through the much deeper Amchitka Pass. The flow through Amukta Pass is particularly important as a source of warm ( $>4^\circ$  compared to  $-3.5^\circ \text{ C}$ ), subsurface (-200 m) water in the southeastern Bering Sea basin. This flow is intermittent, however. The balance of all of these flows includes a net outflow through Bering Strait of about 0.8 Sv, which is quite certain (Coachman and Aagaard, 1988). Thus, there is something less than 5 percent net throughflow in the Bering Sea; it is extremely important, however to global freshwater flux.

### Bering Sea Circulation and Hydrographic Structure

Flow descriptions for Bering Sea circulation have usually been based on inferences from water properties (Figures 3.5 and 3.6), though Stabeno and Reed (1994) use drifter climatology. There is a general cyclonic flow within the basin, with an intensified boundary current, the Kamchatka Current, and a northwestward-flowing eastern boundary associated with the eastern continental slope. The eastern boundary current flow is characterized as weak and variable, typical of eastern boundary currents elsewhere (Schumacher and Reed, 1992). There are two circulation features along this slope, one being the large, persistent salinity front, and the other being the Bering Slope Current, which transports about 5 Sv of water northwest along the shelf edge at speeds in the range of  $10$  to  $20 \text{ cm}^{-1} \text{ s}^{-1}$  (Kinder et al., 1975, 1986), although the speed in winter may be slower (Royer and Emery, 1984). The current intensifies as a western boundary current as it bifurcates and travels north around the Gulf of Anadyr and through Bering Strait, and south along the Kamchatka Peninsula (Kinder et al., 1986).

The physical basis of the Bering Slope Current is poorly known. Kinder et al. (1975) have suggested that it is driven by planetary waves. There is theoretical and observational evidence that it exists—at times—as a series of eddies, or that it includes eddies, some possibly as permanent features that are generated by topographic interactions, baroclinic instabilities, or

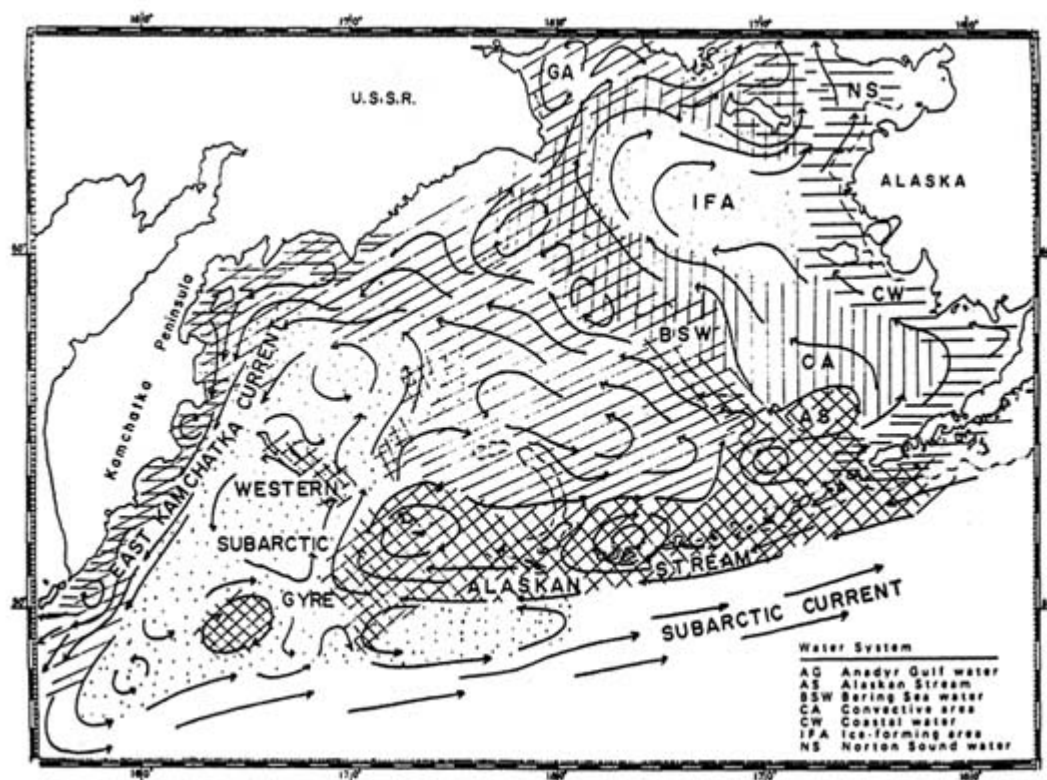


Figure 3.5 Bering Sea circulation schemes with water masses (Takenouti and Ohtani, 1974).

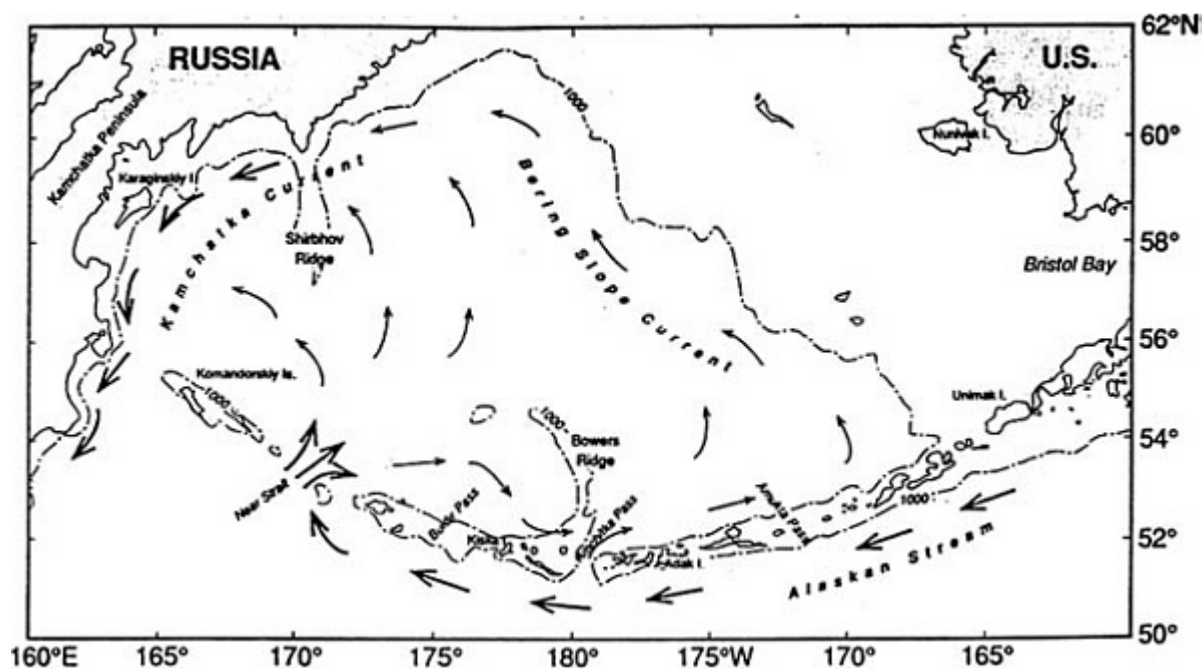


Figure 3.6 Schematic of flow through the passes of the Aleutian-Komandorski chains (Stabeno and Reed, 1994).

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Rossby waves (Karl and Carlson, 1987; Kinder et al., 1975, 1980; Paluszkiwicz and Niebauer, 1984; Royer and Emery, 1984). The eddies are apparent on some satellite altimeter data. Usually, however, it is a well-behaved eastern current. Model results (Overland et al., 1994) and observations (Stabeno and Reed, 1994) show that the Bering Slope Current separates from the shelf break at about 58.5° N. At most a small portion of the current continues to the head of the basin. For the Kamchatka Current, the western and southern branch of the Bering Slope Current in the western Bering Sea, eddies are also apparently a common feature of the flow regime (Verkhunov and Tkachenko, 1992). The transport of water through the Bering Strait from the Bering Slope Current is maintained by a north-south atmospheric pressure differential that tilts sea level down to the north (Coachman et al., 1975).

Hydrographic structure over the eastern Bering Sea is well defined, consisting of three domains separated by physical structural fronts (Coachman, 1986; Coachman and Charnell, 1979; Kinder and Coachman, 1978; Schumacher et al., 1979). The inner front coincides approximately with the 50 m isobath, the middle front with the 80 to 100 m isobath, and the shelf break front with the 170 m isobath (Figure 3.7). The associated domains are referred to as the coastal domain, middle domain, and outer domain. Two other distinct domains exist off the shelf—a narrow, energetic shelf break domain and the oceanic domain. A mixed-layer model reproduces the general structure of the inner, middle, and outer shelves, based on wind mixing, heating, and tidal mixing (Coachman, 1986). The shelf break front is less clearly describable, but is apparent as a change in the horizontal salinity gradient.

There are two water masses on the shelf: Alaska Coastal water and Central water. Coastal water is found shoreward of the 50 m isobath in the southeastern Bering Sea, whereas Central water is found in the middle domain, from the inner front to the middle front at a depth of about 100 m (see Figure 3.7). Alaska Coastal water is the result of coastal freshwater discharge combined with more saline water from the deep basin. It is generally well mixed by winds and tides. Offshore of the inner front, the Central water in the middle domain has a lower layer that is isolated from seasonal heating, producing a two-layer system. Temperatures in the lower layer reflect the prior winter conditions. Water of the outer domain is not really an identifiable water mass, but instead is a mixture of central shelf and Bering Sea basin water. It is less strongly layered because of greater tidal and advective energy (currents), but exhibits vertical fine structure that originates in the middle front and is extremely important to the flux of properties across the domain and vertically in the water column (Coachman, 1986).

Circulation over the shelf is related to domain structure (Coachman, 1986). In the outer shelf, tidal currents account for about 80 percent of the flow, with the mean about 5 cm s<sup>-1</sup> alongshore to the northwest and an onshore-offshore flow of 1 to 5 cm s<sup>-1</sup> that is quite variable on time scales of days. Tidal mixing is very important in the outer domain. In the middle shelf, the only important flow is that due to tides and inertial currents. There is very little net motion. Vertical mixing due to tides is also important here. Tidal currents account for about 95 percent of the flow energy in the coastal zone, and there is a 1 to 5 cm s<sup>-1</sup> mean flow following the 50 m isobath northward (Coachman, 1986). In contrast to the Gulf of Alaska circulation, the circulation of the Bering Sea shelf has relatively small net flows and relatively large tidal forcing.



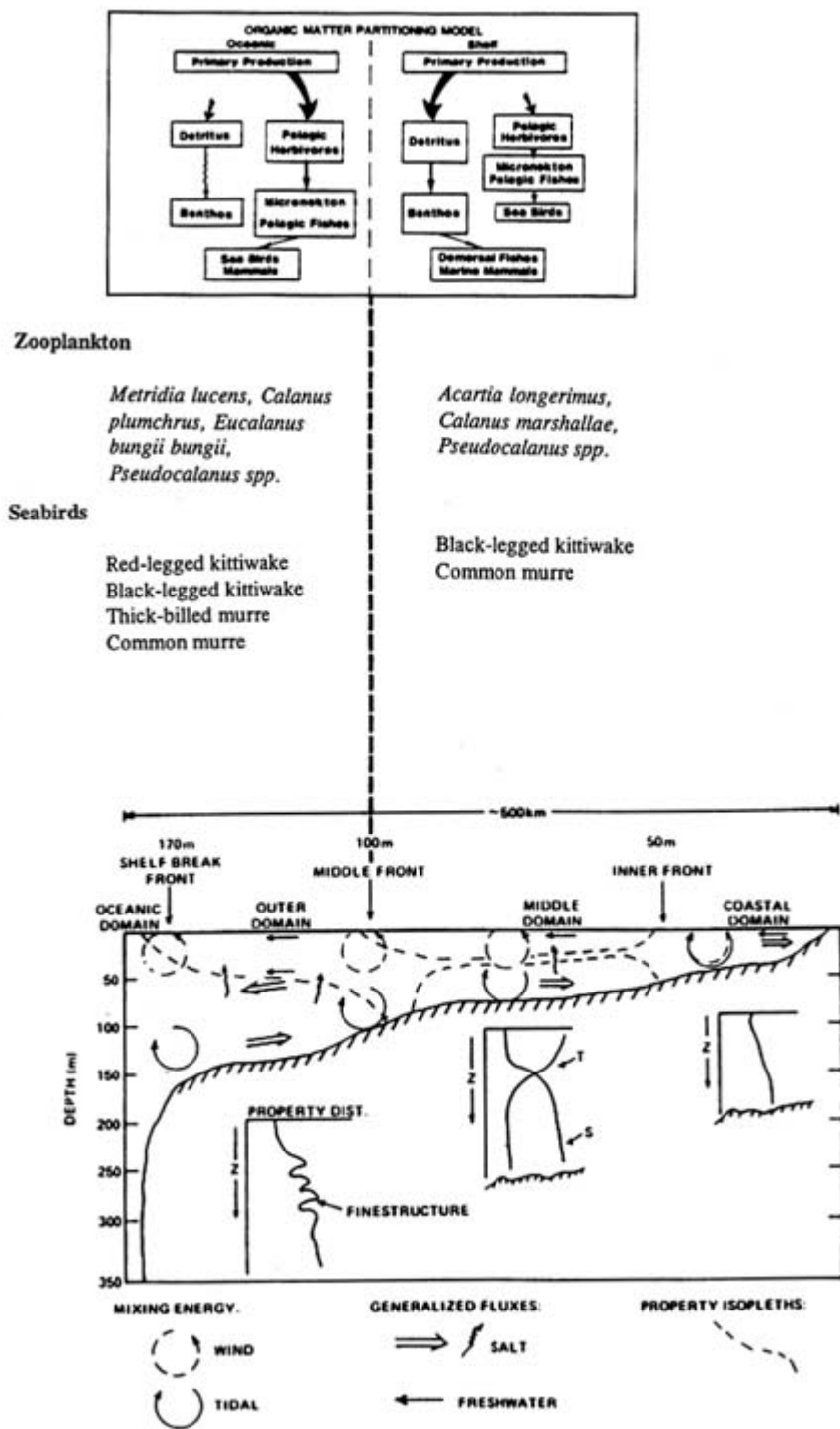


Figure 3.7 A cross-shelf advection model developed by the PROBES, (Processes and Resources of the Bering Sea Shelf) investigators and applied to organic matter partitioning and subsequent distributions of zooplankton and seabirds (McRoy, et al., 1986).

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### Sea Ice

An unusual physical characteristic of the Bering Sea shelf is the annual ice cover that extends more than 1,700 km at its farthest seasonal extent (Walsh and Johnson, 1979). In summer, the ice edge retreats into the Chukchi and Beaufort Seas (Figure 3.8a) (Niebauer and Schell, 1993). In winter, much of the shelf is ice-covered. The growth of ice over deep water is limited by warm water in the central basin (Figure 3.8b). Thus, the maximum extent of the ice is restricted to the shelf (Overland and Pease, 1982).

The sea ice affects exchanges with the atmosphere and inhibits the transfer of freshwater (salt) and heat. It changes the coupling of the oceanic and atmospheric momentum exchanges by altering the surface roughness. The creation and melting of the sea ice alters the horizontal and vertical density gradients. Increases or decreases in the vertical density gradient affect the mixing and transport of nutrients and organisms within the euphotic zone. The ice edge also serves as both source and sink of freshwater that can affect productivity. In fall during freeze-up, freshwater is extracted from the seawater, while during the spring, melting supplies freshwater to the ice edge.

Sea ice is also important in influencing bottom temperatures, and hence influences many species on the shelf. In winter, there is little stratification, and the sea is cold from top to bottom. In colder years, there is more sea ice than in warmer years. The ice helps to cause and maintain stratification when it melts, because water at the melting point of ice is lighter than slightly warmer water. After the ice has melted, the sun further causes stratification, and thus the bottom temperature changes only very slowly. Thus, in cold years—with extensive sea ice—the colder-than-normal bottom temperature is even more persistent than usual (Coachman, 1986); the colder temperatures are also attributed directly to the ice (Ohtani and Azumaya, 1995). Thus, the extent of sea ice is related to the distribution and abundance of temperature-sensitive bottom-dwelling species and some near shore species such as crabs, flatfishes, and herrings.

### Marine Chemistry of the North Pacific and Bering Sea

Measurements of water column chemistry for the North Pacific and Bering Sea are very limited, especially in the coastal regions. Because the deep waters of the North Pacific are quite old, nutrients have accumulated in them during their passage through the deep regions of the world's oceans. An example of the nutrient distribution versus depth can be found in Geochemical Ocean Sections Study (GEOSECS) station 218 (50°27'N, 176°35'W). A layer of maximum nutrients exists at about 1,000 m, with phosphate at about 3  $\mu\text{moles/kg}$ , nitrate at about 4  $\mu\text{moles/kg}$  and dissolved oxygen at about 10  $\mu\text{moles/kg}$ . The dissolved oxygen is at a minimum at this depth, with maximum values approaching 300  $\mu\text{moles/kg}$  at the surface (Reeburgh and Kipphut, 1986).

Cyclonic winds from storms cause upwelling in the deep portions of the Bering Sea and Gulf of Alaska, though the intensity is usually insufficient to bring the nutrient-rich water into the euphotic zone. Van Scoy and others (1991) have evidence from tritium measurements that on rare occasions, the deep water can penetrate the halocline and enter the upper layers.

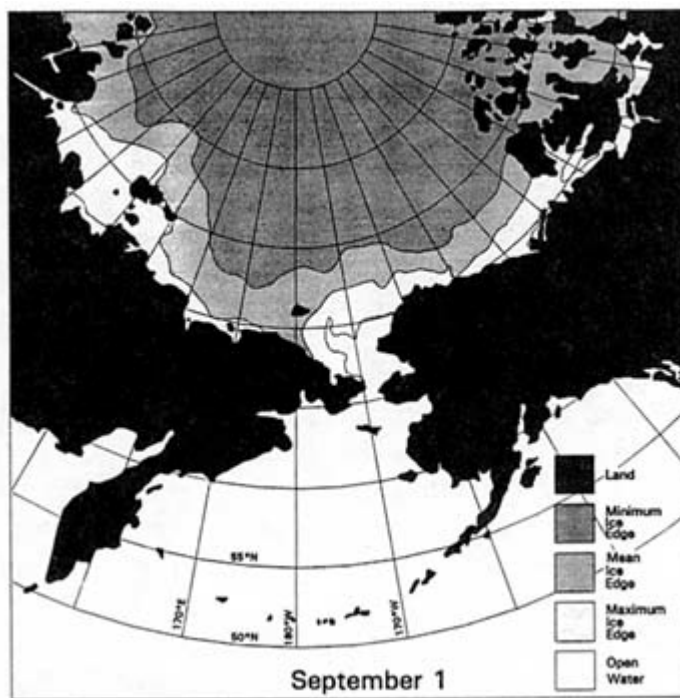


Figure 3.8a Maximum, mean, and minimum extent of ice edges for September 1 in the region of the Bering Sea and Arctic Ocean for the area centered on the Bering Strait, 1973–86 (Niebauer and Schell, 1993).

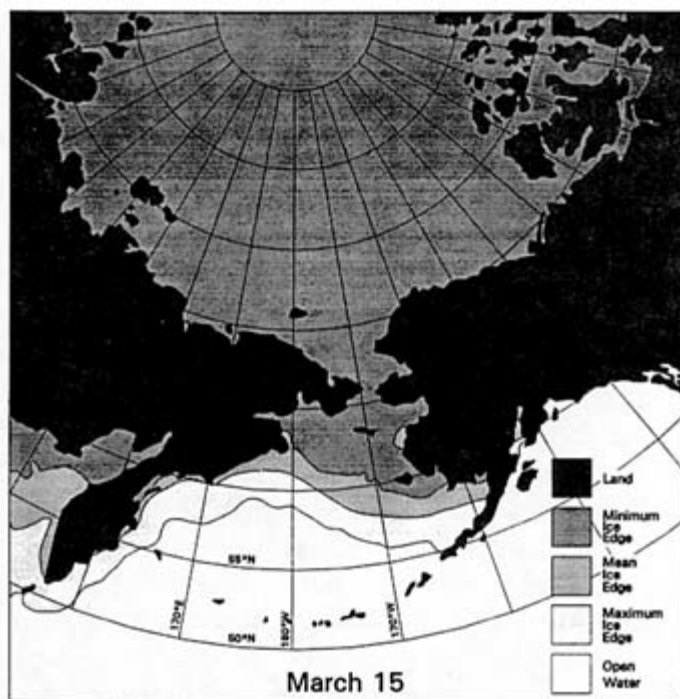


Figure 3.8b Maximum, mean, and minimum extent of ice edges for March 15 in the region of the Bering Sea and Arctic Ocean for the area centered on the Bering Strait, 1973–86 (Niebauer and Schell, 1993).

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However, the central portions of these seas are less relatively productive the shelves and coastal regions.

Coastal freshwater discharge could be a source of nutrients for near shore production, but during periods of peak runoff, the upper layers are devoid of nutrients (Reeburgh and Kipphut 1986). They and others suggest that the deep, nutrient-rich waters must be carried from the deep ocean onto the shelves, where they are mixed upward to supply the nutrients required for high productivity. Because the coastal regions are usually influenced by converging wind systems (downwelling), some other mechanism or mechanisms, such as wind mixing, tidal energy, or eddies near to the shelf break in the southeastern Bering Sea, must be invoked to achieve a vertical movement of the nutrient-rich water over the shelf. Reed and Stabeno (1990) speculate that some of the flows in the Bering Sea are chaotic; thus, there are mesoscale processes that can move the deep nutrients upward into the surface layers, most commonly along the shelf break.

### Sources and Magnitude of Variability

There are various theories about interdecadal changes in the earth's atmosphere and oceans. Potential causes for climate changes include increases of greenhouse gases, El Niño Southern Oscillation (ENSO) events, changes in solar, volcanic, or magnetic activity, collisions with meteors, tidal fluctuations, and anthropogenic effects. Many of these possible influences are believed to be amplified at high latitudes. For example, Spelman and Manabe (1984) and Bryan and Spelman (1985) predict that there will be a "polar amplification" in ocean temperature changes at high latitudes due to increases in greenhouse gases. Roberts and Olson (1973) found that the atmospheric pressure over the Gulf of Alaska responds to geomagnetic storms that are caused by sunspots. Royer (1989) suggests that changes in sea surface temperatures in the high-latitude North Pacific might be caused by changes in atmospheric turbidity as influenced by volcanic eruptions. Interdecadal sea surface temperature changes at high latitude are thought to be caused by lunar nodal tide forcing (Loder and Garrett, 1978; Maksimov and Smirnov, 1965; Royer, 1993). Thus, the high latitudes seem to be regions that have great potential for interdecadal variability. Unfortunately, the environmental records are usually too short to be able to identify, with confidence, the cause or causes of the observed variability, and predicting future atmospheric and oceanic climates is uncertain.

### Atmospheric Forcing and Ocean Circulation

Atmospheric pressure systems propagate across the North Pacific from west to east, often encountering the coastal mountain range of Alaska, where they stagnate and fill. Storm activity in the Gulf of Alaska has a seasonal pattern, with the storm track found south of the Aleutian Islands in winter (October-April) (Wilson and Overland, 1986). This track moves northward into the Bering Sea in spring, ending ultimately in the Arctic Ocean in summer (May-September). It progresses southward in fall, once again entering the North Pacific in winter. Storms pass over the gulf every few days in winter (Hartmann, 1974). These storms

result in nearly continuous cloud cover, winds up to  $40 \text{ m s}^{-1}$ , and precipitation rates of more than  $800 \text{ cm y}^{-1}$  in the coastal mountain ranges (Wilson and Overland, 1986).

The seasonal progression of the storm tracks over the North Pacific and Bering Sea could lead to a large seasonal variability in the ocean circulation, especially over the shelf and near shore. In winter, the Gulf of Alaska has strong upwelling winds over its central (deep water) region, with downwelling winds near shore. High rates of coastal precipitation accelerate the alongshore flow through buoyancy forcing, especially in fall. In summer, the influence of a high-pressure system leads to diminished winds, possibly even upwelling along the northern boundary of the Gulf of Alaska, and relatively low rates of precipitation. Thus, the coastal flow is greatest in fall and winter (Johnson et al., 1988).

High sea level pressure can develop over the region in winter, creating ridges that can deflect storms to the north or south (Wilson and Overland, 1986). These ridges play an important role in year-to-year variability in regional atmospheric conditions, as will be discussed later in this report. The position of these storm tracks is critical to the coupling between ocean and atmosphere in the Bering Sea and Gulf of Alaska, which affects the deep mixing and advection from the deep water of nutrient-rich water onto the shelf of the Bering Sea, and hence the rate of biological productivity.

Interannual variability in the physical parameters in the upper ocean can occur with changes in the rates of exchange with the atmosphere and through changes in ocean advection, both horizontal and vertical. Increased wind stress should increase the vertical exchanges through upwelling-downwelling processes associated with Ekman pumping, and through increased mixing and exchange rates. Increases in storm activity over the Gulf of Alaska or Bering Sea should increase the cyclonic circulation and upwelling from Ekman pumping in the central (deep) regions of the Gulf of Alaska and Bering Sea. Concurrent with an increase in upwelling in the offshore regions, there would be an increase in the downwelling in the coastal regions as a result of coastal convergences. Increased cyclonic atmospheric activity will increase precipitation rates, enhancing the baroclinic coastal flow. The exchanges through the Aleutian Islands and Bering Strait are also altered with changing atmospheric conditions.

Surprisingly, evidence for seasonal changes in ocean circulation is not plentiful. The Alaska Coastal Current has an annual signal (Johnson et al., 1988; Royer, 1982), but similar measured fluctuations of the deep ocean currents in the North Pacific (Musgrave et al., 1992; Tabata, 1991) and Bering Sea are lacking. Nevertheless, a model of the Bering Sea circulation indicates that seasonal increases in circulation of the system should take place (Overland et al., 1994). In addition to the few measurements of seasonal variability, no measurements of interannual fluctuations in the deep ocean currents exist for this region. Short-term fluctuations exist in the flow, through passes into the Bering Sea (Reed, 1990), but current-meter deployments are not of sufficient duration to address seasonal and interannual variability. Fortunately, the interannual variability of the flow out of the Bering Sea through Bering Strait has been determined (Coachman and Aagaard, 1988).

In addition to responding to ENSO events and lunar nodal tide forcing, the upper ocean in the Bering Sea and Gulf of Alaska might be responding to even longer period fluctuations in atmospheric forcing. Several authors (Ebbesmeyer et al., 1991; Francis and Hare, 1994; Graham, 1994; Miller et al., 1994; Trenberth and Hurrell, 1994) have suggested that an atmospheric regime shift has occurred over the North Pacific. An index of a composite of 40



environmental variables made a sudden jump to a new state after 1976. Trenberth and Hurrell's analysis shows that after 1976 the atmospheric circulation of the North Pacific remained in an "abnormal" state until the late 1980s (Trenberth and Hurrell, 1994). Winter sea level pressure for the North Pacific from 1946 to 1992 illustrates the unusual conditions from about 1976 through 1988 and variations since then (Figures 3.9 and 3.10). There is supporting evidence of major interannual changes occurring in the large-scale atmospheric patterns that can cause shifts in the storm tracks. From 1950 to 1970, maximum blocking ridge activity over the North Pacific was in winter (Table 3.1). From 1980 to 1990 this maximum in activity shifted to fall. Though the number of blocking ridges remains nearly constant, there is an interdecadal shift in the marine ridge activity over the North Pacific. This should in turn influence the marine environment by altering the storm tracks over the North Pacific and Bering Sea. Evidence of the interannual changes is the altering of the upper layer structure of the Gulf of Alaska due to changes in Ekman pumping (Lagerloef, 1994); Sambrotto (1985) has also identified changes in productivity due to changes in mixing in the Bering Sea.

### Ocean Temperature

Interdecadal changes in the sea surface temperature of the Gulf of Alaska and Bering Sea since 1947 (Figure 3.11) demonstrate a relatively warm period ( $>1^{\circ}\text{C}$  variance) around 1958 in both basins. Temperatures in both ocean basins decline until about 1973, when they are about  $1^{\circ}\text{C}$  below normal. From 1973 until 1980, there was a relatively rapid increase (about  $0.1^{\circ}\text{C y}^{-1}$ ) for both basins. After 1980, the two temperature histories are more divergent, with the gulf warming until 1984 and the Bering Sea showing a general decline to 1989. Since about 1984, the two temperature anomaly variations have displayed the same temporal pattern, though the Bering Sea has remained about  $0.5^{\circ}\text{C}$  less than the Gulf of Alaska. This pattern differs from the earlier portion of the temperature anomaly record (1956–82); with few exceptions, the sea surface temperature anomalies in the Gulf of Alaska have been lower or similar to those in the Bering Sea. The lower temperature anomalies in the Bering Sea since 1982 could be caused by either the Gulf of Alaska's receiving greater quantities of warmer water, or less warm water entering the Bering Sea. In either case, the differences between the temperature anomalies continued through the end of 1993. The best correlation (0.49) between the monthly mean sea surface temperatures at these two sites was in phase, indicating no propagation of these anomalies. Additionally, there are no long-term water column measurements in the Bering Sea. The closest such time series is for the Gulf of Alaska, and so these data are used as a proxy for the Bering Sea. The low frequency sea surface temperature fluctuations in the Bering Sea follow a similar trend for those at Gulf of Alaska (GAK 1) ( $59^{\circ}50.7'\text{ N}$ ,  $149^{\circ}28.0'\text{ W}$ ) near Seward, Alaska (Figure 3.12). Upper-layer interannual thermal fluctuations with similar amplitudes have been reported for other regions of the North Pacific Ocean (Lie and Endoh, 1991), and they are usually associated at lower latitudes with decadal changes in wind stress (Qui and Joyce, 1992).

A tantalizing choice for the possible forcing of interannual upper ocean temperature fluctuations in the northern North Pacific is the teleconnection from tropical forcing, that is, ENSO events with periodicities of three to six years. They are often associated with interdecadal climate fluctuations in the North Pacific (Philander, 1990). Forcing of the high-

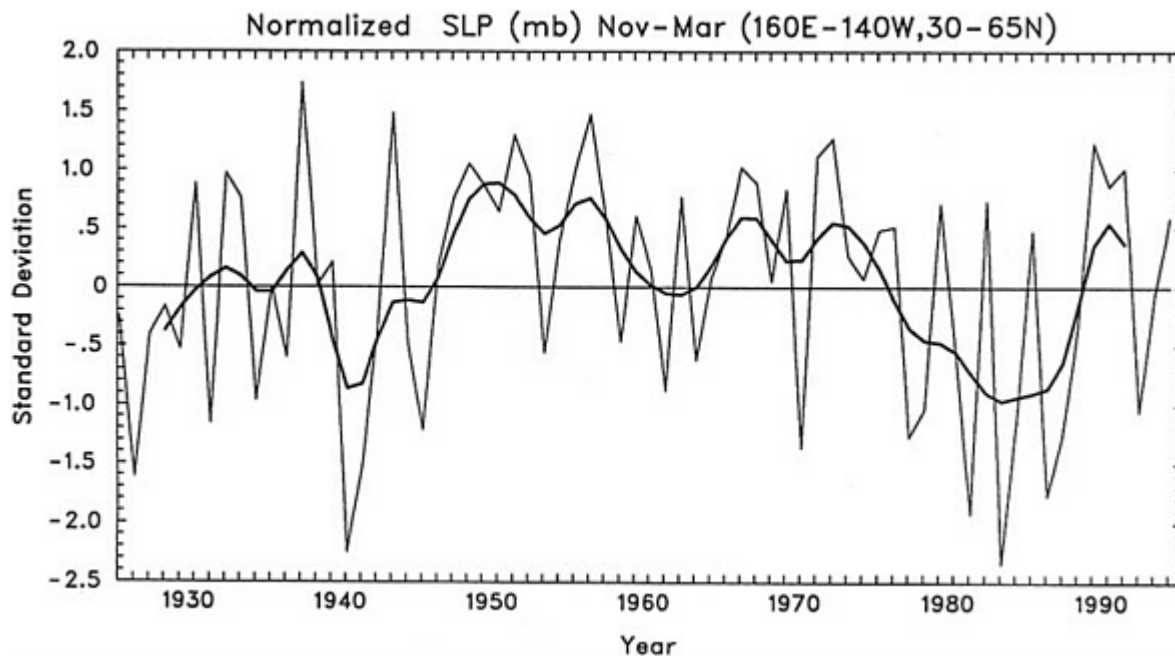


Figure 3.9 Time series of mean North Pacific sea level pressures averaged over 30°-65° N, 160° E to 140° W for the months of November through March beginning in 1925 and smoothed with the low pass filter (Updated from Trenberth and Hurrell, 1994).

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### North Pacific Index - Actual and Intervention Model Fit (1900-92)

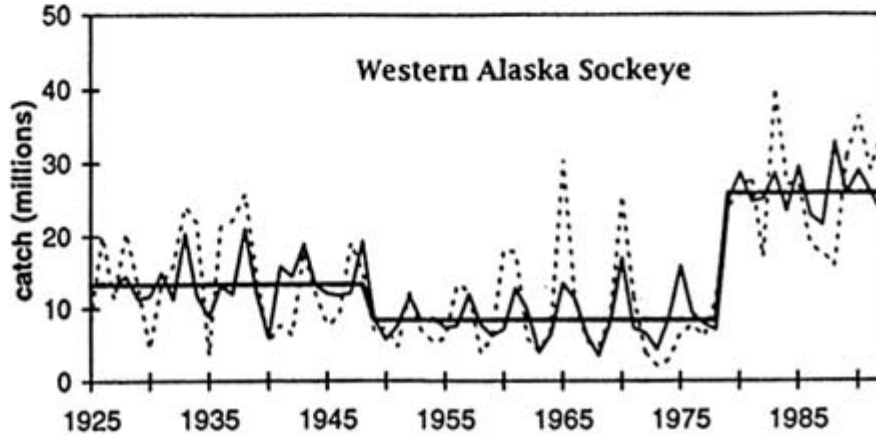
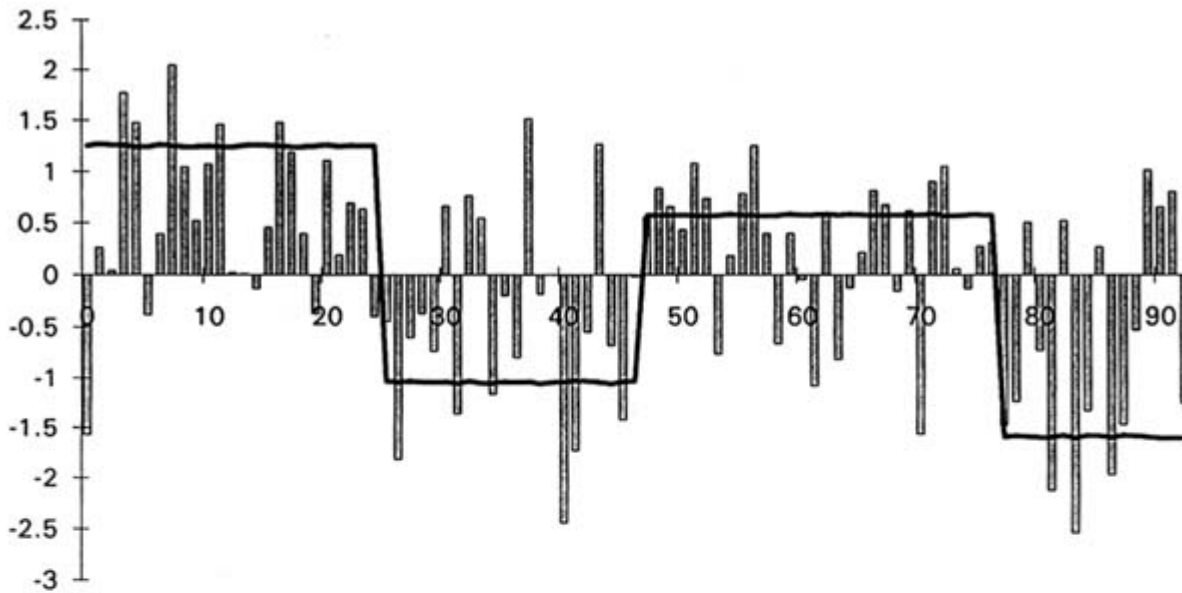


Figure 3.10 Two indicators of large-scale long-term climate variability over the North Pacific and Bering Sea in the twentieth century. Top panel shows Trenberth and Hurrell's (1994) North Pacific index (normalized) and a time series of intervention model fits similar to that of Francis and Hare (1994). Bottom panel shows time history of catch (dashed line), intervention model fit (thin solid line), and estimated interventions (thick solid line) for western Alaska (Bering Sea) sockeye salmon (Francis and Hare, 1994).

Table 3.1 Decadal frequency of occurrence of marine ridges during fall and winter, 1950–89

Season	Frequency of Occurrence			
	1950–59	1960–69	1970–79	1980–89
Fall (Sept.-Oct.)	4	1	4	10
Winter (Nov.-Mar.)	16	17	14	8

Source: Salmon (1992).

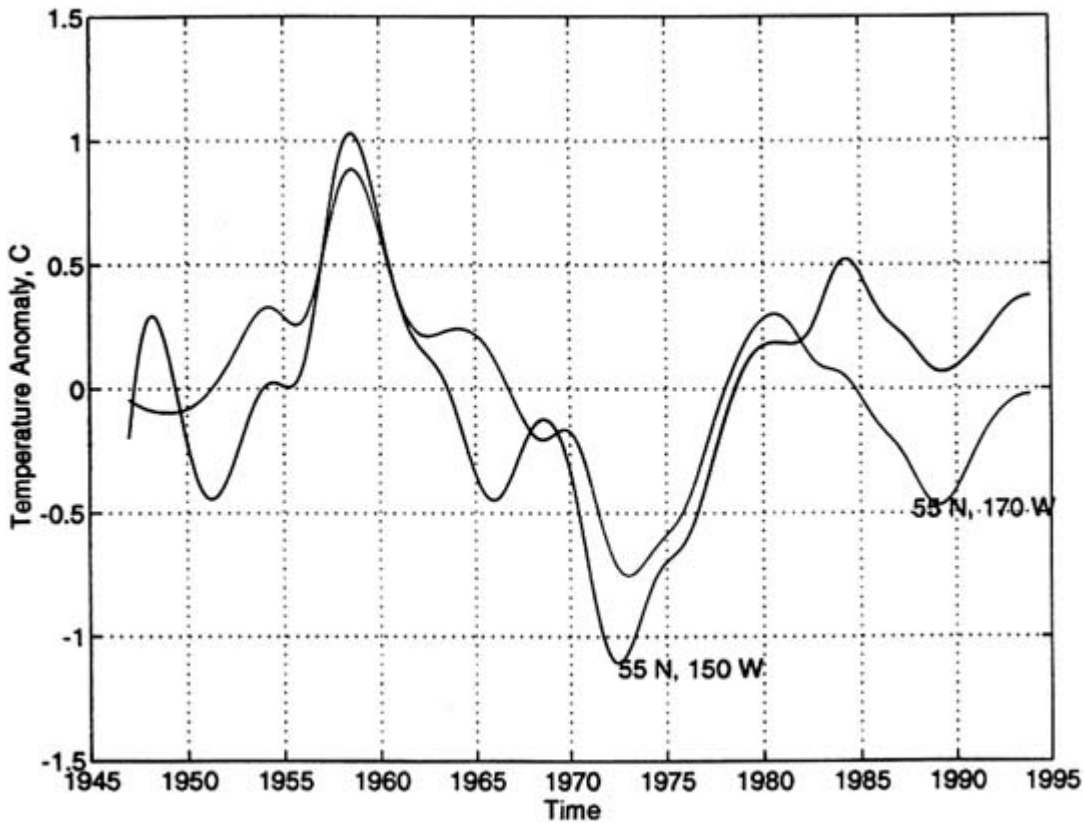


Figure 3.11 Interdecadal changes in the sea surface temperature of the Gulf of Alaska and Bering Sea since 1947 (Committee on the Bering Sea Ecosystem).

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latitude North Pacific by ENSO events can occur through the atmosphere and ocean. The atmospheric connection is through adjustments of global circulation, that is, zonal displacement of atmospheric high- and low-pressure cells. It is manifested as changes in the Pacific North American (PNA) index teleconnection (Wallace and Gutzler, 1981). El Niño accounts for approximately 20 percent of the variance in the centers of action of the PNA pattern (Philander, 1990). A primary feature of the PNA is the Aleutian Low, and during ENSO events it deepens and moves southwestward during the North Pacific winter (Bjerknes, 1969). ENSO forcing in the ocean at high latitudes is primarily through the poleward propagation of Kelvin waves (Jacobs et al., 1994). This conclusion is supported by data of Enfield and Allen (1980), who found poleward-propagating, coastal-trapped disturbances along the west coast of North America correlated with equatorial disturbances. Not surprisingly, the temperature fluctuations at depth at GAK 1 are well correlated with ENSO events ( $R = -.36$ , >99% confidence interval) (three-to-six year intervals) (Royer, 1994).

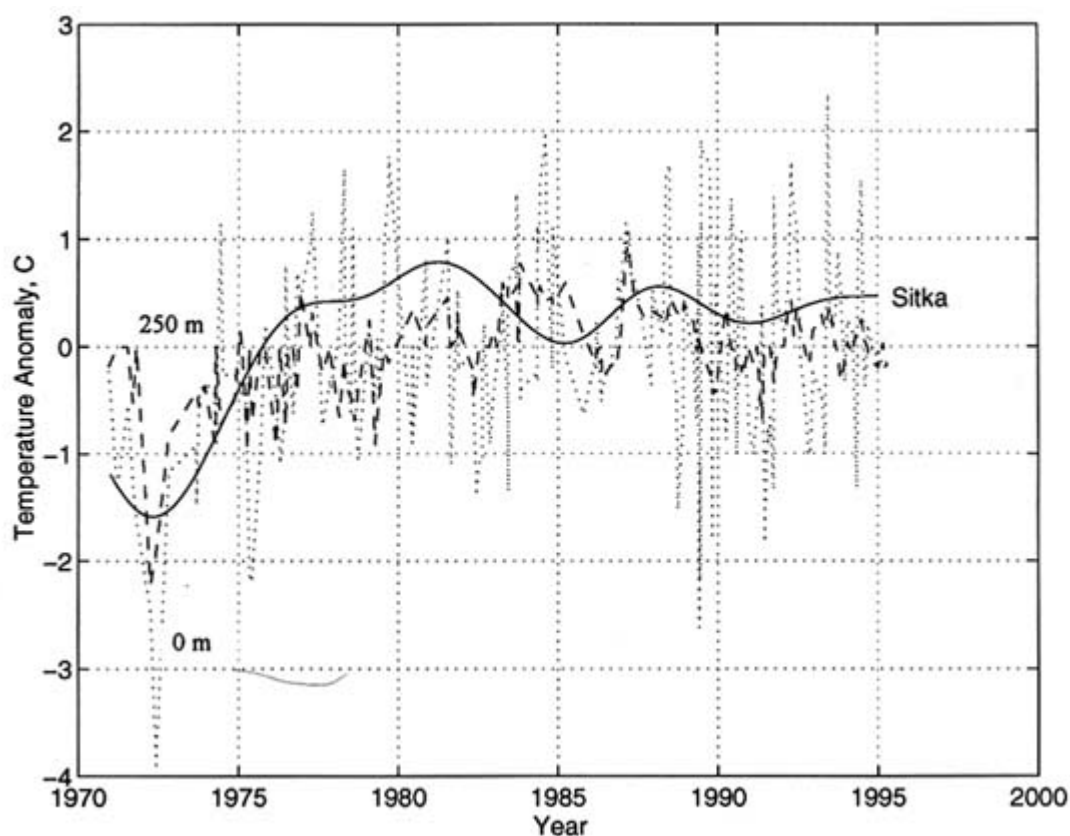


Figure 3.12 Sitka air temperature anomalies (solid curve), GAK 1 sea surface temperature anomalies (dotted curve), and GAK 1 temperature at 250m. (GAK 1 is located at approximately 60° N, 149° W in 263 m of water at the mouth of Resurrection Bay; Sitka air temperature anomalies are smoothed by using a fifth-degree Butterworth filter with a five-year cutoff.) (After Royer, 1993).

In addition to the fluctuations associated with ENSO forcing, however, the water column temperature variations at GAK 1 have been found to be associated with the lunar nodal tide

signal ( $R = -0.6$ , >99% confidence interval) (18.63-year period) (Royer, 1994). The temperature variability at 250 m at GAK 1 associated with the nodal tide is about three times that of ENSO. This lunar nodal tide component is the twelfth-largest tidal component and is related to the changes in lunar declination over the 18.6-year periodicity. Equilibrium tide theory predicts that this tidal component will vary with latitude, with larger amplitude at high latitudes than at mid-latitudes (Parker et al., 1994). Because the interdecadal sea surface temperature variability seems to occur simultaneously in the Gulf of Alaska and Bering Sea (see [Figure 3.11](#)), it is expected that the lunar nodal tide forces Bering Sea parameters in a similar fashion as it does in the Gulf of Alaska. Again, the temperature anomaly patterns are similar, with no phase shift, suggesting simultaneous forcing.

Using air temperatures at Sitka, Alaska, as a proxy for the Gulf of Alaska and Bering Sea surface temperatures, ( $R = 0.21$ ,  $N = 564$ ), the data record can be extended back to 1828 ([Figure 3.13](#)). Semiregular variations of about  $1^{\circ}\text{C}$  in the air temperatures have occurred at Sitka for more than 150 years. Note that the decade of the 1970s was the coolest in the entire record, suggesting that perhaps water temperatures at that time were unusual.

Changes in atmospheric circulation can cause changes in the exchange of water between the North Pacific and Bering Sea. This has been demonstrated on a seasonal basis in numerical models (Overland et al., 1994) ([Figure 3.14](#)), but it has yet to be directly measured, although, Reed (1990) has reported fluctuations in the exchanges through Near Strait. Generally, seasonal ocean circulation responses to wind forcing are surprisingly small. For example, although wind energy increases considerably in winter over the eastern Bering Sea, Schumacher and Reed (1992) found that wind forcing accounted for only a small part of the current fluctuations. Seasonal changes in the Alaska Stream represent at most 10 percent of mean flow (Royer, 1993); some studies question whether the seasonal signal even exists (Musgrave et al., 1992). Tabata (1991) found the ocean's baroclinic transport response (along Line P, at about  $50^{\circ}\text{N}$ ) to seasonal forcing to be insignificant. Hollowed and Wooster (1992) have suggested that the intensity of the Alaskan Gyre can change on an interannual basis in response to changes in atmospheric forcing, but there is no direct evidence that large-scale circulation reacts to seasonal changes in atmospheric forcing. Thus, seasonal responses to wind forcing remain uncertain.

The heat, salt, and nutrient supply for the Bering Sea depends on the exchange of water between the Bering Sea, North Pacific, and Arctic Ocean. Coachman and Aagaard (1988) found that the flow through Bering Strait (at a mean 0.8 Sv) has considerable variability. The variability from 1946 to 1969 was such that 70 percent of the transports into the Arctic Ocean through Bering Strait were greater than the mean, whereas from 1969 to 1985 76 percent of the transports were less than the mean. Smallest transports occurred in 1974, 1976, and 1980 representing three of the four lowest transports in this century. Bering Strait transports apparently depend on large-scale atmospheric pressure patterns, in contrast to deep Bering Sea circulation.

Significant interannual changes in local ocean circulation might be caused by mesoscale eddies that themselves cause significant larger-scale changes in circulation. In a numerical model of the exchange of water between the North Pacific and Bering Sea, Overland et al. (1994) found that the Alaska Stream west of  $175^{\circ}\text{E}$  became unstable, with considerable meandering as it separates from the Aleutian Islands. As the flow becomes unstable, mesoscale



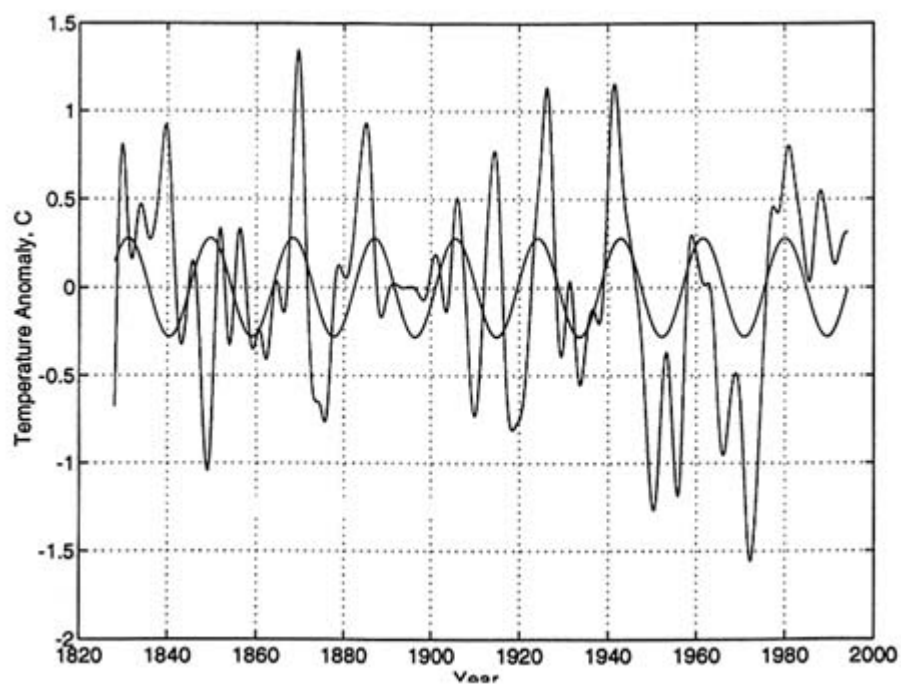


Figure 3.13 Sitka air temperature anomalies with least squares fit of 18.6-year lunar nodal tide cycle (smooth curve, with anomalies smoothed by using a fifth-degree Butterworth filter with a five-year cutoff) (after Royer, 1993).

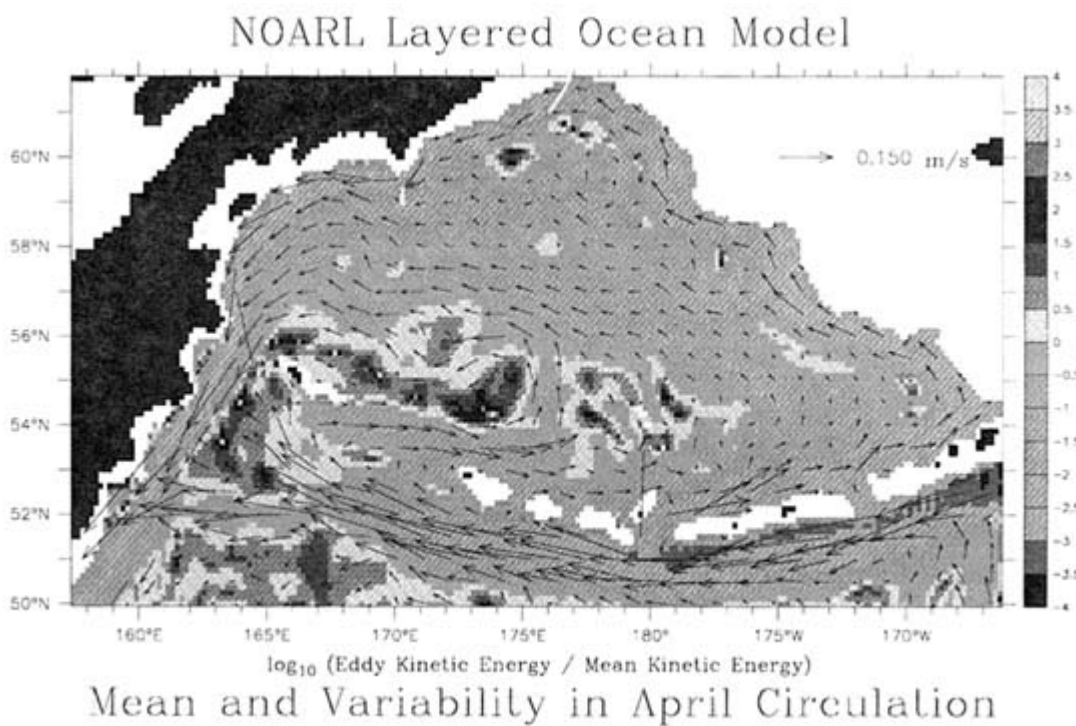


Figure 3.14 Variability in the Bering Sea as determined from eddy and mean kinetic energies (Overland et al., 1994).

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eddies form, as detected in satellite altimetry measurements (Okkonen, 1993). These eddies could block the flow of this relatively warm, high-salinity North Pacific water into the Bering (Reed et al, 1993; Stabeno and Reed, 1992). The length of time of the change in this flow is on the order of months. Mesoscale eddies could also play an important role in the vertical advection of nutrient-rich water into the euphotic zone.

More recently, Jacobs et al. (1994) have observed poleward-propagating Kelvin waves at the shelf break that extend from the equator into the Bering Sea. These waves excite Rossby waves, which propagate westward very slowly at speeds of a few centimeters per second. Their speeds are inversely related to latitude, and it takes up to a decade for the disturbances to travel across the mid-Pacific, more than 5,000 km. Although the zonal expanse of the Bering Sea basin is less than that of the entire mid-latitude Pacific, the Rossby phase speeds are also less, so that interannual time scales are likely. These phenomena contributes to the interdecadal temperature fluctuations. These same Rossby waves that are series of mesoscale eddies enhance the vertical motion that can bring nutrient-rich water into the surface layers, as mentioned in the previous paragraph.

### Ice

There is considerable interannual variability in the ice cover, with values for 1976 being 10 to 15 percent below normal and those for 1979 being 10 to 15 percent above normal (Niebauer and Day, 1989). Large variability in the maximum extent of the ice edge occurred between 1974 and 1976, when the edge was at 56°–56.5° N, and 1978 and 1979, when it was at 58°–58.75° N (T. Wyllie-Echeverria, personal communication). Ohtani and Azumaya (1995) showed how summer bottom temperatures are affected by the existence of ice cover in winter. This interannual variability is attributed to the extent of winter northerly winds, which in turn can be related to winter atmospheric circulation patterns referred to above (perhaps related to ENSO events). Manak and Mysak (1987) have associated changes in the Bering Sea ice cover with atmospheric circulation changes caused by changes in heat and moisture advection.

### Summary

Interannual variability in the North Pacific and Bering Sea exists on a variety of time scales and has multiple causes (Table 3.2). Forcing by seasonal and shorter time scale events (tides and storms) is well documented, though the ocean responses are less well known. Of interannual periodicities, the best known are ENSO events that radiate from the equatorial region at irregular intervals, although intervals most commonly range from three to seven years. This accounts for approximately one-third of the ice and sea surface temperature variability in the Bering Sea (Niebauer and Day, 1989). An interannual periodicity of six to seven years has been found along Line P (about 50° N), but whether this holds north of the line is questionable (Tabata, 1991). Sunspots with periodicities of 11 and 22 years (Hale cycle) have been implicated in upper atmospheric variability over the Gulf of Alaska (Roberts and Olson, 1973), but there is no evidence of their influence on ocean processes. Interdecadal variability of ocean

temperatures in the Gulf of Alaska has been associated with the 18.6-year lunar nodal tide, which accounts for more than one-third of the variability throughout the water column at the coast (Parker et al., 1994; Royer, 1993). Over this tidal cycle, the relative importance of diurnal and semidiurnal tidal components is altered. Influences from this effect in the Bering Sea are undetermined, but responses like those in the Gulf of Alaska are likely. The role of mesoscale eddies in the ocean is not determined, but they may play an important part in controlling the exchange of water between the North Pacific and Bering Sea (Okkonen, 1993). They might also have an important part in mixing water masses and providing microclimates for enhanced productivity. Changes in global atmospheric pressure patterns can create persistent blocking ridges over the North Pacific, leading to decadal and longer shifts in pressure patterns and storm tracks. These changes might be considered "regime shifts", which alter the timing of critical storm events that can affect biological productivity; they are discussed further below.

Table 3.2 Atmosphere-ocean variability time scales and forcing mechanisms

Period	Forcing Mechanism
Diurnal/semidiurnal	Tides
3–10 days	Storms
Seasonal	Solar declination
Interannual (years)	
1+	Mesoscale ocean eddies
3–7	ENSO events
6–7	Mid-latitude atmospheric events
10+	"Regime shift"
11	Sunspots
18.6	Lunar declination
22	Sunspots

Source: Committee on the Bering Sea Ecosystem

The interactions of several or all of the potential long-period forces acting over and in the Bering Sea should be considered. They might have nonlinear or even chaotic interactions (Parker et al., 1994). Some combination of annual, 3-to-7 year, 6-to-7 year, 11-year, 18.6-year, and 22-year cycles could lead to the atmospheric and oceanic variability that takes place at these latitudes.

Interannual changes of the flow into the Bering Sea and subsequent outflows could influence the biota in the Bering Sea, Arctic Ocean, and North Pacific. The transfer of nutrients, salt, and heat are unquestionably important to biological productivity. Upwelling and

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mixing caused by winds will have an interannual response, as suggested by Sambrotto (1985). For example, Brodeur and Ware (1992) show a doubling of zooplankton biomass, pelagic fish, and squid abundance in the northeast Pacific from the periods of 1956 to 1962, and 1980 to 1989. Venrick and others (1987) have observed changes in the epipelagic ecosystem in the North Pacific. Total chlorophyll and phytoplankton increased along with calanoid copepods after 1976, according to McFarlane and Beamish (1992). They attribute the improved primary production in the central North Pacific to increased nutrient supply associated with a more intense low-pressure system in winter (see [Figure 3.9](#)).

The concept of "regime shifts" in this region has been suggested by Francis and Hare (1994). The atmospheric forcing for such regime shifts has been noted by Trenberth and Hurrell (1994), Salmon (1992) (see [Table 3.1](#)), and Schwing (1994). The change in 1976 is just one of many that have occurred over the North Pacific (Namias et al., 1988), although its influence might have been enhanced by an abnormally cold period in the early 1970s and it seems to be important in terms of the current organization of the Bering Sea ecosystem, as described in [Chapter 6](#). Although atmospheric circulation appeared not to have changed back to its previous condition by 1989 (Trenberth and Hurrell, 1994), similar changes are likely to occur in the future.

## PRIMARY AND SECONDARY PRODUCTION

### Water Column Primary Production

As discussed earlier in this chapter, the Bering Sea is distinguished by a very broad continental shelf—approximately half of the geographic area of the Bering Sea is shelf, with an average water depth of only 50 to 75 m. The remainder is an oceanic basin 3,000 to 4,000 m deep. Continental shelves are in general more productive than most other regions of the ocean, because tidal and wind energy can occasionally interact with sufficient strength to resupply nutrients to the euphotic zone from reservoirs beneath the thermocline (Walsh, 1988). The wide shelf in the Bering Sea provides an expansive area over which such physical processes can occur.

Beyond this general setting, other processes lead to important mesoscale variability in patterns of primary production in the Bering Sea and very high production in several regions. These include the flow of Alaska Stream water from the Gulf of Alaska into the Bering Sea through passes in the Aleutian Island arc, upwelling at the edge of the continental shelf and along the Aleutian Island arc, and currents at the shelf edge and across the northern shelf. Each process supplies nutrients to the euphotic zone during summer, and thus extends the growing season well beyond the period of the spring bloom characteristic of this and other high-latitude seas.

The sections that follow highlight information on phytoplankton and zooplankton, including the predominant species known from the Bering Sea. Unfortunately, detailed studies on the distribution, dominance, and fluctuations of these organisms are few.

## Continental Shelf

Production everywhere in the Bering Sea is limited by both nutrients and light. From fall to spring, light levels are sufficiently low that even in the presence of abundant nutrients phytoplankton cannot grow. Over the shelf, seasonal sea ice extends the period of light limitation in spring, particularly in cold years when sea ice extends all the way to the shelf edge and retreats slowly. During winter, a combination of wind mixing and cross-shelf diffusion and tidal mixing resupply nutrients to the depleted waters on the shelf from the reservoir in the basin of the Bering Sea (Coachman and Walsh, 1981; Whitledge et al., 1986).

As ice melts in spring, the freshwater floating on top of the denser seawater establishes a strongly two-layered water column with a sharp but shallow halocline that retards vertical mixing. In the presence of sufficient nutrients, the plankton cells bloom (McRoy and Goering, 1974; Niebauer and Alexander, 1985). The ice-edge bloom follows the retreating sea ice north, and can be short-lived if the upper stable layer is shallow, i.e., low initial nutrient inventory, or if winds break down the density stratification caused by meltwater from the ice on the seawater. Under these conditions, the ice-edge bloom contributes only a small amount, perhaps 10 percent, to the total annual production budget in the Bering Sea (McRoy and Goering, 1974). In years when wind mixing is low, the density stratification of the ice-edge bloom might be subsequently reinforced by surface heating and the ice-edge bloom could become in essence the spring bloom over a portion of the shelf (J. Niebauer, unpublished data).

After the retreat of sea ice and the termination of the ice-edge bloom, the physical zonation of the shelf plays a fundamental role in nearly all aspects of the production regimes of the different domains (Iverson et al., 1979a; Walsh and McRoy, 1986). The fronts retard across-shelf advective and diffusive processes that would otherwise distribute nutrients from the basin reservoir over the shelf. This, together with the breadth of the shelf, greatly slows the rate of nutrient renewal in the coastal domain, and the water column rapidly becomes depleted of nutrients in spring during the bloom. Because of slow renewal and a shallow water column, and hence small initial nutrient inventory, total production in the coastal domain is in the range of only 50 to 100 g C m<sup>-2</sup> y<sup>-1</sup>, of which less than 20 g C m<sup>-2</sup> y<sup>-1</sup> is new production (Figure 3.15) (Hansell et al., 1993; Springer and McRoy, 1993).

Production in the middle domain is greater than in the coastal domain, because it is nearer the basin, the water column is deeper, and there is a larger initial nutrient inventory. The spring bloom is commonly initiated by thermal stratification of the water column after sea ice dissipates, which again reduces wind-mixing depth and allows plankton cells to remain in favorable light conditions (Sambrotto et al., 1986). Production is probably in the range of 150 to 200 g C m<sup>-2</sup> y<sup>-1</sup>, of which 30 to 50 g C m<sup>-2</sup> y<sup>-1</sup> is new production (Hansell et al., 1993). Walsh and McRoy (1986) considered their estimate of 166 g C m<sup>-2</sup> y<sup>-1</sup> to be conservative, because measurements of production had never been taken throughout the entire growing season. Production in the vicinity of the Pribilof Islands and St. Matthew Island, which lie in the middle domain, might be somewhat higher than average for the domain because of episodic upwelling during summer.

Production in the outer domain was estimated to be similar to that in the middle domain, about 160 g C m<sup>-2</sup> y<sup>-1</sup>, which is also considered to be conservative (Walsh and McRoy, 1986). Vertical fine structure in the water column of the outer domain is a feature throughout summer,

and should lead to higher supply rates of nutrients depleted by phytoplankton growth (Whitledge et al., 1986). New production was estimated to fall in the range of 40 to 70 g C m<sup>-2</sup> y<sup>-1</sup> (Hansell et al., 1993), and total production is probably between 200 to 250 g C m<sup>-2</sup> y<sup>-1</sup>.

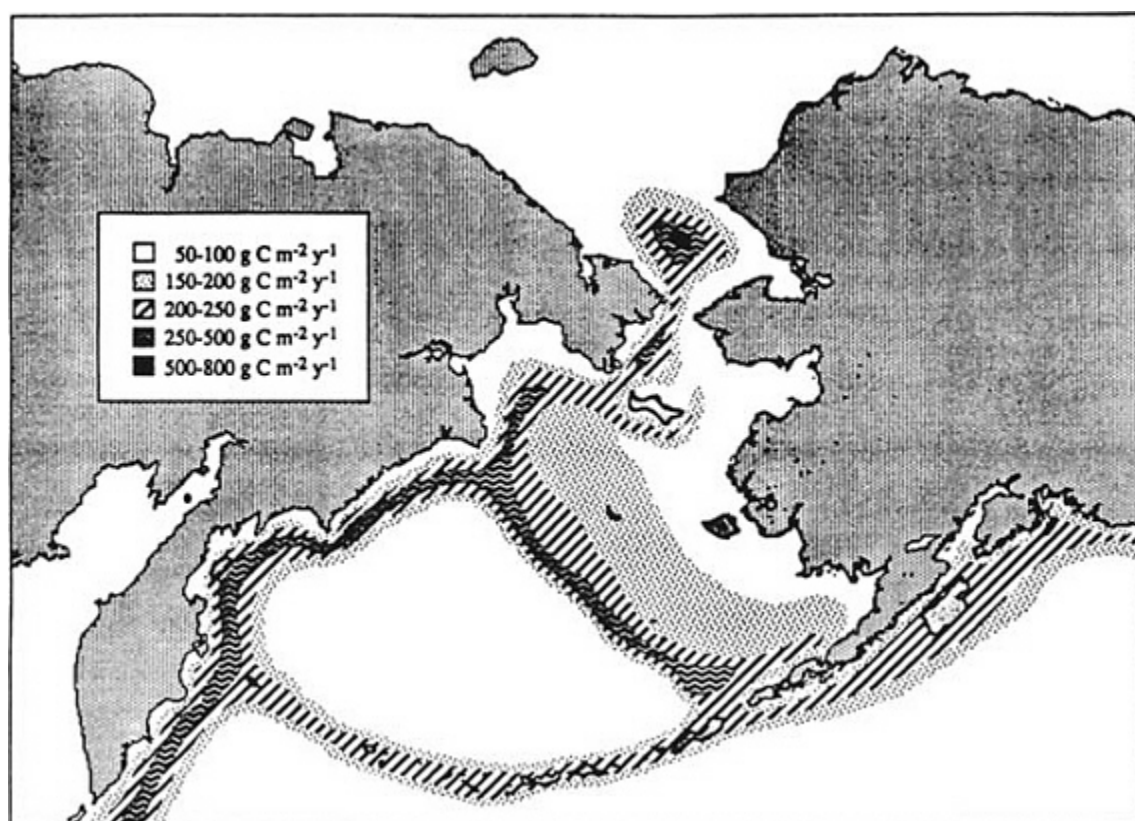


Figure 3.15 Generalized pattern of primary production in the Bering Sea and northern Gulf of Alaska (Springer and McRoy, in review).

Estimates of total production are commonly based on nitrate-nitrogen uptake rates (new production) that are converted by using the *f*-ratio, or ratio between new production and total production (Epley and Peterson, 1979). Sambrotto and others (1993) have recently demonstrated that this approach typically underestimates total production by as much as about 50 percent. Current estimates of production over the shelf and basin of the Bering Sea therefore suffer from the combined effects of short-term measurements, that is, measurements that do not span the entire growing season, as well as conservative methods for converting nitrogen uptake rates to carbon assimilation.

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## Basin

Few estimates have been made of primary production in the Bering Sea basin. New production is apparently only about  $10 \text{ g C m}^{-2} \text{ y}^{-1}$  (Hansell et al., 1993), and total production is probably similar to the inner domain, or 50 to  $100 \text{ g C m}^{-2} \text{ y}^{-1}$  (e.g., Saino et al., 1979; Sapozhnikov et al., 1993; Taniguchi, 1969).

## Shelf Break

The seaward side of the outer shelf domain lies approximately at the shelf edge. It is a comparatively narrow region with distinct physical characteristics and, apparently, a bountiful production regime. The shelf edge domain, or "green belt," apparently extends around the entire perimeter of the Bering Sea continental shelf and across the northern shelf, through Bering Strait, and into the Chukchi Sea.

The eddies along the shelf edge are energetic and might be important to mesoscale nutrient dynamics in the upper water column, and thus to production budgets (e.g., Karl and Carlson, 1987). The interaction of strong tidal currents with the abrupt, steep shelf break promotes upwelling at the front (Coachman, 1986), which also helps supply nutrients to the euphotic zone. As a result, primary production apparently remains elevated throughout summer, long after the termination of the spring bloom (Iverson et al., 1979b; Karl and Carlson, 1987). Up to  $110 \text{ g C m}^{-2} \text{ y}^{-1}$  of new production was estimated near the shelf break (Hansell et al., 1993), compared to the estimates of less than 10, 40 to 70, 30 to 50, and more than  $20 \text{ g C m}^{-2} \text{ y}^{-1}$  of new production over the basin and outer, middle, and inner shelf domains, respectively. Assuming an f-ratio of 0.3, and remembering the caution noted above about f-ratios,  $110 \text{ g C m}^{-2} \text{ y}^{-1}$  of new production would convert to approximately  $365 \text{ g C m}^{-2} \text{ y}^{-1}$  of total production in the green belt. Deposition of phytodetritus from in situ production in this zone might account for high sediment carbon on the slope (Lisitsyn, 1966) and contribute to off-shelf transport of carbon from the outer domain as has been proposed (Walsh, 1983; Walsh et al., 1981).

In the northern branch of the green belt, new production in the Anadyr Stream across the Bering-Chukchi shelf is estimated at up to  $288 \text{ g C m}^{-2} \text{ y}^{-1}$ , or 700 to  $800 \text{ g C m}^{-2} \text{ y}^{-1}$  of total primary production (Hansell et al., 1993; Springer and McRoy, 1993). These values for production on the northern shelf and along the shelf edge in the eastern Bering Sea agree well with estimates of production at the shelf edge along the Kamchatka Peninsula, the western extension of the green belt, which fall in the range of 300 to  $800 \text{ g C m}^{-2} \text{ y}^{-1}$  (Sapozhnikov et al., 1993).

## Aleutian Island Arc

The Alaska Coastal Current, a baroclinic coastal current flowing to the southwest over the shelf of the western Gulf of Alaska, and the Alaska Stream are both important to property distributions across the arc (Favorite, 1974; Reed, 1990; Schumacher et al., 1982) and apparently to local production budgets (Koike et al., 1982). In addition, upwelling at some

locations further contributes to mesoscale nutrient and production budgets (Kelley et al., 1971; Park et al., 1973; Swift and Aagaard, 1976). Depending on spatial variability in the distribution and effects of physical processes, production probably ranges between about 200 and 300 g C m<sup>-2</sup> y<sup>-1</sup> across the arc (McRoy et al., 1972; Sanger, 1972) and along the northern side of the Alaska Peninsula (Schell and Saupe, 1989).

### Water Column Secondary Production

The fronts dividing the continental shelf into domains affect patterns of secondary production also. The distribution of zooplankton communities that results from the physical partitioning of the shelf determines the fate of carbon produced in the water column—that is, the way carbon is divided between pelagic and benthic food webs. Four general groupings of zooplankton have been described for the Bering Sea: oceanic and outer shelf, mixed oceanic-shelf, middle shelf and coastal, and near shore (Cooney, 1981).

Among the numerous species of herbivorous zooplankton in the Bering Sea, large calanoid copepods are a particularly important link in the food web between phytoplankton and higher trophic levels. *Neocalanus cristatus*, *N. plumchrus*, *Eucalanus bungii*, and *Metridia pacifica* are oceanic species found in deep water across the North Pacific. They are large, efficient grazers of large diatoms typical of the spring bloom flora, and are in turn important prey of most species of planktivorous fishes, birds, and mammals. They do not occur over the shelf inshore of the middle front, that is, in the middle or coastal domains, however, because of the effect the fronts have in restricting cross-shelf advective and diffusive exchange. There they are replaced by *Calanus marshallae*, the only large copepod found higher on the shelf, and by various species of small copepods.

Zooplankton biomass changes correspondingly, with a much larger biomass over the outer domain and decreasing biomass over the middle and coastal domains. Likewise, grazing stress is greater in the outer domain than in the middle or coastal domains, resulting in a much larger pelagic shunt of primary production in the outer domain (Cooney, 1981; Cooney and Coyle, 1982). In the middle and coastal domains, a considerably larger proportion of the annual primary production settles to the bottom, where it fuels important benthic food webs. In all domains, the ice-edge production is ungrazed, because it precedes the development of zooplankton populations in spring (Coyle and Cooney, 1988).

The greatest biomass of zooplankton apparently occurs in the green belt from the southeastern Bering Sea into the Chukchi Sea (Cooney, 1981; Springer et al., 1989). Zooplankton biomass is probably high along the coast of the Kamchatka Peninsula as well. Enhanced primary production likely accounts for the high zooplankton biomass along the shelf edge, while advection in the Anadyr Stream is the major factor across the northern shelf (Springer and Roseneau, 1985; Springer et al., 1989). Estimates of annual zooplankton production in the southeastern Bering Sea are as high as 64 g C m<sup>-2</sup> y<sup>-1</sup> for the shelf edge, 40 g C m<sup>-2</sup> y<sup>-1</sup> (range 16 to 50 g C m<sup>-2</sup> y<sup>-1</sup>) for the outer shelf domain, 19 g C m<sup>-2</sup> y<sup>-1</sup> (range 8 to 30 g C m<sup>-2</sup> y<sup>-1</sup>) for the middle shelf domain, and just 4 g C m<sup>-2</sup> y<sup>-1</sup> (range, 2 to 6 g C m<sup>-2</sup> y<sup>-1</sup>) for the coastal domain (Cooney, 1981; Vidal and Smith, 1986).



### Sources and Magnitude of Variability

Primary production in the outer and middle domains apparently can vary by as much as 30 to 50 percent between years, depending on the frequency and intensity of summer storms that mix the water beneath the seasonal pycnocline and resupply nutrients to the euphotic zone (Sambrotto and Goering, 1983; Sambrotto et al., 1986). Production in the coastal domain likely varies little between years because the water column is sufficiently shallow and well mixed that nutrients are depleted during the bloom in all years.

Little is known about variability in the physical system or productivity at the shelf edge. Across the northern shelf and in the Alaska Stream, two highly advective regions, variability in transport has been linked to variability in biomass of phytoplankton and zooplankton.

Annual fluctuations in transport in the Anadyr Stream across the northern shelf of the Bering Sea (Coachman, 1993) can lead to differences in primary production—production appears to be proportional to transport (Springer and McRoy, 1993). The fact that Anadyr Water derives its physical and chemical characteristics (i.e., high nutrients and low oxygen) from the subsurface Bering Sea suggests that variability in transport of the Bering Slope Current (of which the Anadyr Stream is the northern component) is related to large-scale variability in the circulation of the Bering Sea. This variability might be forced by basin-scale changes in the Aleutian Low. Intensified Aleutian Low wind stress curl during 1976 to 1988 could have resulted in increased northward Sverdrup transport in the central and eastern Bering Sea, producing increased southward flow in the western boundary current circulation of the subarctic Pacific (Salmon, 1992). This finding is also consistent with the results of Sekine (1988, 1991), who showed that the Oyashio Current intrudes farther south than normal during years of intensified Aleutian Low wind forcing. However, the possible link between changes in Bering Sea circulation and variations in large-scale wind forcing are tenuous. The Bering Slope Current system should respond to basin scale changes in wind forcing over the Bering Sea, although direct evidence of this is not available. Similarly, it might respond indirectly to changes in the Gulf of Alaska through the effects of wind-forced variations in the flow of the Alaska Stream through the Aleutian Island arc. An analysis of the flow regime along the shelf break using satellite altimeter data revealed coherence between the Bering Slope Current and the Kamchatka current and significant interannual variability in the frequency and intensity of eddies (Fox and Leben, 1993). Eddies were particularly pronounced in 1986 compared to 1985, 1987, and 1988, a pattern consistent with the anomalous circulation and production on the northern shelf observed in 1986 compared to the other years.

Interannual fluctuations in the Alaska Stream are related to transport in zooplankton biomass in the western Bering Sea (Wickett, 1967). On the order of 15 to 20 Sv of water from the Alaska Stream flood through the Aleutian Island Arc into the Bering Sea (Favorite, 1974; Reed, 1990), apparently carrying a great amount of zooplankton. This notion seems plausible in light of evidence that zooplankton are carried to the shelf from within the Alaska Gyre through Ekman transport generated by the Aleutian Low (Cooney, 1986), and that interannual fluctuations in zooplankton abundance on the northern Gulf of Alaska shelf are related to the strength of the Aleutian Low wind field (Brodeur and Ware, 1992; Francis and Hare, 1994). In particular, during years when the Aleutian Low is strong, the shelf of the northern Gulf of Alaska is characterized by high zooplankton abundance due to increased onshore Ekman



transport, while a weak Aleutian Low corresponds to decreased zooplankton abundance on the shelf in conjunction with weakened onshore transport. Tabata (1991) has shown that oceanographic properties such as temperature, salinity, and dissolved oxygen in the Gulf of Alaska undergo oscillations in periods of two to three and six to seven years (see [Table 3.2](#)), while Salmon (1992) has suggested that changes in the strength of transport in the Alaska Gyre might be closely related to changes in wind forcing within the Aleutian Low on these same time scales. Thus, variations in the strength and position of the Aleutian Low might lead to variations in circulation and biomass in the Alaska Stream and account for the observations of Wickett (1967).

Venrick and others (1987) found a significant change in water column chlorophyll concentrations north of Hawaii at the time of the regime shift in the mid-1970s ([Figure 3.16](#)). Most of the change occurred below 100 m and was hypothesized to be due to an increase in the winter production of deep phytoplankton species caused by a deepening of the winter mixed layer. Likewise, Brodeur and Ware (1992) found a significant shift in zooplankton biomass in the Alaska Gyre, which also corresponded to the recent regime shift ([Figure 3.17](#)).

Similar oceanographic time series, both physical and biological, are lacking in literature for the western Bering Sea. Decadal-scale changes in the mean position of the Aleutian Low pressure field and resulting wind fields over the Bering Sea might produce patterns in annual primary and secondary production, with stormy eras characterized by higher production than calmer eras, as the data of Sambrotto and Goering (1983) suggest. Elsewhere, long-term patterns of phytoplankton and zooplankton production do track changes in the mean physical conditions of the marine environment (e.g., Aebischer et al., 1990).

## BIOLOGY OF LOWER TROPHIC LEVELS

### Benthic Production

The benthic communities of the Bering Sea are dominated by a large variety of polychaetes, amphipods, gastropods, and bivalves. They vary tremendously in space due to food supply, bottom depth, disturbance (e.g., ice gouging and marine mammal feeding), sediment type, and predation. The distribution, abundance, and biomass of benthic fauna coincide with physical domains (Feder et al., 1985; Grebmeier et al., 1988; Haflinger, 1981; Stoker, 1981). For example, the middle shelf of the Bering Sea south of St. Lawrence Island is dominated by bivalves and polychaetes (Grebmeier and Cooper, 1995; Haflinger, 1981; Stoker, 1981), the region north of St. Lawrence Island to Bering Strait is dominated by ampeliscid amphipods (Grebmeier et al., 1989; Highsmith and Coyle, 1992). In comparison, the continental slope areas in both Bering and Chukchi seas are dominated by a variety of polychaetes (Feder et al., 1994; Grebmeier, 1993, unpublished data; Stoker, 1981; Zenkevitch, 1963). The highest benthic biomass is attained in the middle shelf of the southeastern Bering Sea and in the northern Bering and southern Chukchi seas as a result of the large amount of food delivered in a shallow water column over the five-to-seven month ice-free period (Grebmeier, 1993; Grebmeier and McRoy, 1989; Haflinger, 1981). In the southeastern middle shelf, carbon flux to the benthos is

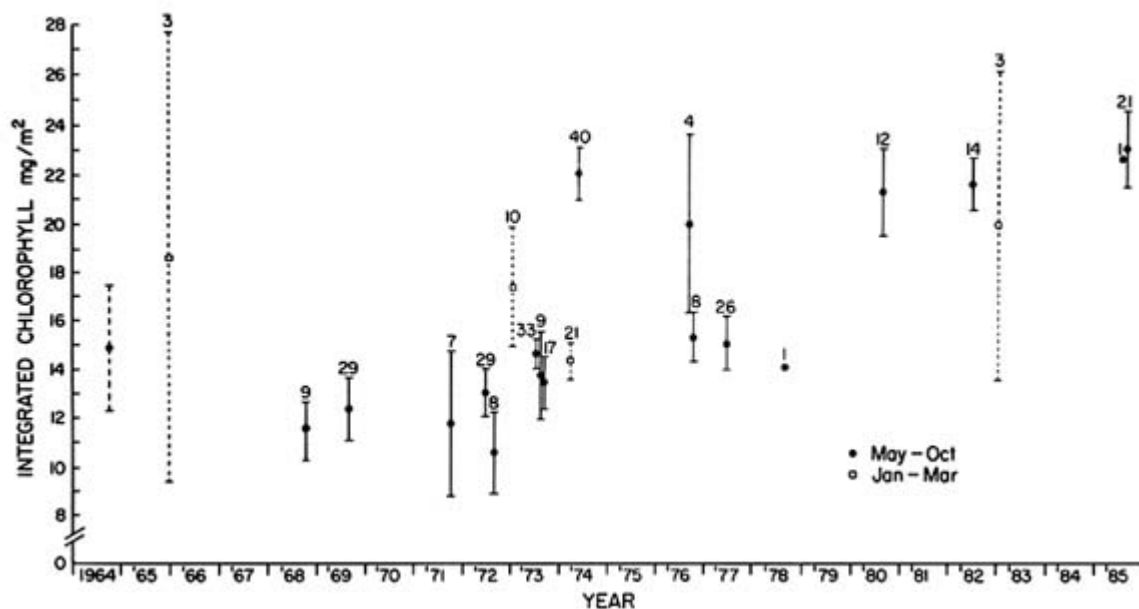


Figure 3.16 Index of phytoplankton production in the central North Pacific (observations of integrated chlorophyll a in the CNP). Bars indicate the 95 percent confidence intervals of the mean  $\bar{x} = r \sqrt{\zeta/n}$ ; the number of observations is shown above each bar. Winter values (open squares) and values before 1968 are excluded from our analyses. Definitions:  $t$ , 97.5 percentile of  $t$  statistic with  $n - 1$  df;  $\zeta$ , the variance of the observations (Venrick et al., 1987).

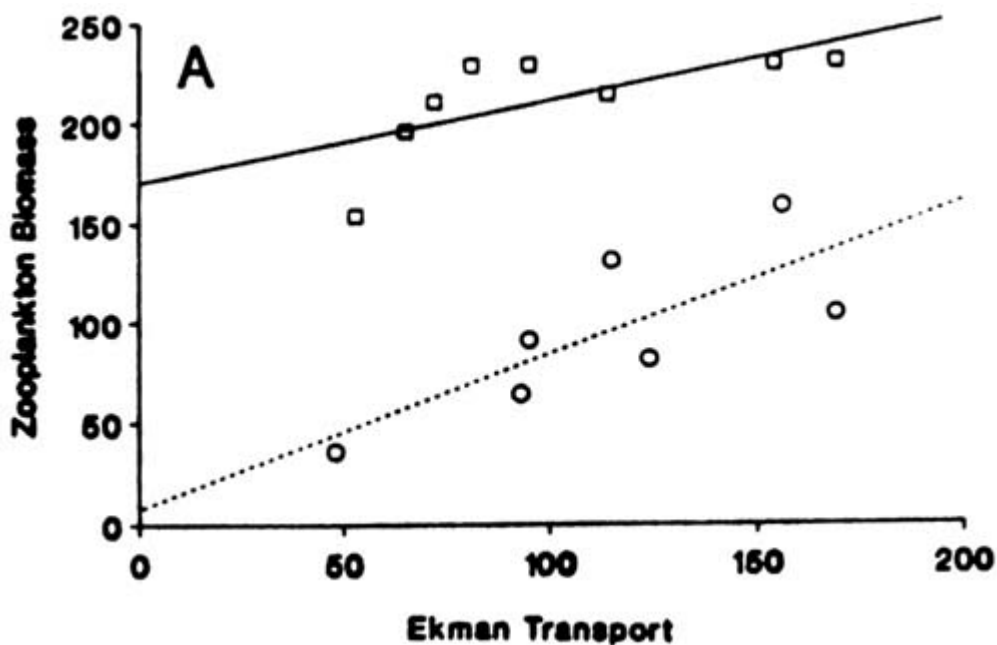


Figure 3.17 Relationship between wind stress (Ekman transport) at 60° N, 149° W in the northern Gulf of Alaska and yearly zooplankton biomass values for the periods 1956–62 (circles) and 1980–89 (squares) (Brodeur and Ware, 1992).

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high, in spite of only moderate primary production, because of inefficient grazing by the herbivorous zooplankton community. In the northern Bering and southern Chukchi, benthic carbon supply results from prodigious primary production that far surpasses the ability of the zooplankton to control. The latitudinal gradient in benthic biomass mirrors the high production on the northern shelf (Figure 3.18).

Benthic infaunal biomass in the southeastern Bering Sea averages 1 to 10 g C m<sup>-2</sup> in the inner domain, 1 to 20 g C m<sup>-2</sup> in the middle domain, and 1 to 11 g C m<sup>-2</sup> in the outer domain (Table 3.3; Figure 3.19; Feder et al., 1980; Haflinger, 1981; Stoker, 1981). It is lowest along the Alaska coastline in the northern Bering and Chukchi seas, where it is limited by ice gouging, river runoff, high current scouring, and low overlying water production (Figure 3.20; Grebmeier et al., 1988, 1989; Stoker 1981). Benthic biomass increases to the west to 20 to 40 g C m<sup>-2</sup> southwest of St. Lawrence Island and in regions of the Gulf of Anadyr (Table 3.3; Figure 3.21; Sirenko and Koltun, 1992; Grebmeier, 1993; Grebmeier and Cooper, 1995). The infaunal community structure is generally dominated by bivalves and polychaetes (Grebmeier, 1993; Stoker, 1981), although it becomes dominated by amphipods in the Chirikov Basin, north of St. Lawrence Island (Table 3.3), with biomass ranging from 10 to 30 g C m<sup>-2</sup> (Figure 3.20; Feder et al., 1985; Grebmeier et al., 1988, 1989; Highsmith and Coyle, 1992; Stoker, 1981). Infaunal biomass peaks at 50 to 60 g C m<sup>-2</sup> in the southern Chukchi Sea, where a downstream deposition of organic materials occurs (Grebmeier and McRoy, 1989; Grebmeier, 1993).

Epifaunal benthos on the eastern Bering Sea shelf (Figure 3.19) is numerically dominated by bivalves, then anthropods and echinoderms; however, nearly 70 percent of the total epibenthic biomass represents sea stars (Jewett and Feder, 1981). The most important epifauna on the southeastern shelf include four species of commercially harvested crabs: king crabs *Paralithodes camtschatica* (red) and *P. platypus* (blue), and the Tanner (snow) crabs *Chionoecetes opilio* and *C. bairdi* (Figure 3.22). In comparison, sea stars (*Asterias amurensis*, *Evasterias echinosoma*, *Leptasterias polaris acervata*, and *L. nanimensis*) dominate in the northeast Bering Sea.

Limited studies of fauna of the shelf break and deep basin in the eastern portions of the Bering Sea indicate the benthic fauna is dominated by polychaetes of low biomass, about 78 g wet wt m<sup>-2</sup>, or less than 5 g C m<sup>-2</sup> (Grebmeier, 1993; Sirenko and Koltun, 1992). Benthic populations in the basin are limited by depth and the reduced carbon supply to the bottom. Few studies are available in western literature related to the western Bering Sea, but it is reasonable that the high primary production reported for this region, similar to the upper estimate for production in the northern branch of the green belt, would directly influence benthic faunal populations and sediment processes on underlying shelf systems that it traverses.

Petersen and Curtis (1980) hypothesized that polar regions exhibits a stronger benthic-pelagic coupling than temperate and tropical areas, and a number of field studies have confirmed this hypothesis (e.g., Grebmeier, 1993; Grebmeier and McRoy, 1989; Stoker, 1981). Regions of high overlying water column production in the Bering and Chukchi seas have a direct influence on underlying benthic biomass (Grebmeier, 1993; Grebmeier et al., 1988; Rowe and Phoel, 1991). Additional studies support these patterns of direct coupling of water column production and underlying benthos in the southeast Bering Sea (Rowe and Phoel, 1991), and on the continental shelf of the Barents Sea, where sediment bacterial growth rates were higher where carbon deposition was greater than in higher-latitude regions (Pfannkuche and Thiel,

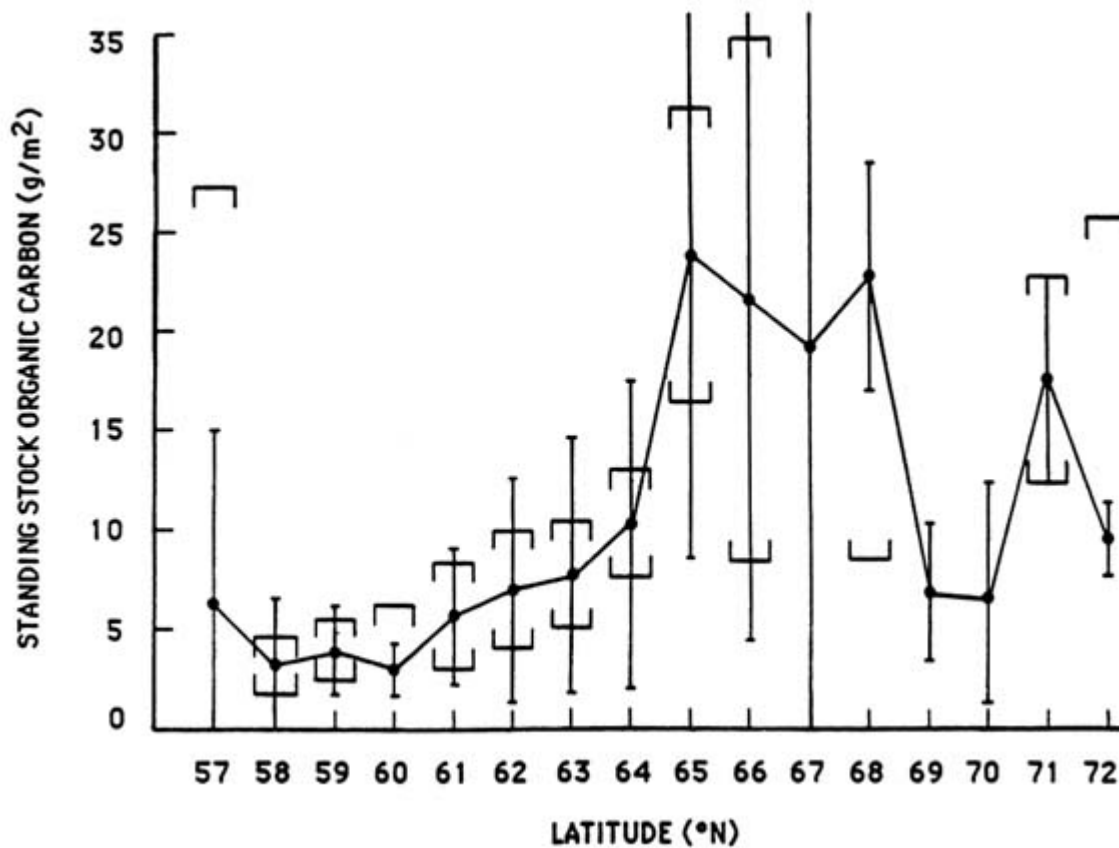


Figure 3.18 Variation of benthic biomass with latitude on the Bering and Chukchi sea shelves (vertical lines indicate standard deviation and brackets indicate the coefficient of variation around the mean) (Stoker, 1981.)

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Table 3.3 Comparison of phytoplankton and zooplankton production, benthic biomass, and sediment oxygen uptake rates for different regions on the continental shelves of Bering and Chukchi seas

Area	Phytoplankton Primary Production (g C m <sup>-2</sup> y <sup>-1</sup> )	Zooplankton Secondary Production (g C m <sup>-2</sup> y <sup>-1</sup> )	Benthic Biomass (g C m <sup>-2</sup> )	Sediment Oxygen Uptake Rates (mmol O <sub>2</sub> m <sup>-2</sup> d <sup>-1</sup> )
<b>Southeastern Bering Sea</b>				
Inner domain	50–80 (1)	-	10 (2)	3–8(3)
Middle domain	166 (1)	8–30 (4, 5)	10–20 (2,6)	3–8 (3)
Outer domain	162 (1)	30–50 (4, 5)	10 (2,6)	5–10 (3)
Oceanic domain	50 (7)	20 (4)	<5 (2)	-
<b>Northern Bering Sea</b>				
Alaska Coastal Water	80 (8)	5 (9)	<10 (11, 12)	<10 (10, 11)
Bering Shelf Water/ Anadyr Water	80–480 (8, 13)	9 (9)	10–30(10, 11)	10–30 (11, 12)
<b>Southern Chukchi Sea</b>				
Alaska Coastal Water	80 (8)	-	<10 (11, 12)	<10(11, 12)
Bering Shelf Water/ Anadyr Water	470–720 (8, 14)	-	10–60 (10, 11)	10–40 (11, 12)
<b>Northern Chukchi Sea</b>				
"Southern group"	50–100 (15, 16)	-	1–11 (17)	5–10 (11, 18)
"Northern group"	50–100 (15, 16)	-	2–20 (17)	5–10 (18)

Source: Modified from Grebmeier et al. (1995).

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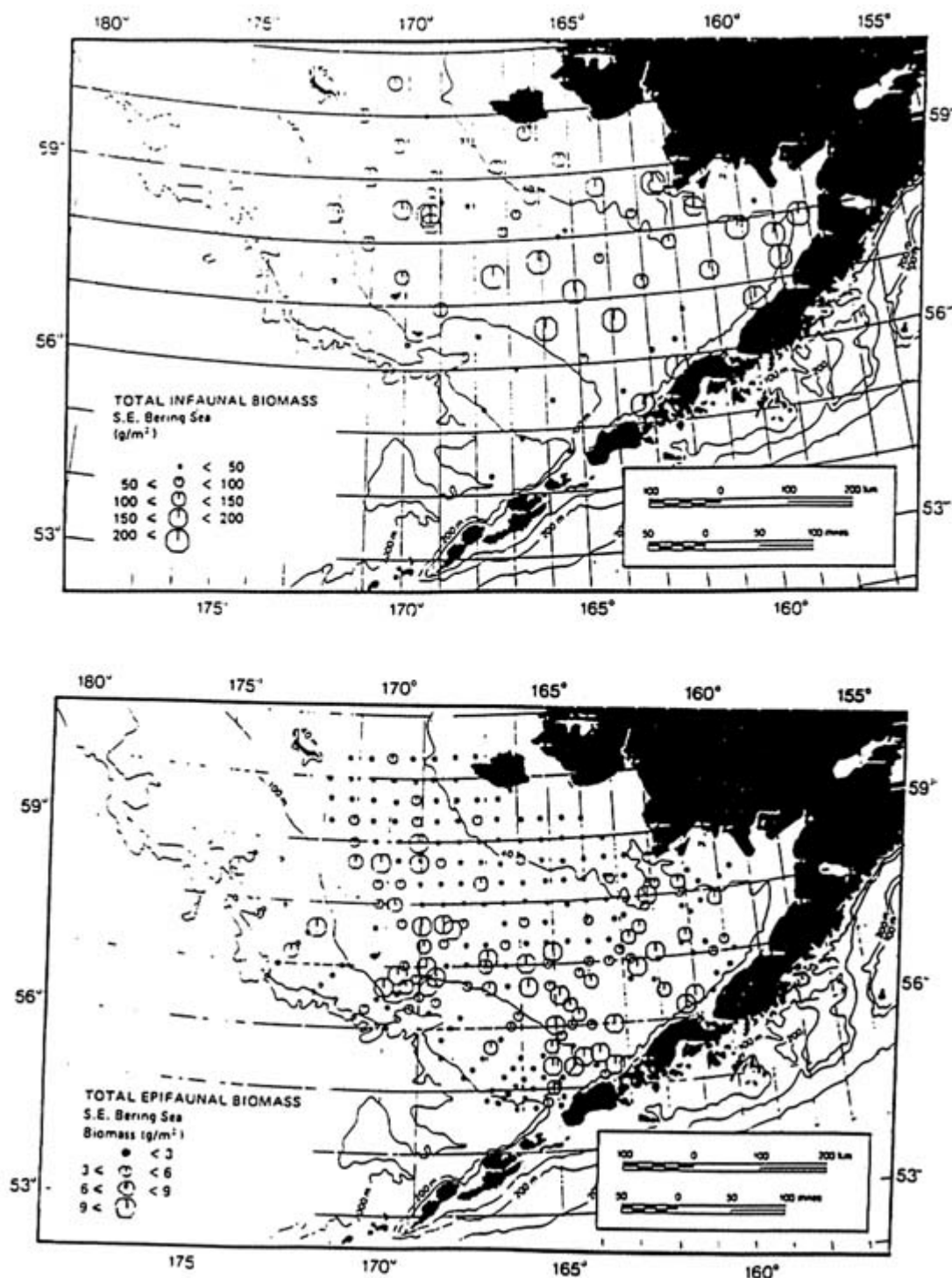


Figure 3.19 Total infaunal and epifaunal biomass in the southeastern Bering Sea (Haflinger, 1981).

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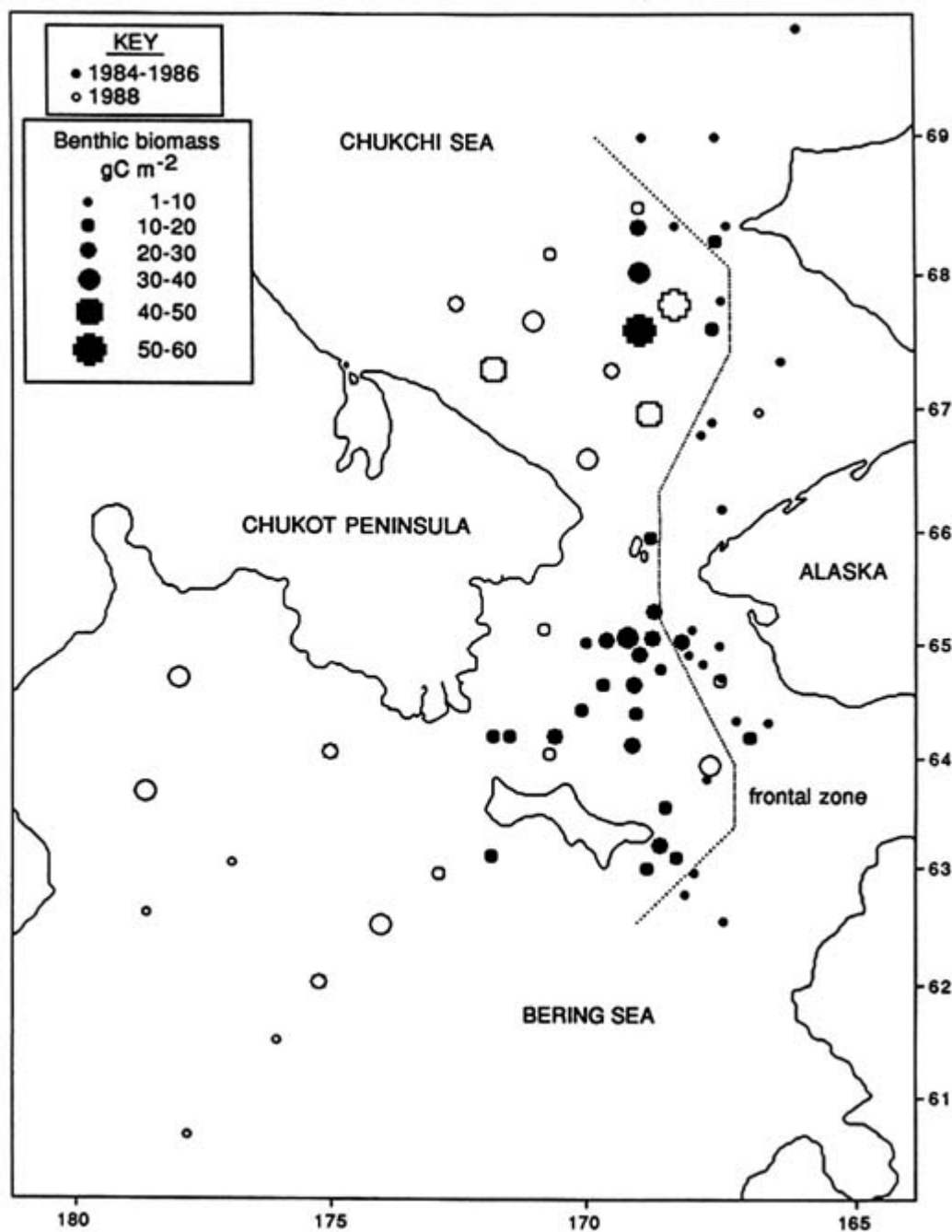


Figure 3.20 Distribution of macrofaunal benthic biomass on the shelves of the northern Bering and Chukchi seas (Grebmeier, 1993).

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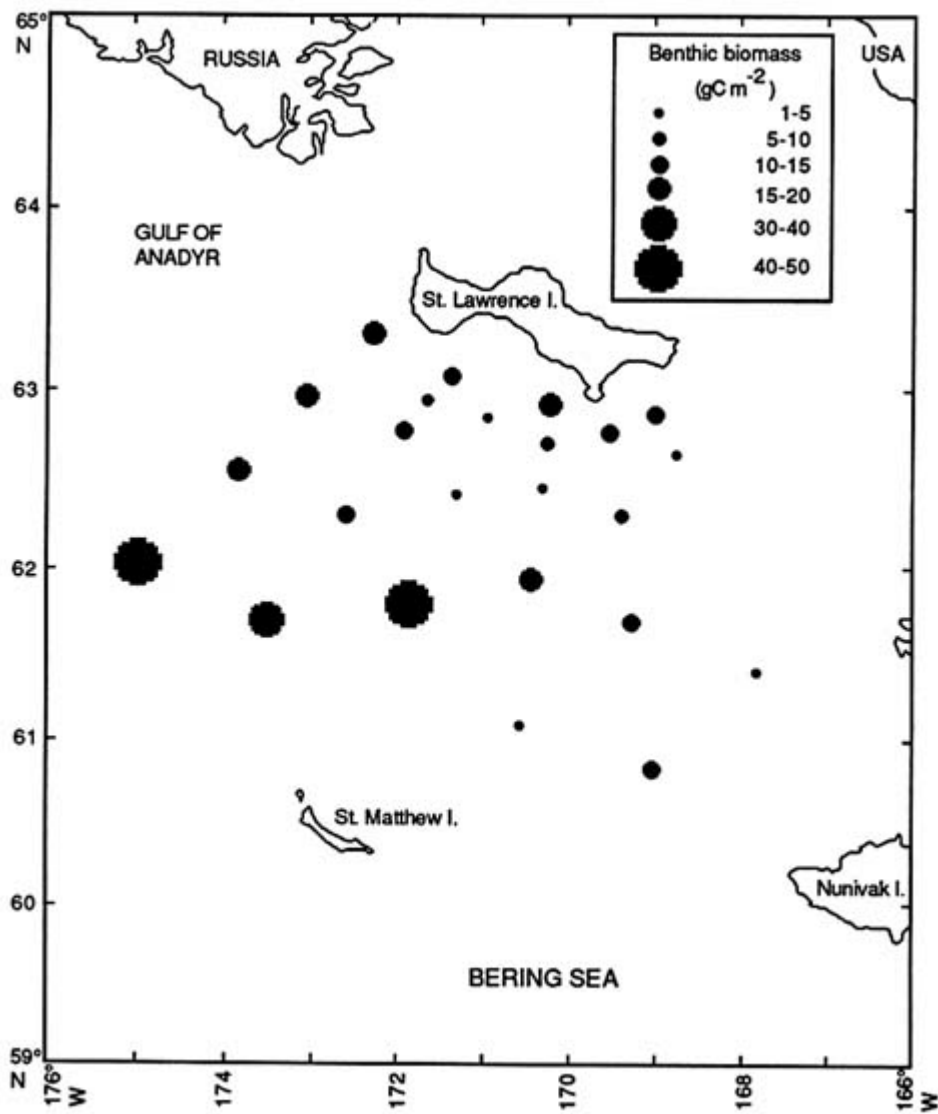


Figure 3.21 Distribution of macrofaunal biomass on the northern shelf of the Bering Sea, June 1990 (Grebmeier and Cooper, 1995).

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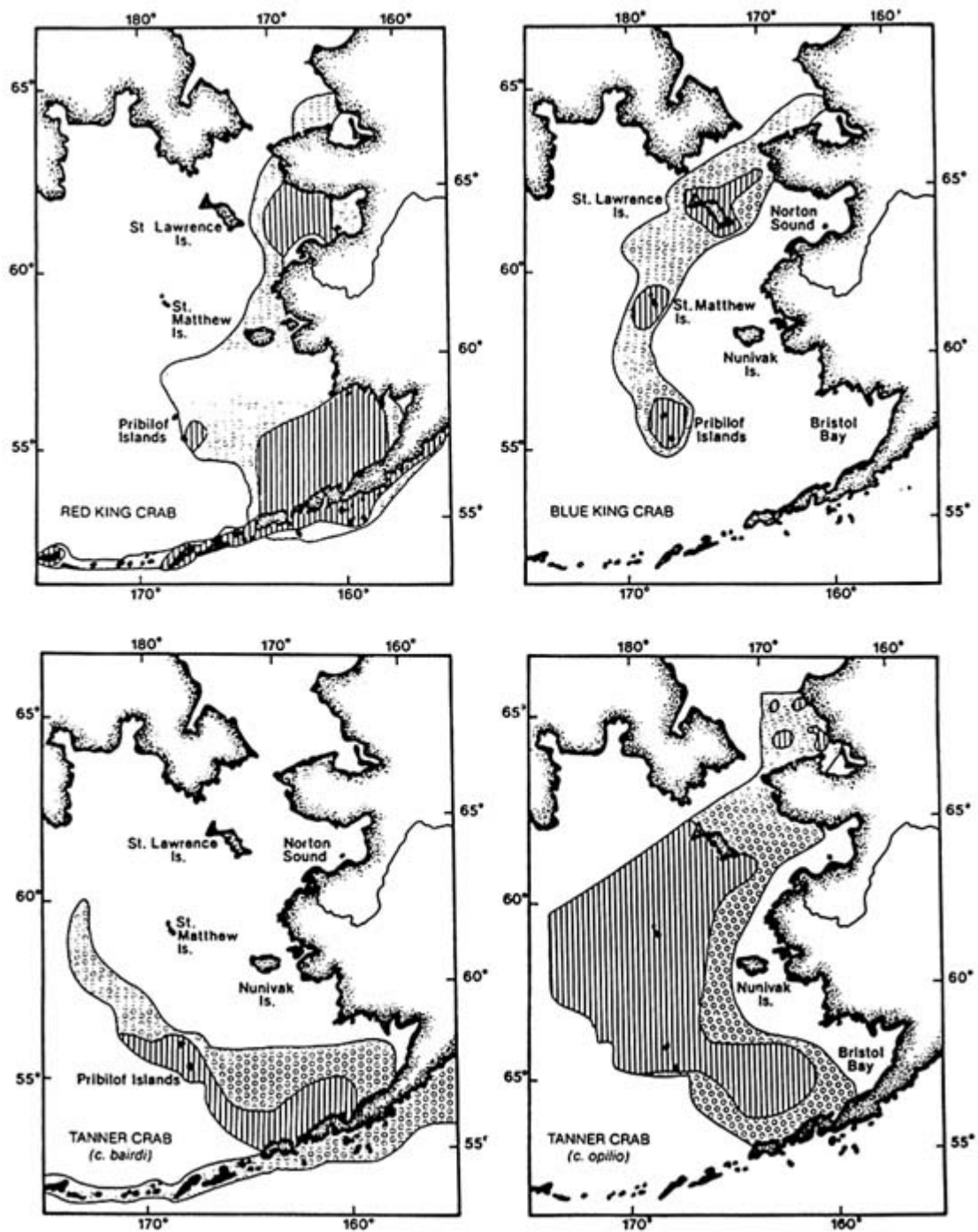


Figure 3.22 Distribution of king and Tanner crabs in the eastern Bering Sea (vertical lines indicate areas of high abundance) (Otto, 1981).

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1987). However, it is not known whether temporal patterns of vertical flux (continuous versus pulsed) give rise to different benthic communities in polar systems.

In the northern Bering and southern Chukchi seas, benthic standing stock is correlated with water column production (Grebmeier, 1993; Grebmeier and McRoy, 1989). Highest values occur under the Anadyr Water and Bering Shelf Water in regions influenced by high water column production, low zooplankton grazing, and presumably high carbon flux of phytoplankton to the benthos. This conclusion is also invoked for the relatively high benthic biomass occurring in the middle domain of the southeastern Bering Sea (Haflinger, 1981; Jewett and Feder, 1981). Sediment respiration experiments on shallow continental shelves provide an indication of organic carbon deposition to the benthos, which in the "hot spots" of the northern Bering and southern Chukchi seas ranged from 20 to 30 mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>, or an average carbon requirement of 0.5 to 1.0 g C m<sup>-2</sup> d<sup>-1</sup>. These values are similar to that obtained in a sediment trap experiment in the Chirikov Basin, where carbon flux averaged 0.5 g C m<sup>-2</sup> d<sup>-1</sup> in an area where sediment respiration rates indicated an average benthic requirement of 0.48 g C m<sup>-2</sup> d<sup>-1</sup> (Fukuchi et al., 1993; Grebmeier and McRoy, 1989). Sediment oxygen uptake under the waters near the Alaska coastline in both the Bering and Chukchi seas indicates reduced carbon flux to the benthos, with values averaging less than 10 mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup> (Grebmeier, 1993; Grebmeier and Cooper, 1995).

### Sources and Magnitude of Variability

Benthic populations provide a long-term, integrated value for processes occurring in the overlying water column. Both physical and biological parameters directly influence benthic populations. For example, changes in current transport and water mass conditions influence water temperature, nutrient influx, and oxygen concentrations to various regions of the Bering Sea ecosystem, thus influencing subsequent water column production and potential food supply to the sediments and underlying benthic fauna. Changes in physical transport mechanisms also influence sediment transport and deposition; sediment composition determines benthic community structure, whereas food supply drives benthic biomass (Grebmeier et al., 1988, 1989).

Sediment processes can provide indications of variability in the water column. Sediment oxygen uptake rates reflect short-term, seasonal carbon supply to the benthos. Cycling of organic carbon back into inorganic carbon dioxide and nutrients and/or organic compounds (e.g., dissolved organic carbon) can influence both overlying and downstream production in the system. Therefore, any climatic or human-induced changes that effect the ecosystem will have long-term impacts on benthic populations and carbon turnover on these shallow shelves; the actual magnitude is as yet unknown.

The green belt regime, described in the previous section (see [Figure 3.15](#)), extends along the shelf break of the entire Bering Sea continental shelf and across the northeastern shelf through Bering Strait and into the Chukchi Sea. Sediment carbon is higher on the slope than in the shelf system (Lisitsyn, 1966), and it is proposed that high production in the green belt may account for this accumulation.

Benthic production reaches its highest levels in both the Bering and Chukchi seas under the northern branch of the green belt in regions influenced by nutrient-rich Anadyr Water (see [Table 3.3](#)). If changes in the Bering Sea ecosystem were to occur that directly influenced green

belt production, whether via natural or anthropogenic effects at either primary or secondary production level in the water column, one would expect a direct impact on the carbon being deposited to the benthos and subsequent impact on underlying benthic populations. Changes in benthic populations, particularly fauna that are a food source to commercially harvested demersal fish and crabs, could have a long-term impact on these fisheries that are currently so productive in the Bering Sea. Marine mammal populations (e.g., gray whales, walrus, and bearded seals) that feed on the productive benthic fauna could also be affected.

Studies of benthic infauna populations have been done since the early 1930s in the Bering Sea (Grebmeier and Barry, 1991; Sirenko and Koltun, 1992, and references therein), but few have been extended long enough to investigate the population dynamics that are needed to differentiate natural environmental impacts from anthropogenic ones. However, a few studies over multiple years do indicate possible ecosystem-level changes and are especially informative because they occur in the northern Bering Sea, where commercial fishing pressure is minimal. Variability in benthic macroinvertebrate epifauna (crabs) is discussed in the following chapter.

A recent three-year study of the dominant ampeliscid amphipods in the northern Bering Sea, one of the most productive benthic communities in the world (Grebmeier et al., 1988; Highsmith and Coyle, 1990), found a decrease in production from 1986 to 1988 (Highsmith and Coyle, 1992). The authors indicate, however, that further long-term studies are needed to determine whether this decrease in amphipod production is due to natural predation cycles by benthic-feeding gray whales or to a long-term climate trend (Coyle and Highsmith, 1994). Their modeling results predict that perturbations in predation on the amphipod populations will have long-term effects (tens to hundreds of years) because these invertebrates are slow-maturing species, a common characteristic of high-latitude organisms.

The large species of this amphipod community, *Ampelisca macrocephala*, requires a high carbon flux to the detrital pool it utilizes for food, and with low predation rates, which limits its occurrence to the northern cold, productive waters (Highsmith and Coyle, 1991). The modeling study by Coyle and Highsmith (1994) indicates that any decrease in carbon flux would be detrimental to such large species, shifting the population to smaller species that would out compete the large amphipods, thus changing the benthic community structure. In addition, the low bottom temperatures of the northern Bering Sea exclude most bottom-feeding fish (Bakkala, 1981; Jewett and Feder, 1980); thus, any shift to higher temperatures would extend their range and could increase predation pressure by fish, gray whales, and crabs on these amphipod populations.

Another issue is the apparent spatial shift and population decline of a bivalve community, dominated by nuculanid, nuculid and tellinid bivalves, south and southwest of St. Lawrence Island in the northern Bering Sea. The single most common bivalve, *Nuculana radiata*, is a surface deposit feeder associated with finer silt sediments, which is consistent with the higher total organic carbon (and lower C/N values) observed in these surface sediments (Grebmeier and Cooper, 1995). Although benthic sampling in this region has not been extensive, apparent shifts in species dominance over the past few decades suggest that other processes are influencing the biomass and community structure of these Bering Sea benthic communities.

Abundant benthic populations and high biomass have been documented near the St. Lawrence Island polynya and westward into the Gulf of Anadyr, including both infauna (Feder et al., 1985; Grebmeier, 1993; Grebmeier et al., 1988, 1989; Neiman, 1963; Sirenko and



Koltun, 1992; Stoker, 1981) and epifauna (Jewett and Feder, 1981). The dominant benthic fauna in the Gulf of Anadyr region until the late 1980s were reported to be the common arctic tellinid bivalve *Macoma calcarea* and the nuculid bivalve *Nucula belloti*. Since then there has been a change in the dominance and distribution patterns of the major bivalves, however with the surface deposit feeding *N. radiata* (a more cold-water tolerant species than *Macoma*) moving west into the Gulf of Anadyr (Grebmeier, 1993; Grebmeier and Cooper, 1995; Sirenko and Koltun, 1992). Both *N. belloti* and *M. calcarea* declined in abundance and were observed at more westerly locations (Sirenko and Koltun, 1992). In contrast, the *Nuculana* community was the same in 1960 as in the 1930s, and then started to expand in the late 1970s and early 1980s, reaching its current population structure and position in 1988 (Sirenko and Koltun, 1992).

Sirenko and Koltun (1992) suggest that the change in bivalve community dominance in the Gulf of Anadyr may be due either to a northward shift of cold water since the 1930s or to preference by the dominant bivalve fauna for a specific sediment type or associated chemical composition (*Nuculana* prefers a muddier sediment regime than *Macoma*). Grebmeier and Cooper (1995) hypothesize that variable transport conditions, such as a decrease in the size of the Gulf of Anadyr gyre or the intensity of circulation around the gyre, could have influenced carbon supply rates to the benthos, leading to increased settling of finer-grained sediments over a larger area, or at least further to the west. A continuing decline in both abundance and biomass values of the dominant bivalve species and associated benthic fauna in the St. Lawrence island Polynya and Gulf of Anadyr region may indicate that a larger, ecosystem-scale change is responsible (Grebmeier and Cooper, 1995, unpublished data). Studies over both interannual and decadal time scales are required to elucidate factors influencing observed changes in benthic populations in the northern Bering Sea.



## 4

# Biology of Higher Trophic Levels

The Bering Sea contains many bird, mammal, and commercially important fish and invertebrate species. The Bering Sea ecosystem can be divided into five major regions: the eastern Bering Sea, the Aleutian Islands, the Gulf of Alaska, the Aleutian Basin, and the western Bering Sea. The state of knowledge and the history of exploitation vary for different regions of the Bering Sea. For some species with relatively good histories of exploitation or protection, statistical data are available that provide information on species distributions and magnitude of variability. Generally, the most information is known about the eastern Bering Sea, Aleutians, and Gulf of Alaska, followed by the Aleutian Basin and then the western Bering Sea. This imbalance in data and knowledge on the five regions and the species themselves makes the study of the Bering Sea ecosystem as a whole very difficult.

### INVERTEBRATES

#### Life History and Distribution

Although there are many benthic and pelagic invertebrates in the Bering Sea, only a few are commercially significant. Because of their commercial importance, the most data are available on the squid, crabs, scallops, and shrimp.

#### Squid (*Berryteuthis* sp. and *Gonatus* sp.)

Several species of squid inhabit the Bering Sea seasonally and also are widely distributed. The exact nature and size of the resource are poorly understood. Squid populations are thought to be large and mobile and to live at both mid-water and near-surface depths. Spawning for some species may extend from spring to fall; sexual maturity may be reached in two years or less. Fertilization is internal. The number of eggs spawned per individual is low compared to groundfish, and the eggs may be attached to seaweeds or the seafloor. Predators of squid are marine mammals and pelagic fishes.

### King Crab (*Paralithodes* spp. and *Lithodes* sp.)

Three species of king crabs are found in the Bering Sea and Aleutian Islands region. The red king crab (*P. camtschatica*) is the largest, most widespread, and most abundant. They are generally found on the continental shelf in the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska to northern British Columbia, generally at depths of 180 m or less (Hayes, 1983). In the western Bering Sea, two large populations of red king crab have been identified—the first in the Sea of Okhotsk region along its broad continental shelf and the west Kamchatka shelf (Vinogradov, 1970), and the second in the northwest Ayano-Shantarskii (Rodin and Myasoyedov, 1982). In addition, relatively small populations exist along the seacoast, including western Sakhalin, Aniva Bay, Tereniya Bay, and east Kamchatka, and near the southern Kurile Islands (Rodin, 1989).

The blue king crab (*P. platypus*) has a more limited distribution. Bering Sea populations are found around St. Lawrence Island, St. Matthew Island, and the Pribilof Islands. Life history is similar to that of the red king crab, described below, though the blue king crab may only breed only on a biennial basis, with spawning occurring during the spring (Stevens et al., 1993). When in the juvenile stage, it tends to concentrate in rocky and shell hash substrates (Armstrong et al., 1985). The brown, or golden, king crab (*L. aequispina*) is the smallest of the three commercial species, and it inhabits deep water (> 180 m) along the continental slopes of the North Pacific Ocean and the Bering Sea. Little is known of its life history.

Whereas adult red king crab feed offshore and migrate inshore for spawning, juveniles are found in the littoral zone and shallower water. In the Bering Sea, adults prefer bottom temperatures of 0° to 5.5° C, suggesting a temperature influence on distribution. Molting and spawning take place in shallow (10 to 50 m) waters in late winter and early spring. Growth of red king crab is discontinuous at time of molts. The U.S. fishery begins to capture them when they are around eight years old. King crab are bottom-foraging omnivores. Principal food sources includes starfish, clams, other mollusks, small crabs, shrimps, other crustaceans, worms, fish, and algae. Predators of king crab include yellowfin sole, Pacific cod, walleye pollock, and Pacific halibut (Wooster, 1992). Females can carry up to 200,000 eggs for a year in the brood pouch before they hatch. Larvae molt four times in a pelagic phase and then settle to the seafloor. Juveniles move into shallow waters to create dense pods ranging from thousands to hundreds of thousands of individuals. King crabs reach maturity at four or five years of age and breed annually (Gusey, 1979).

Trawl surveys provide the longest limited information on interannual variation among king and Tanner crab stock units; fishery scientists have conducted independent stock assessments and surveys. Regular systematic trawl surveys for king crab began in the eastern Bering Sea in 1955 and, except for a hiatus from 1962 to 1966, have continued to date. Beginning in 1971, the station pattern of the trawl survey was expanded to include the full range of eastern Bering Sea crabs. Also in 1971, a pot survey for king crab was initiated in the Kodiak region of the Gulf of Alaska. The data from these surveys provide the longest and most consistent time series of survey data available to measure fluctuations in North Pacific crabs. The results of these surveys and comparisons with commercial catch statistics are given in

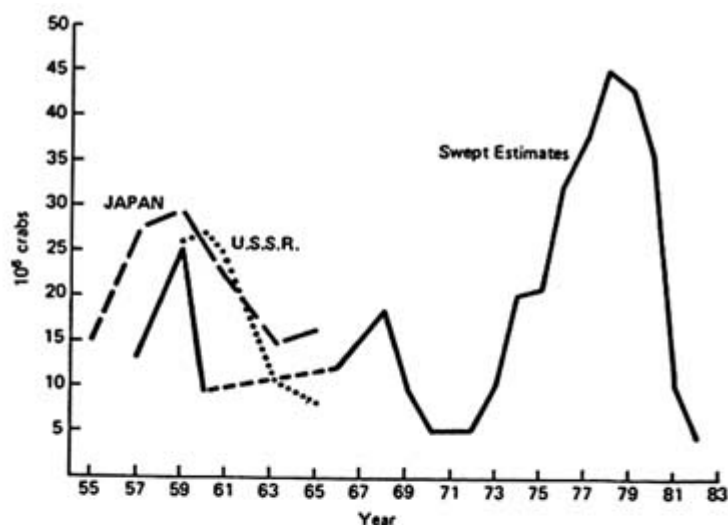
Figures 4.1 (eastern Bering Sea; Hayes, 1983; R.S. Otto, personal communication) and 4.2 (Kodiak; Hayes, 1983). Hayes (1983) concluded that interannual variations in abundance of the exploitable portion of king crab stocks have ranged over an order of magnitude in both the eastern Bering Sea and Kodiak. These fluctuations result from the occurrence of particularly successful cohorts that can be observed to grow and progress through successive sample years, indicating that the sources of these variations operates early in the crab's life history. Similar patterns can be seen for eastern Bering Sea Tanner crab and snow crab. Wooster (1992) chronicled the sporadic fluctuations of king crab over the last three decades. Combining his data (Figure 4.3) with those already shown, patterns in crab dynamics emerge. Red king crab biomass seems to grow quickly, owing to a small number of strong cohorts, and decline quickly as the cohorts either die or are fished out. This happened in Kodiak (central areas in Figure 4.3) in the late 1960s and early 1980s and in the Bering Sea (Figure 4.1) in the late 1950s, late 1970s, and early 1980s.

### **Tanner Crab (*Chionoecetes* spp.)**

Tanner crabs are found throughout the Bering Sea region. Two species are relatively large and therefore are of commercial importance. The Tanner crab *C. bairdi* is the larger of the two species and is usually encountered in the same habitat as red king crab. The snow crab *C. opilio* is smaller but believed to be the most abundant of the Tanner crabs. It is found in the northern and central Bering Sea on the continental shelf of Russia and Alaska (Slizkin 1989). Eastern Bering Sea Tanner crab (and snow crab) exploitable biomasses peaked in the mid-1970s and again in the late 1980s and early 1990s. The food and feeding habits of Tanner crab are similar to those of king crab; in the larval phase they feed on plankton, in the juvenile phase on benthic diatoms, hydroids, and detritus, and in the adult phase on such benthic organisms as crustaceans, bivalves, brittle stars, echinoids, worms, fish and gastropods. They are eaten by eelpouts, sculpins, and skates (NPFMC, 1994). Breeding occurs in winter, in waters of 500 to 700 m. Eggs in female abdominal brood pouches can number up to 200,000 and can be carried for up to a year before hatching. Larval release may coincide with spring plankton blooms, and the larvae go through several molts before going to the sea bottom as immature crabs (Lewbel, 1983).

### **Hair Crab (*Erimacrus Isenbeckii*)**

Korean hair crab, sold commercially by the Japanese, was fished commercially for the first time by the U.S. fleet in 1979. Found primarily near the Pribilof Islands area, this species was used to support an experimental fishery, where crab are shipped live to markets in Japan. Hair crab were first considered as a supplement to ongoing king and Tanner crab operations. Catch quickly increased to about 2.5 million lb by 1980–81 and stabilized at about 1 million lb for the next two years. Beginning in 1983–84, catches have been steadily declining to about 1,000 lb annually beginning in 1988. A similar decline in fishing effort reflects both a decline in the resource as well as poor market conditions.



### TRAWL SURVEY ABUNDANCE INDICES OF COMMERCIAL - SIZE BERING SEA CRABS

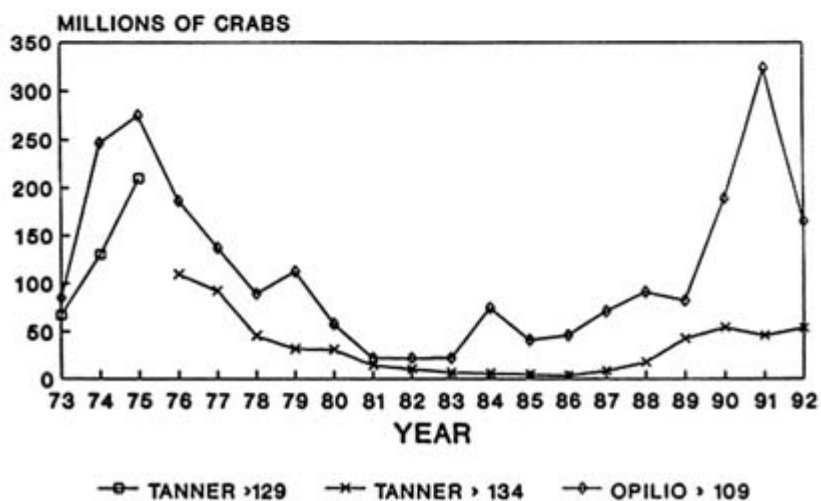


Figure 4.1 Abundance estimates for large male king crabs, *Paralithodes camtschatica*, from National Marine Fisheries Service trawl surveys in the eastern Bering Sea (solid lines are swept estimates, dotted line is an index based on Japanese catch per unit effort (CPUE), and dashed line is an index based on USSR CPUE).

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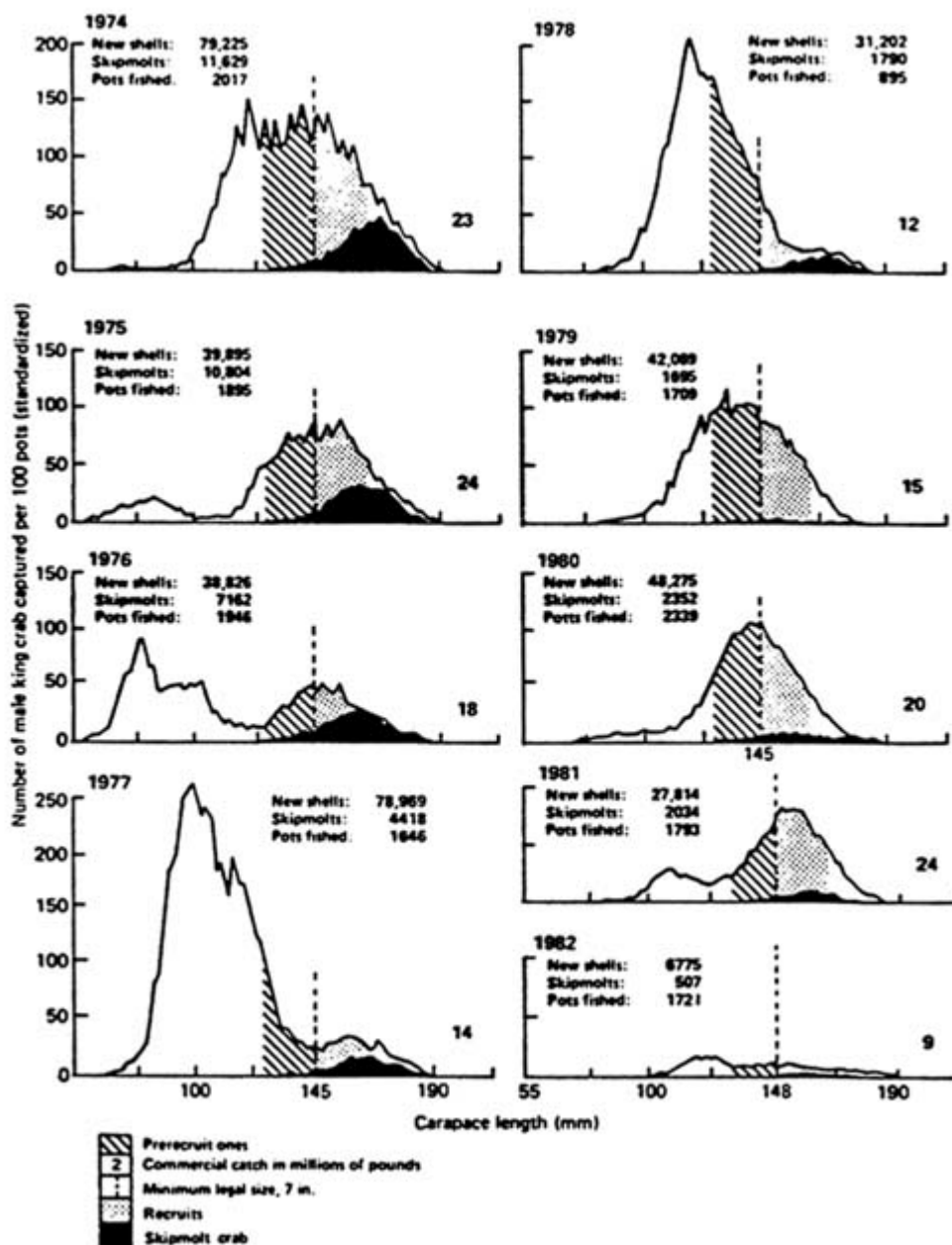


Figure 4.2 Kodiak male red king crab size distribution, for each year from 1974 to 1982 (as determined by research pot sampling; skipmolt crab—the black area—masks new shell crab) (Hayes, 1983).

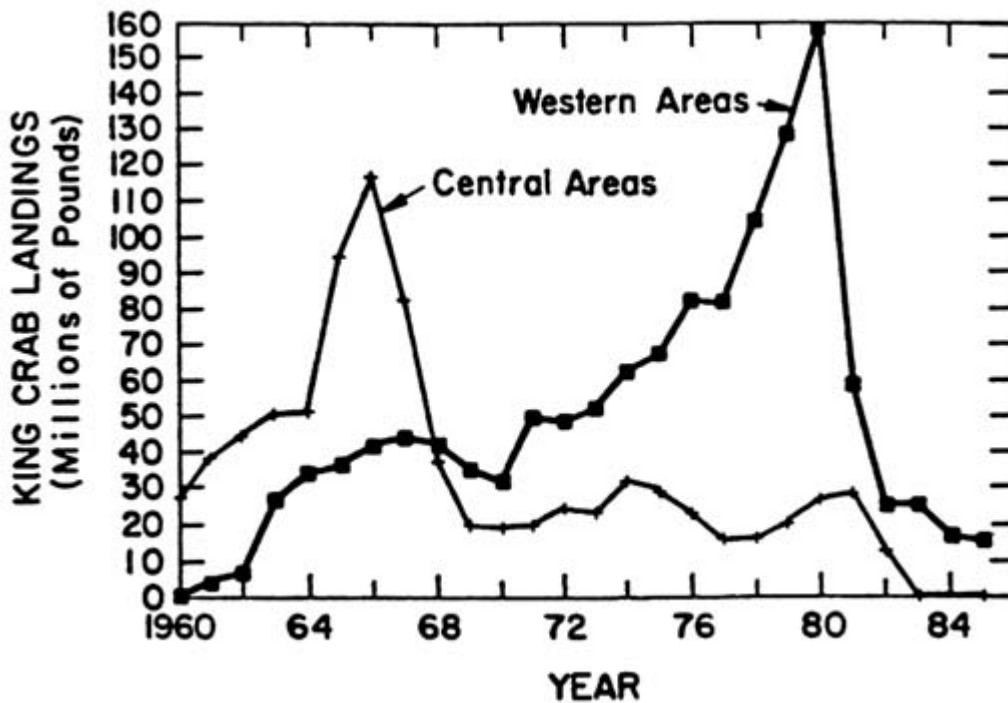


Figure 4.3 Alaska king crab landings from central and western areas (central areas include Prince William Sound, Lower Cook Inlet, Kodiak Island, and South Peninsula; western areas include Bristol Bay, Dutch Harbor, Adak, and the eastern Bering Sea) (Wooster, 1992).

### Shrimp (Family Pandalidae)

Eight pandalid shrimp species representing two genera are taken in commercial and subsistence fisheries off Alaska, but only five are of commercial importance. For many years, shrimp fishermen have targeted primarily pink shrimp (*Pandalus borealis*), with up to 85 percent of shrimp catch in some years made up of this single species. Other pandalid species, i.e., *P. hypsinotus* (coonstripe), *P. goniurus* (humpy), and *P. dispar* (sidestripe), are most often taken incidental to the fishery for pink shrimp. Humpy and sidestripe shrimp have at times been dominant in trawl catches from specific areas and have supported small fisheries. Other pandalids, i.e., *P. danae* (dock), *P. montagui tridens*, *P. jordani* (ocean pink), and *P. platyceros* (spot), are also taken incidentally in trawl fisheries. The former two species are the least common of the pandalids found in commercial catches and dock shrimp are rarely taken in Kodiak and the Bering Sea/Aleutian Island regions. Spot and coonstripe shrimp have supported small pot fisheries in Prince William Sound and in the eastern Gulf of Alaska.

The extent of pandalid research on Alaskan species has closely followed the rise and fall of the commercial shrimp fishery. As interest in the species grew, government agencies



dedicated funds and staff to shrimp research. When the pink shrimp fishery crashed in the mid-1980s, fiscal priorities likewise changed (in this case to king crab) and nearly all shrimp research ended. As a result, most of the literature concerning the life history of pandalid shrimp consists of studies of pink shrimp (*P. borealis*). Fishery scientists have been working under the assumption that characteristics of pink shrimp life history closely mirror those of other species within the genus *Pandalus*, while recognizing that regional and species differences likely occur. Balsiger (1981) presents an excellent review of pandalid research.

The life history of pink shrimp can be separated into seven distinct development stages. The female carries from 900 to 4,000 developing eggs in her abdomen. Larger, older females normally carry more eggs than do small females (Fox, 1972; Mistakidis, 1957; Haynes and Wigley, 1969). Female pandalid shrimp carry their fertilized eggs until the eggs hatch; thus, mortality to the female precipitates mortality to her egg clutch. Spawning normally occurs in August through October depending on region, with differences in water temperature the apparent controlling factor (Rasmussen, 1969). The incubation stage may last six months. In the Gulf of Alaska, pink shrimp larvae hatch from February through April or early May, whereas other species hatch from April into mid-July (Buck et al, 1975). The unique water circulation patterns of bays and island regions benefit spawning shrimp by preventing planktonic larvae from drifting into unfavorable areas. Larvae are free-swimming for approximately two and one-half months and then settle to the bottom as postlarvae to assume adult behavior. These juveniles are most abundant in waters deeper than 20 fathoms (120 feet). At the onset of winter, however, they appear to migrate to shallow waters of less than 20 fathoms (Buck et al, 1975). Mortality rates are believed to be high for shrimp but are difficult to quantify. Natural mortality estimates have ranged from 22 percent to 85 percent per year, depending on size and age (Gotshall, 1969; Rinaldo, 1976; Anderson, 1978). Predators include cod, sablefish, sole, flounder, halibut, rockfishes, and salmon.

One unique aspect of shrimp life history is individual transformation of sex. Almost all shrimp develop as males, although initial development as females has been reported in a few species. Shrimp reach maturity as adult males two years from hatching. At two and one-half years of age, most breed as males, although at three and one-half years a few have already transformed into females. By four and one-half years of age, all shrimp have transformed into sexually mature females. Six months is the average time required for an individual to change sex. Few females live beyond six years.

Little is known of the food and feeding habits of pandalid shrimp, but in general they are predators and scavengers. Shrimp feed principally upon a wide variety of organisms, including worms and larvae (Butler, 1964; Fox, 1972; Dahlstrom, 1970). The most common food item identified in studies on shrimp was crab larvae.

Mortality rates are believed to be high for shrimp but are difficult to quantify. Natural mortality estimates have ranged from 22 percent to 85 percent per year, depending on size and age (Anderson, 1978; Gotshall, 1969; Rinaldo, 1976). Virtually any large fish in their vicinity, including cod, sablefish, sole, flounder, halibut, rockfishes, and salmon, is a potential predator.

Pandalid shrimp species move off the ocean bottom at night. Each species of shrimp differs in the proportion of individuals that migrate upward and in the upward distance of migration (Barr and McBride, 1967). Different species can be found from the surface to at least 230 fathoms (1,380 feet). In the Kodiak and Cook Inlet areas, large concentrations of pink

shrimp have been found over sand, silt, or mud substrates. Exploration in more rocky and more difficult trawling areas such as those located in Prince William Sound has been too limited to assess accurately the harvest potential of spot shrimp with trawl gear from these areas. However, it appears that spot shrimp clearly prefer rocky bottoms, usually the bottom of deep canyons or crevices, or pockets along steep, rocky cliffs. As mentioned previously, we understand that Alaska Department of Fish and Game (ADF&G) intends over the short-term to conduct a series of pot surveys on spot shrimp.

### Scallops (Family Pectinidae)

Five species of scallops are commonly found in the Bering Sea and Aleutian Islands area. The most common and the primary target of the commercial fishery is the weathervane scallop (*Patinopecten caurinus*). Taxonomic classification and evolutionary relationships among weathervanes and other commercially important scallop species are described by Waller (1991). Weathervane scallops are found in intertidal waters to depths of 300 m (Foster, 1991), but abundance seems to be greatest between the depths of 45 and 130 m on beds of mud, clay, and sand (Hennick, 1973). Little is known about the biology of these species, and according to the North Pacific Fishery Management Council (NPFMC, 1993), there have been no routine biological or fishery programs to sample scallops.

Scallops develop through a series of growth stages. In the Atlantic, scallop beds are thought to be strongly affected by ocean current patterns (New England Fishery Management Council, 1982), which in turn can affect local recruitment and settling of larvae; the beds tend to be elongated in the current direction and can include different age and/or size groups (Caddy, 1989; Robert and Jamieson, 1986). Weathervane scallops mature by age three, with rapid growth observed through the first 10 years of life (Hennick, 1973). Scallops are long-lived species and may reach an age of 28 years or more. Principal predators of scallops are various invertebrates (such as crabs and starfish) and fish (such as flatfish). The commercial fishery (a primary source of biological information) has experienced a variable history, during which the fishery exists for a number of years followed by a period of no activity. Alaska scallop resources appear to be healthy, which has stimulated renewed fishery activity.

## FINFISH

### Life History, Distribution, and Variability

Of the approximately 450 fish, shellfish, and crustacean species in the eastern Bering Sea, only about 25 are commercially important. The discussions that follow provide background data on the known life habits and biological attributes of significant species in the Bering Sea, including their spatial and temporal variability. Information on the commercial industry that depends on some of these species is covered in [Chapter 5](#). A number of previous histories and compilations (e.g., NPFMC, 1993; Lewbel, 1983; Hood and Calder, 1981) were used as references for this section.

Most commercial finfish species have experienced some variation in abundance over the years, and in some cases the variability has been extreme. Abundance trends can be measured by a variety of methods. For most species, historical catch statistics and catch per unit effort can be used as measures of relative abundance. Absolute abundance estimates be arrived at only through stock assessment surveys combined with a variety of statistical techniques and modeling. For species such as salmon, run sizes can be determined from a combination of catch and escapement estimates. Most of the information on which these reports and analyses are based is meant to provide advice on the short-term (year-to-year) management of commercial fisheries. Thus, those reports and analyses focus on commercially important species and on the distribution and size of the population or stock. This may not be an appropriate scale at which to approach the kinds of ecosystem questions that this study is asked to address. There is information in these reports and stock assessments, however, which provides insight into ecosystem-scale processes that might be operating in the Bering Sea. Once again, most of the information relates to the eastern Bering Sea and Aleutian Islands, with limited information on the Aleutian Basin (pollock only) and sparse information on the western Bering Sea. In addition, many fish species—especially pelagic species—are not commercially significant and might have significant effects on ecosystem organization. However, little information is available on those species compared with the commercially important ones and we have not discussed them.

Details on groundfish<sup>1</sup> (excluding halibut) can be found in the NPFMC 1994–95 Stock Assessment and Fishery Evaluation reports for the Bering Sea/Aleutian Islands area and the Gulf of Alaska (NPFMC, 1993). In general both NPFMC and the National Marine Fisheries Service (NMFS) are of the opinion that the groundfish stocks of the eastern Bering Sea/Aleutian Islands are in "good" condition. This is certainly the case if the resources of the eastern Bering Sea are compared to those of other regions of the world. However, as should be expected for a dynamic system, all species are unlikely to be at their peaks in abundance at the same time. Some species, such as sablefish, offshore pollock in the Aleutian Basin, and Greenland turbot, are currently at relatively low levels. Others, such as a number of flatfish (yellowfin sole, rock sole, arrowtooth flounder, flathead sole, and Alaska plaice) on the eastern Bering Sea shelf and Atka mackerel in the Aleutian Islands are currently at relatively high levels of abundance.

### **Walleye Pollock (*Theragra chalcogramma*)**

Walleye pollock is a semidemersal species that inhabits continental slope and shelf waters along the northern rim of the North Pacific, extending from southern Oregon into the southern Chukchi Sea and south along the Asian coast to the southern Sea of Japan (Bakkala, 1993). At present, the walleye pollock stock represents the greatest single-species biomass in the Bering Sea, accounting for approximately 50 percent of the total biomass of all groundfish in the eastern Bering Sea, Aleutian Islands, and Bogoslof district (NPFMC, 1993). They probably account for at least that proportion of the biomass in the western Bering Sea as well (Sabolevsky et al., 1989; Wabkabayashi and Bakkala, 1985).

<sup>1</sup> Fish normally caught with bottom-fishing gear, usually bottom trawls. Some of these species (e.g., pollock) also spend time higher in the water column.

In the Bering Sea, pollock are found throughout the water column along the eastern and western continental shelves and throughout the deep Aleutian Basin. Massive schools occur on the outer shelf and upper slope from the surface to 500 m. In the eastern Bering Sea, walleye pollock undergo extensive seasonal migrations associated with feeding and reproduction. Overwintering takes place along the outer shelf and upper slope and over deep water where bottom temperatures are relatively high. As temperatures on the shelf rise in spring, part of the walleye pollock population moves to shallower waters (90 to 140 m) to spawn. They first reproduce at the age of three or four years.

Spawning occurs primarily in the first quarter of the year in the Aleutian Basin, with major aggregations occurring in the vicinity of Bogoslof Island, and from March through October along the eastern Bering Sea outer shelf (Hinckley, 1986), with major spawning concentrations occurring between the Pribilof Islands and Unimak Island. Along the eastern Bering Sea shelf and slope, each female produces approximately 60,000 to 400,000 pelagic eggs. Fecundity is much lower in the basin.

Walleye pollock eggs hatch in two to three weeks, depending on temperature, and larvae tend to inhabit surface waters. Larval pollock begin feeding on copepod eggs and nauplii; as they grow, they feed successively on larger prey such as small copepods. Diets of adult pollock consist mainly of copepods, euphausiids, and fish, the majority of which are juvenile pollock. Pollock are a major part of the diets of northern fur seals and other marine mammals, and are also important prey for many seabirds and fish (Frost and Lowry, 1981b; Pereyra et al., 1976).

The population and stock structure of walleye pollock deserves special attention because of its economic and political importance. Much of the literature on stock structure of pollock in the North Pacific is inconclusive. In terms of genetic differences, Bakkala (1993) reported major genetic differences between populations in the Sea of Okhotsk and those in the eastern Bering Sea and Gulf of Alaska. Within North American waters, small but detectable genetic differences were found between pollock from the eastern Bering Sea and the Gulf of Alaska.

The genetic relationships among pollock from the eastern Bering Sea, Aleutian Islands, and western Bering Sea are less clear. Dawson (1994) provided an excellent overview of these relationships as well as a clear discussion of the concepts of population and stock with particular reference to Bering Sea pollock. He analyzed several independent data sets, using abundance at age from research and commercial samples, size at age, and morphometric analysis, to assess the degree of isolation of populations of juvenile and adult pollock sampled across all four major areas of the Bering Sea. He concluded that there are several phenotypic stocks of pollock. One is on the eastern Bering Sea shelf, with the main spawning area on the southeastern shelf (southeast of the Pribilof Islands) and with a main juvenile rearing ground on the northeastern shelf (northwest of the Pribilof Islands). Another stock is in the Aleutian Basin with its main spawning ground in the southeast basin near Bogoslof Island. This stock probably occupies the same rearing area as the eastern Bering Sea shelf stock. Dawson's analyses led him to conclude that pollock from the Aleutian Basin and eastern shelf do not move back and forth in large numbers as adults. A third stock was in the Aleutian Islands. Less information was available for western Bering Sea pollock, although Dawson speculated that a fourth stock might be in the southwestern Bering Sea and that pollock in the northwestern Bering Sea in Russian waters might be part of the eastern Bering Sea shelf stock.

The relationship between pollock in the Aleutian Basin and the eastern and western Bering Sea shelves is of special interest to fishery scientists and managers. Most important for life history and distribution is the fact that only large, older pollock (older than four years) occupy the pelagic waters of the basin, whereas all ages occupy the shelf and Aleutian Island areas. As Bakkala (1993) pointed out, the absence of juveniles in the basin suggests that these pollock originate, or at least spend their early lives, in other areas, presumably one or more of the shelf areas surrounding the deep basin.

Figure 4.4 gives estimates of adult biomass of walleye pollock (ages three and up) in the eastern Bering Sea shelf and Gulf of Alaska from 1964 to 1993. Figure 4.5 gives estimates of pollock year class strength. The most recent surges in pollock biomass, in the late 1970s and early 1980s, represent the very strong 1978 year class in the Bering Sea, and a succession of strong year classes from 1972 to 1979 in the Gulf of Alaska. It appears that the strong 1978 year class accounted for the increase in pollock biomass and resultant catch in the area around Bogoslof Island and the Aleutian Basin (donut hole) (Wespestad, 1993) (Figure 4.6). Although the fishery for pollock has remained relatively constant in time and space, if not in biomass removed, in the Gulf of Alaska, the fishery in the Bering Sea has moved considerably in both space and time (Figures 4.6 and 4.7). Figures 4.8 and 4.9 give the distribution of catch and relative contributions of year classes in the 1970s and early 1980s to the pollock fisheries of the eastern Bering Sea shelf and slope, northwest and southeast of the Pribilof Islands (Francis and Bailey, 1983). The strong 1972 and 1973 year classes appear to have supported the fishery in the northwest in the early and mid-1970s (62 percent of the catch between 1973 and 1977 was taken in the northwest). The strong 1978 year class, in contrast, appears to have supported the fishery in the southeast in the late 1970s and early 1980s (75 percent of the 1982–83 catch was taken in the southeast), as well as the fishery in the Bogoslof and Aleutian Basin areas in the 1980s. Figure 4.10 shows how the center of activity of the pelagic pollock winter trawl fishery moved from the slope around the Pribilof Islands in 1979, to the Unimak/Bogoslof region in 1991 (L. Fritz, personal communication).

Not only do the centers of activity of pollock fishing move around from year to year in the eastern Bering Sea (including the basin), within a year the distribution of pollock spawning changes considerably from season to season (Hinckley, 1987; Figure 4.11), moving from the basin in winter to the southeast shelf in spring and up the shelf northwest of the Pribilofs in the summer. Bering Sea pollock are quite different in their population dynamics from Gulf of Alaska pollock. This can be understood best by examining the seasonal, annual, and decadal spatial movements of centers of activities of various life history stages (e.g., spawning and availability of adults to fishing).

### **Pacific Cod (*Gadus macrocephalus*)**

Pacific cod also have a broad distribution in the North Pacific, extending along the North American coast from southern California to Norton Sound in the Bering Sea, and along the Asian coast south to the southern tip of the Korean Peninsula and into the Yellow Sea (Bakkala, 1993). This species is common at depths of 80 to 260 m. In the Bering Sea, Pacific cod schools are most abundant on the shelf and upper slope. They migrate seasonally between the



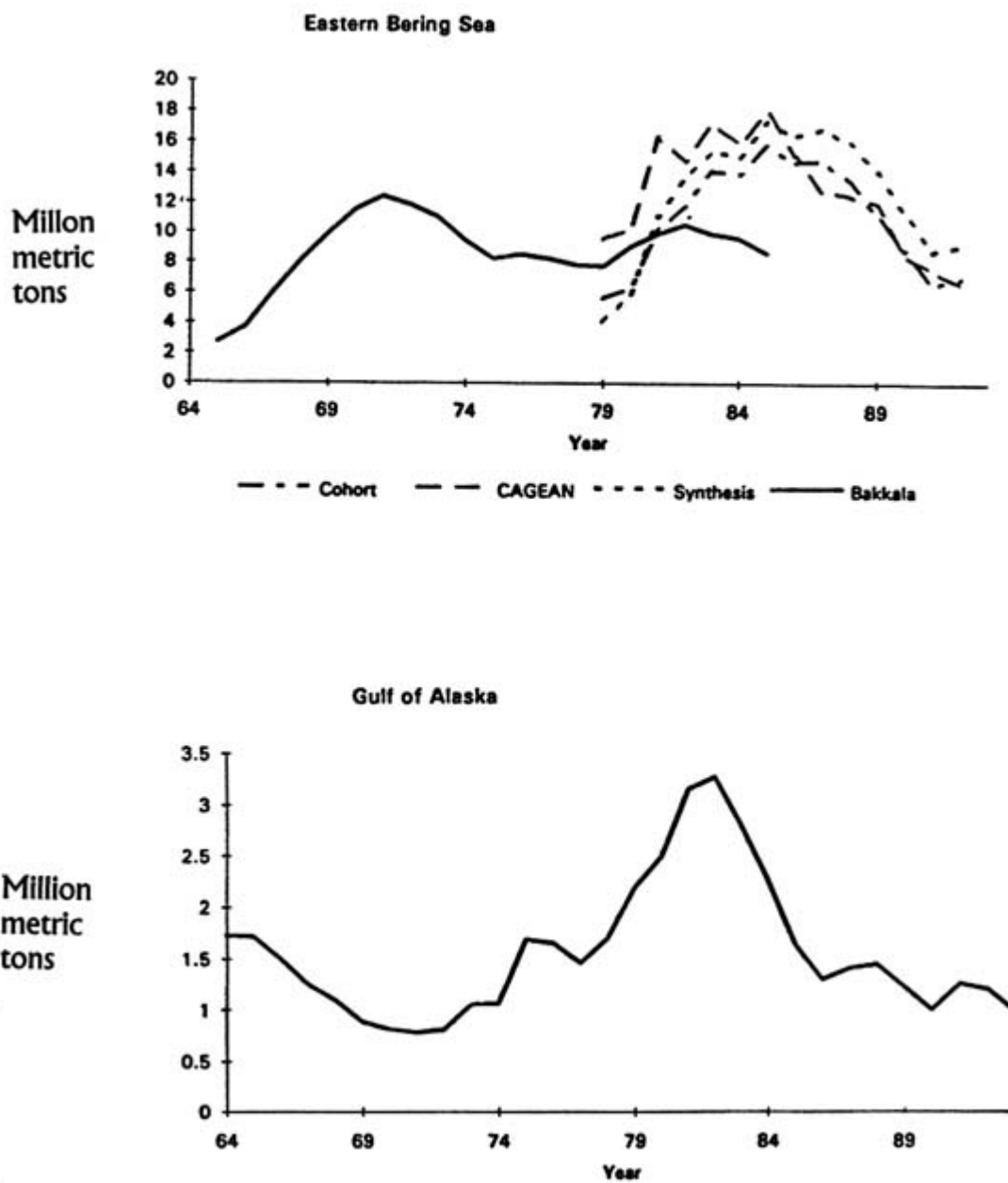


Figure 4.4 Estimates of adult (ages three and up) biomass of walleye pollock in the eastern Bering Sea and Gulf of Alaska, 1964–93 (NPFMC, 1993; Bakkala, 1993). "CAGEAN" = catch at-age analysis.

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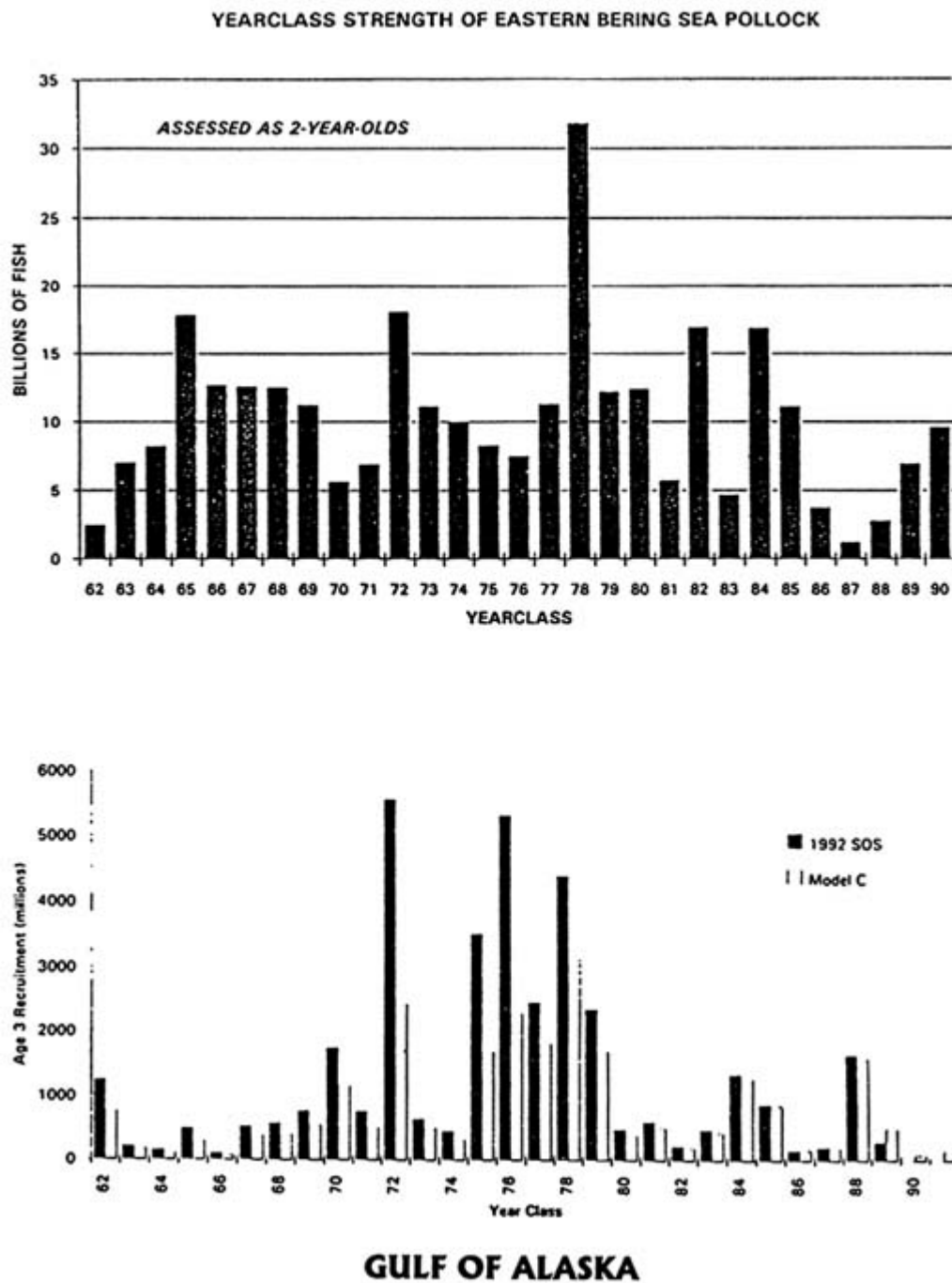


Figure 4.5 Pollock year class strength in the eastern Bering Sea and Gulf of Alaska (showing a succession of strong year classes 1972–79 in the Gulf of Alaska) (Wespstad, 1993).

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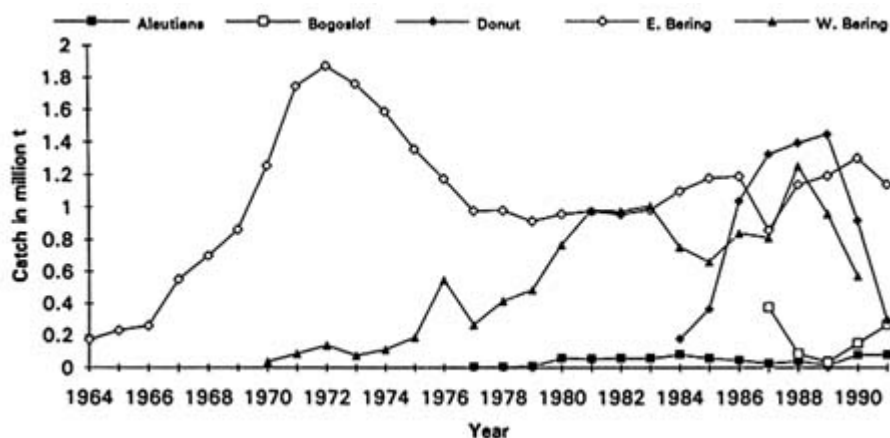


Figure 4.6 Walleye pollock catch in the Bering Sea by area, 1964–91 (Wespestad, 1993).

### Eastern Bering Sea Pollock Catch Quarterly Distribution

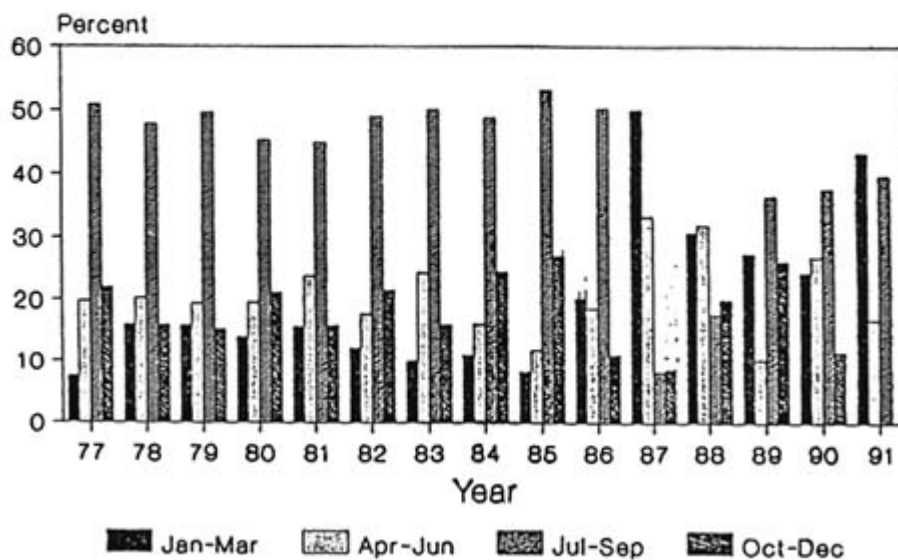


Figure 4.7 Eastern Bering Sea pollock catch quarterly distribution (Wespestad, 1993).

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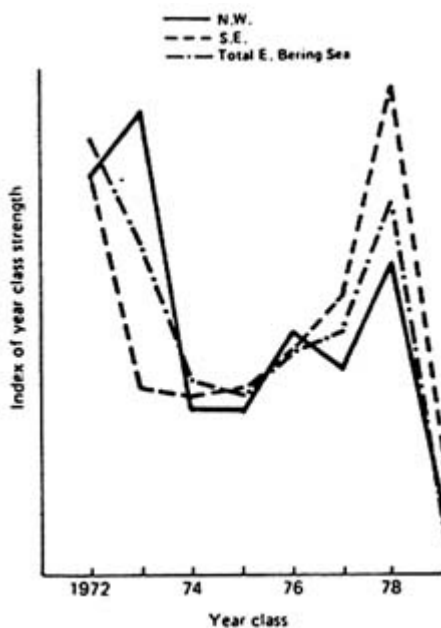


Figure 4.8 Normalized indices of pollock year-class strength (recruitment at age two) northwest and southeast of the Pribilofs, and for the two areas combined, 1972–79 (Francis and Bailey, 1983).

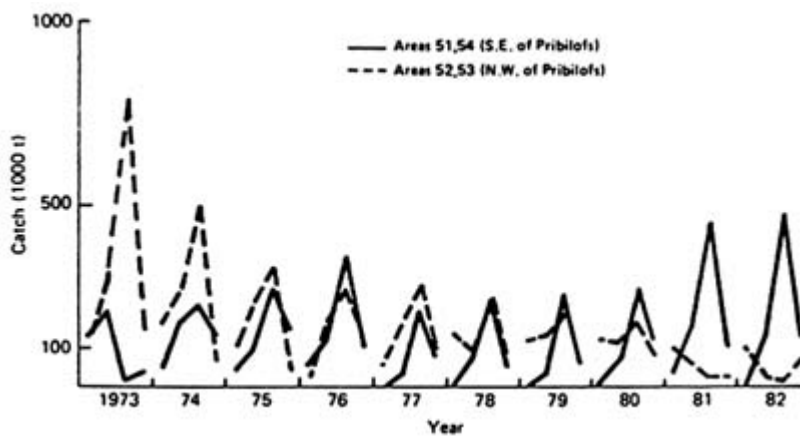


Figure 4.9 Estimates of quarterly catch (1,000 t) of pollock in the eastern Bering Sea northwest and southeast of the Pribilofs, 1973–82 (Francis and Bailey, 1983).

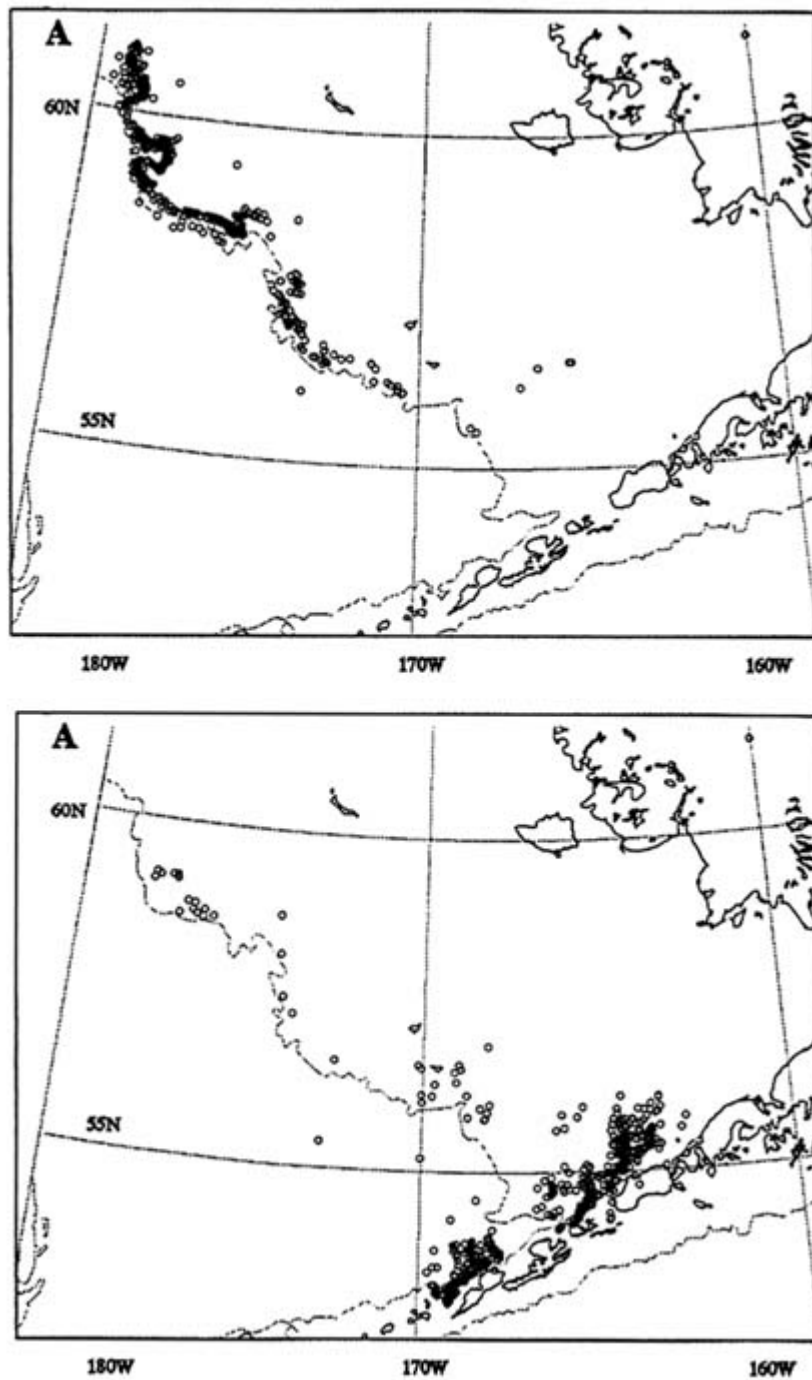


Figure 4.10 Pelagic trawl fishery locations (Fritz, in press). Upper panel, 1979; lower panel, 1991.



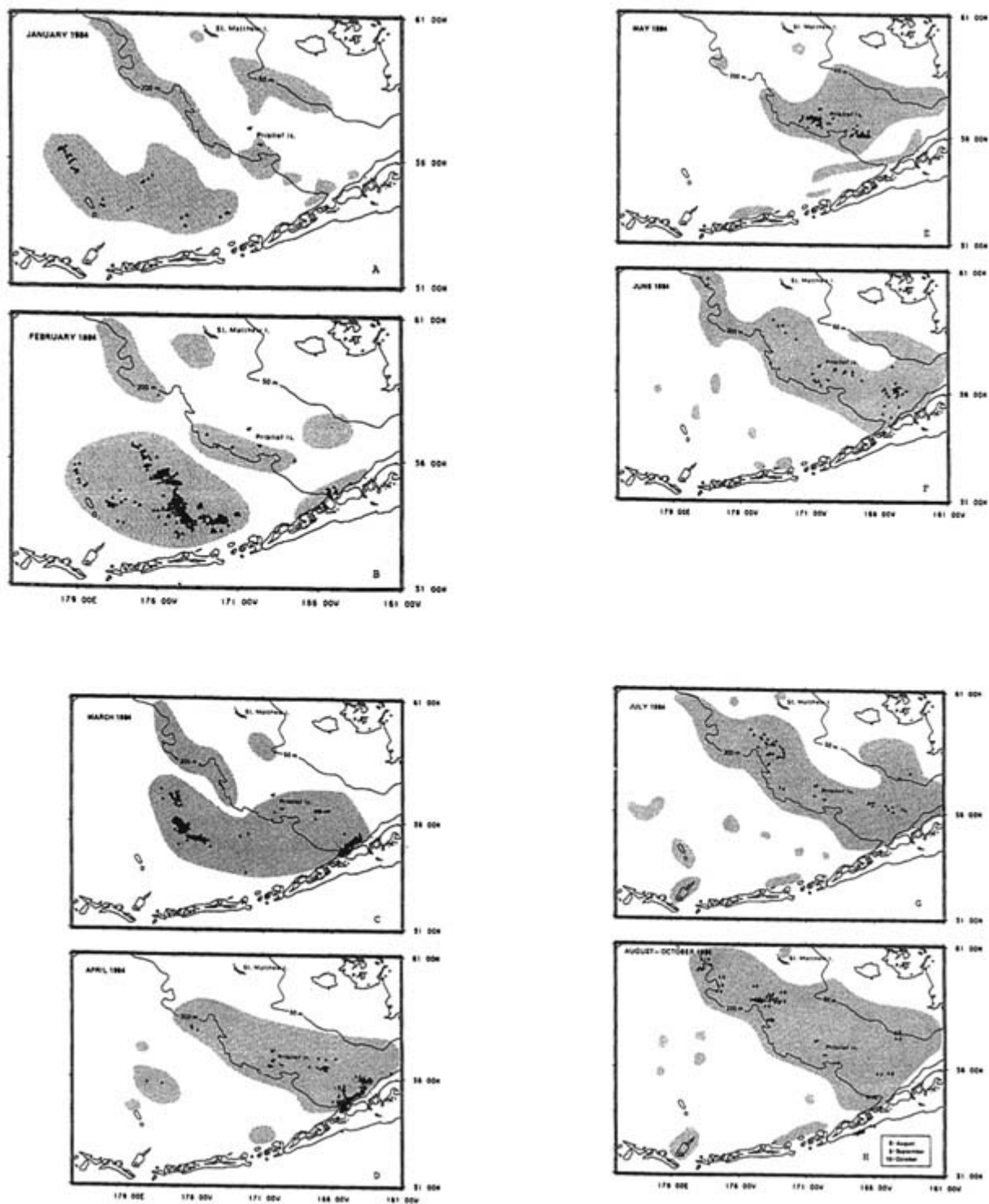


Figure 4.11 Center of activity for pollock fishing (Hinckley, 1987).

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continental slope and shelf and along the continental slope. Spawning begins in January, but exact timing and areas of spawning are not known. Females produce from 0.2 to 5.7 million eggs, which are benthic and initially slightly adhesive. The eggs hatch within 10 to 20 days, and larvae are distributed at depths from 25 to 150 m, with the largest numbers at 75 to 100 m. Adults are mostly semidemersal and feed on benthic epifauna, planktonic crustaceans such as shrimp and crabs, and juvenile fish such as pollock (Hood and Calder, 1981). Pacific cod are used as food by northern fur seals, halibut, beluga, and sperm whales.

Pacific cod is a species that shows significant changes in catch over time, both in the eastern Bering Sea and in the Gulf of Alaska (Figure 4.12). Trends in biomass and recruitment in the eastern Bering Sea fishery are shown in Figure 4.13. The impact of the 1977 year class (recruited at age three in 1980) can be seen in the increase in biomass and fishery production in the early 1980s.

### **Sablefish (*Anoplopoma fimbria*)**

Sablefish, also known as black cod, range from the waters off northern Mexico to the northern Bering Sea, and south into Asian waters to the northeast coast of Japan (Bakkala, 1993). Maximum abundance occurs in the Gulf of Alaska. Sablefish occupy the water column from the surface to a depth of 1,200 m, most abundantly between 100 and 1,000 m on the outer continental shelf and continental slope, where 80 to 85 percent of the total species biomass is found. Some sablefish migrate between different areas in the North Pacific; more localized cross-shelf migrations have also been observed. Sablefish spawn during winter (February) at depths of around 550 m, where females release up to 1 million pelagic eggs, which rise toward the surface as they develop and hatch. Later stage larvae are found near the surface. Little is known of egg or larval development, although one-year-old juveniles appear annually in shallow coastal waters. As pelagic juveniles mature, they move into deeper waters and become demersal. Sablefish feed on a wide variety of prey, both pelagic and benthic, depending on location, season, and age of fish. Prey include squid, capelin, pollock, euphausiids, shrimp, pleuronectid species, cottids, and benthic invertebrates. Predators on sablefish include Pacific halibut, ling cod, and sea lions.

### **Atka Mackerel (*Pleurogrammus monopterygius*)**

Atka mackerel are distributed from the east coast of the Kamchatka Peninsula, throughout the Komandorsky and Aleutian Islands, north to the Pribilof Islands in the Bering Sea, and east through the Gulf of Alaska as far south as waters off southeast Alaska (NPFMC, 1993). They are most abundant in the Aleutian Islands from Buldir Island to Seguam Pass. Atka mackerel spawn near the bottom. They spawn from June to September in coastal areas with stony or rocky bottoms. The eggs are demersal and are deposited in large masses on stones or in cracks among rocks. Hatched larvae are found at depths of 2 to 30 m and move to the surface at night. The larvae are widely dispersed for distances of up to 200 to 500 miles from shore. Adults feed

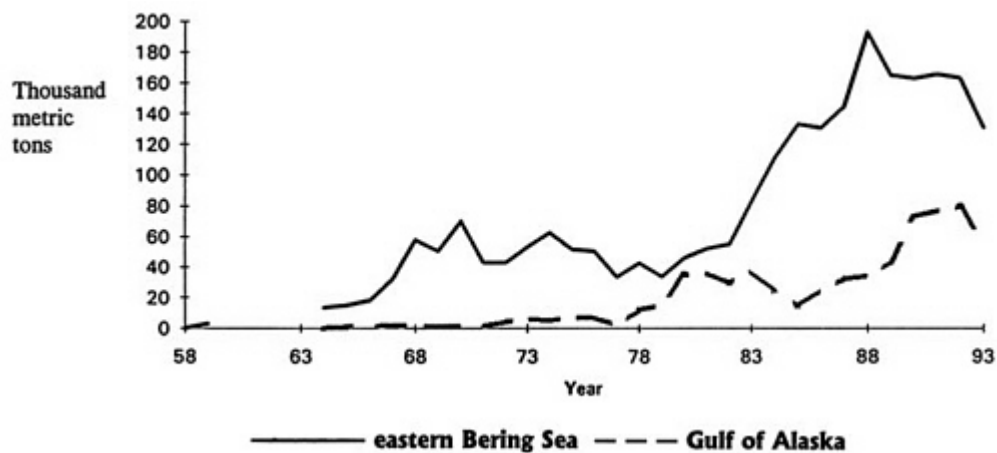
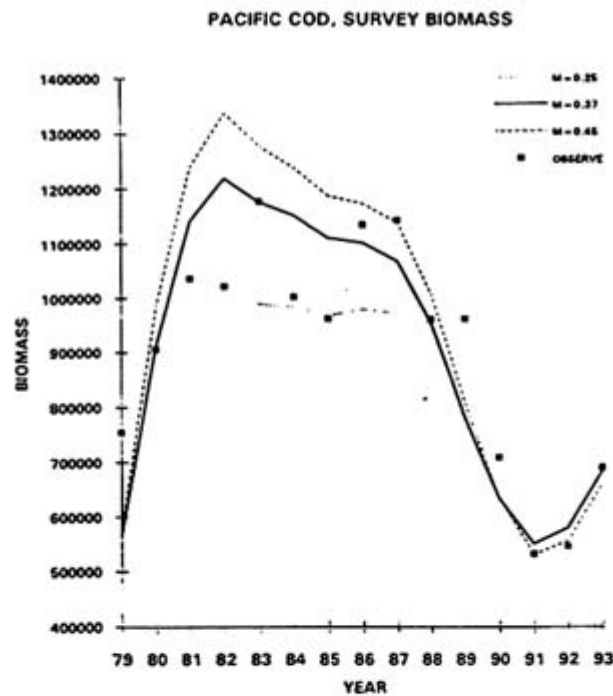


Figure 4.12 Pacific cod catch (based on unpublished data from the Alaska Fisheries Science Center [AFSC], NMFS, [National Oceanic and Atmospheric Administration]).

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E. Bering Sea Pacific Cod Recruitment at Age 3 (millions)

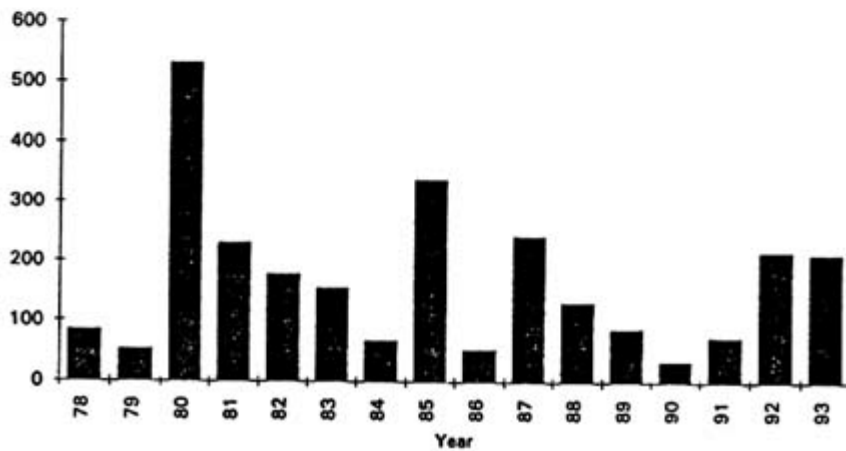


Figure 4.13 Trends in biomass and recruitment of Pacific cod in the eastern Bering Sea (based on unpublished data from the [AFSC], NMFS, [National Oceanic and Atmospheric Administration]).

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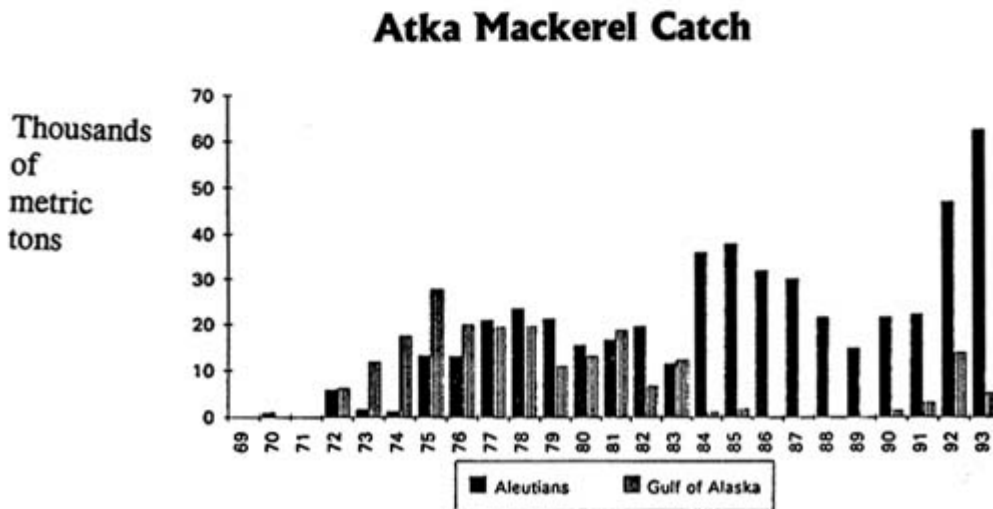
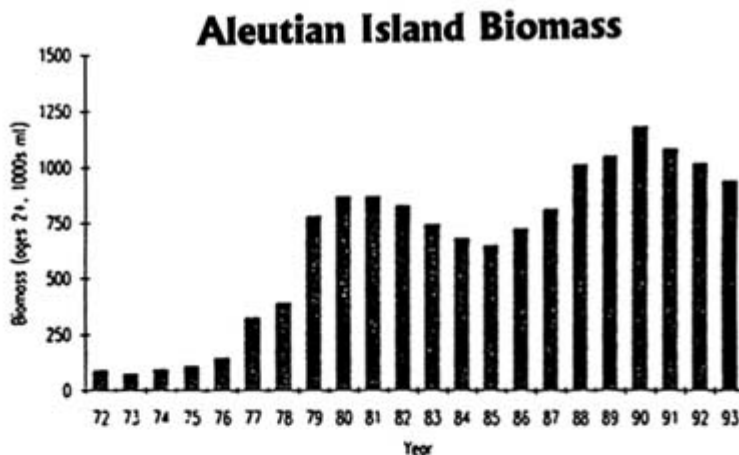


Figure 4.14 Biomass and recruitment of Atka mackerel (top and middle graphs: NPFMC, 1993; bottom graph: based on unpublished data from [AFSC], NMFS, [National Oceanic and Atmospheric Administration]).

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largely on euphausiids. Predators on Atka mackerel are marine mammals and the larger pelagic fishes, such as salmon and sharks.

Atka mackerel are caught by bottom trawl in depths of 25 to 78 m. Figure 4.14 gives biomass and recruitment trajectories for Atka mackerel in the Aleutian Island area. Because similar stock assessments are not available for Atka mackerel in the Gulf of Alaska, Figure 4.14 also gives catch trajectories for the Aleutian Islands and Gulf of Alaska. Like cod in the eastern Bering Sea, Atka mackerel biomass surged in the Aleutian Islands in the late 1970s and early 1980s as a result of one or two strong year classes (in particular, for the year 1977). Unlike cod, Atka mackerel catch surged once again in the late 1980s and early 1990s (both in the Aleutians and Gulf of Alaska) as a result of a succession of relatively strong year classes.

### **Yellowfin Sole (*Limanda aspera*)**

Yellowfin sole are rarely found south of the northern Gulf of Alaska and range through the eastern Bering Sea to the southern Chukchi Sea. Their range continues southward along the Asian coast to Hokkaido Island in Japan and Peter the Great Bay on the Russian coast (Bakkala, 1993). The eastern Bering Sea contains the largest single population of this flatfish, which occurs on the shelf at depths from 5 to 360 m. Yellowfin sole undergo complex seasonal movements (both vertical and horizontal) that are not fully understood. During winter, adults congregate in large, dense schools on the outer shelf and upper slope from 100 to 270 m. In spring, fish begin moving into shallower waters, and by summer the main body of the stock is found on the middle and inner shelf at depths of less than 50 m. At this time of year, feeding and spawning take place. In late autumn, the fish migrate back to deeper waters, apparently to avoid cold bottom water and ice cover. Distribution and movements of yellowfin sole are associated with environmental factors, including ice distribution, temperature, salinity, and bottom sediment type. Adult yellowfin sole are not confined to the bottom, but make periodic vertical movements through the water column. Spawning takes place predominantly in June and July on the inner shelf, with females releasing from 1 million to 3 million pelagic eggs, which accumulate in central areas of well-developed gyres. The larvae are pelagic for four to five months before undergoing metamorphosis; at lengths of about 17 mm, the juvenile sole settle to the bottom along the inner shelf. As the juveniles grow, they apparently move gradually into deeper water. Their principal prey include benthic infauna and epifauna, although they also eat euphausiids, copepods, and fish. Skalkin (1963) suggested that their food sources vary by subregion of the Bering Sea, depth, and season. Important predators of yellowfin sole include Pacific halibut, humans, and northern fur seals (Lewbel, 1983).

### **Greenland Turbot (*Reinhardtius hippoglossoides*)**

Greenland turbot has an amphiboreal distribution, occurring in the North Atlantic and North Pacific, but not in the intervening Arctic Ocean (Alton et al., 1988). In the North Pacific, it occurs continuously from the northern Gulf of Alaska through the Aleutian Islands region and eastern and northern Bering Sea into Asian waters south to the Sea of Japan (Bakkala, 1993).

Large concentrations of Greenland turbot are found in the eastern Bering Sea and Navarin Basin, at depths of about 70 to 670 m. Seasonal movements by Greenland turbot are complex and not fully understood. They are generally found at shallower depths in the summer than in winter. Spawning occurs from October to December in waters greater than 100 m; the eggs are apparently bathypelagic, developing in deep water. After hatching, the larvae are pelagic and found at 30 to 130 m depth, until they reach a length of about 80 mm, when they transform and become demersal. The overall life history of Greenland turbot is unique among flatfish in that they spend the first three or four years of life on the continental shelf and move to the continental slope where the older juveniles and adults reside (Bakkala, 1993). Greenland turbot feed on a variety of foods, including pelagic, mid-water, and demersal fishes, crustaceans, and squids. Little is known about the predators of Greenland turbot other than humans (Lewbel, 1983).

Biomass estimates for Greenland turbot (and arrowtooth flounder, which is discussed further below) and recruitment estimates for Greenland turbot from 1970 to 1993, as shown in [Figure 4.15](#), provide a very interesting contrast. Like the other four flatfish species, they both seemed to respond to the climatic regime shift (discussed in more detail in [Chapters 3 and 6](#)) of the late 1970s. Even more interesting is how the distribution of (primarily) juvenile Greenland turbot seems to have been pushed to the northwest along the outer Bering Sea shelf as the ocean climate warmed in the late 1970s and early 1980s ([Figure 4.16](#)). As was mentioned earlier, Greenland turbot and arrowtooth flounder both occupy continental shelf waters during their first few years as juveniles (Bakkala, 1993) and then deeper waters of the shelf and slope as older juveniles and adults. However, Greenland turbot prefer colder waters than arrowtooth flounder. According to NPFMC (1993), Greenland turbot biomass doubled in size during the 1970s (a very cold period) over early 1960s level.

### **Pacific Halibut (*Hippoglossus stenolepis*)**

Pacific halibut ranges from off southern California to as far north as the southern Chukchi Sea along the North American coast and south along the Asian coast to Hokkaido Island, Japan (Bakkala, 1993). Distribution is widespread on the shelf and slope to depths of up to 700 m. These fish undertake seasonal migrations to shallow spring feeding areas and to deeper waters (250 to 550 m) in the fall, where they spawn and remain in the winter. Seasonal movements can extend as far as 800 km. Spawning takes place from November through February, and females release up to two million pelagic eggs. Larvae are also pelagic until they reach a length of about 10 cm after about six months; at that time they settle to the bottom to begin a benthic existence. During the pelagic life stage, eggs and larvae may be transported by currents several hundred kilometers. Pacific halibut are long-lived and may reach ages in excess of 40 years. They are opportunistic feeders, consuming a variety of prey, which varies with age and area. Juvenile fish feed mainly on crustaceans, whereas older fish eat mostly other fish, particularly flounders. Predators of Pacific halibut are poorly known. Bering Sea halibut biomass increased significantly throughout the 1980s, as did recruitment and catch ([Figure 4.17](#)). Similar increases were estimated to have occurred over the entire range of the species in the northeast Pacific. The International Pacific Halibut Commission determined that the biomass

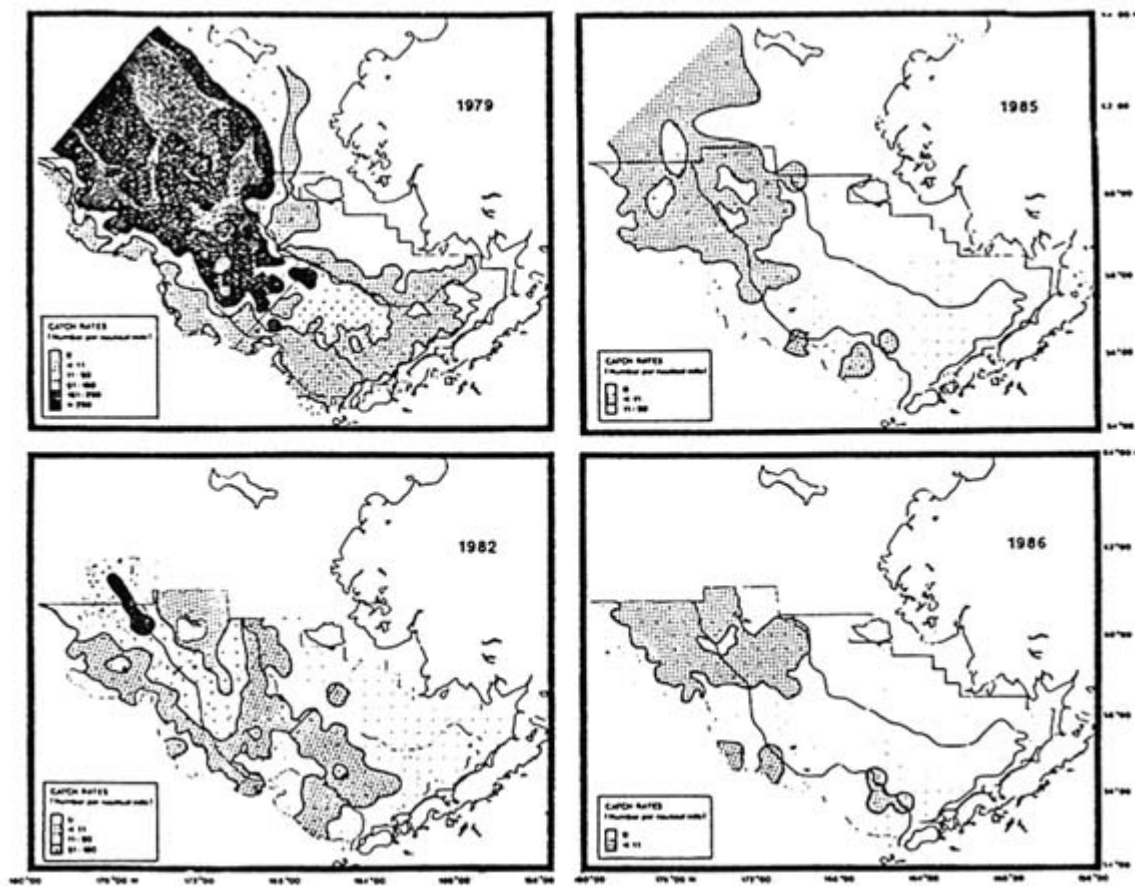


Figure 4.16 Distribution and density of Greenland turbot on the continental shelf of the eastern Bering Sea, as shown by northwest and AFCC survey data, 1979–86 (Bakkala, 1993).

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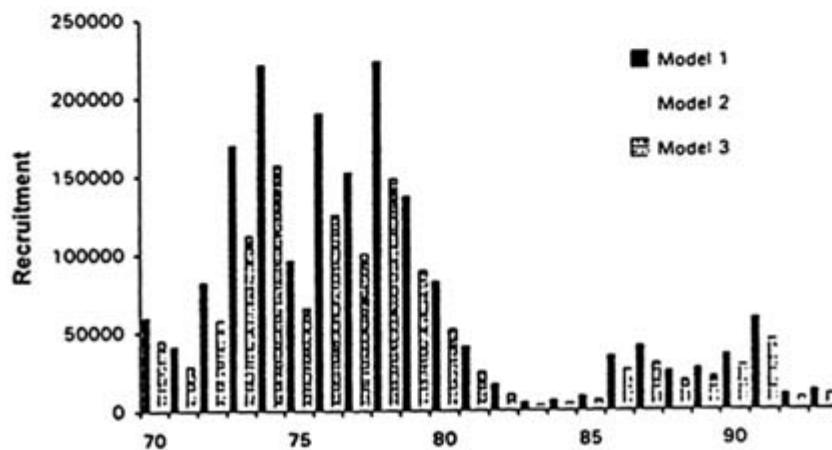
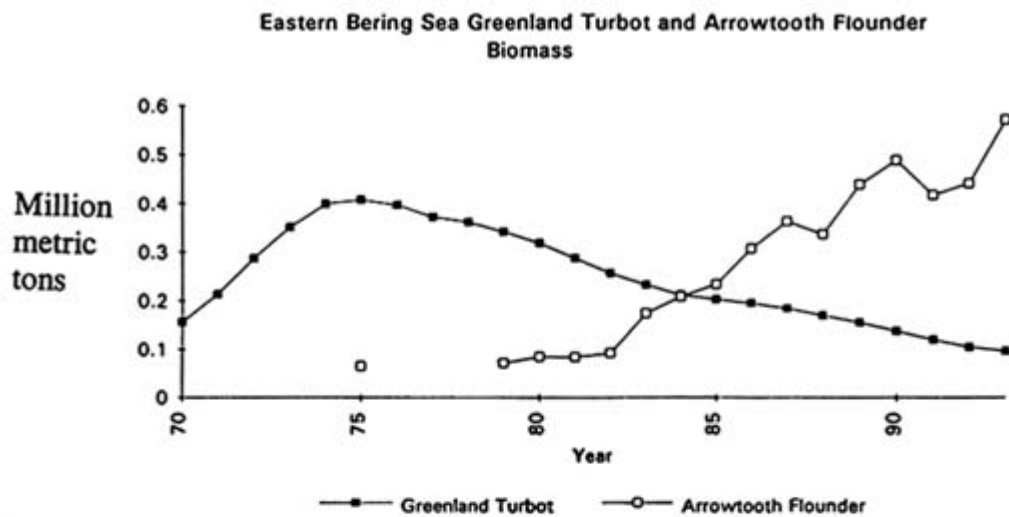


Figure 4.15 Biomass estimates of Greenland turbot and arrowtooth flounder (top graph: based on unpublished data NMFS, NOAA); recruitment estimates for Greenland turbot (bottom graph: NPFMC, 1993).

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### Coast Wide Stock Biomass, Recruitment, and Catch Per Unit Effort

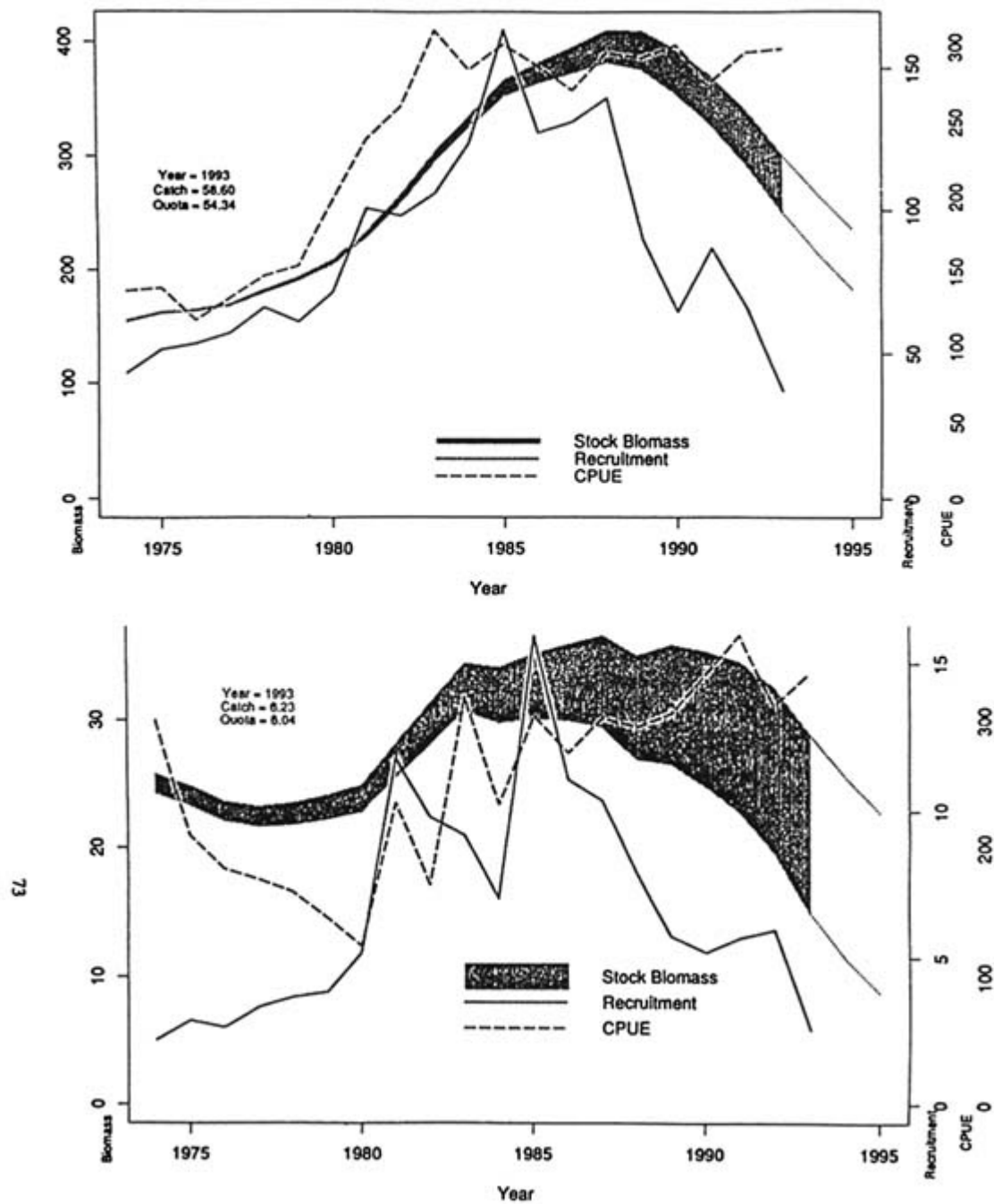


Figure 4.17 Pacific halibut indices of abundance (IPHC, 1994).

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in the 1980s was at a record high level (IPHC, 1982a). At the end of the decade, halibut abundance entered a period of decline, although large year classes are expected to maintain commercial fisheries near peak levels for some time.

### Other Flatfishes (Family Pleuronectidae)

Other flatfishes of the Bering Sea include rock sole (*Lepidopsetta bilineata*), flathead sole (*Hippoglossoides elassodon*), arrowtooth flounder (*Atherestes stomias*), rex sole (*Glyptocephalus zachirus*), butter sole (*Isopsetta isolepis*), longhead dab (*Pleuronectes proboscideus*), Dover sole (*Microstomus pacificus*), starry flounder (*Platichthys stellatus*), and Alaska plaice (*Pleuronectes quadrituberculatus*). A few of the more important species are described briefly below.

Rock sole range from southern California northward through the Bering and Okhotsk seas and southward to waters off Korea and the Sea of Japan (Bakkala 1993). They are most abundant in the southeastern region of the Bering Sea, where they occupy areas of the shelf with water depths less than 300m. Seasonal movements are not well known. Spawning takes place from March to June at depths near 100 m. Eggs are adhesive and demersal, sinking to the bottom; larvae are pelagic. Adults prey on benthic invertebrates and occasionally on fish. Predators include fish and marine mammals.

Flathead sole and a similar form (Bering flounder, *Hippoglossoides robustus*), range from off northern California to the northern Bering Sea and south to the waters of Japan (Bakkala, 1993). They are most abundant in the eastern portion of the Bering Sea. They range in depth from the surface to 550 m. Seasonal distributions consist of concentrations overwintering in depths of 70 to 400 m on the outer shelf, which then migrate to shallower waters (20 to 180 m) in the spring. Reproduction takes place during February to May within the shelf boundaries; eggs and larvae are pelagic and become widely distributed. The adults prey primarily on benthic crustaceans, mollusks, brittle stars, fish, and squid. Predators of flathead sole are not well known, but are thought to be Pacific halibut and marine mammals.

Arrowtooth flounder can be found in waters off central California to the northern Bering Sea. A closely related species, Kamchatka flounder (*Atheresthes evermanni*), extends south along the Asian coast to the Sea of Japan. The two species may overlap considerably in the eastern Bering Sea and Aleutian Islands (Bakkala, 1993). Arrowtooth flounder are most abundant on the continental slope of the southeastern, central, and northwestern Bering Sea at depths of 200 to 500 m. They move seasonally, from 300 to 500 m depth in the winter, to 200 to 400 m depth in the summer, apparently associated with water temperatures. Adults are thought to spawn from December to February, releasing up to 500,000 bathypelagic eggs. Hatched larvae remain in shallow near shore waters over the shelf for several months and then settle to the bottom (Bakkala and Smith, 1978). Juveniles gradually move into deeper waters as they grow. Major foods include crustaceans and fish, particularly juvenile pollock (Hood and Calder, 1981). Predators on arrowtooth flounder are thought to be Pacific halibut, Greenland halibut, and marine mammals.

The catches and estimates of biomass (where and when available) for four flatfish species of commercial importance in the eastern Bering Sea are shown in [Figure 4.18](#). This figure

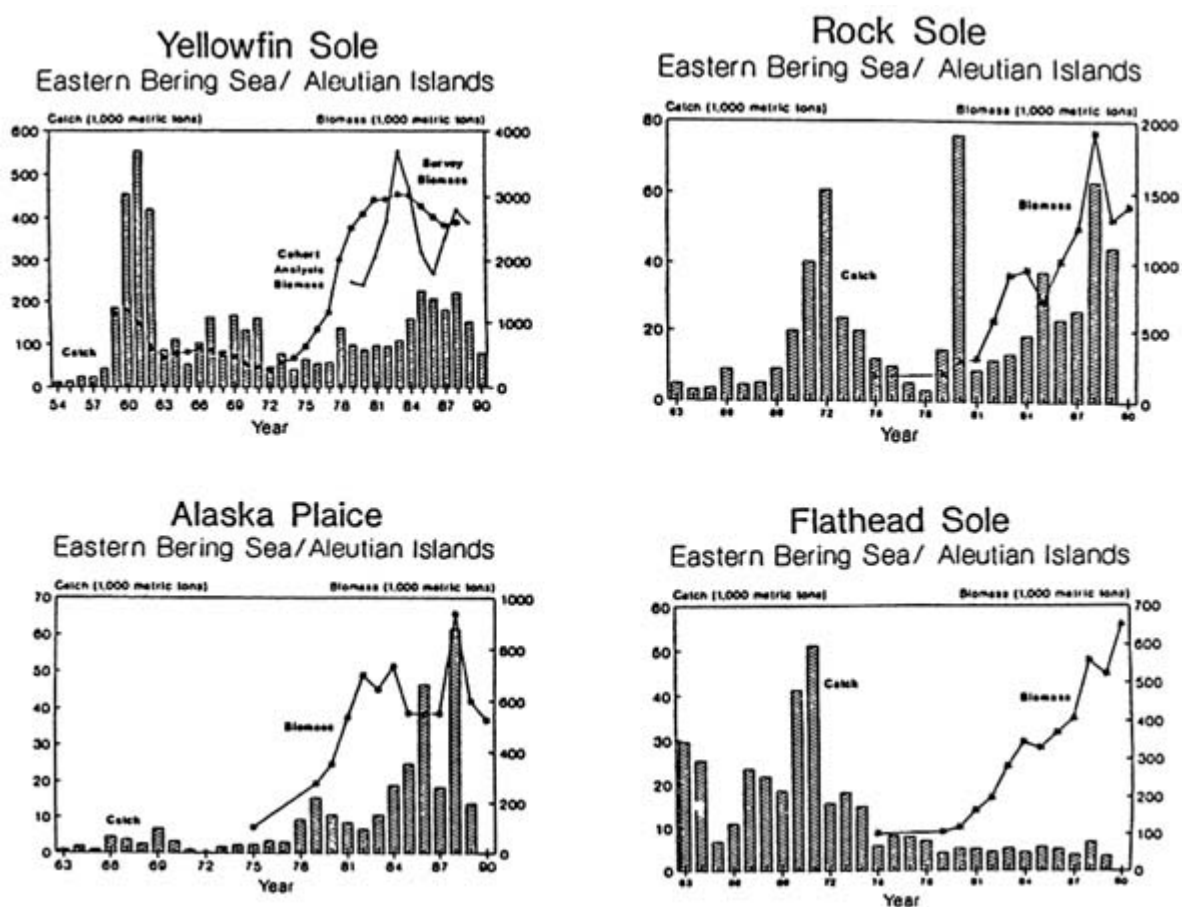


Figure 4.18 Catch and biomass estimates of flatfish of commercial importance in the eastern Bering Sea (NPFMC, 1993).

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illustrates a number of interesting points. First, yellowfin sole were heavily exploited in the late 1950s and early 1960s, and the population was significantly reduced (NPFMC, 1993). It increased again in the late 1970s and early 1980s. Second, from an ecosystem perspective, note that the biomasses of all four commercially important flatfish species increased significantly in the late 1970s and early 1980s. Figure 4.19 shows estimates of relative changes in flatfish abundance in the Gulf of Alaska between the 1987 and 1990 NMFS triennial trawl surveys. Most striking is the most doubling of the arrowtooth flounder biomass over this period, a pattern similar to that observed in the eastern Bering Sea. Thus, the recent warm regime may have been favorable to most flatfish species of the region, with the exception of Greenland turbot. Greenland turbot seems to prefer colder ocean regimes; it is an amphiboreal species (Alton et al., 1988).

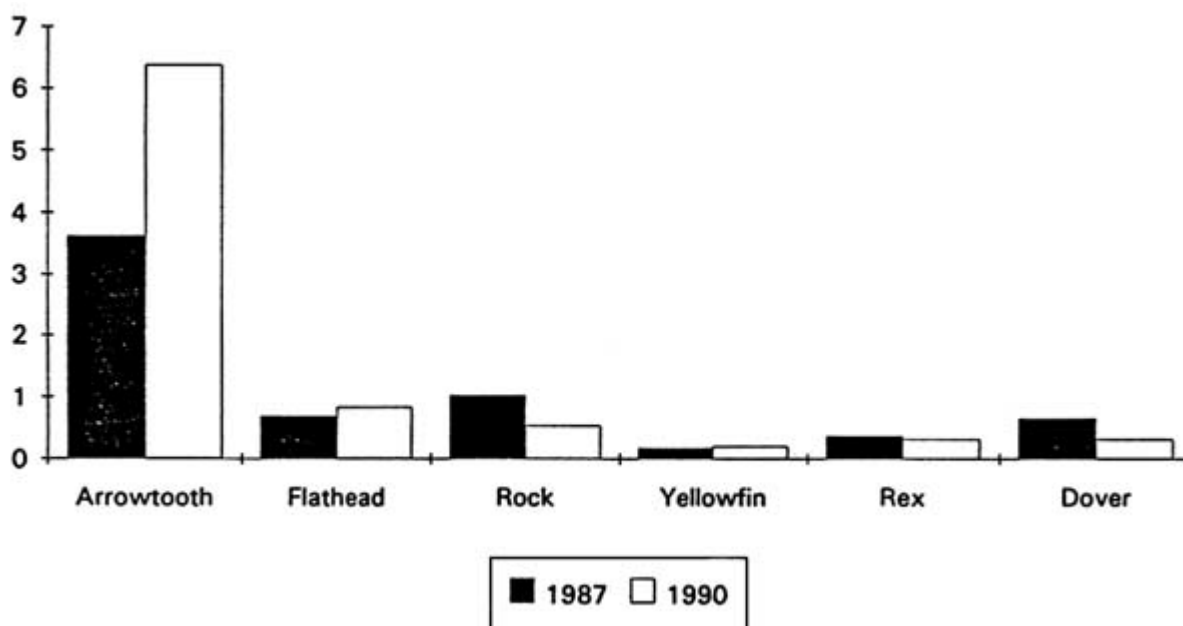


Figure 4.19 Gulf of Alaska flatfish relative survey abundance (kg/km<sup>2</sup>) (NPFMC, 1993).

### Pacific Ocean Perch (*Sebastes alutus*)

Pacific Ocean perch range from southern California to the northern Bering Sea and south to northern Honshu Island in Japan (Bakkala, 1993). They are more abundant in the Aleutian Islands region and particularly in the Gulf of Alaska than in the eastern Bering Sea. In the

eastern Bering Sea, the species is common in and along canyons and depressions on the upper continental slope. The densest concentrations occur from January to May, during spawning, west of the Pribilofs at depths of 340 to 420 m. During this period, the species undergoes daily vertical migrations, probably for feeding. Because Pacific Ocean perch inhabit such deep waters, tag and recapture studies are virtually impossible. Any statements about their migration patterns are therefore speculation.

Pacific Ocean perch are live bearers (as are all rockfishes), and probably mate during the period of October through February. Young are born in springtime (March-June). Larvae at birth are 5 to 8 mm long and are planktonic for an undetermined period of time. The juveniles (ages one to five) feed mainly on copepods and euphausiids; adults feed on euphausiids, copepods, fish, and squid. Predators of this fish are mostly humans and fish, particularly halibut (Pereyra et al., 1976).

Figure 4.20 gives biomass trajectories for the Pacific Ocean perch complex,<sup>2</sup> and Figure 4.21 gives recruitment time series for the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska. Pacific Ocean perch were heavily fished in the 1960s in the Aleutian Islands, eastern Bering Sea, and Gulf of Alaska regions (as far south as northern Oregon). Populations were severely reduced and, with the exception of the Aleutians, have only recently shown indication of recovery. Rockfish in general, and Pacific Ocean perch specifically, are extreme examples of what Appollonio (1994) refers to as K-selective species. They are very long-lived (some individuals reaching up to 100 years of age) and have low natural mortality rates, and as a result, their populations have very low rates of production. Consequently, any kind of sustained heavy fishing, such as that experienced in the 1960s by the Pacific Ocean perch populations, amounts to mining of the stocks.

#### **Other Rockfishes (Family Scorpaenidae)**

This family of rockfishes includes rougheye rockfish (*Sebastes aleutianus*), dusky rockfish (*S. ciliatus*), northern rockfish (*S. polyspinis*), shortspine thornyhead (*Sebastolobus alascanus*), shortraker rockfish (*S. borealis*), darkblotched rockfish (*S. crameri*), yelloweye rockfish (*S. ruberrimus*), and blue rockfish (*S. mystinus*). Rockfishes are mostly demersal and found from the surface to very deep waters. Little is known about the biology of Bering Sea rockfishes other than Pacific Ocean perch.

#### **Pacific Herring (*Clupea harengus pallasii*)**

The most widely studied forage (small pelagic) fish in the Bering Sea ecosystem is Pacific herring. This is the only such species for which there is a significant fishery and for which either fishery or survey statistics are collected. Pacific herring range from northern Baja California

<sup>2</sup> The Pacific Ocean perch complex is defined as a group of rockfishes including Pacific Ocean perch and northern, rougheye, shortraker, and sharpchin rockfish. These five species are commonly targeted as a group by commercial fishermen.

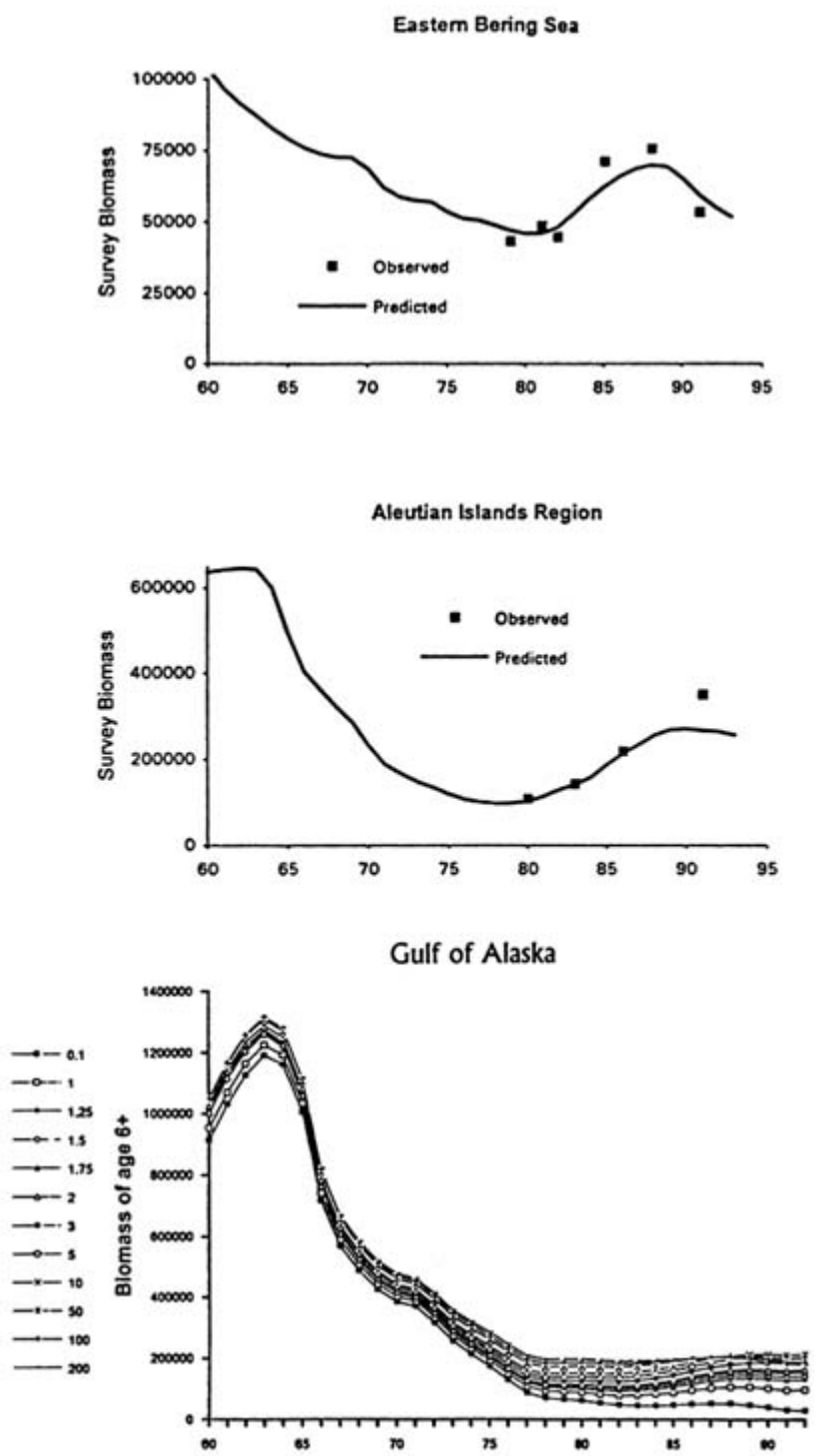


Figure 4.20 Biomass trajectories of age six and older Pacific Ocean perch (NPFMC, 1993).

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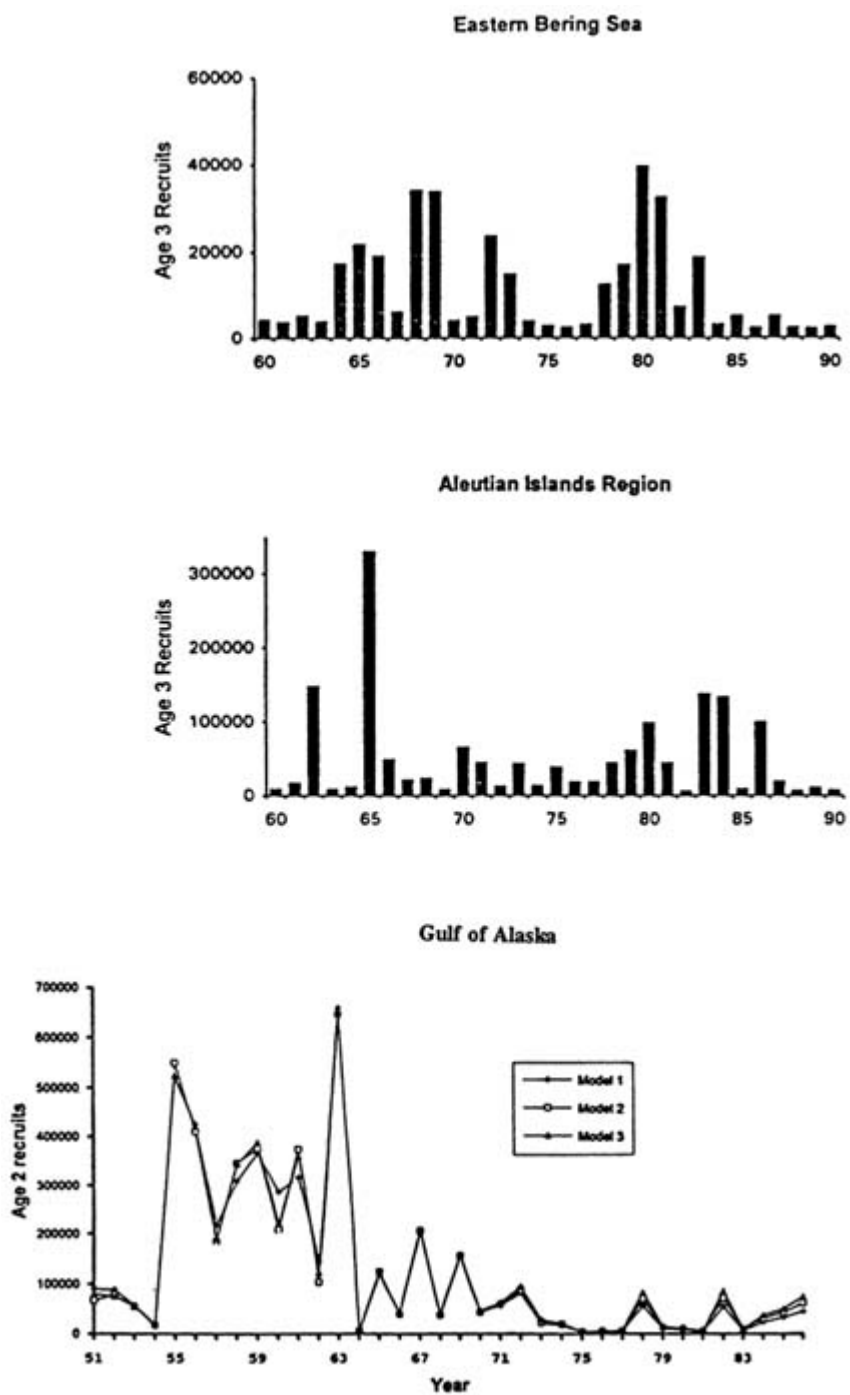


Figure 4.21 Estimated recruitment of two- and three-year-old Pacific Ocean perch for the three regions (NPFMC, 1993).

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to the Beaufort Sea and south to the coast of Korea (Hart, 1973). They are commonly found throughout the Bering Sea region and in coastal embayments of the Gulf of Alaska. In the eastern Bering Sea, they generally winter northwest of the Pribilof Islands, migrating to the Alaska coast in the spring to spawn from Bristol Bay to the Yukon River (Figure 4.22). This migratory behavior is unique among North American herring stocks. The primary reason for this long-range movement may be to avoid the low water temperatures on the shelf in winter. Herring have been observed to winter north of Norton Sound in brackish lagoons and along the Aleutian Islands, but their numbers suggest they are a relatively small component of the total population. Two other Bering Sea wintering concentrations occur in the Gulf of Olyutorski and off Cape Navarin (Figure 4.22). Spawning occurs from late April to mid-June along the Alaska Peninsula, Bristol Bay, and northeastern Bering Sea. Most herring appear immediately after ice breakup, which would indicate a high tolerance to low temperatures. The arrival at spawning grounds appears to be greatly influenced by climate and oceanographic conditions, particularly the extent and distribution of the Bering Sea ice pack. Herring are substrate spawners, producing as many as 134,000 eggs, and their eggs are highly valued by commercial fishermen. Following spawning, herring appear to remain in coastal waters for feeding. The low abundance of herring in the middle shelf domain may relate to the persistence of cold water in this area in summer (Wespestad, 1991). Offshore migration begins in August (Figure 4.23). Migration pathways may relate to the thermal structure of the eastern Bering Sea. Juvenile herring are planktonic predators, switching to small fishes as they get older. Herring can live as long as 10 years, with sexual maturity occurring by age three or four coinciding with the ages of recruitment to the fishery. Little is known of larval and juvenile stages. Principal predators of herring are kittiwakes, gulls, arctic terns, harbor, ringed, and spotted seals, other fish, and humans (Lewbel, 1983).

Estimates of herring biomass and year-class strength from the late 1950s to the mid-1980s are shown in Figures 4.24 and 4.25. Large year classes in the late 1950s supported a brief but very intense winter trawl fishery on the offshore winter grounds. Since then most of the catch has been taken inshore on the spawning grounds. It is interesting that the three largest year classes appear in 1957, 1958, and 1977, years of significant pulse warming in the eastern Bering Sea. It appears that these year classes supported the two major increases in population biomass observed over the last four decades.

### **Pacific Sand Lance (*Ammodytes Hexapterus*)**

Pacific sand lance range from southern California to the Chukchi Sea and from Anadyr Gulf as far south as the Sea of Japan (Hart, 1973). Sand lance are small fish and have been found in many areas of the Bering Sea region. They are usually found on the bottom, at depths between 0 and 100 m, except when engaged in pelagic feeding on crustaceans and zooplankton. Spawning is believed to occur in the winter. Sand lance mature at ages two to three and lengths of 10 to 15 cm. Little is known about their seasonal distribution and abundance. They are rarely captured in commercial or survey trawls. In the Bering Sea, sand lance have been commonly found in the stomachs of salmon, northern fur seals, and many species of marine birds.

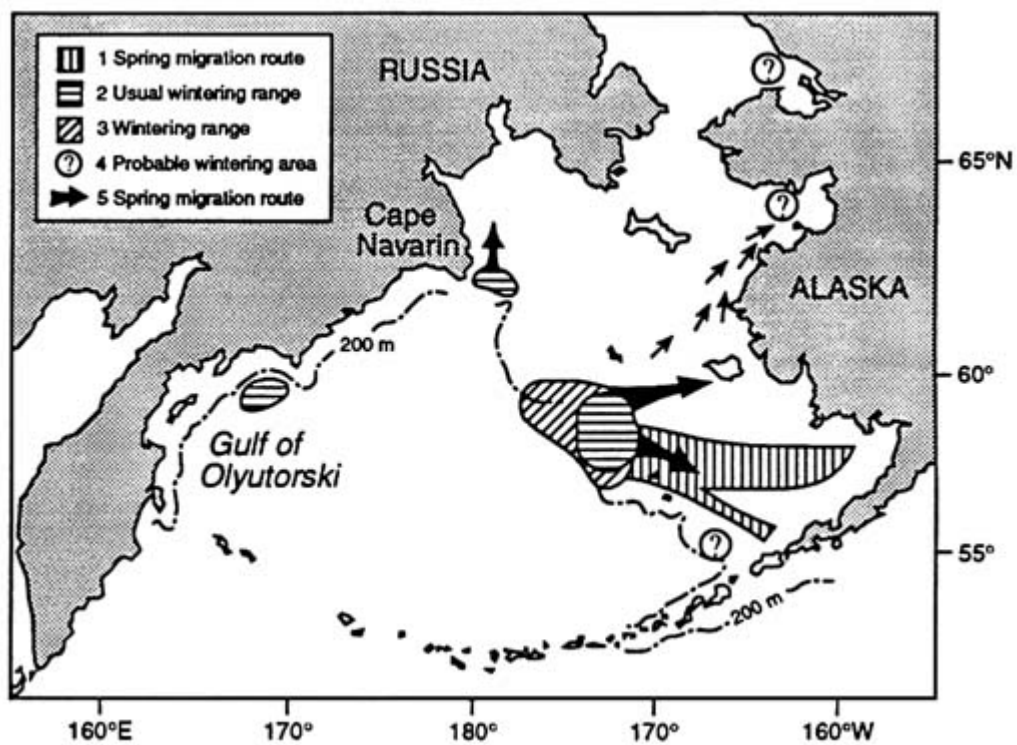


Figure 4.22 Winter grounds of major Bering Sea herring concentrations (large arrows from Soviet data; vertical stripes from Japanese catch data; small arrows inferred migration) (Barton and Wespestad, 1980).

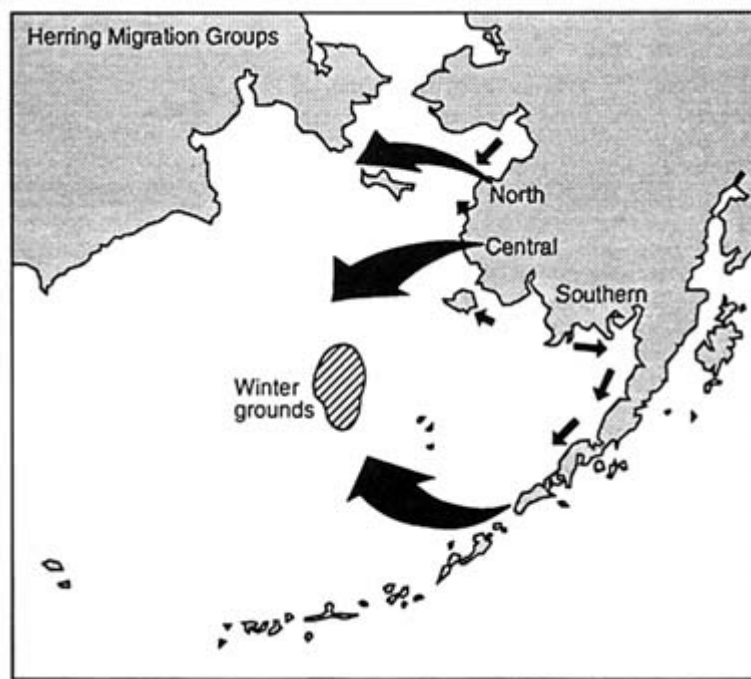


Figure 4.23 Migration routes to the eastern Bering Sea winter grounds from coastal spawning sites as inferred from fishery and research catches (Wespestad, 1991).

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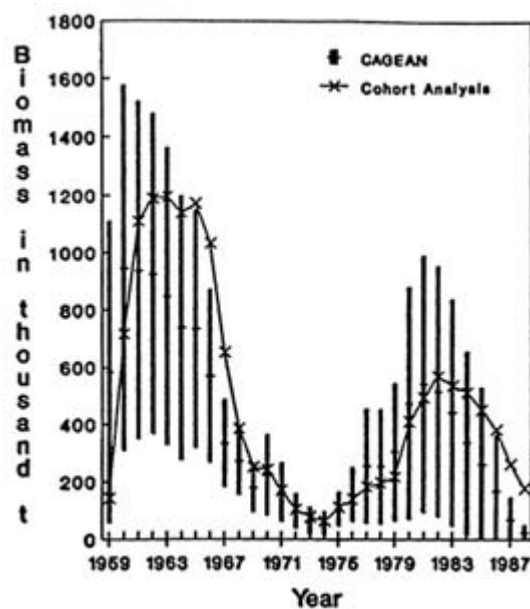


Figure 4.24 Estimated biomass of herring ages three to nine in the eastern Bering Sea, 1959–88, as estimated by cohort and catch at age analysis (Wespestad, 1991).

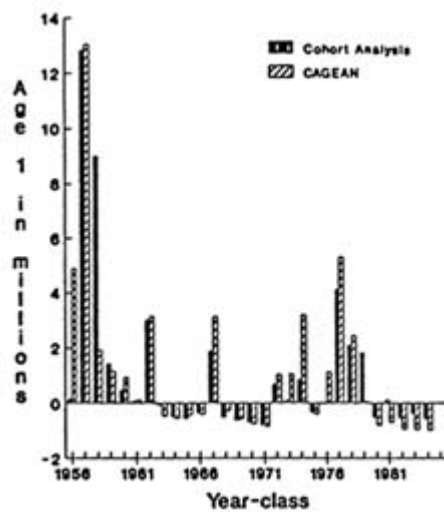


Figure 4.25 Estimated abundance of Pacific herring in the eastern Bering Sea at age one, 1958–84, as estimated by cohort and catch at age analysis (estimates are deviations from the geometric mean year class) (Wespestad, 1991).

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### Capelin (*Mallotus villosus*)

Capelin are widely distributed in the Gulf of Alaska, Bering Sea, and Sea Okhotsk, and along the Kamchatka Peninsula. They range from Juan de Fuca Strait through arctic Alaska and south to the Korean coast (Hart, 1973). A member of the smelt family, capelin have been known to be very abundant in the Bering Sea. In the North Pacific, they can grow to a maximum of 25 cm at age four. Most capelin spawn at ages two to three. Spawning occurs in spring in intertidal zones of coarse sand and fine gravel. In the Bering Sea, adult capelin are found near shore only during the months surrounding the spawning run. At other times of the year, capelin are found far offshore in the vicinity of the Pribilof Islands and the continental shelf break. Their seasonal migrations may be associated with the advancing and retreating polar ice front in the Barents Sea. Capelin (and other smelts, including rainbow smelt and eulachon) are commonly found in the stomachs of seabirds, marine mammals (particularly those feeding along the ice edge), and forage fishes, and therefore are believed to be important prey when abundant (Anonymous, 1993).

Few data exist on distribution or abundance trends in capelin and other smelt species. [Figure 4.26](#) shows what is known about their distributions and [Figure 4.27](#) shows their abundances (capelin and eulachon only). Indications are that both capelin and eulachon may have declined significantly in the 1980s.

### Pacific Salmon (*Oncorhynchus* spp.)

All five Pacific salmon species are found in the Bering Sea area. Sockeye salmon (*O. nerka*) is the most common, and Bristol Bay supports the largest sockeye fishery in the world. Chinook (*O. tshawytscha*), chum (*O. keta*), coho (*O. kisutch*), and pink (*O. gorbuscha*) salmon are all found in lesser degrees of abundance. Much has been written describing the life history and distribution of Pacific salmon in the North Pacific region (Groot and Margolis, 1991).

Depending on the species, juvenile salmon migrate from their freshwater rearing areas between birth and age two. Once in the marine environment, juvenile fish follow an annual migration pattern that takes them away from the coast and into the Bering Sea and North Pacific Ocean. Once the fish achieve the proper age and size for reproduction, they return to their freshwater streams of origin to spawn, an event that takes place between early summer and early winter. After spawning, all salmon of these five species die. Ages of adult fish range from two to six years, depending on species and population. Smolt out migration from rivers occurs in the spring and summer following ice breakup. Returning adult salmon migrate into coastal areas during the summer months where they support large commercial and subsistence fisheries. During their oceanic lives, salmon live on zooplankton, squid, crab larvae, and other fish. Predators in the oceans include seals, killer whales, and humans. During spawning returns to land, salmon are preyed on by bears, other large mammals, and humans (Lewbel, 1983).

The long-term dynamics of Pacific salmon production in the eastern Bering Sea (and Alaska region in general) has been well documented by Francis and Hare (1994). Further discussion is given in [Chapter 5](#). Those studies have shown that salmon production in the northeast Pacific exhibits time and space variability that is closely linked to similar dynamics



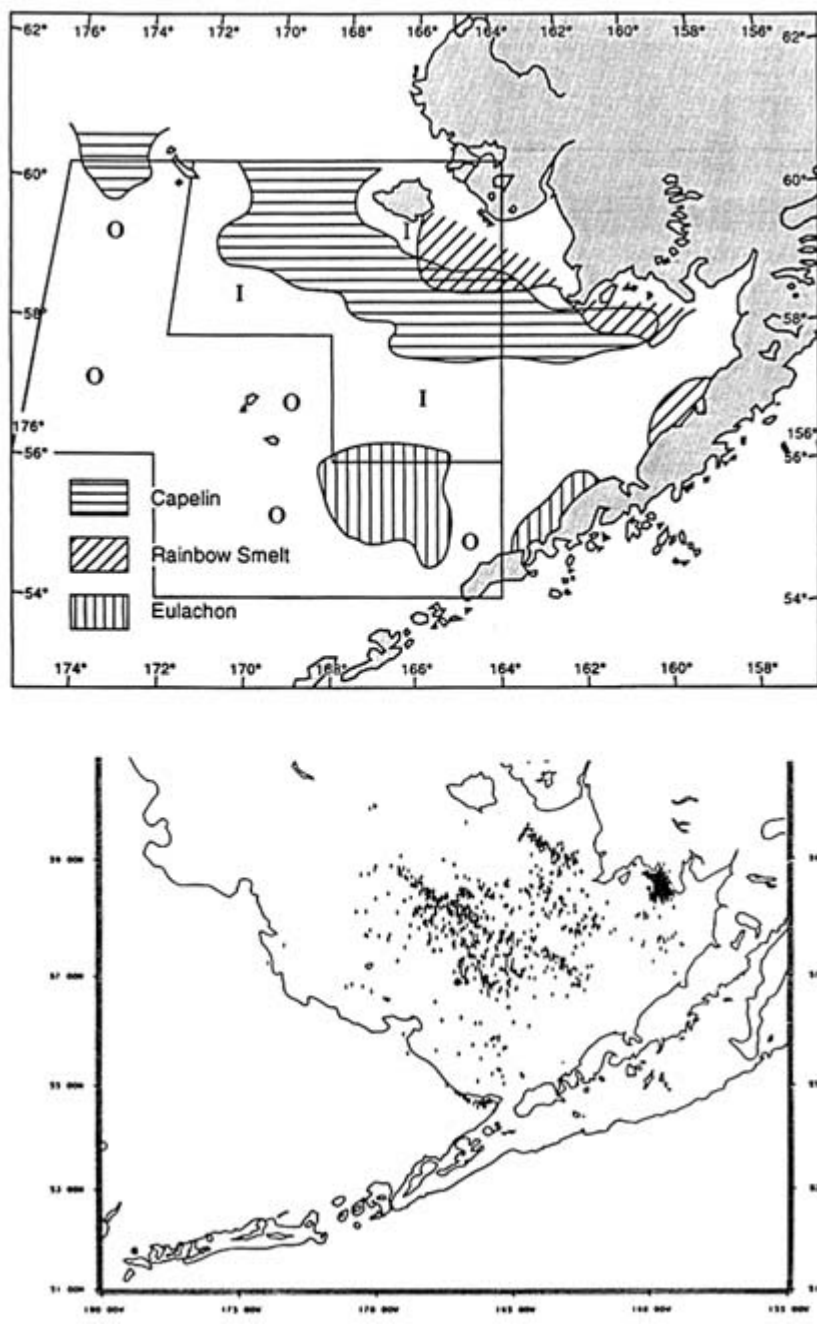


Figure 4.26 Generalized distribution of smelts in the eastern Bering Sea based on NMFS groundfish trawl surveys and fisheries observer data (Os and Is represent outer and inner shelf areas, respectively, over which fisheries observer data are pooled for analysis of eulachon abundance trends) (upper figure: Fritz et al., 1993; lower figure: Hinckley, 1987).

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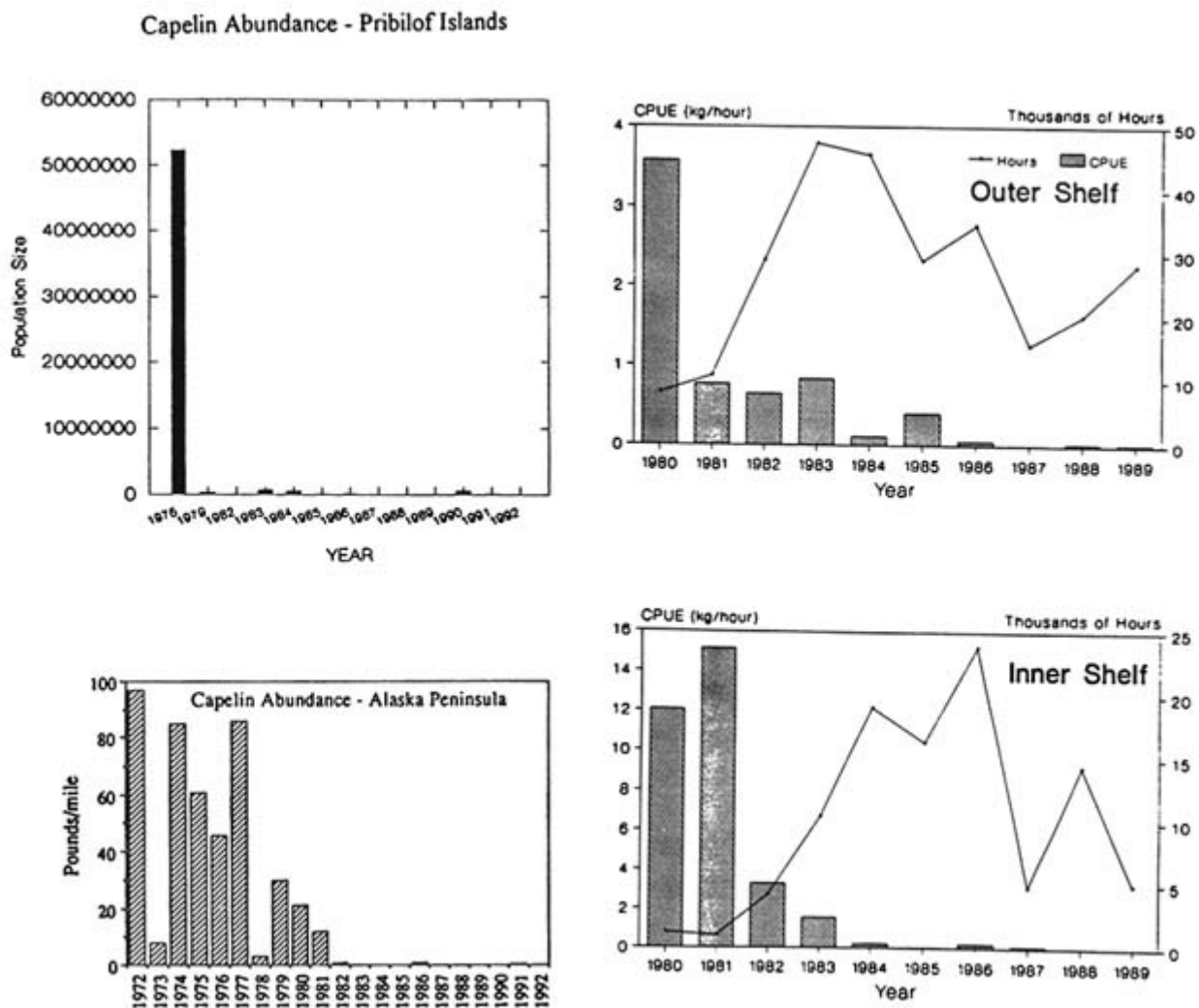


Figure 4.27 Trends in capelin abundance in the Pribilof Islands region (Hunt et al., 1981b) and in the Gulf of Alaska (Piatt and Anderson, in press), and trends in CPUE (catch per unit effort) of eulachon from fisheries observer data on outer and inner shelf areas of the eastern Bering Sea (hours represent total duration of sampled trawls in region for each year) (Anonymous, 1993).

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in the North Pacific atmosphere and ocean physics. Estimates of salmon production (catch plus escapement for the three major species—chum, sockeye, and pink) for the eastern and western Bering Sea for 1952–91 (Figure 4.28) are based on estimates of Rogers (1992). Estimates of production for the western Bering Sea (Rogers, 1992) are production statistics for Russia, adjusted by the estimated mean ratios of eastern Kamchatka to total USSR catches for 1952–75 from the International Pacific Fisheries Commission (1979) (sockeye, 33 percent; pink, 18 percent; chum, 14 percent). These data illustrate that there was an enormous increase in eastern Bering Sea production in the late 1970s. Eastern Bering Sea salmon production is dominated by sockeye, whereas western Bering Sea production is dominated by pink salmon. Summaries of recent trends in fish populations and biomass are given in Table 4.1, Table 4.2, and Figure 4.29.

## BIRDS

### Life History and Distribution

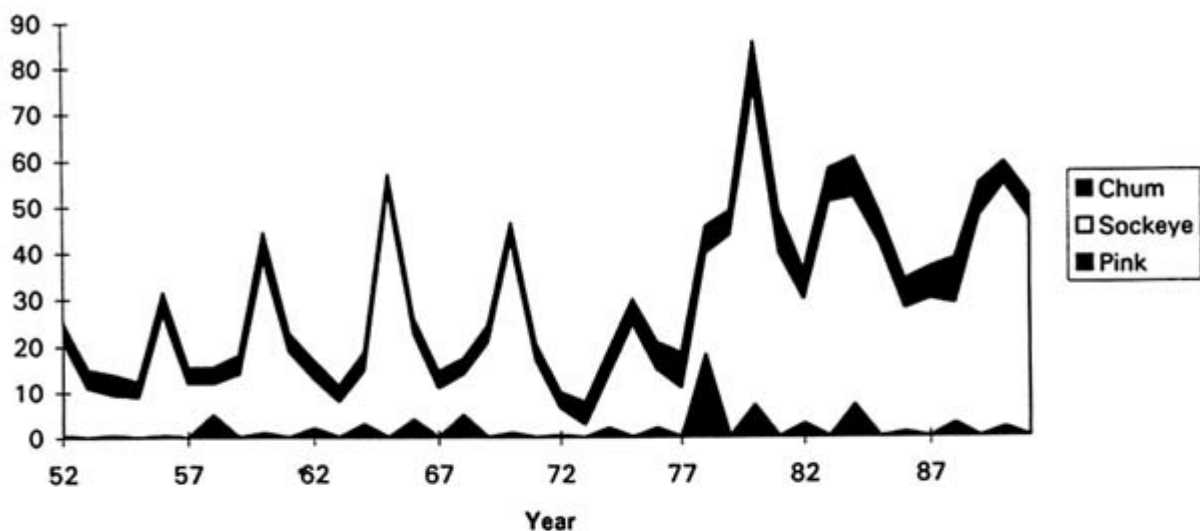
Thirty-six species of seabirds nest in Alaska, with 32 of them nesting on the coast of the Bering Sea and Gulf of Alaska; an additional three species nest elsewhere but spend significant parts of the year in the Bering Sea and Gulf of Alaska (Table 4.3). There are also 12 species of sea ducks (Table 4.4) and five species of geese (Table 4.5) that nest near the coast or on islands of the Bering Sea, or winter in the Bering Sea and Gulf of Alaska.

In addition, there are a wide variety of other species of seabirds, waterfowl, shorebirds, and others such as raptors that inhabit or migrate through the region during the year; many of the most important have been described (Hood and Calder, 1981; Lewbel, 1983; NPFMC, 1993; USFWS, 1989). Distributions and presence of these migratory and nonmigratory species are based on species evolution, geology and geography, and climate (Hood and Calder, 1981). Bird habitats of the Bering Sea region include near shore waters, lagoons, unvegetated intertidal areas (such as the outer Yukon delta), and vegetated intertidal areas. Shore and waterbirds tend to move north in the spring as part of a great migration, where they await the ice breakup. The search for nesting grounds occurs both on the margins of the Bering Sea and the lands of the American and Asian continents. With freeze-up in the fall, the migratory birds move from northern wetlands to the marine habitats in the south.

The seabirds of the region include such families as Diomedidae, Procellariidae, Hydrobatidae, Phalacrocoracidae, Laridae, and Alcidae. These include the albatrosses, shearwaters, fulmars, storm petrels, cormorants, pelagic gulls (kittiwakes), murrelets, guillemots, auklets, murrelets, and puffins.

In addition, there are a wide variety of other species of seabirds, waterfowl, shorebirds, and others such as raptors that inhabit or migrate through the region during the year. Waterfowl are members of the family Anatidae, which includes geese, ducks, and swans. The shorebirds are members of the families Charadriidae, Scolopacidae, and Phalaropodidae; these include wading birds, such as turnstones, godwits, curlews, plovers, dowitchers, and other sandpipers. Other important birds that nest and feed along the margins of the Bering Sea include the bald

### Estimated E Bering Sea Salmon Production (millions)



### Estimated W. Bering Sea Salmon Production (millions)

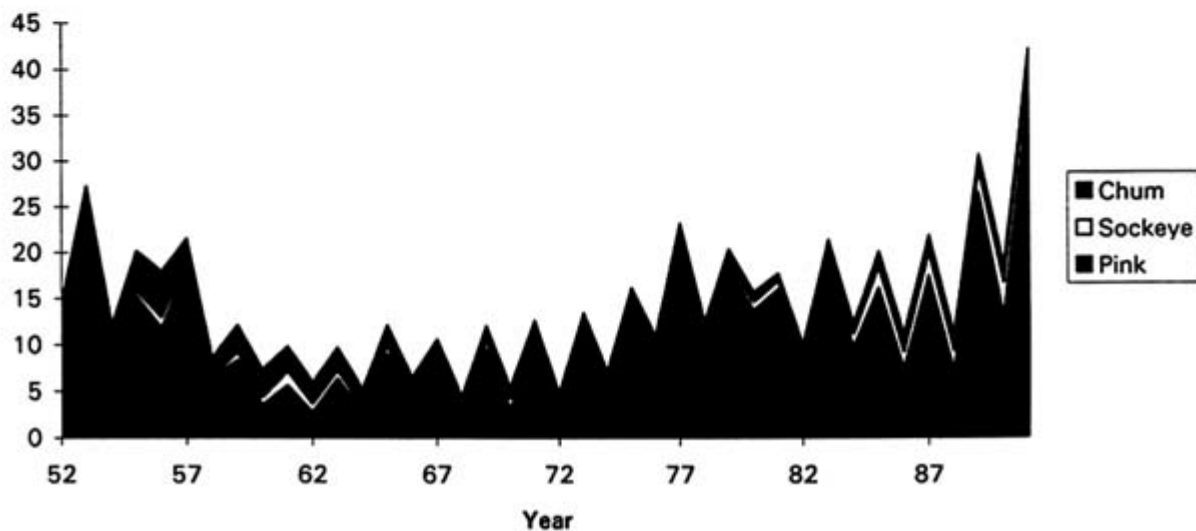


Figure 4.28 Estimated salmon production (catch and escapement) for eastern and western Bering Sea, 1952–91 (based on unpublished data, from Alaska Fisheries Science Center, NMFS [National Oceanic and Atmospheric Administration]).

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Table 4.1 Total allowable catch quota or harvest prediction, actual harvest, and current status of major resources in the exclusive economic zone off Alaska, 1995

SPECIES	TOTAL ALLOWABLE CATCH AND HARVEST (1)					STATUS OF RESOURCE	
	1995 BIOMASS (6)	1995 ABC	1994 TAC/Pred (2)	1994 HARVEST	1995 TAC/Pred (2)	CONDITION OF RESOURCE	TREND IN RESOURCES ABUNDANCE
Pollock	9,264,000	1,394,060	1,496,750	1,482,676	1,372,960	EBS/Al-Average, GOA-Low	EBS/Al-Stable, GOA- Decreasing
Pacific cod	2,193,000	397,200	241,400	244,148	319,200	EBS/Al-Average, GOA-High	EBS/Al- Increasing, GOA- Decreasing
Flatfish	9,622,470	1,303,990	378,525	298,249	401,167	EBS/Al- Very High, GOA- Unknown	EBS/Al- Increasing, GOA- Uncertain
Rockfish	1,020,111	50,265	43,207	35,192	41,648	EBS/Al- Low, GOA- Low	EBS/Al- Stable, GOA- Increasing
Sablefish	225,300	25,300	28,840	23,905	25,300	EBS/Al- Average, GOA- Average	EBS/Al- Increasing, GOA-Stable
Atka Mackerel	846,000	128,240	71,505	73,120	83,240	EBS/Al- High, GOA- Unknown	EBS/Al- Stable, GOA- Uncertain
Other Groundfish	682,000	30,710	39,581	28,556	34,226	EBS/Al- High, GOA- Unknown	EBS/Al- Increasing, GOA- Uncertain
Total Groundfish	23,831,881	3,329,765	2,299,808	2,185,846	2,277,741	EBS/Al- High, GOA- Low	EBS/Al- Stable, GOA- Stable/ Decreasing
Halibut (8)	87,906	17,282	21,500	20,679	17,245	EBS/Al- Avg, GOA- Avg	EBS/Al- Decreasing, GOA- Increasing
Salmon (3)	(4)	(4)	167,000,000	197,000,000	147,000,000	EBS/Al- High, GOA- High	EBS/Al- Stable, GOA- Stable/ Decreasing
King Crab (5)	(4)	(4)	(4)	3,865	(4)	EBS/Al-V. Low, GOA- V. Low	EBS/Al- Decreasing, GOA-Stable
Tanner Crab (9)	(4)	(4)	72,065	73,155	(4)	EBS/Al- Avg, GOA- Low	EBS/Al- Decreasing, GOA-Stable
Dungeness Crab	(4)	(4)	1,987	635	1,500	GOA-Avg/ Low	GOA-Stable
Pink Shrimp	(4)	(4)	900	1,179	1,200	EBS/Al-V. Low, GOA- V. Low	EBS/Al- Stable, GOA- Stable
Herring (7)	(4)	(4)	61,741	43,401	44,270	EBS/Al- High, GOA- Avg	EBS/Al- Stable, GOA- Stable

Note 1: Unless otherwise indicated quotas and harvest values are given in metric tons.

Note 2: Total groundfish TAC includes reserves for all species.

Note 3: Salmon predicted and actual run size and catches given in number of fish.

Note 4: Prediction and/or mid-season quotas not available for all Alaska areas.

Note 5: Combines calendar year and split year seasons for some species.

Note 6: Exploitable biomass for some species unknown.

Note 7: Includes roe and roe on kelp harvests & predictions in short tons.

Note 8: Exploitable biomass and harvest of halibut for Alaska only.

Note 9: Includes 1993/94 T. bairdi and excludes Nov/Dec 1994 T. bairdi catch.

Source: Based on data from NMFS, ADF&G, and Committee on the Bering Sea Ecosystem.

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Table 4.2 Total allowable catch or harvest prediction, actual and current status of major resources in the eastern Bering Sea/Aleutian Islands, 1995

SPECIES	TOTAL ALLOWABLE CATCH AND HARVEST					STATUS OF RESOURCE	
	1995 BIOMASS (1)	1995 ABC	1994 TAC (2)	1994 HARVEST	1995 TAC (3)	CONDITION OF RESOURCE	TREND IN ABUNDANCE
Pollock (EBS)	8,080,000	1,250,000	1,330,000	1,313,135	1,250,000	Average	Stable
(AI)	189,000	56,600	56,600	57,097	56,600	Average(?)	Stable(?)
Bogoslof (518)	442,000	22,100	850	922	1,000	Low	Stable
Pacific cod	1,620,000	328,000	191,000	196,569	250,000	Average	Increasing
Yellowfin	2,770,000	277,000	170,325	144,544	190,000	High	Increasing
Sole							
Greenland Turbot	150,000	7,000	7,000	10,321	7,000	Low	Declining
Arrowtooth Flounder	625,000	113,000	10,000	14,366	10,227	High	Increasing
Rock Sole	2,330,000	347,000	63,750	60,544	60,000	High	Increasing
Flathead	725,000	138,000	(4)	(4)	30,000	High	Stable
Sole							
Other Flatfishes	677,000	117,000	47,600	29,766	19,540	High	Stable
Sablefish (EBS)	16,500	1,600	540	699	1,600	Low	Increasing
(AI)	13,900	2,200	2,800	1,745	2,200	Average	Declining
Pacific Ocean Perch (EBS)	47,100	1,850	1,910	1,906	1,850	Low	Stable
(AI)	252,000	10,500	10,900	10,932	10,500	Low	Stable
Other POP Complex (EBS)(4)	29,700	1,400	1,190	127	1,260	Unknown	Unknown
Sharp/ Northern (AI)	94,500	5,670	5,670	5,090	5,103	Unknown	Unknown
Short/ Rougheye (AI)	45,000	1,220	1,037	935	1,098	Unknown	Unknown
Other Rockfish (EBS)	7,300	365	310	133	329	Average	Stable
(AI)	15,500	770	655	297	693	Average	Stable
Atka Mackerel	825,000	125,000	68,000	69,559	80,000	High	Stable
Squid	Unknown	3,110	2,644	588	1,000	Unknown	Unknown
Other Species	682,000	27,600	22,432	24,518	20,000	High	Increasing
Total Groundfish	19,636,500	2,836,985	1,995,213	1,943,793	2,000,000	High	Stable

Note 1: Exploitable biomass for some species unknown.

Note 2: 1994 TAC includes the final allocated portion of the 15% reserve allocation & CDQ quota and catch.

Note 3: 1995 TAC includes the 15% reserve allocation.

Note 4: Flathead sole was grouped with other flatfish in 1994 allocation.

Source: based on data from NMFS, ADF&G, and the Committee on the Bering Sea Ecosystem.

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EASTERN BERING SEA AND ALEUTIAN ISLANDS

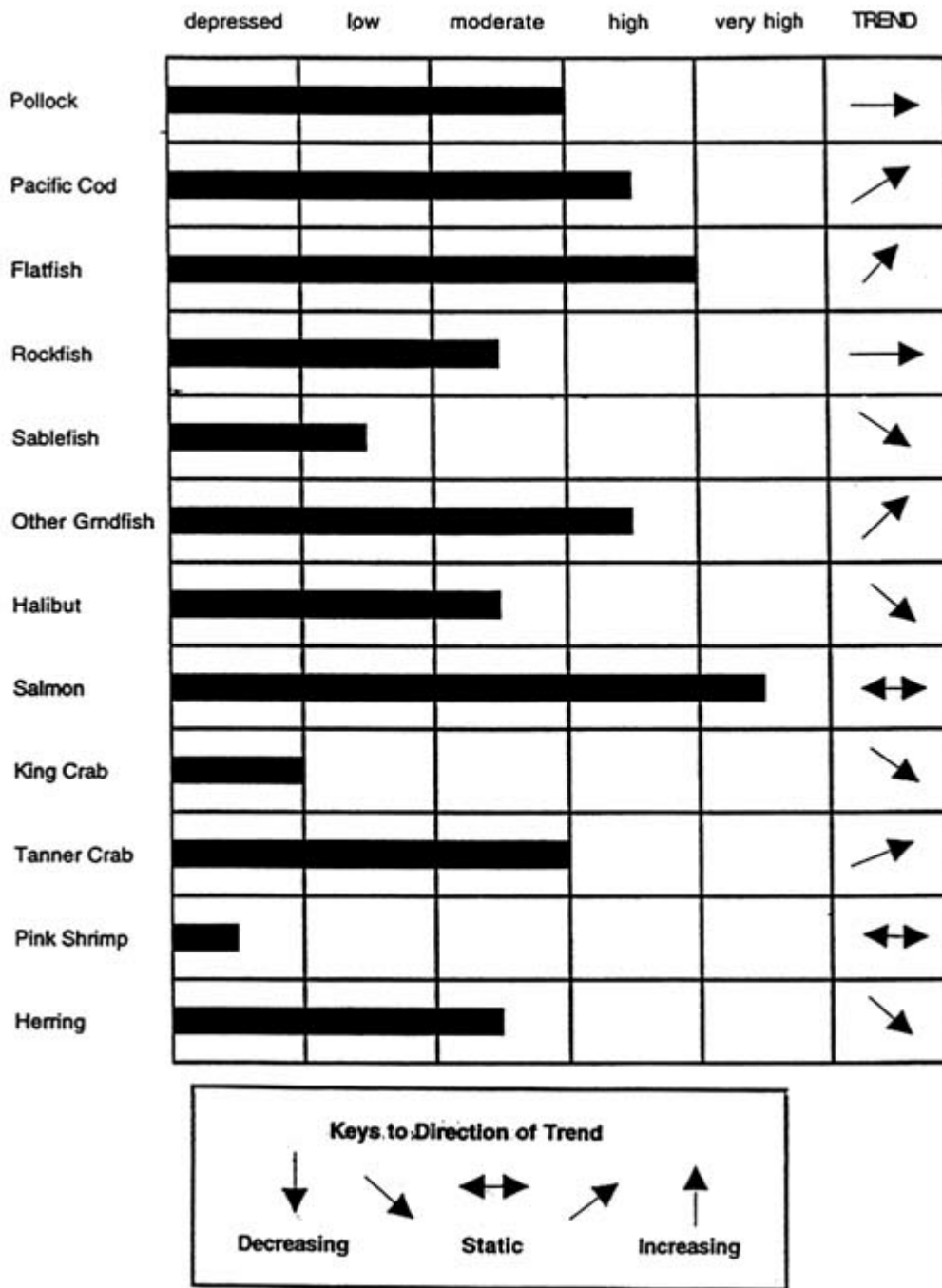


Figure 4.29 Trends in fish populations and biomass (based on data from NMFS, ADF&G, and the Committee on the Bering Sea Ecosystem).

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Table 4.3 Numbers of seabirds and seabird colonies in Alaska.

Species	Number of Sites	Catalog Total	Estimated Total
Northern fulmar	30	1,451,980	2,000,000
Sooty shearwater	0	-	21,000,000
Short-tailed shearwater	0	-	20–80,000,000
Fork-tailed storm petrel	60	1,148,500	5,000,000
Leach's Storm petrel	38	1,709,600	4,000,000
Double-crested cormorant	82	4,701	7,000
Brandt's cormorant	1	11	100
Pelagic cormorant	285	40,888	90,000
Red-faced cormorant	179	51,613	130,000
Pomarine jaeger	-	-	?
Parasitic jaeger	-	-	?
Long-tailed jaeger	-	-	?
Bonaparte's gull	-	-	?
Mew gull	44	3,442	10,000 (?)
Herring gull	12	28	300 (?)
Glaucous-winged gull	547	229,022	500,000
Glaucous gull	115	5,719	30,000
Black-legged kittiwake	263	1,752,906	2,500,000
Red-legged kittiwake	6	226,802	250,000
Ross's gull	0	-	20–30,000
Sabine's gull	-	-	?
Arctic tern	131	13,586	25,000
Aleutian tern	28	3,403	10,000
Dovekie	-	-	100
Common murre	42	1,690,584	5,000,000
Thick-billed murre	76	1,768,536	5,000,000
Black guillemot	12	323	400
Pigeon guillemot	363	40,571	200,000
Marbled murrelet	?	?	250,000
Kittlitz's murrelet	?	?	100,000
Ancient murrelet	40	113,302	400,000
Cassin's auklet	21	319,140	600,000
Parakeet auklet	125	429,436	800,000
Least auklet	31	3,432,068	6,000,000
Whiskered auklet	10	6,400	20,000
Crested auklet	38	1,343,750	2,000,000
Rhinoceros auklet	12	112,618	200,000
Tufted puffin	502	2,108,535	4,000,000
Horned puffin	435	768,011	1,500,000

Source: Sowls et al. (1978).

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Species	Range		Population Breeding	Current 10 yr.	Comments
	Breeding	Wintering			
<i>Somateria mollissima v-nigra</i>	From Victoria Is., NWT west along Beaufort Sea & Bering Sea Coasts of AK., Aleutian Islands & Siberia east from Chaun Bay & along Bering Sea Coast,	Bering Sea esp. in Bering Strait near Diomedes Is. & St. Lawrence Is. Chukchi Sea & east coast of Kamchatka Peninsula	Unknown Guestimates: 81,500 - W. Can. Arctic 25,500 - Ak 20,000+ - Russia	Declining in Russia by 3 to 4 fold since early 1970's. Thought to be declining in Alaska	Hunted species in fall and winter and especially for subsistence in spring
<i>S. spectabilis</i>	Northern Russia, eastern Siberia, Alaska and Arctic Canada west of Victoria Is.	Bering Sea, notably near Chukotka coasts, St. Lawrence Is., Pribilof Is. Alaskan Pen. & Aleutian Is.	Unknown Guestimates: >100,000 - Russia - 1 million in central & W. Arctic and Alaska	Thought to be decline in Alaska & Western Arctic. Stable in Russia	Most common marine duck. Heavily hunted in certain portions of its range, especially for spring subsistence
<i>S. fischeri</i>	Narrow coastal strip from Yana R. to Chaun Bay in Siberia, Y-K Delta & Pt. Barrow to Prudohoe Bay, Alaska	Unknown but probably Bering Sea toward the Siberian Coast	<50,000	Declining in Alaska & western Arctic at 14% per year	Threatened - listing in U.S. Hunting in Siberia & Alaska for spring subsistence
<i>Polysticta stelleri</i>	In Russia, narrow coastal strip from western Siberian coast to N. of Chukotski Pen., esp. in Lena & Yana deltas, and in AK from Norton Sound to Pt. Barrow	Southern Bering Sea, notably along Aleutian Islands & Alaskan Pen. Occurs along Kamchatka Pen. Commander Is., & Pribilof Islands	<100,000	Declining	Threatened - US listing proposed Hunting in Siberia & AK esp. in spring. Formerly an important component of sport outfitting hunts in AK due to accessibility
<i>Histrionicus histrionicus</i>	In Russia NW coast of Balkal east to Kamchatka & on Commander Is. and S.E. Siberia. Alaska south to British Columbia, Alberta, Washington, Idaho, & Montana and Oregon	Commander Island & Aleutian Islands Alaskan coast south to California SE portions of Russia esp. Kamchatka, Kuril Is., Sakhalin Is. to Sea of Japan	USA & CANADA - 165,000 Russia - guestimate: 50,000 - 100,000	Declining rapidly in eastern Siberia. Slight decrease in B.C. Retraction from former breeding range in Southwestern U.S.	Hunted species especially in Alaska. Breeding population of Prince William Sound, AK declined by Exxon Valdez oil spill.
<i>Ciangula hyemalis</i>	Circumpolar & ubiquitous to Arctic	At edge of ice in Bering Sea, esp. Aleutian Islands, Commander Islands. South to Korea and California	Unknown Russia - 500,000 USA & CANADA 2.5 million	Declining in AK & Yukon Stable in Russia	Hunted species throughout range esp. in Russia where considerable commercial importance
<i>Melanitta migrata</i>	Northeast Siberia and NW North America	Kamchatka and Commander Islands. South to Sea of Japan, Korea and Occasionally China. Aleutian Islands & E. Alaskan Pen. south to Mexican border	Unknown Guestimates: NW N.A. = 282,000 Russia - 200,000	Declining in NW North America; possibly stable in Russia	Hunted species. Very important component of market hunt in spring in northern Siberia & sport hunt in eastern U.S.
<i>M. perspicillata</i>	Western Canada to Yukon and northeast Alaska	Aleutian Islands & S. coast of AK to California. Only stragglers to the Pacific northeast	Unknown Guestimates: NW N.A. = 536,200	Declining in northwest North America	Hunted species in North America, especially eastern United States
<i>M. deglandi</i>	E. Siberia, notably middle Anadyr, Kolyma, Yakuto Koryak and other high mountain plateaus. Arctic Ocean to Prairie Plateau, west to B.C. & east to Manitoba	From Kamchatka Pen. to Japan, Korea & China notably, Sakhalin & Kurile Islands. From Alaska to California	Unknown Guestimates: W.N.A. = 592,600 Russia - < 200,000	Possibly unchanged in North America Declining rapidly in east Siberia where declines of 10 fold are reported since the 1970's	Hunted species especially in eastern U.S. some market & spring hunting in Russia. Large kills of molters localized 1970's
<i>Bucephala clangula</i>	Most of Boreal Forest Zone of Europe, Asia and North America	In Asia, in Issykkal & Iran, some in India, Baluchistan & Mongolia. Commander Islands & Kamchatka, south in large numbers to Korea, Japan, China, & Taiwan. Aleutian Islands to California	Unknown Guestimates: W.N.A. - 570,000 Russia - 400,000	Declining in NW N.A. Perhaps stable in Russia	Hunted species. Not of market significance in Asia. Reported to have declined considerably in Europe & attributed to deforestation
<i>B. islandica</i>	Southern B.C. to Western Alaska	Alexander Arcipelago, AK to California including interior lakes & rivers. Accidental straggler in Russia	Unknown Guestimates: W.N.A. - 150,000	Declining in B.C.	Hunted species in fall & winter range
<i>B. albeola</i>	Central and western North America to western Alaska	Aleutian Islands to southern California. Only a straggler in Russia	Unknown Guestimates: NW N.A. - 887,000	Declining in NW N.A.	Hunted species in fall & winter range
<i>Lophodytes cucullatus</i>	Areas of boreal western North America	Southeastern Alaska south to California. Coastal & interior lakes & rivers	Unknown Guestimate: W.N.A. - 15,000	Unknown	Hunted species in fall & winter range
<i>Mergellus albellus</i>	Forested zone of Russia, Siberia and Far East	Japan, Korea & China. Coastal & large lakes & rivers	Unknown Guestimate: Russia = 100,000 Dispersed in low densities	Perhaps stable in Russia	Hunted species, incidental to other diving ducks
<i>M. serrator</i>	Throughout southern Tundra lakes or boreal Russia except for northern coastal zone. Throughout boreal N.A.	From Kamchatka and Commander Islands to Kuril Is., Japan, Korea, China & Taiwan. Aleutian Islands and S.E. AK to Washington	Unknown Guestimates: W.N.A. = 237,000 Russia = 100,000	Increasing W.N.A. Possibly stable in Russia	Hunted species of low interest
<i>M. merganser</i>	Closed boreal forests of Eurasia & N.A.	Aleutian Islands to Mexico and from Kamchatka and Kuril Islands south to Japan, Korea, China & Taiwan	Unknown Guestimates: W.N.A. = 641,000 Russia = 140,000	Increasing in W.N.A. possibly stable in Russia	Hunted species of low interest
<i>M. squamatus</i>	Mid & S. portions of Sikhote - Allin Range in hilly portions of N.E. Manchuria	Korea, China, Tonkin & Burma mires on river habitats	Unknown but very small 500 to 1400	Declining rapidly	very rare with an extremely restricted range

Source: Goudie et al. (1994).

eagle, peregrine falcon, sandhill cranes, Aleutian tern, and McKay's bunting. Brief descriptions of the principal bird species undergoing population fluctuations of note are presented.

Table 4.5 Trends in the abundance of geese nesting and wintering in the eastern Bering Sea

Species	Nesting	Wintering	Status
Greater white-fronted goose	+		Increasing
Emperor goose	+	+	Decreasing
Brant	+		Decreasing
Cackling Canada goose	+		Increasing
Aleutian Canada goose	+		Increasing

Source: Springer (1993).

Diets of the seabirds range from almost entirely zooplankton to primarily fish; there are no strictly piscivorous seabirds. All of them consume many types of prey but most actually depend on only a few kinds of zooplankton, squids, and fishes (Hatch, 1984; Hatch and Sanger, 1992; Hunt et al., 1981a; Sanger, 1986; Springer and Roseneau, 1985; Springer et al., 1984, 1986, 1987). Important zooplankton are large calanoid copepods, euphausiids, and hyperid amphipods. Most of the fishes consumed by seabirds are pelagic species, including primarily lanternfish, sand lance, capelin, greenlings, arctic cod (*Boreogadus saida*) saffron cod, and pollock. Wintering sea ducks and emperor geese feed mainly on invertebrates, particularly mollusks and crustaceans.

### Sources and Magnitude of Variability

Mass mortalities and major declines in the abundance of marine birds in Alaska have been documented in the past 200 years and have had numerous causes, including predation by introduced mammals, oiling, drowning in drift nets, and hunting. Since the early to mid-1970s, when widespread, systematic studies of seabird colonies were initiated, fluctuations in population sizes and productivity have been common. Recent changes have been both downward and upward.

### Prey Availability

The population dynamics of seabirds in general appears to be governed primarily by the availability of prey (Furness and Monaghan, 1987); productivity of seabirds is sensitive to food supply, and population abundance fluctuates in response to trends in recruitment. The failure of prey resources can lead to mass mortalities of seabirds that can cause or contribute to population declines, while increases of prey can cause increases in seabird survival and



populations. Papers in Croxall (1987) demonstrate the impacts of commercial fisheries on seabird food availability, citing the experience of various species declines offshore California, Salvador, and Norway. In the Norwegian case, for example, Atlantic puffins, common guillemots, and razorbills suffered drastic breeding reductions due to intensive herring fishing from 1958 to 1969.

### **Productivity**

Seabird productivity depends on prey being adequate for females to lay eggs, for the eggs to be incubated successfully, for healthy chicks to be raised, and for the juvenile birds to make the transition to independence, which includes surviving through the winter. Insufficient prey at any one of these stages, which span an interval of up to approximately eight months, can dramatically reduce productivity.

Productivity of seabirds varies greatly between years and over longer intervals. For example, kittiwake productivity on the Pribilofs during just the first half (laying-fledging) of the critical period has varied by nearly two orders of magnitude between years (Dragoo and Sundseth, 1993). Interannual variability in productivity of kittiwakes is common elsewhere in Alaska, as it is for murre, cormorants, and other species (Hatch, 1993; Hatch et al., 1993; Murphy et al., 1986, 1991; Springer, 1991). Years of poor productivity are characterized by small clutch sizes, nest abandonment, and chick starvation, all of which are indicative of food stress.

### **Die-Offs**

At least five large wrecks, or die-offs, of seabirds have occurred in the past decade in the Bering Sea and Gulf of Alaska—in 1983, 1984, 1989, 1991, and 1993 (Nysewander and Trapp, 1984; Piatt and van Pelt, 1993; Piatt et al., 1990; A.M. Springer, unpublished data). Estimates of the numbers of birds (including murre, black-legged kittiwakes, and shearwaters) that died in each range from 10,000 to 100,000. The most likely cause in all years but 1984 was starvation. The die-off in 1984 was reported only from St. Lawrence Island and apparently was not caused by starvation, although the exact cause is not known (A.M. Springer, unpublished data). The only reported die-off of a similar magnitude before 1983 was in 1970 (Bailey and Davenport, 1972).

There are no estimates of the effects that any of the die-offs might have had on regional abundances of seabirds. It is improbable that changes in numbers at nesting colonies could be detected following particular die-offs, because they occurred either in winter or over a broad area, or both, and thus likely included birds from numerous nesting locations. The cumulative effect, however, might have contributed to an apparent widespread decline in murre populations in the Gulf of Alaska (Piatt, 1994).

## Abundance

Change in the abundance of seabirds in Alaska appears to be the norm (Table 4.6), and it seems likely that most declines result from decreased productivity, including the survival of juvenile birds through their first winter. There are no known catastrophic declines for entire species over short intervals that can be attributed to wrecks. Rather, all of the declines have had a similar, gradual rate averaging 4.4 percent per year ( $N = 19$ ,  $S = 2.1$  percent per year).

In contrast, increases in numbers have been both gradual and extreme. Of 23 recorded occasions when numbers have increased, the rates have been greater than about 20 percent per year in 10 cases, with a high of 78 percent per year for common murrelets at Middleton Island between 1956 and 1974. That change and the growth in numbers of black-legged kittiwakes (+26 percent per year) and glaucous-winged gulls (+50 percent per year) on Middleton Island likely resulted in large part from immigration following the creation of extensive nesting habitat by the earthquake of 1964. Likewise, other cases of rapid colony growth—of thick-billed murrelets (+19 percent per year) and black-legged kittiwakes (+38 percent per year) at Buldir Island, black-legged kittiwakes at Margerie Glacier in Glacier Bay (+30 percent per year), and northern fulmars at St. George Island (+25 percent per year)—probably were accounted for in part by immigration. Nur and Ainley (1992) concluded that seabirds can be divided into two groups based on maximum potential population growth rate from productivity alone: species with an upper-quartile growth rate of around 19 percent or more and those with an upper-quartile rate of 13 percent or less. The first group includes species that lay many eggs in each clutch, such as cormorants and gulls. The second group includes species that lay just one or two eggs, such as murrelets and kittiwakes. Among species in these groups, immigration is the cause for populations that exhibit growth rates greater than the upper theoretical limit.

There are other cases where colony growth has been more gradual. Because of the important role that immigration can play, however, it is difficult to estimate the relative contributions of productivity and immigration. Growth from immigration consists primarily of the recruitment of prebreeders from other locations; adult birds generally have high fidelity to their nesting colonies. Thus, emigration would not be expected to rapidly deplete colonies in the same way that immigration can swell their ranks.

The concern over seabird population trends has an important spatial context, namely, the decline of five piscivorous species on the Pribilof Islands. In general, those declines contrast with stable or increasing populations of seabirds elsewhere in the Bering Sea.

**Red-faced Cormorant (*Phalacrocorax urile*).** Whereas there are three species of cormorants in the Bering Sea region, the red-faced cormorant is found mostly in the Aleutian Islands and Alaska Peninsula. Its breeding range is from the Komandorsky Islands through the Aleutians, to the Pribilofs, and east along the Gulf of Alaska coast to Prince William Sound (Kessel and Gibson, 1978; Sowers et al., 1978). Nests are usually found along lower cliff faces and constructed of seaweed, with clutches of two to three eggs on St. Paul Island and with broods of up to four found in the western Aleutians (Dick and Dick, 1971; Hunt et al., 1981b; Trapp, 1975). Red-faced cormorants live all year on the Pribilofs, feed near shore, and do not hunt more than a few kilometers from their nesting area, though they may venture out into open water in the spring and fall. They obtain their prey—fish (primarily sculpins), shrimp, crabs, and

Table 4.6 Trends in the abundance of seabirds in Alaska<sup>a</sup>

Species/Location	Range of Years	Trend	Rate (% / y)	Reference
<b>Northern Fulmar</b>				
St. George I.	1976–1988	0		Dragoo and Sundseth, 1993
	1988–1992	up 100%	25	
St. Paul I.	1976–1992	up 230%	38	L. Climo and A. Golovkin, unpubl. data
Semidi Is.	1976–1989	up 40%	3.1	Dragoo and Bain, 1990; Hatch, 1992
<b>Pelagic Cormorant</b>				
Cape Thompson	1960–1977	down 40%	2.4	Springer et al., 1985
Middleton I.	1974–1991	up 100%	5.9	Gould et al., 1984; S. Hatch, unpubl. data
<b>Red-faced Cormorant</b>				
St. Paul I.	1976–1992	down 70%	4.4	L. Climo and A. Golovkin, unpubl. data
<b>Glaucous-Winged Gull</b>				
Middleton I.	1955–1974	up 900%	47	S. Hatch, unpubl. data
	1974–1991	up 900%	53	S. Hatch, unpubl. data
<b>Black-legged Kittiwake</b>				
Cape Lisburne	1977–1985	up 27%	3.4	Springer et al., 1985; unpubl. data
Cape Thompson	1960–1976	down 45%	2.8	Springer et al., 1985
	1976–1990	up 300%	2.1	Springer et al., 1985; Sharp, 1991
Bluff	1975–1992	0		Murphy et al., 1992; unpubl. data
Nunivak I.	1987–1990	0		McCaffery, 1989
St. Paul I.	1976–1992	down 50%	3.1	Climo, 1993
St. George I.	1976–1984	down 50%	6.3	Dragoo and Sundseth, 1993
	1984–1992	up 30%	3.8	Dragoo and Sundseth, 1993
Cape Peirce	1976–1993	up 22%	2.2	Haggbloom, 1994
	1986–1992	0		
Agattu I.	1975–1985	up 66%	6.6	Williams and Byrd, 1992
	1985–1991	0		Williams and Byrd, 1992
Buldir I.	1974–1988	up 530%	38	Williams and Byrd, 1992;
				Williams and Byrd, Unpub. data
	1988–1992	0		Williams and Byrd, 1992;
				Williams and Byrd, unpubl. data
Kiska I.	1978–1988	up 38%	3.8	V. Byrd, unpubl. data
Semidi Is.	1973–1989	0		Hatch et al. 1993
Chiniak Bay	1975–1984	up 200%	22	Hatch et al. 1993
	1984–1989	0		Hatch et al. 1993
Chiswell Is.	1976–1991	0		Nysewander and Dipple, 1992
Barren Is.	1977–1991	0		Nysewander and Dipple, 1992
Puale Bay	1976–1991	0		Nysewander and Dipple, 1992
Prince William Sound	1973–1989	0		Irons et al., 1987; unpubl. data
Middleton I.	1956–1975	up 500%	2.6	Gould et al. 1984
	1975–1989	down 40%	2.9	Gould et al. 1985; Hatch et al. 1993
Margerie Glacier	1967–1983	up 500%	31	Climo and Duncan, 1991
	1983–1991	up 230%	29	Climo and Duncan, 1991
Boussole head	1974–1991	down 70%	4.1	Climo and Duncan, 1991
Cenotaph I.	1976–1989	down 100%	7.7	Climo and Duncan, 1991

Source: Committee on the Bering Sea Ecosystem

<sup>a</sup> This table does not include information on changes in numbers of seabirds on islands where foxes were introduced.

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amphipods—by pursuit diving close to shore and near the sea bottom (Ashmole, 1971; Hunt et al., 1981b).

The number of nests on St. Paul Island has declined by an estimated 70 percent since the mid to late 1970s (Table 4.3). In contrast, red-faced cormorants apparently have expanded their range into Prince William Sound in recent years—none were found until 1969 and they are now numerous (Kessel and Gibson, 1978). Information on trends is lacking for all other colonies.

**Black-legged Kittiwake (*Rissa tridactyla*).** Black-legged kittiwakes are probably the most widely distributed of the seabirds in Alaska. They are pelagic gulls that are found across the Arctic and are numerous in the eastern Bering Sea. Their nests, made of vegetation and mud, are found on cliff ledges and sometimes slopes if ground predators are absent. Numbers of eggs laid are one to three (Hunt et al., 1981a). The pelagic density of this species is dispersed and low. Most of the breeding population leaves the Bering Sea in winter, though some individuals are still found ranging from the Aleutians to the Pribilofs (Shuntov, 1972). With respect to feeding method, black-legged kittiwakes mostly dip, though they are also known to surface seize or use shallow pursuit diving (Hunt et al., 1981). The principal food is fish (cod, myctophids, sand lance, and capelin), but also includes crustaceans and cephalopods.

On St. George Island, numbers of black-legged kittiwake fell sharply between 1976 and 1984, but have been recovering since then, while on St. Paul Island the decline continued through at least 1989 (Table 4.3). These are the only locations known in the Bering Sea where black-legged kittiwakes are known to be less abundant now than in the past.

In contrast, black-legged kittiwakes have increased dramatically since the 1970s at all three colonies where they have been censused in the western Aleutians—Buldir Island (+530 percent), Agattu Island (+50 percent), and Kiska Island (+38 percent). Black-legged kittiwakes on or near the coast of the eastern Bering Sea—Bluff (Norton Sound), Nunivak Island, and Cape Peirce (Bristol Bay)—have been stable since the mid-1970s, notwithstanding considerable interannual variability at Bluff. Likewise, numbers have also been stable or increasing at most colonies in the eastern Chukchi Sea and Gulf of Alaska. Kittiwakes are known to have declined only at Middleton Island in the eastern Gulf of Alaska, about 40 percent since the early 1980s following a fivefold increase between the mid-1950s and mid-1970s, and at two very small colonies, Boussole Head and Cenotaph Island, in southeastern Alaska, at the edge of the species range. Nearby in Glacier Bay, however, kittiwake numbers at the largest colony in southeastern Alaska have increased by an order of magnitude since the early 1970s (Climo and Duncan, 1991).

**Red-legged Kittiwake (*Rissa brevirostris*).** Red-legged kittiwakes are endemic to the Bering Sea and are known to nest at only four locations in the world—the Pribilof Islands, Bogoslof Island, Buldir Island, and the Komandorsky Islands (Byrd, 1978). This species of kittiwake nests on cliffs, sheltered ledges and smaller ledges than do black-legged kittiwakes. Their nests usually have just one egg (Hunt et al., 1981b). During the summer, red-legged kittiwakes can be found on the shelf break adjacent to the Pribilofs, and seldom in water shallower than 100 m. In the fall and winter, most of the birds leave the Bering Sea (Kessel and Gibson, 1978). They feed by dipping or surface seizing (Ashmole, 1971), and much of this activity takes place at night.

According to Hunt et al., (1981b), myctophids (lantern fish) are an important food for this kittiwake, which also consumes pollock and cephalopods.

The total nesting population of red-legged kittiwakes was approximately 230,000 in the mid-1970s, with about 95 percent nesting on St. George Island. Numbers have declined by about 40 to 60 percent on the Pribilof Islands since then (Table 4.3), and this seabird is now a candidate for protection under the Endangered Species Act (Byrd, 1994). However, like black-legged kittiwakes, red-legged kittiwakes also have increased dramatically on Buldir Island since the mid-1970s (Byrd, 1994).

**Common and Thick-billed Murre (*Uria lomvia* and *U. aalge*).** Murres are also widely distributed throughout Alaska, with a total population on the order of 10 million individuals about evenly divided between the two species. These birds are found in the Bering Sea, northern Pacific, and North Atlantic. The greatest concentrations of murres in the Bering Sea region are on the Pribilof Islands, St. Matthew Island, St. Lawrence Island, the Semidi Islands, and the Cape Peirce-Cape Newenham region. Common murres are found mostly on the mainland coasts. These birds tend to nest in mixed colonies. Both species lay a single egg on bare cliff rocks, but the common murres prefer broader ledges and flatter areas than the narrow cliff ledges preferred by thick-billed murres. Juvenile birds jump from their cliff nests into the water at three weeks of age and stay in the water for another three weeks before they can fly.

Murres are long-lived birds and begin mating at five years of age. They migrate north in April following leads along the northern Bering and into the Chukchi Sea, and then return to colonies for mating. In the fall, they are found offshore, from Bristol Bay to the Gulf of Anadyr, until forced southward by the ice front (Shuntov, 1972). When the ice has advanced well into the Bering, the murres are found primarily in the extensive shelf areas of the southern Bering Sea. Murres obtain food by diving to depths of up to 130 m (Forsell and Gould, 1981), where they catch fish and invertebrates. Thick-billed murres have a more varied diet and venture farther from shore than common murres; common murres tend to feed on near shore mid-water fish, such as cod, sand lance, capelin and pricklebacks, whereas thick-billed murres also depend on demersal fishes, such as sculpins and invertebrates (Hunt et al., 1981a; Springer et al., 1984, 1987).

Common murres at St. George Island declined in number by about 30 percent between 1976 and 1987, but have recovered by about 12 percent since then (Dragoo and Sundeth, 1993). They declined by about 70 percent on St. Paul Island between 1976 and 1988. No trend is apparent at either Nunivak Island or Cape Peirce. Common murres apparently declined at Bluff between 1975 and the early 1980s, but numbers have been stable since that time. Abundance of common murres on Agattu Island has nearly doubled since the mid-1970s.

Thick-billed murres decreased by about 30 percent on the Pribilof Islands since the mid-1970s, although numbers on both islands have been relatively constant since the mid-late 1980s. They have increased by 300 to 400 percent on Buldir Island in the past 15 years. Estimates of total murre abundance in four colonies in the eastern Aleutians in periods sampled between the early 1970s and late 1980s (Bailey and Trapp, 1986; O'Daniel et al., 1990), while inconclusive, indicate possible declines of 30 to 90 percent. The abundance of murres (predominantly thick-billed) on St. Lawrence Island apparently did not change overall in the



interval 1972 to 1981 (Roseneau et al., 1985), but it might have increased somewhat since then (Piatt et al., 1988).

Numbers of murre apparently have declined by 25 to 60 percent at several inshore colonies in the western Gulf of Alaska for reasons that predate the oil spill of the *Exxon Valdez* (Piatt, 1994). The pattern is different at two offshore colonies, Middleton Island and the Semidi Islands. Numbers of murre at both locations appear to have fluctuated since the mid-1970s, but there is no indication of consistent change during that time (Dragoo and Bain, 1990; Gould et al., 1984; S. Hatch, unpublished data). Between the mid-1950s and mid-1970s, however, murre increased by about an order of magnitude on Middleton Island. The increase, like that of kittiwakes on Middleton Island, may have resulted from the creation of nesting habitat by the 1964 earthquake.

One of the longest records of murre abundance in Alaska is from Cape Thompson, in the eastern Chukchi Sea, where Swartz (1966) took a through census of the birds in 1960–61. Since then murre have steadily declined by about 50 percent overall. In contrast, murre have been gradually increasing nearby at Cape Lisburne, at least since the mid-1970s.

### Introduced Mammals

Introduced mammals have devastated seabird populations throughout the Aleutian Islands and on many islands in the Gulf of Alaska (Bailey, 1990; Bailey and Kaiser, 1993; Murie, 1959). As long ago as 1750 and peaking in the early years of this century, foxes were released on islands where they were raised for the fur trade. The abundant natural food (birds) and the escape-proof nature of islands made them ideal location for raising foxes. Foxes caused the greatest damage, but microtine rodents and ground squirrels, which were released on numerous islands as additional sources of food for the foxes, added to the problem by preying on eggs and chicks that were inaccessible to foxes. Hardest hit were ground-nesting species, particularly Leach's and fork-tailed storm petrels, ancient murrelets, Cassin's auklets, crested auklets, tufted puffins, Canada geese, ptarmigan, passerines, and various species of ducks.

Rats have long been a threat to seabirds in Alaska. Increased shipping from new ports on the Pribilofs is a cause for concern, as evidenced by the sighting in 1992 of a rat on a mooring rope of a ship docked at St. Paul Island (A. Sows, personal communication). Rats have wiped out six species of seabirds on Langara Island (Bailey and Kaiser, 1993; Bertram, 1989), which lies off the northern coast of the Queen Charlotte Islands, British Columbia. Rats escaped onto Kiska Island in the western Aleutians during World War II. The recent removal of foxes may be responsible for the marked increase in rats that now threatens the enormous colony of least auklets more than the foxes did (V. Byrd, personal communication). At present, it appears to be virtually impossible to eliminate rats from large islands such as Kiska.

### Gill Net Mortality

Mortality of seabirds in salmon gill nets in the North Pacific was a major concern for many years (Ainley et al., 1981; DeGange and Day, 1991; DeGange and Newby, 1980;

DeGange et al., 1985, 1992; Jones and DeGange, 1988; King et al., 1979). Japanese high-seas and land-based salmon fisheries operated in the western North Pacific south of the Aleutian Islands and in the western Bering Sea since 1952. Estimates of the total annual loss of seabirds were as high as 700,000 in the early 1970s and 450,000 in the mid-1970s. Mortality in the offshore component of the land-based fishery declined from about 150,000 in 1977 to 57,000 in 1987 because of a reduction in fishing effort.

Seabirds killed in gill nets included birds from the Bering Sea and probably the Sea of Okhotsk, as well as shearwaters from the southern hemisphere. Of particular concern to the United States was the potential loss of seabirds from the western Aleutian Islands, which lie near the center of the region occupied by the Japanese mothership fishery. This fishery killed on the order of 95,000 to 250,000 seabirds annually in the early 1980s, approximately 80 percent of which were tufted puffins. Drift net fishing in U.S. waters was banned in 1988.

Recent increases in puffin populations cannot be ascribed with certainty to the ban on gill net fishing in U.S. waters (Byrd et al., 1992). The number of nesting puffins on Agattu Island and Nizki-Alaid Island has increased since the mid-1970s, but not on nearby Buldir Island. The increases on Agattu Island and Nizki-Alaid Island followed not only the ban on gill nets, but also the removal of foxes from the islands in 1976 and 1977. Foxes were never introduced to Buldir Island. Therefore, it is difficult to distinguish between the effects of fishing and those of foxes on the Near Islands, and an increase on Buldir might be only now beginning (puffins do not recruit to the breeding population until the age of three to five).

### Consumption of Plastic Particles

Several species of seabirds consume large numbers of plastic particles that they apparently mistake for prey. Plastic has been found in the stomachs of 50 species of marine birds around the world, of which the procellariids, phalaropes, and certain alcids—primarily Cassin's auklets, parakeet auklets, and puffins—are the most contaminated (Day, 1980; Day et al., 1985; Hatch, 1993; J. Piatt, unpublished data). Plastic pollution of the oceans apparently began in the 1960s and has been increasing since, with a corresponding increase in the consumption of plastics by birds. Plastic particles in the North Pacific apparently originate in the west and are carried eastward in the Subarctic and Kuroshio currents (Day and Shaw, 1987; Day et al., 1990). There is some evidence for short-tailed shearwaters and tufted puffins that particles accumulated during summer might be eliminated during winter (Day et al., 1985). Numerous effects of plastic particles on seabirds, including starvation, intestinal blockage, and ulceration, have been documented but there is little evidence that plastic consumption is detrimental to species productivity or survival.

### Oiling

Approximately 30,000 carcasses of oiled seabirds were recovered following the grounding of the *Exxon Valdez*, of which about 22,000 were murrelets, mainly common murrelets (Piatt et al., 1990). Surveys at selected colonies hit by oil indicated that possibly as many as 120,000 to

140,000 adult murre, or 60 to 70 percent of the breeding birds, were killed at those colonies (Nysewander and Dipple, 1992). A reevaluation of the data indicates that the total mortality probably was about 240,000 seabirds, including about 180,000 murre (Piatt, 1994). Piatt (1994) further argues that murre populations were in decline in the Gulf of Alaska well before the oil spill and the recent declines must be viewed in a broader context.

### Hunting

Four species or subspecies of geese nest along the coast of the Bering Sea, particularly on the Yukon-Kuskokwim delta: greater white-fronted geese, emperor geese, cackling Canada geese, and black brant. During the 1960s and 1970s, numbers of all declined precipitously (Raveling, 1984). Restrictions on hunting during the spring subsistence harvest and during winter on the west coast of North America and in Mexico led to appreciable recoveries. However, dramatic declines in numbers of brant nesting on the Yukon-Kuskokwim delta continued into the 1980s (Sedinger et al., 1993), raising fears that management actions were not effective or that other factors were operating on the population. Sedinger et al. (1993) have suggested that continued subsistence harvest together with heavy predation on nesting birds likely explains the recent decline.

The abundance of emperor geese has apparently recovered only slightly from its low point in the mid-1980s, and is still only about half as great as in the 1960s (U.S. Fish and Wildlife Service, 1989). The major difference between emperor geese and the other species is that the majority of the population winters in the Bering Sea and on the south side of the Alaska Peninsula. They were not subjected to heavy hunting pressure on the wintering grounds, and thus must be influenced more by other factors in winter that increase mortality, or by factors such as the summer subsistence harvest, which likely compounds the effects of winter mortality (Schmutz et al., 1994). Most species of juvenile geese, including emperor geese, suffer high post-fledging mortality. Mortality during winter is high for emperor geese also (C. Dau, personal communication). It is possible that winter mortality has increased in recent years, or that management of the subsistence harvest has not been effective in curtailing the take to the point that the species has been able to recover to acceptable levels.

Numerous species of sea ducks also nest on the Yukon-Kuskokwim delta. Prominent among these are spectacled eiders and Steller's eider. Steller's eiders have not nested on the delta since 1975, whereas as many as 3,500 pairs might have nested there during the 1950s and 1960s (Kertell, 1991). Steller's eider is presently a candidate for threatened or endangered status under the Endangered Species Act (Quakenbush and Cochrane, 1993). Spectacled eiders have declined about 14 percent per year since the early 1970s, from an estimated historical population size of more than 47,000 pairs to fewer than 2,000 pairs today (Stehn et al., 1993). The spectacled eider was declared a threatened species in 1993.

As a group, the sea ducks, like emperor geese, are very K-selected, which makes populations highly susceptible to adult mortality (Goudie et al., 1994). Thus, speculation about the cause of the declines has focused on effects of subsistence harvests, predation, and other sources of adult mortality in summer and winter (Kertell, 1991; Stehn et al., 1993).

Sport hunting for eiders is not considered to be important, as it is for other ducks that migrate to wintering grounds south of Alaska. However, the role of the subsistence harvest is thought by some to be particularly important (e.g., Goudie et al., 1994). Alternatively, predation rates on nesting eiders might have risen as populations of geese and ducks on the Yukon-Kuskokwim delta fell during the 1960s and 1970s; predator (primarily arctic fox) numbers could have remained the same but inflicted proportionally greater losses on all species as the total number of potential prey declined.

Lead poisoning has recently been identified as another possible source of adult mortality in summer. In 1992 and 1993, two spectacled eiders and one common eider were found dead or dying on the Yukon-Kuskokwim delta. All of the birds had high levels of lead in their livers and two of them had several pieces of lead shot in their digestive tracts. The presence of lead shot, the elevated lead levels in livers, and the poor body condition of the birds indicated that lead poisoning was at fault (U.S. Fish and Wildlife Service, unpublished data).

Mortality during winter in the Bering Sea is also a possible factor, although very little is known about this. The wintering area of the spectacled eider is still obscure, but is probably in the western Bering Sea south of the seasonal sea ice and in polynyas south of St. Lawrence Island. Steller's eiders winter throughout the Aleutian Islands and Alaska Peninsula. The diets of both species include crustaceans and bivalves; whether these organisms have changed in abundance sufficiently to cause declines in eider populations is not known.

In addition to the eiders, four other species of sea ducks that nest inland in Alaska and winter along the coast of the Gulf of Alaska and Pacific Northwest have also declined considerably in the past 30 years (Hodges et al., 1994). Surf scoters (*Melanitta perspicillata*), white-winged scoters (*M. fusca*), and black scoters (*M. nigra*) declined in aggregate an estimated 33 percent between 1957 and 1992, while oldsquaws (*Clangula hyemalis*) declined 67 percent between 1977 and 1992. The reason for the declines is not known.

## MARINE MAMMALS

### Life History and Distribution

The marine mammal fauna of the Bering Sea is particularly rich because it includes north temperate, subarctic, and arctic species (Table 4.7). Several species of the North Pacific fauna (e.g., harbor seal, Steller sea lion, sea otter, beluga whales, and Dall's porpoise) are resident in the area throughout the year. Other species (e.g., gray, fin, blue, and humpback whales) migrate into the Bering Sea during summer months to feed. Marine mammals occur in all types of habitats, including deep oceanic waters, the continental slope, and the continental shelf (Table 4.8). The majority of species are found mostly over the continental shelf and in coastal waters. Ice-associated species (e.g., polar bears, walruses, ringed and bearded seals, and bowhead whales) are found in the Bering Sea mostly during the fall and winter in association with seasonal sea ice. Ice plays a particularly significant role in the ecology of marine mammals, as it provides habitat for some species while serving as a barrier to others (Fay, 1974). Ice-associated species are not found in the Gulf of Alaska, but otherwise the fauna is similar to that of the Bering Sea (Calkins, 1986).

Table 4.7 Marine mammal species in the Bering Sea

Common Name	Scientific Name	Abundance/Trend <sup>a</sup>	Status <sup>b</sup>
Baleen whales			
Gray whale	<i>Eschrichtius robustus</i>	Moderate/increasing	Recovered
Fin whale	<i>Balaenoptera physalus</i>	Low/unknown	Endangered
Minke whale	<i>Balaenoptera acutorostrata</i>	Low/unknown	Unknown
Blue whale	<i>Balaenoptera musculus</i>	Low/unknown	Endangered
Sei whale	<i>Balaenoptera borealis</i>	Low/unknown	Endangered
Humpback whale	<i>Megaptera novaeangliae</i>	Low/unknown	Endangered
Right whale	<i>Balaena glacialis</i>	Low/unknown	Endangered
Bowhead whale	<i>Balaena mysticetus</i>	Low/increasing	Endangered
Toothed whales and dolphins			
Sperm whale	<i>Physeter macrocephalus</i>	Moderate/unknown	Endangered
Cuvier's beaked whale	<i>Ziphius cavirostris</i>	Low/unknown	Unknown
Baird's beaked whale	<i>Berardius bairdi</i>	Low/unknown	Unknown
Stejneger's beaked whale	<i>Mesoplodon stejnegeri</i>	Low/unknown	Unknown
Beluga whale	<i>Delphinapterus leucas</i>	Moderate/stable	OSP
Killer whale	<i>Orcinus orca</i>	Low/unknown	Unknown
Dall's porpoise	<i>Phocoenoides dalli</i>	Moderate/unknown	Unknown
Harbor porpoise	<i>Phocoena phocoena</i>	Low/unknown	Unknown
Pinnipeds			
Northern fur seal	<i>Callorhinus ursinus</i>	High/stable	Depleted
Steller sea lion	<i>Eumetopias jubatus</i>	Moderate/declining	Threatened
Pacific walrus	<i>Odobenus rosmarus divergens</i>	High/stable	OSP
Harbor seal	<i>Phoca vitulina richardsi</i>	Moderate/declining	Unknown
Spotted seal	<i>P. largha</i>	High/unknown	Unknown
Ribbon seal	<i>P. fasciata</i>	Moderate/unknown	Unknown
Ringed seal	<i>P. hispida</i>	High/unknown	Unknown
Bearded seal	<i>Erignathus barbatus</i>	High/unknown	Unknown
Others			
Polar bear	<i>Ursus maritimus</i>	Low/stable	OSP
Sea otter	<i>Enhydra lutris</i>	Moderate/stable	OSP

<sup>a</sup> Low = less than 10,000; moderate = 10,000–100,000; high = more than 100,000.

<sup>b</sup> Endangered and threatened refer to Endangered Species Act listings. OSP means within the optimum sustainable population range as defined by the Marine Mammal Protection Act. Depleted means below the OSP range.

Source: Based on Lowry and Frost (1985).



Table 4.8 General oceanographic/habitat associations of Bering Sea Marine mammals

Oceanic/Deep Water	Continental Slope/ Slope Break	Continental Shelf/ Coastal Waters
Sei whale	Fin whale	Gray whale
Right whale	Minke whale	Humpback whale
Sperm whale	Blue whale	Minke whale
Cuivier's beaked whale	Dall's porpoise	Bowhead whale
Baird's beaked whale	Stejneger's beaked whale	Beluga
	Steller sea lion	Killer whale
	Ribbon seal	Harbor porpoise
		Pacific walrus
		Northern fur seal
		Steller sea lion
		Harbon seal
		Spotted seal
		Ringed seal
		Ribbon seal
		Bearded seal
		Polar bear
		Sea otter

Source: Based on Lowry et al. (1982).

Information on the distribution and abundance of Bering Sea marine mammals is incomplete (see review in Lowry et al., 1982). For most species, seasonal distribution is known only in general terms and winter distributions are poorly understood. Available estimates of population sizes are generally imprecise, and many of them are out of date. The abundance of most whales and dolphins is low, and species such as right and blue whales are (Table 4.7). Bowhead and gray whales are increasing in numbers. Beluga whale abundance is probably stable, and the trend in abundance of all other cetaceans is unknown. Seven species of large whales are classified as endangered under provisions of the Endangered Species Act. Pinnipeds are generally more abundant than cetaceans with the population size of several species estimated to number over 100,000. Steller sea lions are classified as threatened under the Endangered Species Act, and northern fur seals on the Pribilof Islands are listed as depleted under provisions of the Marine Mammal Protection Act.

Bering Sea marine mammals prey on a wide array of species and feed at several different trophic levels (Frost and Lowry, 1981a; Lowry et al., 1982). Most phocid seals, fur seals, and sea lions feed principally on fishes, with invertebrates making up a relatively small part of the diet (Table 4.9). Bearded seals and walruses eat mostly epifaunal and infaunal invertebrates, and thus their diets differ greatly from other pinnipeds. Toothed whales feed principally on fishes

Table 4.9 Relative importance of major prey types in the diets of pinnipeds in the Bering Sea

Species	Pelagic and Semidemersal Fishes	Demersal Fishes	Pelagic Nektonik Invertebrates	Nekto-benthonic Invertebrates	Epifaunal benthic Invertebrates	Infaunal benthic Invertebrates
Harbor seal	Major	Minor	---	Minor	---	---
Spotted seal	Major	Minor	Major <sup>a</sup>	Major	---	---
Ribbon seal	Major	Major	---	Minor	---	---
Ringed seal	Major	Minor	Major	Major	---	---
Bearded seal	Minor	Minor	---	Major	Major	Major
Walrus	---	---	---	Minor	Minor	Major
Fur seal	Major	Minor	Major	---	---	---
Sea lion	Major	Major	Minor	---	---	---

<sup>a</sup> For juveniles

Source: Based on Frost and Lowry (1981a).

Table 4.10 Relative importance of major prey types in the diet of cetaceans in the Bering Sea

Species	Pelagic and Semidemersal Fishes	Demersal Fishes	Octopus and Squids	Copepods	Euphausiids	Nekto-benthonic Invertebrates	Epifaunal Invertebrates	Marine Mammals
Right whale	---	---	---	Major	Minor	---	---	---
Bowhead whale	---	---	---	Major	Major	Minor	---	---
Blue whale	Minor	---	Minor	Minor	Major	---	---	---
Fin whale	Major	---	Minor	Major	Major	---	---	---
Sei whale	Minor	---	Minor	Major	Minor	---	---	---
Minke whale	Major	---	Minor	Minor	Major	---	---	---
Gray whale	Minor	---	Minor	---	---	Major	Major	---
Sperm whale	Minor	Major	---	---	---	---	Minor	---
Beaked whale	Minor	Major	Major	---	---	Minor	---	---
Killer whale	Major	Minor	Major	---	---	---	---	Major
Beluga whale	Major	Minor	Minor	---	---	Minor	---	---
Harbor porpoise	Major	---	Minor	---	---	Minor	---	---
Dall's porpoise	Minor	Major	Major	---	Minor	Minor	---	---

Source: Based on Frost and Lowry (1981a) and Lowry et al. (1982).

and cephalopods, whereas most baleen whales eat planktonic crustaceans and small schooling fishes (Table 4.10). Important exceptions to this pattern are killer whales, which commonly eat other marine mammals, and gray whales, which feed mostly on epibenthos. Sea otters eat primarily benthic invertebrates, whereas polar bears consume mainly phocid seals.

The biology and population dynamics of Bering Sea marine mammals have been reviewed by Lowry and others (1982). Calkins (1986) reviewed information on marine mammals in the Gulf of Alaska. Summaries are provided here for species of concern in the Bering Sea because they have shown unexplained population declines. Similar information is presented for some of the large whales, because the large reduction in the abundance of these species could have contributed to changes in the ecosystem that are of concern today.

### Steller Sea Lion

Steller sea lions inhabit waters of the North Pacific rim from California through the Aleutian Islands to Japan (Loughlin et al., 1984). They pup and breed in June and July in rookeries on relatively remote islands, rocks, and reefs. Sea lions disperse widely during the nonbreeding season, and marked animals have been seen far from the locations where they were tagged (NMFS, 1992). There is some evidence, however, that females generally return to rookeries where they were born to give birth and mate (Calkins and Pitcher, 1982; Loughlin et al., 1984). Recent genetics studies suggest that there are two relatively well-differentiated populations, one of animals inhabiting the region from Oregon through southeast Alaska, and the other of those in the region from the northern Gulf of Alaska through the Aleutian and Komandorsky island (Bickham et al., in press).

In the Bering Sea and Gulf of Alaska, sea lions eat a variety of fishes and cephalopods (Calkins and Goodwin, 1988; Lowry et al., 1982; Merrick and Calkins, in press). Walleye pollock are an important food (Lowry et al., 1989). Small pollock (those less than 20 cm) appear to be more commonly eaten by juvenile sea lions than by older animals (Merrick and Calkins, in press). Table 4.11 provides information on sea lion diets.

Sea lion rookeries and haulout sites are widely distributed, from British Columbia and southeast Alaska, throughout the Aleutians to the Sea of Okhotsk. In the late 1950s and early 1960s, Steller sea lions were abundant, with the total population in the North Pacific estimated to be about 240,000 to 300,000 (Kenyon and Rice, 1961). However, these early sea lion surveys were conducted in conjunction with sea otter surveys over a period of several years during various months of the year. Although the estimate produced by Kenyon and Rice provides some indication of sea lion abundance at that time, there is general agreement that these early surveys are not directly comparable to those conducted from the 1970s to the present. Recent efforts have attempted to maximize the number of animals counted by conducting surveys at midday during the peak of the pupping season (Braham et al., 1980; Loughlin et al., 1992; Merrick et al., 1987). Sea lion counts (Table 4.12) are not estimates of total population size, but rather minimum estimates of the number of animals using a site or group of sites (Loughlin et al., 1984, 1992; NMFS, 1992).

Loughlin and others (1984) conducted the first comprehensive review of population trends in Steller sea lions between 1956 and 1980. They found evidence for an increase in numbers

Table 4.11 Geographic and temporal distribution of samples used to determine the composition of Steller sea lion diets.

AREA	N	DATE	MAJOR PREY	SOURCE
Western Bering Sea	86	1981	Pollock	Calkins, cited in Lowry et al., 1989
Bering Sea/Aleutians	2	1949–51		Wilke and Kenyon, 1952
		1958–63		Fiscus and Baines, 1966
	10	1976		
	4	1990–91		Lowry et al., 1982
	16	1945–46	Atka mackerel	Merrick et al., 1993
	3			
		1958		
Gulf of Alaska	7			Imler and Sarber, 1947
	11	1959	Smelt, greenling, cephalopods	Mathinsen et al., 1962
	4	1958–63		
	56		Cephalopods, sand lance, rockfish	Thorsteinson and Lensink, 1962
	6	1985–86		Fiscus and Baines, 1966
		1945–46		
Southeast Alaska	15		Pollock, squid, herring	Calkins and Goodwin, 1988
	8			Imler and Sarber, 1947
	2			Fiscus and Baines, 1966
	14		Pollock	Calkins and Goodwin, 1988

<sup>a</sup> Major prey are listed only for samples of 15 or greater.

Source: Committee on the Bering Sea Ecosystem.

Table 4.12 Counts of adult and juvenile Steller sea lions at rookery and haulout sites in seven subareas of Alaska during June–July, 1975–92

Year	Southeast Alaska	Gulf of Alaska			Aleutian Islands		
		Eastern	Central	Western	Eastern	Central	Western
1975					19,769		
1976		7,053	24,678	8,311	19,743		
1977					19,195		
1979	6,376					36,632	14,011
1982	6,898						
1985			19,002	6,275	7,505	23,042	
1989	8,471	7,241	8,552		3,908	3,032	7,752
1990	7,629	5,444	7,050	3,915	3,801	7,988	2,327
1991	7,715	4,596	6,273	3,734	4,231	7,499	2,411
1992	7,558	3,738	5,721	3,720	4,839	6,399	2,869
Change 1975/79–1992	+19%	-47%	-77%	-55%	-76%	-83%	-80%

Source: Sease et al. (1993).

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in the central and western Aleutians, but for a large decrease in the eastern Aleutians, confirming the results of Braham et al. (1980). Loughlin et al. (1984) reported that both increases and decreases were evident in the Gulf of Alaska. The number of sea lions counted in surveys of the Kenai Peninsula to Kiska Island (i.e., the central and western Gulf of Alaska and the eastern and central Aleutian Islands) between 1985 and 1989 declined by 63 percent (Loughlin et al., 1990). In 1989, the range-wide population estimate of 116,000 was only about 39 to 48 percent of that estimated 30 years before (Loughlin et al., 1992). This documented decline resulted in a December 1990 listing of Steller sea lions as threatened under provisions of the Endangered Species Act (NMFS, 1992).

Based on these surveys, it appears that the numbers of sea lions initially began to decline in the eastern Aleutians and that this decline likely began by the early 1970s. A decline in counts of adult and juvenile sea lions had become apparent in the central Gulf of Alaska by the late 1970s and in the western Gulf of Alaska and the central Aleutians perhaps a few years later, by the early 1980s (Byrd, 1989; Merrick et al., 1987; NMFS, 1992; Trites and Larkin, 1992). Counts at rookeries in the central and western Aleutians showed considerable variation, but clear evidence of decline since the mid-1980s. Counts of pups confirmed that a major population decline occurred in this region (Sease et al., 1993). Although some authors differ regarding when these declines began, all agree the declines began later in the Gulf of Alaska and western and central Aleutians than in the eastern Aleutians.

In Russia, the situation is similar to that in the eastern Bering Sea and Gulf of Alaska, with the present abundance of sea lions much reduced from historical levels. According to Perlov (1991), in 1988–89 there were 13,800 to 16,300 animals counted in Kamchatka, the Kuril Islands, and the Okhotsk Sea, compared to 42,500 to 52,300 in the 1970s. Counts made in summer 1994 indicate that sea lion numbers have continued to decline in Kamchatka and the Kuril Islands. In the Komandorsky Islands, the number of animals breeding at the Medney Island rookery appears to be stable, but overall numbers have declined since 1989 (V. Burkanov, personal communication).

In contrast to the pattern of declining counts elsewhere, counts in the eastern Gulf of Alaska and southeast Alaska have been stable or increasing over the past two decades (NMFS, 1992; Trites and Larkin, 1992). Similarly, the number of Steller sea lions (both pups and older animals) in British Columbia has increased at about 2.5 percent per year between the early 1970s and 1992 (P. Olesiuk, personal communication).

There is little information on fluctuations in Steller sea lion numbers that may have occurred before 1960. Fluctuations in numbers that have been documented at the Pribilofs and in British Columbia and Oregon before the mid-1960s have all been explained as due to direct human exploitation (Bigg, 1985; Kenyon and Rice, 1961; Lyman, 1988). According to Kenyon (1962), Steller sea lions were very abundant in the Pribilof Islands when the islands were discovered in 1786, but they were soon overhunted. When they were afforded a measure of protection, numbers grew from a few hundred in 1914 to about 6,000 in 1960 (Kenyon, 1962). Bigg (1985) speculated that the number of animals in British Columbia may have been depressed in the early 1800s by the native hunt for meat and other products. Numbers were thought to have increased in the late 1800s when the level of native hunting was reduced. Sea lion pup production increased at a rate of 6.8 percent per year at Forrester Island, British Columbia, during 1961–73, a period when animals there were not exploited (Bigg, 1985).



## Northern Fur Seal

Northern fur seals breed on a few major rookeries in the North Pacific Ocean and range widely at sea during the nonbreeding season. Five stocks have been identified that breed on six island groups: (1) Komandorsky Islands, (2) Kuril Islands, (3) Robben Island, (4) Pribilof Islands and Bogoslof Island, and (5) San Miguel Island (NMFS, 1993a). Adults belonging to these stocks are for the most part geographically separated during the breeding season, but some interchange does occur. Rookeries on St. Paul and St. George islands in the Pribilof Islands account for over 70 percent of the world population.

A number of studies have been conducted on the diets of northern fur seals, beginning with the work of Lucas (1899). However, the most extensive study of northern fur seal diets is based on the pelagic sampling of over 18,000 fur seals between 1958 and 1974 (reanalyzed by Perez and Bigg, 1986). Of the fur seal stomachs collected, 7,373 contained food and an additional 3,326 had trace remains of food. These data showed marked seasonal and geographic variation in the species consumed. In the eastern Bering Sea, pollock, squid, and capelin accounted for about 70 percent of the energy intake by fur seals (Perez and Bigg, 1986). In contrast, sand lance, capelin, and herring were the most important prey in the Gulf of Alaska (Table 4.13). Since 1974, only three relatively small samples have been taken (in 1981, 1982, and 1985) to investigate fur seal diets. Analysis of these data showed that pollock and squid were the most frequently eaten prey in the eastern Bering Sea, and that there was a positive correlation between pollock year-class strength and the frequency of pollock in fur seal diets (Sinclair et al., 1994). No data are available for either region since 1985.

The abundance of northern fur seals has fluctuated greatly over the past 200 years, largely due to commercial harvesting (NMFS, 1993a). Excessive harvests reduced the number of fur seals in the Pribilof Islands, from an estimated 3 million animals in the 1867 to only 200,000 to 300,000 by 1910 (Kenyon et al., 1954; Lander and Kajimura, 1982). By the 1940s, the Pribilof population had recovered substantially, but, as the estimated number of seals approached 1.5 million, the growth rate of the population was reduced. Between 1956 and 1968, 315,000 male fur seals were killed in an attempt to increase productivity, and thus increase the size of commercial harvest (Chapman, 1961; Lander, 1980). The expected increase in productivity did not occur. Rather pup production on St. Paul Island declined by 7 percent per year from 1975 to 1983, and that on St. George Island declined by 6 percent per year from 1973 to 1990 (York, 1990). The size of the Pribilof Islands population peaked in about 1950 at over 2 million animals, but it has declined by over 50 percent since then (Table 4.14). The Pribilof Islands stock of fur seals was declared depleted under provisions of the Marine Mammal Protection Act in June 1988 (NMFS, 1993a).

Fur seal numbers on the Komandorsky Islands, Kuril Islands, and Robben Island (in the Sea of Okhotsk) were greatly reduced by the early 1900s (Lander and Kajimura, 1982). They increased in these areas through the mid-1960s (Vladimirov, 1991). By the late 1960s, pup production at Robben Island had begun to decline, and the decline has continued to the present (Yoshida and Baba, 1982). In 1989–90, the estimated Robben Island population of 60,000 was only about one-third as large as its maximum in 1967 (190,000) (Vladimirov, 1991). In contrast seal populations in the Komandorsky and Kuril islands have been comparatively stable. In 1988–1990 the Komandorsky Island population numbered 225,000 to 230,000, only slightly less than

Table 4.13 Geographic and temporal distribution of samples used to determine the composition of northern fur seal diets<sup>a</sup>

Area	n	Year	Major Prey	Source
Bering Sea	373	<1900	Pollock, squid	Lucas, 1899
	1749	1958–74	Pollock, squid, capelin	Perez and Bigg, 1986
	73	1981, 1982, 1985	Pollock, squid	Sinclair et al., 1993
Aleutians	309	1958–74	Sand lance, capelin, mackerel	Perez and Bigg, 1986
North Pacific	562	1958–74	Herring, anchovy, squid	Perez and Bigg, 1986
Gulf of Alaska	38	<1900	Rockfishes	Alexander, 1892
	36	<1900	Squids, rockfishes	Lucas, 1899
	12	1930s		May, 1937
	104	1950–51	Herring	Wilke and Kenyon, 1952
	1163	1958–74	Sand lance, capelin, herring	Perez and Bigg, 1986

<sup>a</sup> Major prey are listed only for samples of 15 or greater.

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its maximum of 255,000 in the late 1970s. In the Kuril Islands, the 1988 population estimate of 45,000 to 50,000 was about 20 percent lower than the 1977–78 peak of 60,000 (Vladimirov, 1991).

Table 4.14 Estimates of population abundance and pup production for northern fur seals on the Pribilof Islands

Year(s)	Stock size	Number of pups born
1949–1951	2,100,000	531,000
1970	1,200,000	306,000
1974	1,250,000	326,000
1983	877,000	198,000
1990	1,012,000	253,000

Source: NMFS (1993a).

With respect to newly colonized areas, northern fur seal pups were first born on San Miguel Island in 1968, and pup production increased to over 1,000 in 1982 (DeLong et al., 1991) on Bogoslof Island, pups were first noted in 1980 (Lloyd et al., 1981), and production has increased to more than 500 pups born in 1993 (NMFS, unpublished data).

Because they have been heavily exploited, there is little understanding of the frequency or magnitude of natural fluctuations in northern fur seal populations. When the Pribilof Islands population was recovering the overexploitation in the first half of this century, increased at about 8 percent per year, despite limited commercial harvests (NMFS, 1993a). By contrast previously depleted but currently unexploited stocks of antarctic (*Arctocephalus gazella*) and subantarctic (*A. tropicalis*) fur seals have been increasing at rates of about 15 percent per year (Croxall and Gentry, 1987). There is no information that can be used to estimate the likely rates of natural declines.

### Harbor Seal

Harbor seals occur in coastal waters of the North Pacific from Baja California through the Aleutian Islands to Japan. Within this broad range there may be two subspecies, *Phoca vitulina richardsi* in western North America and *P. v. stejnegeri* in eastern Asia (Shaughnessy and Fay, 1977). In the Bering Sea, harbor seals occur mostly south of areas affected by seasonal sea ice. To the north, they are replaced by a closely related species, the spotted seal.

There is relatively little known about the foods of harbor seals in the Bering Sea (Lowry et al., 1982), however, the existing data are summarized in [Table 4.15](#).

Abundance estimates of harbor seals in Alaska consist, for the most part, of single counts made at individual haulout sites (Hoover, 1988b). Surveys designed to estimate regional abundances and trends were begun in the mid-1970s, and counts have been made in Bristol Bay at intervals since then ([Table 4.16](#)). At sites along the Alaska Peninsula, recent counts are lower than in the mid-1970s, but if the high counts from 1975 and 1976 are discounted, the decline has not been dramatic. In contrast, it appears that the number of harbor seals using Nanvak Bay has decreased by more than 80 percent. Harbor seal numbers have also declined dramatically in the Gulf of Alaska at Tugidak Island and in Prince William Sound. At Tugidak Island, counts dropped by about 85 percent between 1976 and 1988 (Pitcher, 1990). In Prince William Sound, harbor seals have declined by an estimated 57 percent between 1984 and 1992 (Frost and Lowry, 1994). In southeast Alaska, seal numbers have been relatively stable since 1984 (J. Lewis, personal communication; Loughlin, 1994). Long-term records of harbor seal abundance in the North Pacific are not available. Heavy hunting pressure in the mid-1900s, often associated with bounty programs, very likely resulted in reduced harbor seal populations in some areas. Since harbor seals in British Columbia were protected from hunting in 1970, the population has grown at an average rate of about 12.5 percent per year (Olesiuk et al., 1990). In recent years, the numbers of harbor seals and California sea lions (*Zalophus californianus*) have increased greatly in California, Oregon, and Washington (Boveng, 1988a, 1988b).

### Baleen Whales

With the exception of the bowhead, all large whales of the Bering Sea and Gulf of Alaska are summer seasonal residents (Lowry et al. 1982). They winter in temperate waters of the North Pacific and migrate north to feed in summer. Feeding grounds correspond to locations where prey of the appropriate type are concentrated. For example, gray whales are often found in the northern Bering and Chukchi seas where the benthic infauna are particularly abundant (Highsmith and Coyle, 1992; Johnson and Nelson, 1984). A large number of blue, fin, sei, and humpback whales have been found in comparatively small areas with high concentrations of primary and secondary productivity (e.g., Nemoto, 1963). Currently, bowhead whales leave the Bering Sea in the summer and go to the eastern Beaufort Sea, where they apparently do most of their feeding (Lowry, 1993). However, before their decimation by commercial whalers, some bowheads spent the summer, and presumably fed, in the Bering and Chukchi seas.

Available data on the prey of baleen whales in the Bering Sea were reviewed in Frost and Lowry (1981a) and Lowry et al., (1982). In general, descriptions of diets come from studies conducted in conjunction with commercial whale harvests, and they may or may not reflect recent diets. Gray whales are unique in that they feed principally on several species of benthic gammarid amphipods. Right whales appear to have the most specialized feeding strategy. Studies conducted in the North Atlantic suggest that right whales require high densities of copepods concentrated in surface waters for effective feeding (Kenney et al., 1986; Mayo and Marx, 1990). Sei whales eat copepods and euphausiids, while blue whales eat primarily

Table 4.15 Geographic and temporal distribution of samples used to determine the composition of harbor seal diets<sup>a</sup>

Area	n	Year	Major Prey	Source
Bering Sea	6	1973		Lowry et al., 1979
	8	1979		Lowry et al., 1982
	19	1981	Sand lance, Smelt, sculpins	Lowry et al., 1982
	20	1985	Herring, capelin	L.F. Lowry, unpubl. data
	7	1954		Wilke, 1957
	11	1959–62		Kenyon, 1965
	17	1968–73	Shrimp, mysids, octopus	Burns and Gol'tsev, 1984
Gulf of Alaska	3	1972		Lowry et al., 1979
	67	1945–46	Eulachon	Imler and Sarber, 1947
	269	1973–78	Pollock, octopus, capelin	Pitcher, 1980
	99	1945–46	Pollock, herring, flatfishes	Imler and Sarber, 1945

<sup>a</sup> Major prey are listed only for samples of 15 or greater.

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Table 4.16 Counts of harbor seals in Bristol Bay

Year	North Side of Alaska Peninsula <sup>a</sup>	Nunivak Bay <sup>b</sup>
1975	17,245	2,918
1976	23,805	---
1977	12,584	---
1979	---	2,000
1981	---	3,100
1983	---	2,500
1985	11,728	---
1990	10,105	470
1991	10,192	400

<sup>a</sup> Sum of maximum counts at each of four haulouts made in June.

<sup>b</sup> Maximum count made in August-September.

Source: Sease (1992).

euphausiids. Fin whales, humpback whales, and minke whales have a more diverse diet, eating euphausiids as well as schooling fishes such as capelin, herring, and pollock.

Estimates of stock sizes of baleen whales (Table 4.17) refer to North Pacific (or eastern North Pacific) populations and do not represent the actual number of animals using the Bering Sea and Gulf of Alaska regions. Nonetheless, it is clear that baleen whales were once numerous in these regions, and with the exception of gray whales, their populations are now much smaller. Reliable estimates of the absolute former abundance of most species in the Bering Sea and Gulf of Alaska are lacking, but a sense of their initial stock sizes can be inferred from the numbers harvested. For example, between 1955 (when fin whales began to be heavily harvested in the Bering Sea) and 1970 (when they were rare) about 11,000 whales were killed. Between 1960 and 1967, an additional 4,000 were killed in the northern Gulf of Alaska, which virtually eliminated the species from that region as well. During the same intervals, about 5,000 sei whales were killed in the northern Gulf of Alaska, and about 1,500 blue and 3,300 humpback whales were killed in the northern Gulf of Alaska and Aleutian islands. An even greater slaughter of sperm whales occurred during this time, with some 26,000 animals taken from the Bering Sea alone (International Whaling Commission, unpublished data; Kasuya, 1991).

With the exception of gray and bowhead whales, for most species the current trend in population size in the Bering Sea and Gulf of Alaska region is uncertain. Gray whales have increased in numbers, and the current population size is about the same as that which probably existed before commercial whaling (Buckland et al., 1993). Surveys of whales in the Gulf of Alaska in 1980 indicated that populations of the other previously exploited species remained very depressed (Rice and Wolman, 1982). Although completely protected from commercial whaling since 1946, North Pacific right whales have shown no signs of recovery and are still extremely rare (Scarff, 1991). In contrast, the Bering-Chukchi-Beaufort stock of bowhead whales is now increasing, and the population may number one-half to one-third its former size (Zeh et al., 1993).

#### DISCUSSION OF POPULATION DECLINES

In the absence of significant human exploitation, the size of marine mammal populations can be expected to change over time in response to natural changes in the availability of resources and, in some cases, to changes in the physical environment. In general, marine mammal populations are thought to be food-limited (Estes, 1979), and therefore population changes are most likely to reflect changes in the amount of food available to individuals rather than a direct response to physical changes in the environment. Natural frequencies of population change will differ among different species or groups, but in marine mammals, like other large mammals, natural changes can be expected to occur on interdecadal time scales (Fowler and Smith, 1981). Pinnipeds and cetaceans are long-lived species, with delayed sexual maturity, low fecundity (i.e., single young), and high adult survival rates. These characteristics constrain the annual finite rate of increase of pinniped and cetacean populations to about 3 percent to 15 percent (Best, 1993; Cooper and Stewart, 1983; Lander and Kajimura, 1982; Olesiuk et al., 1990; Reilly and Barlow, 1986; Zwanenburg and Bowen, 1990). At these rates of increase, the potential doubling time of population size is about 5 to 23 years.

Table 4.17 Estimates of initial and current populations of exploited North Pacific baleen whales

Species	Stock	Stock Size		
		Initial	Current	Current % of Initial
Blue whale	North Pacific	4,900	1,600	33
Fin whale	North Pacific	<45,000	16,625	<37
Sei whale	North Pacific	40,000	9,110	23
Humpback whale	North Pacific	15,000	<2,000	13
Right whale	North Pacific	No est.	No est.	No est.
Bowhead whale	Western Arctic	18,000	7,800	43
Gray whale	E. North Pacific	<20,000	21,113	>100

Source: NMFS (1991b).

Although life history characteristics constrain marine mammals to low rates of population increase, the rate of population decline is not similarly constrained. Populations can decrease at rates that greatly exceed their rates of increase, even in the absence of hunting. The large and rapid reductions in harbor seal populations and several other species of marine mammals as a result of viral epizootics serve to illustrate this point (see review by Harwood and Hall, 1990). The recent mass mortality of harbor seals in Europe is particularly well documented. The first indications of this event occurred in February and March 1988, and by December of that year more than 18,000 carcasses had been reported. In the main areas affected by the virus, populations were reduced by 40 to 75 percent in less than one year (Heide-Jorgensen et al., 1992). The underlying cause of these deaths was a previously undescribed morbillivirus, now known as phocine distemper virus (Breuer et al., 1988; Kennedy et al., 1988; Osterhaus and Vedder, 1988).

In the absence of a major disease event, however, marine mammal populations do not normally decline rapidly, because they have life history traits that tend to dampen the influence of factors that might negatively affect population size (Estes, 1979). For example, relatively short-term changes in climate, such as El Niño Southern Oscillation (ENSO) events, are known to have widespread effects on marine ecosystems (Trillmich and Ono, 1991). Reduction in the availability of prey resulting from ENSO events causes increased pup and juvenile mortality and reduced adult survival in some pinniped populations (Trillmich and Ono, 1991). Reduced productivity for one of two years has had relatively little overall effect, however, because of the typically high adult survival rates and the large number of age classes in the population.

Few marine mammal populations have been monitored for long periods. In most cases, the longest time series have been obtained for commercially exploited species, and in cases where populations are no longer harvested, there are data only on the recovery phase (e.g., Cooper and Stewart, 1983; Zwanenburg and Bowen, 1990). As a result, there is little information on natural frequencies or amplitudes of population change. Testa and others (1991) reported quasi-cyclic patterns in three species of antarctic pinnipeds over a period of about 20 years, suggesting changes in productivity separated by four-to-six-year intervals. They speculated that these changes might be associated with large-scale oceanographic variations. Although these data point to the possibility of relatively high-frequency change in some systems, neither the rate of change nor the magnitude of the effects on population size is known.

Because marine mammal population sizes fluctuate over time, can it be determined whether an observed decline is unusual and should be of concern? An unusual decline could simply be one that is encountered infrequently. In this sense, the population changes caused by recent viral epizootics in regions other than the Bering Sea would constitute unusual declines. In this and similar situations, however, the underlying causes of the declines are reasonably clear and thus they are not unusual in the sense of being unexplained changes. Some southern elephant seal populations have been declining at a rate of about 2 to 5 percent per year for periods of up to 40 years with no direct exploitation. These changes have been described as drastic, in that populations have declined by more than 50 percent in less than three generations (Hindell and Burton, 1987). By such criteria, the observed declines in the numbers of Steller sea lions, northern fur seals, and harbor seals in the Bering Sea and Gulf of Alaska have also been "drastic." In describing these declines in this way, there is the clear implication that in light of existing knowledge, the nature of these declines is cause for concern.

For the Bering Sea and Gulf of Alaska, it is the broad-scale, large, and sustained nature of the declines in some pinniped populations that is thought to be unusual. In part, these declines seem unusual because the same species are stable or increasing in numbers in other parts of their range in the North Pacific. Regardless of what terms are used to describe the recent declines of Bering Sea and Gulf of Alaska pinnipeds, given the lack of data on natural frequencies of population change, it will be difficult to distinguish between human- and nonhuman-induced population changes, and even more difficult to attribute causation.

Declines in the number of Steller sea lions have occurred over most of the species range in the Bering Sea and west-central Gulf of Alaska, but not in the eastern Gulf of Alaska and southeastern Alaska or in British Columbia. In the case of harbor seals, the decline in numbers is well documented only in the Prince William Sound and Kodiak regions of the Gulf of Alaska, whereas numbers are clearly increasing in British Columbia. The number of fur seal pups born on St. Paul Island declined until 1983 but has been stable over the past decade, while the decline in pup production on St. George Island has continued. The number of fur seals born on Robben Island in the Sea of Okhotsk has been declining since the late 1960s, but pup production at the Komandorsky and Kuril islands has been relatively stable.

For each of these species, then, understanding why numbers in some regions are declining while others are not could provide important clues about the causes of the declines. This comparative approach could be extended to ask whether species in the Bering Sea and Gulf of Alaska other than fur seals, sea lions, and harbor seals have shown similar changes in abundance. Although population trends in ice-breeding seals of the northern Bering Sea and cetaceans in the Bering Sea and Gulf of Alaska are poorly known, it is clear that not all species are declining or failing to recover from overexploitation. Gray whales, walruses, and sea otters have recovered from drastic reductions caused by hunting, and their populations now appear to be relatively stable. Bowhead whales are increasing at about the rate that would be expected for such a population. It is perhaps significant that these mammals are not linked to the pelagic food web of the Bering Sea and Gulf of Alaska. Gray whales, walruses, and sea otters feed mostly on benthic organisms, while bowhead whales feed principally in the Beaufort and Chukchi seas.

On the other hand, whale populations that do not seem to be recovering rapidly from depletion (e.g., right, blue, fin, sei, and humpback) are those that feed on zooplankton and/or small fishes. However, the apparent failure of most Bering Sea and Gulf of Alaska whales to increase after hunting was stopped may be something of an artifact of poor monitoring, because there have been relatively few comprehensive and dedicated survey efforts. The few surveys that have been carried out (e.g., Brueggeman et al., 1984; Rice and Wolman, 1982), however, have not detected substantial increases. It is also possible that for some of the species harvested more recently, not enough time has elapsed for significant increases to have occurred. To the extent that significant recovery has not occurred, it appears that the Bering Sea situation is unusual. Best (1993) compiled data from severely depleted whale stocks worldwide and concluded that at least 77 percent of all monitorable stocks are either believed or known to be increasing. Included among those increasing are several stocks of right whales in the southern hemisphere, which is marked contrast to the situation for right whales in the Bering Sea and Gulf of Alaska. Although there is no good estimate of stock size for North Pacific right whales, it is clear that they are rare. Scarff (1991) stated that Japanese scouting boats operating in the North Pacific during 1965 to 1979 saw only one right whale per 14,000 miles of searching

effort. Brueggeman et al. (1984) saw only two in more than 5,000 nautical miles of dedicated survey effort from ships and aircraft in the Bering Sea during 1982.

The three species of pinnipeds that have declined in abundance feed largely on forage fishes and commercially exploited species in the northern Gulf of Alaska, Bering Sea, and Aleutian Islands. When Lowry and Frost (1985) examined the information available on population biology and feeding of Bering Sea marine mammals, they concluded that three species overlapped significantly in the foods they prey on and commercial fisheries. The species were northern fur seals, Steller sea lions, and harbor seals.

Based on first principles, a population that is not subject to immigration or emigration will decline only when the number of deaths exceeds the number of births. Therefore, changes in population parameters, at least in U.S. waters, must have occurred such that fecundity has declined, mortality has increased, or both. It is therefore important to understand what parameters have changed before trying to explain what has caused the changes.

Population modeling is a useful tool for examining how changes in various parameters may affect population trends. For example, York (1994) modeled the population dynamics of Steller sea lions at Marmot Island, where numbers had declined about 5 percent per year between 1975 and 1985 (Merrick et al., 1992). She concluded that a 10 to 20 percent decrease in the survival of juveniles (i.e., from birth to age three) was most consistent with the changes in demographic data observed over the period. While these results are useful for suggesting which population parameters may have changed and for estimating minimum levels of change, they are based on only two samples taken in one area and therefore cannot be considered an adequate basis for drawing firm conclusions about the widespread declines.

There is other support for the conclusion that juvenile survival has been low in Steller sea lions. In 1987 and 1988, 424 female and 376 male pups were marked on Marmot Island in the Gulf of Alaska. During the summers of 1991 to 1993, the rookery was examined for the return of marked females and only 14 were seen—far fewer than expected based on previously estimated survival curves and age-specific pregnancy rates (R. Merrick, personal communication).

These results suggest either very low survival or significant movement to other rookeries. However, none of the marked females was sighted at other rookeries and only one was seen at a different haulout site (R. Merrick, personal communication). It will be important to continue monitoring the sea lions in this study to confirm the early results, which suggest low survivorship.

Two studies measured population parameters of Steller sea lions in the Gulf of Alaska during 1975 to 1978 (Calkins and Pitcher, 1982) and 1985 to 1986 (Calkins and Goodwin, 1988). Results indicated late-term pregnancy rates of 60 to 67 percent, lower than for other otariid species. For example, the pregnancy rate of cape fur seals (*Arctocephalus pusillus*) over age 5 is 83 percent (Butterworth and Wickens, 1990) and that of 8 to 13-year-old northern fur seals varies from about 80 to 95 percent (Trites and York, 1993). Although there was a small decline in estimated pregnancy rate from the 1970s to the 1980s, the change was not statistically significant. Thus, it is possible that the pregnancy rate of Steller sea lions was depressed even in the 1970s (Calkins and Goodwin, 1988). Because it is not certain that these rates are below normal (there are no estimates from populations that have not declined), it is difficult to know whether low pregnancy rates are contributing to the population decline. Despite these



uncertainties, a population with low birth rates is clearly more sensitive to small changes in mortality than it would be otherwise.

A number of explanations have been advanced to explain the recent declines (i.e., those since about 1980) in the numbers of fur seals, sea lions and harbor seals. These are discussed in Alverson (1992), Anonymous (1993), Calkins and Goodwin (1988), Hoover (1988a, 1988b), Loughlin (1987), Loughlin and others (1984), NMFS (1992), Pascual and Adkinson (1994), and Sease (1992). Most of the proposed causes have been rejected by previous workers. The committee's assessment of the likelihood that each proposed cause has been a significant factor is given in [Table 4.18](#). In some cases, there are insufficient data to reasonably evaluate a factor as a cause; in other cases, data are not available at the appropriate temporal and spatial scales. Although available data are not adequate to critically evaluate alternative explanations for the declines, it seems unlikely that a single factor has been responsible for the declines in all species and over all time periods and areas. More likely, several factors are responsible for the declines, the combination of which and their relative importance may have varied over time and by species. The remainder of this section discusses those causes that have been proposed, with particular attention to those that appear most influential. The committee found that, with the exception of food, the various identified potential causes are not believed to play a major role in marine mammal declines.

### Disease

Although capable of causing population declines (e.g., Heide-Jorgensen et al., 1992), increased mortality due to disease is not thought to have been a major factor in the observed declines of pinnipeds in the eastern Bering Sea/Gulf of Alaska area (Calkins and Goodwin, 1988; NMFS, 1992; Sease, 1992). However, the importance of disease as a factor in the declines is currently difficult to evaluate because there are no estimates of trends in disease-related deaths in these species. Monitoring disease at breeding colonies or major haulout sites is possible, but would be prohibitively costly and would likely not be very productive, especially if most mortality is occurring at sea.

### Pollution

Chemical pollutants can negatively affect pinnipeds in a number of ways (Reijnders et al., 1993). However, there is little evidence that chemical pollution has been a significant factor in the recent populations declines (Hoover, 1988a, 1988b; NMFS, 1992). One exception to this is the Exxon Valdez oil spill, which resulted in some mortality of seals in the Prince William Sound area (Frost and Lowry, 1994).

Table 4.18 Committee's assessment of potential causes of recent declines in abundance of fur seals, sea lions, and harbor seals in the eastern Bering Sea and Gulf of Alaska

Cause	Likelihood of Involvement in Declines since 1980			Comment
	Fur Seal	Sea Lion	Harbor Seal	
Disease	Low	Low	Low	Few data, but no evidence of increased effects that could explain declines
Chemical pollution	Low	Low	Low	Few data; levels low relative to known effects in other populations
Entanglement	Moderate	Low	Low	Could only have been a contributing factor in the fur seal declines
Harassment	Low	Low	Low	Local effects only; not important for the geographic scale over which the declines have occurred
Commercial harvest	Low	Low	Low	Could not explain observed declines beyond the mid 1970s
Subsistence harvest	Low	Low	Low	Not a factor in the widespread declines
Incidental take	Moderate	Moderate	Low	Contributed to the declines, but not a major factor; cannot explain continued declines
Predation	Low	Low	Low	Few data; could not explain the declines, but may affect recoveries
Direct climate effects on survival	Low	Low	Low	Cannot explain the declines
Fishery effects on food availability	Moderate	High	High	Could have played a major role in all declines
Climate effects on food availability	Moderate	Moderate	Moderate	Could have played a role in all declines
Competition from fish predators	Moderate	Moderate	Moderate	Could be a major factor in the declines, given observed changes in community structure that were most likely caused by commercial fishing and environmental changes

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### Entanglements

Fowler (1987) concluded that entanglement of juvenile fur seals in trawl net fragments could account for the decline in the Pribilof population. However, Trites (1992) examined the evidence supporting the entanglement hypothesis and concluded that while large numbers of fur seals have no doubt died in lost and discarded fishing gear, it is unlikely that entanglement has been the major cause of the decline. Steller sea lions also become entangled in packing bands and net fragments, but available data indicate that entangled adults are rarely seen, and entanglement rates of pups and juveniles appear to be even lower than those observed for adults (Loughlin et al., 1986). Based on the admittedly limited data, it is unlikely that entanglement in debris is a major factor in the decline of this species (NMFS, 1992). Entanglement of harbor seals in lost or discarded net fragments has not been observed at Tugidak Island (Pitcher, 1990), the site of the most dramatic decline in numbers, or in the Aleutian Islands (Loughlin et al., 1986).

### Human Disturbance and Takings

Human disturbance of rookeries and haulout sites can have negative effects on pinnipeds (see review by Reijnders et al., 1993). The sites used by pinnipeds in the Bering Sea and Gulf of Alaska are generally in areas that are relatively remote or are protected from human activities. Direct human taking of marine mammals is now limited almost exclusively to subsistence hunting and to incidental kills by commercial fisheries. Based on the results of a simulation model, Trites and Larkin (1992) concluded that direct kills of sea lions in commercial harvests reduced some rookeries and may have stabilized the number of sea lions breeding in the Gulf of Alaska and Aleutian Islands. The commercial harvests, coupled with subsistence harvests and intentional and incidental kills by fisheries, would have had some depressing impact on the population up to about 1980. However, the model indicated that since 1980 over 10,000 sea lions per year were disappearing from the population, and even the highest estimates of fishery kills could not account for these missing animals (Trites and Larkin, 1992). Based on simulation modeling, Pascual and Adkinson (1994) concluded that the observed declines were unlikely to be the result of pup harvests. Merrick et al. (1987) came to the same conclusion.

Population declines in northern fur seals of greater magnitude than those observed recently have occurred in the past century at the Pribilof Islands, as a result of commercial overexploitation (Kenyon et al., 1954). The recent decline in pup production at the Pribilof Islands from the mid-1950s to about 1970 can reasonably be explained by the commercial harvesting of adult females between 1956 and 1968 and a series of years of poor juvenile survival (Eberhardt, 1981; Trites and Larkin, 1989; York and Hartley, 1981). The reason for this poor juvenile survival is not known. The continued decline through the early 1980s at St. Paul Island and to the present at St. George Island cannot be explained by the commercial harvest of juvenile males that occurred until 1985 on St. Paul and until 1972 on St. George.

While the data collected by fishery monitoring programs are incomplete, it is unlikely that incidental takes of fur seals have been large enough to be a significant factor in the population decline (NMFS, 1993a).

Subsistence harvests of harbor seals in the Aleutian Islands and south-central and southeastern Alaska in the late 1960s were estimated to be roughly 5,000 annually (Hoover, 1988a). Approximately 4,000 phocid seals, including an unknown number of harbor seals, were also taken in Bristol Bay and the Yukon-Kuskokwim region (Hickok, 1978, cited Hoover, 1988). Since 1972, subsistence takes appear to be lower, and probably do not exceed 3,000 per year (Hoover, 1988a; Pitcher, 1984; Wolfe, 1993). It is unclear whether recent subsistence harvests had a local effect in recent declines in seal numbers. Bounty harvests in Alaska varied from about 6,000 to 24,000 seals annually between the 1930s and 1950s. A commercial harvest that developed during the 1960s had peak harvests of between 40,000 and 60,000 seals annually, and by 1967 harvest stabilized at 8,000 to 10,000 annually. Commercial harvesting ended in 1972 (see review in Hoover, 1988a). The influence of these harvests on population size is not known, but their effect on population trend should have ended by the late 1970s. The decline of harbor seals at Tugidak Island began in the mid-1960s and was influenced by commercial harvests, mainly of pups, between 1964 and 1972. However, the population continued to decline in the absence of commercial harvests, and after the effect of the harvests would have passed through the age structure of the population (Pitcher, 1990). The continued decline of harbor seals at Tugidak Island cannot be explained by the harvest history of this population.

There are no estimates of the total number of harbor seals killed as a result of fishing operations (Sease, 1992). Recent observer and logbook data suggest that a minimum of several hundred harbor seals were killed as a result of encounters with fishing operations (Sease, 1992). Possible local or regional effects of these takes on harbor seal numbers are unknown.

### Predation

Killer whales and sharks are probably the only significant natural predators of the pinnipeds whose populations have declined. While sharks are known to be major predators of pinnipeds in some other areas (e.g., Ainley et al., 1985; Brodie and Beck, 1983), such interactions appear to be rare in the Gulf of Alaska and Bering Sea. Predation on pinnipeds by killer whales has been documented in the Bering Sea, and there have been some recent changes in killer whale activities (Frost et al., 1992). Although there are no estimates of total predation mortality on Bering Sea/Gulf of Alaska pinnipeds, it is unlikely that increased predation could account for the declines, particularly the widespread declines in Steller sea lions (NMFS, 1992). However, predation could have some effect on the recovery of the currently reduced populations.

### Direct Climate Effects on Survival

The possible direct effects of weather on pinniped survival are poorly known. Scheffer (1981) reported large numbers of dead northern fur seal pups on the Oregon and Washington coasts after a period of severe storms. LeBoeuf and Condit (1983) documented significant mortality in young northern elephant seals as a result of storm-driven waves. Studies on captive animals have shown that California sea lions cannot rely on physiological mechanisms alone to avoid hyperthermia at air temperatures above 22°C (Whittow et al., 1972; Whittow, 1987). A

number of pinniped species are known to alter behavior to avoid thermal stress which could result in increased mortality, particularly in pups (e.g., Francis and Boness, 1991; Gentry, 1973; Heath, 1989; Limberger et al., 1986). However, species such as the northern fur seal and Steller sea lion can tolerate a wide range of environments from the cool, wet summers that occur in the Bering Sea to the hot, dry summers of southern California.

Several approaches have been used to study the direct effects of climate on the survival of northern fur seals. Trites (1990) used a physiological model to investigate the weather conditions that pups can tolerate during the first week of life on land. The results of this work indicate that healthy, average-sized pups on the Pribilofs can tolerate any combination of wind speed, temperature, and humidity recorded since the mid-1950s. However, the model suggested that pups of low birth weight could have reduced survival during periods of cold, wet, and windy weather. Overall, these results suggest that direct effects of weather are unlikely to cause increased pup mortality in northern fur seals, or in the larger, newborn Steller sea lions and harbor seals, during their time on land.

However, as Trites (1990) and others have noted, a second critical stage in juvenile survival is the transition from land to the sea. Survival of male northern fur seals from weaning to two years of age is only about 40 percent, with most deaths thought to occur in the first winter (Lander, 1979). As water conducts heat 25 times more effectively than air, thermoregulation is energetically more costly for young pinnipeds when they are at sea. York et al. (in press) used cross-correlation analysis to investigate possible relationships among juvenile (i.e., less than two years of age) northern fur seal survival and air and sea surface temperatures. Although estimates of early survival on land and at sea were significantly correlated with the environmental indices, the pattern of correlations did not provide convincing clues about the underlying mechanisms. In general, the analysis suggested that environmental conditions had a greater influence on survival at sea than on land. These results are consistent with the results of physiological modeling and observations that young northern fur seals appear to have difficulty in maintaining body temperature at low seawater temperatures (Trites, 1990). Pups lose almost 50 percent of their body mass during the first winter at sea (Scheffer, 1981). Thus, there is some reason to believe that changes in ocean temperature could affect survival of young pinnipeds.

Climate events, such as El Niño, can have marked effects on pinniped populations, which are mediated through impacts on the availability of food (Trillmich and Ono, 1991). The 1982–83 El Niño event produced drastic changes in the marine environment off the west coast of North America, and detailed studies were done to document the effects on some species of pinnipeds (Trillmich and Ono, 1991). El Niño had a measurable effect on California sea lion pup production and growth rates in southern California (DeLong et al., 1991). However, the result was only a pause in the long-term pattern of population growth, and this pause was compensated for by a faster rate of increase in pup production after the El Niño than before (Boveng, 1988a). A study that compared effects of the 1973, 1983, and 1992 El Niño events on Steller sea lions at Año Nuevo Island concluded that there was some indication of limited prey availability in 1992 (Hood et al., 1993). Simulation models indicate that short-term stochastic environmental fluctuations have very likely not been responsible for the recent sea lion decline (Pascual and Adkinson, 1994).

### Life History Patterns

Pinniped reproductive and foraging strategies are constrained by the need to give birth on land or ice and to obtain food from the sea (Bartholomew, 1970). Pinnipeds must also seek a solid substrate during the annual molt of their pelage, and they may haulout at other times of the year as well. This dependence on land can result in a spatial and temporal separation between seals and their food (Bartholomew, 1970). The extent of this separation is likely to vary seasonally, and to affect males and females of different ages in different ways. Thus, the effect of changes in food availability is most likely a complex function of many factors, including the age and sex of the individual and the season.

Of the three pinniped species known to have declined in abundance, two are members of the family Otariidae (northern fur seal and Steller sea lion), and one is a member of the family Phocidae (harbor seal). These two groups have very different maternal reproductive strategies: otariids exhibit a "foraging cycle strategy," whereas phocids typically exhibit a "fasting strategy" (see reviews in Bonner, 1984; Costa, 1991). The foraging cycle strategy of otariids is characterized by females having moderate energy stores on arrival at the rookery that are used to support maternal and offspring requirements during a short perinatal fast (Costa et al., 1988). This is followed by regular feeding trips at sea alternating with brief visits to the rookery to nurse young over a period lasting from four months to more than a year. Thus, there is a long period of maternal care during which the foraging success of mothers has direct consequences for the growth and survival of offspring. In contrast, when the larger phocid species give birth, they have large maternal energy stores that are sufficient to support maternal maintenance and the cost of lactation over a 4- to 50-day nursing period (Bowen, 1991; Oftedal et al., 1987). This strategy reduces the reliance of females on food availability during the period of maternal care. Although the harbor seal is a phocid, recent studies have shown that females are not large enough to store sufficient reserves to support the energetic cost of lactation, and thus they need to supplement energy stores by beginning to feed after a perinatal fast of about one week (Boness et al., 1994; Bowen et al., 1992). Therefore, as for both northern fur seals and Steller sea lions, the growth and survival of harbor seal pups is likely to be affected by the foraging success of females during the lactation period.

Adult male otariids are typically much larger than adult females, and as a result they have greater daily energy requirements, and perhaps larger and/or different forage areas, than females (French et al., 1989; Stewart and DeLong, 1993). Harbor seal adults of both sexes are similar in size and thus might be expected to have similar foraging ranges. Adult male otariids establish and defend territories on rookeries and do not feed for several weeks during the breeding season. The breeding biology of harbor seals is poorly known, but male seals spend much of their time in the water during the breeding season, and they therefore are not precluded from feeding.

Distribution patterns may also influence the response of pinnipeds to food limitation. Northern fur seals that pup and breed in the Bering Sea undertake an annual migration that takes them out of the area, whereas both Steller sea lions and harbor seals are year-round residents of the Bering Sea and Gulf of Alaska. Thus, the population dynamics of northern fur seals will be influenced by events that occur both in the Bering Sea and elsewhere in the North Pacific. Steller sea lions and harbor seals, on the other hand, are more likely to be affected by regional conditions.



## Food

### Fishery Effects on Pinniped Foods

The key to understanding the effects of fisheries on pinniped populations most likely lies in understanding the spatial and temporal scales that are critical to the nutrition of individual animals. Normal growth and survival of individuals depends on minimum levels of resources being available at a particular times and places, and not on mean abundance of those resources over some large area such as the eastern Bering Sea. Thus, determining that the mean abundance of food at large spatial scales, as is typical in fishery resource assessments, is likely to be at or above the requirements of a pinniped population may be not only uninformative but in fact misleading. Pinnipeds and modern offshore fishing fleets differ greatly in their abilities to determine the distribution and abundance of fishes in the ocean, and to capture them. To date, there has been inadequate attention to the importance of scales in the analysis of nutritional requirements of pinnipeds in the Bering Sea and Gulf of Alaska.

After reviewing the available information on the temporal and spatial pattern of declines in Steller sea lions and harbor seals, and the pattern of fishing in areas that are thought to be important feeding locations for these species, one can hardly avoid the conclusion that the removal of fish biomass from these areas has in some way contributed to the declines, at least on localized bases. Analysis of the distribution of fishing effort in the Gulf of Alaska led NMFS to the same conclusion (Fritz, 1993b). The exact nature of these fishery effects cannot be determined from the sparse available data. However, they likely include the direct effects of reduced biomass of prey needed by pinnipeds and indirect effects on community structure that may have resulted in reduced availability of alternative prey (see [Chapter 6](#)).

A recognition of the importance of considering scale with respect to food requirements of Steller sea lions is reflected in the establishment, in 1992, of fishing exclusion zones around important Steller sea lion rookeries. As stated by Fritz (1993b), "NMFS concluded that spatial and temporal concentration of trawl fishing for pollock in the 1980s could have contributed to the decline in the sea lion population." Thus, year-round exclusion zones of 10 nautical miles were placed around 37 sea lion rookeries, and zones of 20 nautical miles were established around 6 rookeries in the eastern and central Aleutians from January 1 to April 15 during the pollock roe season (Fritz, 1993).

It is premature to attempt an evaluation of the effects of these exclusion zones on Steller sea lion population trends in these areas. However, it may be useful to consider the following points. First, it is unfortunate that these exclusion zones are not being designed and used in an experimental way to ensure that maximum knowledge is derived from their use. With the current approach, it will likely be impossible to determine whether changes in sea lion populations are a response to these zones or to changes in other factors. Second, recent work on the distribution of foraging (Merrick and Loughlin, 1993) suggests that these exclusion zones may be too small to effectively separate the local effects of trawlers on sea lion prey from foraging sea lions.

### Diets and Food Limitation

A reasonable understanding of the composition of diets is necessary to determine how populations satisfy their energy requirements and whether or not they are limited by food availability. It is difficult to accurately describe pinniped diets for a number of reasons, however. Pinnipeds spend much of the year at sea, where it is costly or impossible to observe them. Prey size and species composition of the diets are usually derived from fish otoliths and other hard structures recovered from stomach contents or feces, but such analyses can result in a biased view of prey consumption (Dellinger and Trillmich, 1988; Harvey, 1989; Jobling, 1987; Jobling and Breiby, 1986; Murie and Lavigne, 1985). For wide-ranging species, data collected at or near coastal haulout sites may not adequately represent prey consumed offshore (Bowen et al., 1993). Diets may also differ seasonally and throughout the geographic distribution of the species. Finally, diet composition of pinnipeds may vary in response to both the absolute and the relative availability of the prey (e.g., Bailey and Ainley, 1982; Sinclair et al., 1994). In addition to these inherent limitations, dietary information for eastern Bering Sea and Gulf of Alaska pinnipeds suffers from irregular and inadequate sampling, especially in recent years (see reviews in Lowry et al., 1982, 1989).

Available data on the diets of Steller sea lions, northern fur seals, and harbor seals are summarized in Tables 4.9, 4.11, and 4.13. There is some evidence to suggest that Steller sea lions diet had changed over time, with pollock becoming a more important food in mid 1970 and mid 1980 samples (Calkins and Goodwin, 1988). Calkins and Goodwin also indicate that pups consume somewhat smaller pollock than older animals, and it is likely that the proportion of small pollock in their diet increased in the 1980s (Merrick and Calkins, in press). However, sample sizes in most of these studies are too small to provide much confidence in such conclusions. Furthermore, few data are available through the 1980s to address the question of changes in diet. Considerably more is known about the diet of northern fur seals, but even here there is little recent information. Our knowledge of diets of harbor seals in the Bering Sea is scanty, and the good studies in the Gulf of Alaska are more than 20 years old. Thus, even if food is limiting, it seems clear from the above analysis that we will not find evidence for this by examining trends in the species composition of the diets of any of these species. Data suitable for such an analysis simply do not exist.

### Other Evidence of Food Limitation

The "Is It Food?" workshop (Anonymous, 1993) considered a number of demographic, behavioral, and physiological responses that might be taken as evidence of there being insufficient food to meet the energy requirements of declining pinniped populations in the Bering Sea and Gulf of Alaska. Following that approach, those that the committee considered might be particularly informative with respect to the food limitation hypothesis are listed in Table 4.19. Individually, these responses would be consistent with a number of alternative hypotheses and would not in themselves allow the conclusion that food limitation was responsible for the responses. However, the combinations of these responses, together with information on other potential sources of morbidity or mortality (i.e., pollutants, parasites, and disease), could

provide more convincing evidence that food was indeed limiting. For example, reduced fecundity could be a result of food limitation, but it could also result from ingestion of high levels of polychlorinated biphenyls, chemicals that are known to cause reproductive failure (Reijnders, 1986). However, in the absence of certain levels of pollutants or other agents known to cause reproductive pathology, we are more likely to conclude that food limitation was responsible for reduced fecundity. The evidence concerning food limitation for three species of pinnipeds is discussed below.

### Northern Fur Seals

The northern fur seal is mainly a summer resident of the Bering Sea. After the breeding season all age groups undertake migrations which take them, for the most part, to other areas of the North Pacific (see review in French et al., 1989). In general, rapid growth or fattening occurs during a one-to-three month period before the seals arrive on the Pribilof Islands in July. During the rest of the year, fur seals gradually lose body mass and condition (Trites and Bigg, 1992). Although fur seals do feed in the Bering Sea, there is no evidence to suggest that food is limited in that area. In fact, available data suggest that during the fourth-month lactation period, a time of high energy expenditure, adult female foraging trips were shorter during the 1980s, which could indicate that food was relatively more abundant, or that food was closer to the Pribilof Islands than it was earlier (Loughlin et al., 1987). Pup body mass at two months of age has also increased over time, suggesting an increase in food availability for lactating females (Fowler, 1990). The size of juveniles returning to the Pribilof Islands has also increased in recent years (Baker and Fowler, 1992). All of these observations have been interpreted as density-dependent responses to reduced competition for food (Fowler, 1990). Furthermore, since 1984 pup production on St. Paul, where most pups at the Pribilof Islands are born, has been relatively stable (York, 1990), suggesting an improvement in survival and/or reproductive rates.

Recent studies indicate that pups generally leave the Bering Sea within two weeks of weaning (Ragan et al., 1993), such that they are reliant on food resources in the eastern Bering Sea for only a brief period. It has been suggested that low availability of food in the Aleutians could compromise pups as they leave the Bering Sea (Trites, 1992). At present, there are no data to support this speculation, which stems from the temporal correspondence between the rapid development of commercial fisheries in the early 1970s and the "unexplained" continued decline of the fur seal population. It is also possible that large-scale changes in ocean climate have reduced winter food availability in areas of the North Pacific outside of the eastern Bering Sea, through effects on either prey population abundance or distribution. Large-scale changes in the environment are known to have occurred in the North Pacific (see Chapters 3 and 4). However, it is not possible to directly relate these changes to the survival of fur seal juveniles.

Table 4.19 Demographic, behavioral, and physiological responses that could indicate food limitation in pinnipeds

Factor Expected to Change	Observed Change		
	Northern Fur Seal	Steller Sea Lion	Harbor Seal
Lower birth mass	Unknown	No change	Unknown
Reduced growth rate	Increased	Reduced	Unknown
Reduced body condition	Increased	Reduced	Unknown
Reduced milk production/intake	Unknown	Unknown	Unknown
Increased foraging trip duration	Decreased	No change	Unknown
Reduced weaning mass	Increased	No change	Unknown
Reduced juvenile survival	Reduced	Inferred	Unknown
Increased age at first birth	Unknown	Maybe	Unknown
Decreased birth rate	Unknown	Maybe	Unknown
Reduced adult survival	Inferred	Inferred	Unknown

Source: Committee on the Bering Sea Ecosystem.

### Steller Sea Lions

Two lines of evidence have been used to support the hypothesis that food limitation may be responsible for the population decline of Steller sea lions. Calkins and Goodwin (1988) compared size-at-age data for sea lions in the Kodiak area in 1985–86 with similar data for animals collected during 1975–78 (Calkins and Pitcher, 1982). They found that sea lions 1 to 10 years old were shorter and leaner and weighed less in the 1980s than those examined during the 1970s. With the declining trend in population size over this period, a density-dependent increase in size at age should have occurred if the overall amount of food available for sea lions had remained constant. The decreased growth rates suggest that food availability must have declined more than population size. Although this conclusion appears to be warranted, it is important to remember that it is based on limited data from only one area where sea lions have declined. Similar comparisons have not been made in southeast Alaska where the sea lion population has increased.

The second line of evidence indicating nutritional stress was a reduction in hemoglobin levels in seal lions examined during the 1980s compared to those sampled in the 1970s (Calkins and Goodwin, 1988). Hemoglobin level is a useful indicator of anemia, dehydration, or iron deficiency (Bossart and Dierauf, 1990). However, the mean levels measured in Steller sea lions in both periods are well within normal ranges reported for several other otariid species (Bossart and Dierauf, 1990) and for Steller sea lion pups two to three weeks of age (Castellini et al.,

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1993). Although the normal range of erythrocyte indices has not been established for Steller sea lions, the suggestion that sea lions in the 1980s sample were anemic is equivocal.

The hypothesis that reduced survival of juveniles may be the cause of the population decline (York, 1994) is attractive because recent studies have shown that weaned pups have limited foraging abilities compared to older sea lions (Merrick and Loughlin, 1993). Using satellite-linked, time-depth recorders, Merrick and Loughlin (1993) studied the foraging ranges and diving behavior of 19 adult female sea lions and 5 pups. They found that during the summer adult females with pups generally foraged within 20 km of land, made brief trips of less than two day's duration, and dived to depths of 830 m. In winter, some females traveled over 300 km offshore for up to several months and often dived to >250 m. Pups, on the other hand, were able to cover more than 300 km in a trip but their dives were generally brief (less than 1 minute) and shallow (less than 20 m). These preliminary results suggest that pups may rely heavily on prey near the surface, and that small changes in prey abundance in near-surface waters may have large effects on pup foraging success and thus on pup survival. There is also evidence that, like other pinnipeds, sea lion pups consume smaller prey than those taken by older sea lions (Merrick and Calkins, in press; Lowry et al., 1989). This may further constrain the array of prey available to pups compared to older animals.

Based on studies on other pinniped species (e.g., Costa et al., 1989); Trillmich and Ono, 1991), one would expect changes in the availability of food to be reflected in the foraging behavior of lactating female sea lions and the growth and behavior of their suckling offspring. However, when Davis et al. (1993); Merrick et al. (1995) compared data for a declining population at Chirikof Island to data for a stable population at Lowrie Island they found no significant difference in female foraging trip duration, pup birth mass, or pup growth rates between the two areas. This suggests that mothers are not food-limited during the early part of lactation. Given the long period of maternal care in this species, it is possible that the effect of food limitation on lactating females and pups may become evident only later in lactation. Thus, further study is needed to determine both interannual variation and how these patterns may change during the entire lactation period.

As noted earlier, pregnancy rates in Steller sea lions are lower than for other otariids for which data are available. It is not known whether low food availability is a contributing factor to these relatively low rates. It may be significant, however, that adult Steller sea lions consume more fish of the size range removed by commercial fisheries than do other Bering Sea pinnipeds (Lowry and Frost, 1985; Lowry et al., 1989).

### Harbor Seals

There are no data that can be used to examine the hypothesis that food limitation has caused or contributed to the decline in the number of harbor seals in the Bering Sea or Gulf of Alaska (Table 4.19). A reasonably comprehensive study was conducted in the late 1970s to describe the biology of this species (Pitcher and Calkins, 1979). However, virtually no biological research was conducted on the biology of Alaskan harbor seals between then and the time of the *Exxon Valdez* oil spill in 1989. Recent studies initiated in response to the oil spill

and the general population decline may provide some insight into factors affecting harbor seals in these areas.



## 5

# Human Use—Fisheries

This chapter provides a brief history of commercial and subsistence fisheries on invertebrate, fish, and mammal populations in the Bering Sea region, including interactions of indigenous peoples with the marine ecosystem. Because the states of knowledge and the histories of exploitation are so different for the eastern and western Bering Sea, exploitation and management are described separately for those two regions. Note that some fishery data may be inaccurate because of underreporting of landings. Although examples of underreporting likely occur in all nations, recent studies suggest that underreporting is especially prevalent in fishery data from the former Soviet Union (Izvestiia, 1994; The Guardian, 1994).

### FISH AND INVERTEBRATES

#### Eastern Bering Sea, Aleutian Islands, and Aleutian Basin

##### Finfish

Landings of commercially valuable fish in the eastern Bering Sea range from 1 to 2 million t annually. Before the establishment by the United States of an exclusive economic zone beyond the former 3- and 12-mile limits, a large international fishery existed in this area. Countries other than the United States that had major trawling and harvesting operations during this time included the former Soviet Union, Japan, Germany, Korea, Mexico, Taiwan, China, and Poland. The discussion below examines fisheries from the perspective of the historical effort expended in the eastern half of the Bering Sea.

**Salmon.** The earliest fisheries for salmon in the eastern Bering Sea and Aleutian Islands were likely native subsistence fisheries. Salmon, which are anadromous, return to their natal streams to spawn. Coastal peoples often established villages or temporary fishing camps at the mouths

of rivers and along streams to take advantage of this annual event. The importance of salmon to native peoples of the Bering Sea is reflected in their culture, art, and song.

Figure 5.1a shows total salmon and sockeye salmon catch of fish originating in watersheds of western Alaska (essentially salmon originating in streams and lakes that empty into the eastern Bering Sea) from 1910 to 1993. Francis and Hare (1994) showed that salmon production, as reflected bycatch in all three major regions of Alaska (western, central, and southeastern), tends to vary on both interannual and interdecadal time scales. In particular, they showed that there are very significant and coherent links between relatively sudden interdecadal shifts in northeast Pacific atmosphere and ocean physics and Alaska salmon production (discussed further in Chapter 6).

Sockeye salmon from the Bristol Bay area have always dominated the eastern Bering Sea salmon catch and continue to do so. There have been record-setting catches of sockeye salmon since the late 1970s, although some fluctuation in catch has occurred annually. The Bristol Bay catch for all salmon species in 1993 totaled approximately 42 million fish. Sockeye salmon comprised 41 million of that total, the largest sockeye catch on record, exceeding the previous high of 37 million fish in 1983.

A fundamental problem of the Bering Sea salmon fishery, like almost all salmon fisheries, is known as the gauntlet problem. It occurs because different species and stocks tend to mix in the ocean and because salmon migrate from the high seas back to their natal streams in highly aggregated and linear fashions. As a result, coastal ocean salmon fisheries tend to target mixed stocks. In the 1950s to 1970s, Japanese high-seas salmon fisheries created great concern for coastal Alaska communities and fishermen. However, high-seas salmon interceptions have been essentially eliminated in recent years through international agreements (Figure 5.1b). More recently, it has become known that salmon destined for the Bering Sea may be incidentally captured by fishers who are attempting to exploit stocks destined for their own areas. Recent concerns over the decline of western Alaska salmon stocks, particularly chum salmon stocks associated with the Yukon-Kuskokwim area, have forced managers to take action to reduce the interception of these salmon by fishers in other areas.

The June salmon fisheries on the south side of the Alaska Peninsula, commonly called the False Pass fishery, have been a subject of controversy since nearly the time of their inception in the early 1900s. Tagging studies indicate that most of the sockeye salmon caught in this fishery are bound for rivers in Bristol Bay. For this reason, managers have been obligated to manage the fishery in a very conservative manner (Rogers, 1992), as is evidenced in the historically high abundance of sockeye salmon over the past 10 years. Perhaps even more controversial is the recent increase in incidental catch of nonlocal chum salmon, in particular those originating in the Yukon-Kuskokwim area. This issue has forced managers to institute a chum salmon cap on the predominantly sockeye fishery in the False Pass region.

**Groundfish and Halibut.** The earliest fisheries for groundfish in the eastern Bering Sea region were probably native subsistence fisheries. Although the subsistence fisheries did not represent

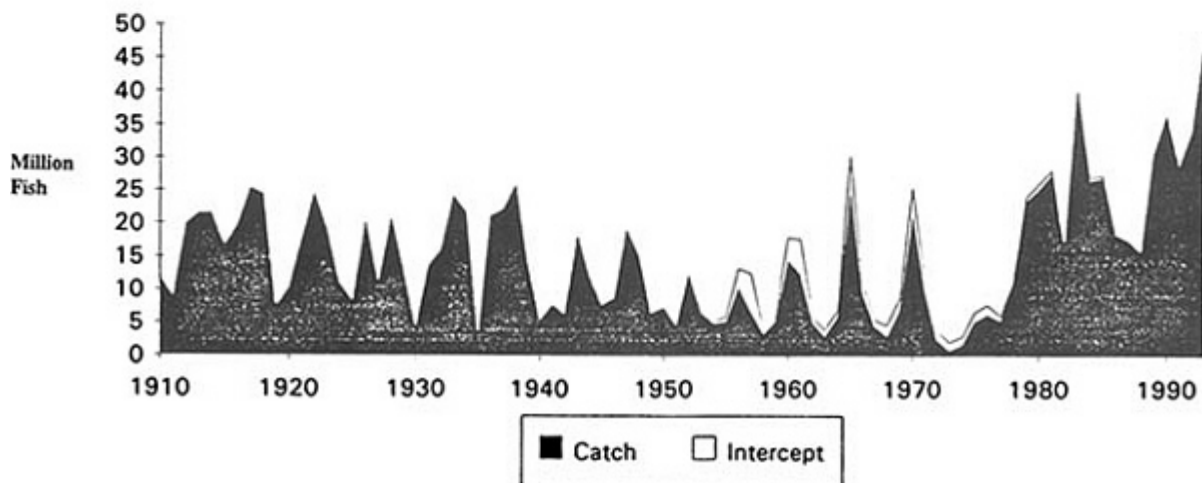
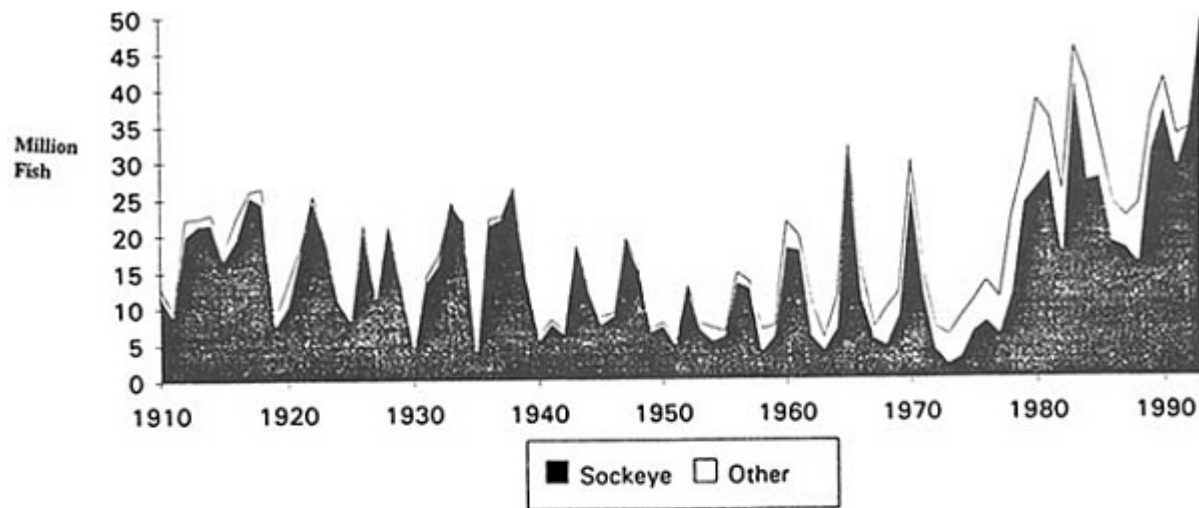


Figure 5.1a,b Western Alaska total and sockeye salmon fishery production; western Alaska sockeye salmon in-area catch and interceptions (R. Francis, Personal Communication).

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a food source as accessible as the returning salmon, native peoples quickly learned to utilize those marine fishes that were common to their area. These fish were an important part of the life of native people, and dependence on demersal species may have been critical to their survival during those seasons when other sources of food were scarce or lacking. Fishing for such species as cod, halibut, and rockfish occurred in near shore waters. These small-scale subsistence fisheries have continued to the present time.

The first commercial venture for bottomfish occurred in 1864, when a single schooner fished for Pacific cod in the Bering Sea (Cobb, 1927). The cod fishery did not commence on a regular annual basis until 1882. Catches were relatively low until World War I, when the demand for cod-liver oil stimulated greater effort. Between 1915 and 1920, as many as 24 vessels operated and produced 12,000 to 14,000 t annually (Pereyra et al., 1976). This domestic fishery continued until 1950, when demand for cod declined and economic conditions caused the fishery to be discontinued (Alverson et al., 1994). Fishing areas in the eastern Bering Sea ranged from north of Unimak Island and the Alaska Peninsula to Bristol Bay (Cobb, 1927).

Halibut were reported in the Bering Sea by U.S. cod vessels as early as the 1800s. However, Bering Sea halibut did not reach North American markets until 1928 (Thompson and Freeman, 1930). Small and infrequent landings of halibut from the Bering Sea were made by U.S. and Canadian vessels between 1928 and 1950, but catches were not landed every year until 1952 (Figure 5.2) (Dunlop et al., 1964). The catch by North American setline vessels increased sharply between 1958 and 1962 (exceeding 3,300 t), then fell to a low of 130 t by 1973 before recovering to a high in 1987, and then declined slowly. Following a six-year down cycle, Bering Sea halibut catches began to increase in 1982. The International Pacific Halibut Commission (IPHC), established in 1923 by convention between Canada and the United States to preserve the halibut fishery of the North Pacific Ocean and Bering Sea, issued the opinion that the reduced halibut abundance was the result of a combination of factors: the North American setline fishery, the Japanese setline fishery, incidental catches of juvenile halibut in foreign trawl fisheries, and adverse environmental conditions (S.H. Hoag, personal communication).

Exploitation of groundfish resources in the eastern Bering Sea and along the Aleutian Islands changed dramatically in 1959 (Figure 5.3). Following several years of prospecting, foreign fleets from Japan and the Soviet Union (USSR) began harvesting yellowfin sole (on the eastern Bering Sea shelf) and other flatfish, and Pacific Ocean perch (in the Aleutian Islands, and Gulf of Alaska) and other slope rockfish. Harvest of eastern Bering Sea shelf flatfish peaked in 1961 at nearly 700,000 t, and harvest of the Aleutian Island and Gulf of Alaska slope rockfish complex peaked in 1965 at over 450,000 t (NPFMC, 1993). Between 1959 and 1964, over 1.8 million t of yellowfin sole was taken from the eastern Bering Sea shelf; between 1962 and 1968, almost 1.7 million t of slope rockfish (primarily Pacific Ocean perch) was taken from the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska (as far south as southeastern Alaska). In the mid 1960s, some non-U.S. fishers switched their target species to pollock and Pacific cod, and catches quickly grew to more than 2 million tons (primarily eastern Bering Sea pollock) per year by 1971. Catch by non-U.S. fishermen peaked at approximately 2.25 million tons in 1972 before declining again (Figure 5.3). By that time, other nations and additional vessels were joining the fleet in increasing numbers.

Between 1864 and 1960, most commercial groundfish fisheries of the Bering Sea used hook-and-line techniques. With the advent of fisheries for flatfish and rockfish in the late 1950s,

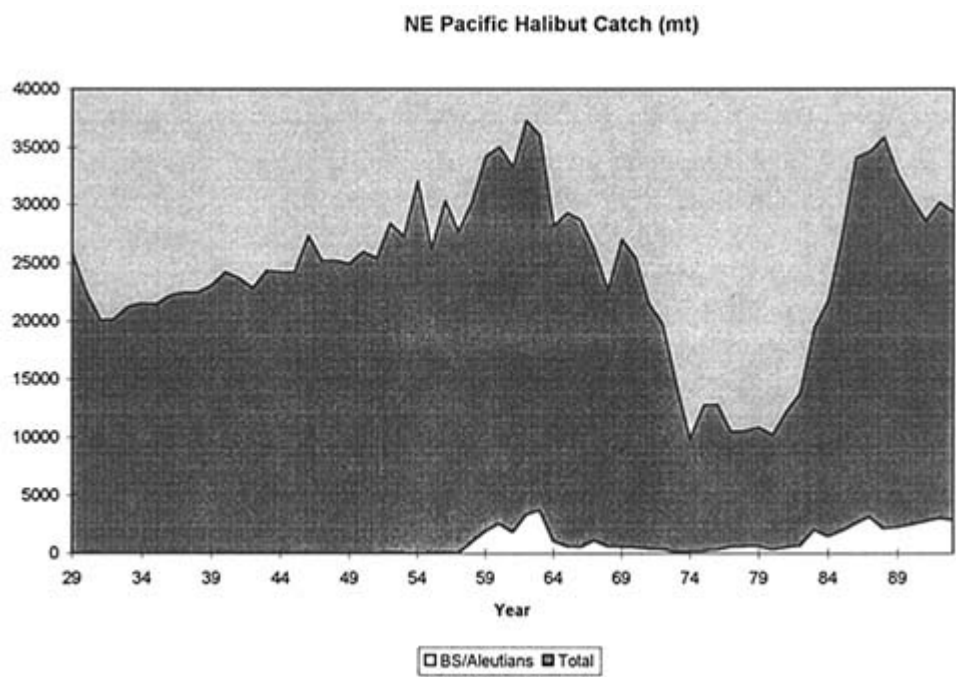


Figure 5.2 Northeast Pacific halibut catch in the Bering Sea and Aleutians, 1929–90 (IPHC, 1994).

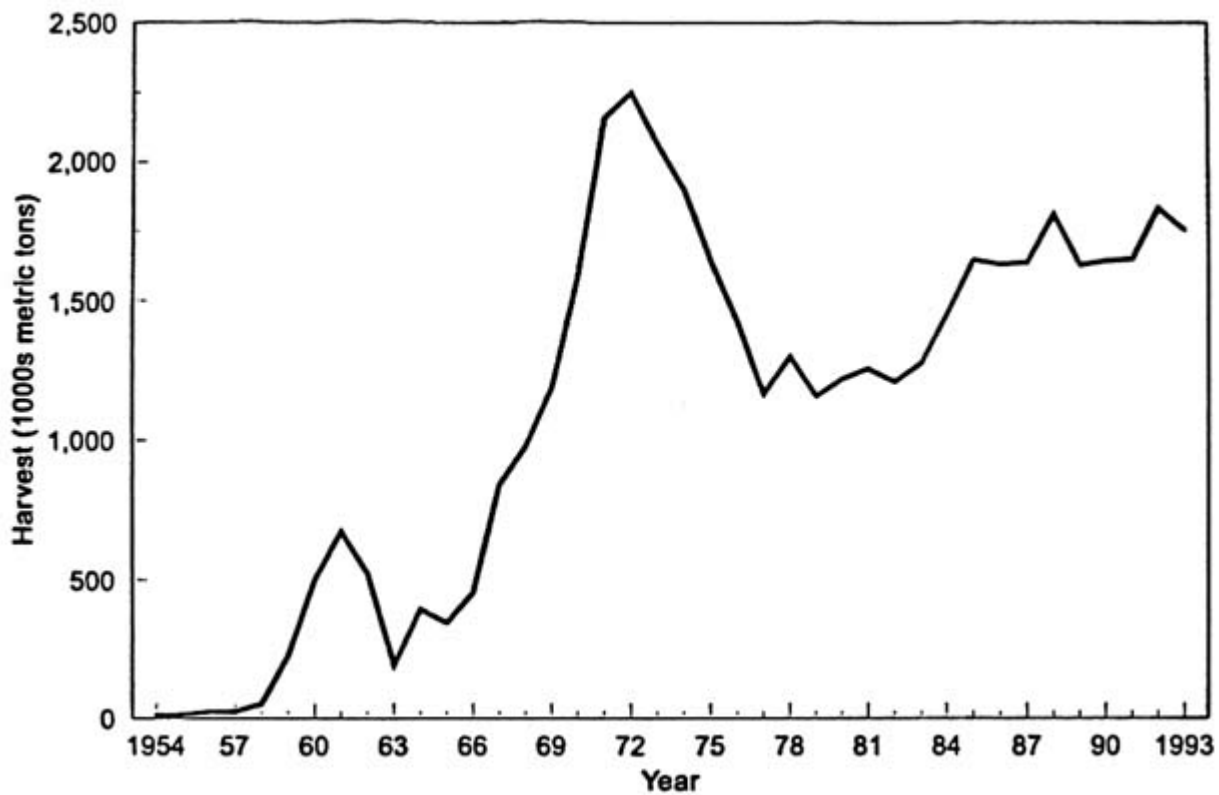


Figure 5.3 Groundfish catches in the eastern Bering Sea and the Aleutians, 1954–93 (R. Francis, personal communication).

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fishermen began using benthic trawl gear. Since 1960, a combination of hook-and-line, trawl (both benthic and pelagic nets), and pots has been routinely used, with trawl being the predominant method.

With the implementation of the Fishery Conservation and Management Act (FCMA) in 1977 (later renamed the Magnuson Fishery Conservation and Management Act [MFCMA]), a major change occurred in U.S. fishery policy, which would later result in shift of Bering Sea resources away from foreign fishers and to a growing fleet of American fishers. This federal law established the United States' rights to manage fishery resources and set priorities for U.S. citizens. In many ways, it mirrored the extended jurisdiction laws being adopted by most other maritime nations at that time. With its approval, the United States had for the first time a national policy for fisheries and institutionalized criteria for use in management decisions. A key element of the FCMA was the government's acceptance of stewardship over the adjacent fishery resources and responsibility to stimulate growth and economic viability of the U.S. fishing industry. In the Bering Sea and Aleutian Islands region, this meant that foreign fleets, which before 1976 could fish freely beyond 12 miles of the Alaska coast, would now have to conduct their operations under approval of the U.S. federal government.

Beginning in 1978 and until the present time, the annual catch of all groundfish species in the eastern Bering Sea has averaged about 1.5 million tons annually (Figure 5.3). After implementation of the MFCMA, foreign fisheries were allowed to continue for another decade. A milestone was reached in 1978 when the first joint-venture operation was formed whereby a domestic catcher vessel delivered its catch to a foreign processing ship. These joint-venture operations were viewed by U.S. government as a way to transfer fishing technology and experience to domestic fishermen, who up to that time had little real experience in fishing for most groundfish species in the Bering Sea.

The government supported the growth of joint ventures and the domestic industry by instituting a preferential policy whereby available fish resources were first allocated to wholly domestic operations (i.e., U.S. catching and processing), then available surpluses were allocated to joint ventures, and finally any remaining surpluses to were allocated to totally foreign operations. This latter allocation was often made to a foreign nation following a review to determine its level of support of domestic operations. Soon joint ventures became a major factor in the overall harvest. In 1981, the North Pacific Fishery Management Council (NPFMC) developed its Bering Sea and Aleutian Islands Groundfish Fishery Management Plan, and placed an overall catch limit for the Bering Sea at 2 million tons beginning with the 1984 season. With the help of its allocation policy and with a significant increase in the market price of whitefish in the next few years, joint ventures, and hence U.S. harvesting capacity, continued to grow. As a result, foreign fisheries were reduced and eventually phased out entirely by 1988. The strong markets, the technology transfer, and the federal government's willingness to finance capitalization of the fishery continued to stimulate the domestic industry and resulted in a complete phase-out of all remaining joint-venture fishing by 1990.

Two significant developments occurred in the Bering Sea pollock fishery in recent years (Wespestad, 1993). The first was the initiation of pollock fisheries in the central Bering Sea (Aleutian Basin) outside of the U.S. and Russian exclusive economic zones (commonly referred to as the "donut hole"). The second was the development of a U.S. fishery for deep water spawning pollock in the area of Bogoslof Island in the southeastern Aleutian Basin. Reported



catches peaked at over 1.4 million t in 1989 in the donut hole, and at over 260,000 t in 1991 near Bogoslof Island. Both of these fisheries had virtually disappeared by 1992. These fisheries raised significant issues about the relationships between pollock populations inhabiting the deep Aleutian Basin and those of both the eastern and western Bering Sea shelves.

The 1992 eastern Bering Sea (including the Aleutian Islands area) groundfish catch was approximately 1.8 million t, with pollock (1.4 million t), Pacific cod (163,000 t), and yellowfin sole (147,000 t) comprising over 90 percent of the total (NPFMC, 1993). These figures now include the incidental and discarded catches (known as bycatch), which could be sizable, and until recently were not included in the fishery statistics.

**Herring.** Pacific herring of the Bering Sea were first used by native peoples inhabiting the coastal perimeter. During spawning, herring are present near shore in massive schools, and early inhabitants took advantage of this readily available fishery resource (Wespestad, 1991). Native fishers caught these fish, which preserved well because of their high oil content. Today, herring continues to be an important food in many native villages along the Bering Sea coast, especially in villages between the Yukon and Kuskokwim rivers, where alternative food resources (e.g., salmon and moose) are absent or in low abundance. The largest catches of herring occurred all along the coast of Alaska in the 1930s, and during the foreign herring fishery in the eastern Bering Sea in the late 1960s (Figure 5.4). Foreign catch in the eastern Bering Sea offshore Alaska peaked in 1969 at more than 145,000 t. After a slow start in the mid-1960s and 1970s, coastal herring roe fisheries rose in response to exclusion of Japanese fisheries from the Soviet and U.S. exclusive economic zones and the resultant increases in Japanese imports of herring roe. The roe fishery occurs in May and June along the entire U.S. Bering Sea coast as far north as Norton Sound. Predominant gear types are gill net north of Bristol Bay and purse seine (manned primarily by fishermen from central and southeastern Alaska and Washington) in Bristol Bay. Since the early 1980s, Bering Sea landings have averaged around 25,000 t (Figure 5.5). Excellent recruitment from the 1988 year class has caused recent stock levels to increase (ADF&G, 1993).

### Invertebrates

Commercial fisheries for king and Tanner crabs in the eastern Bering Sea and Aleutian Islands have long been among the world's most important sources of crabs (Otto, 1981; 1990). While landing statistics are impressive, these (and central Gulf of Alaska) crab fisheries have undergone radical changes over their decades of existence, particularly since the late 1970s. Whereas in 1978 red king crab made up over 90 percent of the king crab landings of the eastern Bering Sea and Aleutians, by 1988 red king crab landings were no longer dominant among king crabs (Figure 5.6). Similarly, Tanner crab fisheries were developed in the late 1970s by exploiting primarily *C. bairdi*, and *C. opilio* (snow crab).

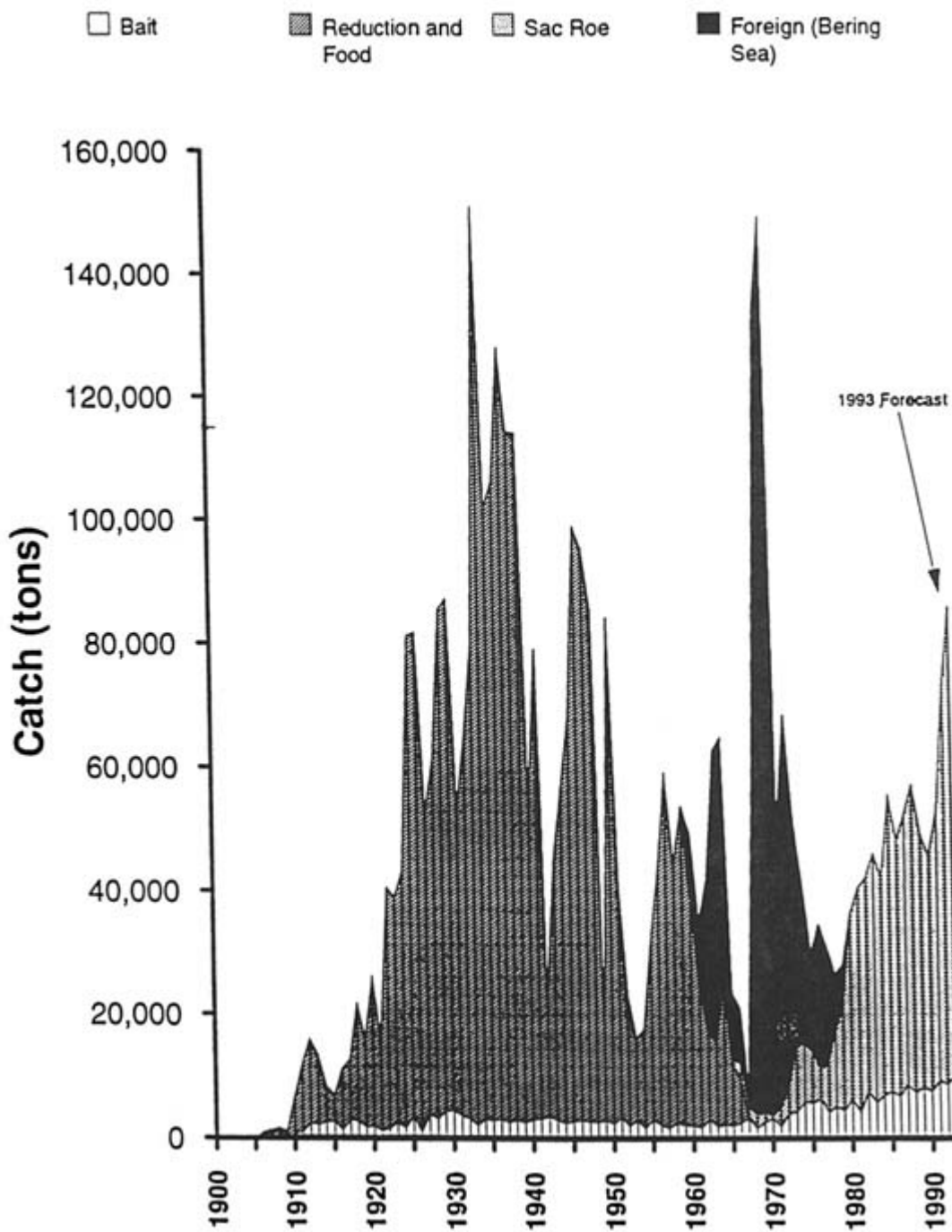


Figure 5.4 Herring catches from all Alaska herring fisheries, 1930-92 (with the projected 1993 catch) (ADFG, 1993).

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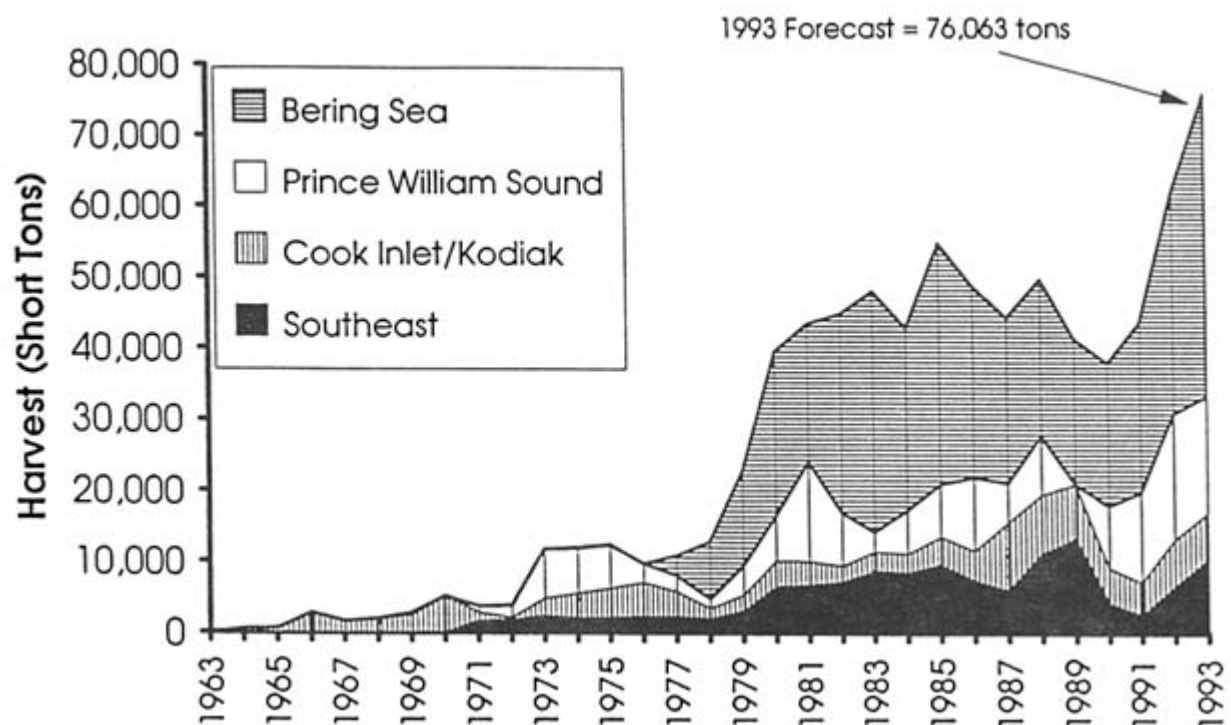


Figure 5.5 Alaska herring sac roe take harvests from all areas, 1978–92 (with the projected 1993 sac roe take) (ADFG, 1993).

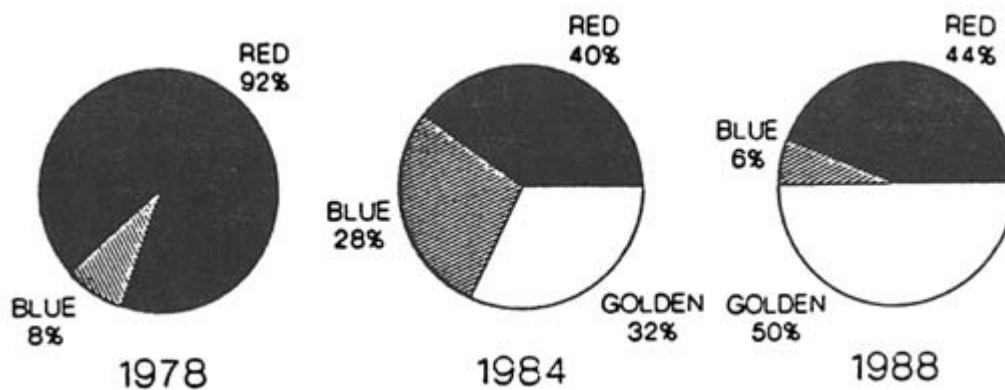


Figure 5.6 Relative contributions of red king crab, blue king crab, and golden king crab to landings of king crabs from the eastern Bering Sea and Aleutian Islands (Otto, 1990).

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**King Crab.** Commercial king crab fishing in the eastern Bering Sea began with the Japanese in 1930 and continued until 1940. Japanese king crab vessels using tangle nets returned to the Bering Sea in 1953 and remained until 1974. U.S. fishermen entered the king crab fishery with trawl gear in 1947. Effort and catches declined in the 1950s and then underwent a period of fluctuating low catches through 1966 before expanding to the current, full-scale fishery. The Soviet king crab fleet operated in the eastern Bering Sea from 1959 through 1971.

During the late 1960s catches ranged from 1 million lb in 1966 to 10.4 million lb in 1969 (Figure 5.7a). During the 1970s, catches grew further from 12.9 million lb in 1971 to about 108 million lb in 1979. An all-time high catch of 130 million lb was landed in 1980 by American fishermen in the eastern Bering Sea (i.e., Bristol Bay). This large catch was taken by a record 236 vessels using pot gear. Trawl gear and tangle nets had been prohibited in the 1960s, when management established a males-only catch policy and the commercial marketplace demanded whole, live, undamaged crab.

In 1981, the eastern Bering Sea king crab catch crashed from its all-time high to a little more than 33 million lb. By 1982, only 3 million lb of king crab were caught, and in 1983 there was no commercial fishery allowed because of low stock abundance of adult, sexually mature males and females, and no apparent sign of recruitment into the fishery of smaller size crabs. In terms of poundage and value, this fishery grew rapidly during 1971–81 to become an important fishery. In less than half that time it crashed, and it has yet to recover to catch levels seen in the 1970s. A similarly timed decline occurred in the red king crab resource and fishery around Kodiak Island (Blau, 1986).

Considerable research was undertaken during this period to determine the cause for the king crab decline. A list of possible causes, including overfishing, cod predation, disease, and handling mortality, were all shown to have the potential, either alone or in combination, to have caused such a disastrous effect on crab populations (Otto, 1986; 1990). However, it cannot be denied that, in addition to fishing, the climatic shift that occurred in the late-1970s may have been a significant factor. Since 1984, when the abundance of adult, sexually mature male and female crabs increased to permit a fishery, red king crab catches have ranged from 4.2 million lb to 18 million lb (Figure 5.7a). The eastern Aleutian Islands provided good red king crab fishing in the 1960s. An all-time high catch was achieved in 1966–67, when 33 million lb were landed. However, since that period the catch has fluctuated widely, declining to a low of 9 million lb in 1970, rebuilding to a peak in 1976, and then crashing again. The eastern region near Unalaska Island has been closed to commercial red king crab fishing since 1983. The western region, toward Adak Island, has continued to produce catches at relatively low levels (less than 1 million lb annually).

The blue king crab fishery is situated close to the Pribilof Islands, where the species is most abundant. The fishery was developed by the Japanese in the late 1960s. The U.S. fishery began in 1973 between St. Paul and St. George islands as an interim activity between red king crab seasons. The first reported catch was 1.2 million lb taken by eight vessels. In 1974, 70 vessels participated and more than 7 million lb were landed (Figure 5.7c). At that point, catch per unit effort began to decline even though total catch averaged about 6 million lb for the next 10 years. In 1988, the Pribilof blue king crab fishery was closed due to low stock abundance, and it has remained closed ever since.

Brown (or golden) king crab is a deep water crab and the smallest of the three king crab species. Commercial fishers began utilizing this species as an incidental catch to red king crab. Few landings were recorded before 1981. Most brown king crab have been taken along the Aleutian Island chain, along steep canyon walls. The western portion of the chain (Adak) has historically produced the most catch, with an all-time high of 8 million lb in 1984. Since 1988, catches have been less than 2 million lb annually.

**Tanner Crab.** Tanner crab from Alaska comprise two species, *Chionoecetes bairdi* and *C. opilio*. In the commercial marketplace they are most often referred to as Tanner crab or snow crab. *C. bairdi* is the larger of the two species, and therefore fishing this species became an attractive supplement to king crab fishing. When both Bering Sea king crab and *bairdi* stocks crashed in the early 1980s, *C. opilio* became the predominant target. Unfortunately, these stocks followed a similar pattern of decline.

The Bering Sea *C. bairdi* fishery began in 1974, at which time the first reported *C. opilio* catch was taken. *C. bairdi* catches quickly grew from 5 million lb in 1974 to 66 million lb in 1978 (Figure 5.7b). In that year, scientists began forecasting a decline based on survey estimates, and the catch fell to 42 million lb in 1979, 11 million lb by 1982, and 3 million lb in 1985. Managers closed the commercial fishery until 1988 when it appeared that some stock recovery had occurred. In 1990 the catch had increased to 24.5 million lb and by 1993 the catch was over 30 million lb. Assessment surveys indicate a declining trend beginning in 1994.

The smaller but more abundant *C. opilio* crab has filled an important market niche as king crab and *C. bairdi* crab have become less abundant. *C. opilio* catches initially were incidental to king and *C. bairdi* fisheries but began in earnest in 1979, when more than 32 million lb were landed (Figure 5.7d). In 1981 more than 52 million lb were landed. A small decline in catch then followed after which the level increased again. An all-time record catch was taken in 1992, when about 316 million lb were taken. Since then *C. opilio* populations have undergone a decline, reflected in both the surveys and catch.

**Shrimp.** The Bering Sea shrimp fishery began in 1960, when Japanese mothership operation targeted pink shrimp and humpy shrimp near the Pribilof Islands. The fishery peaked rapidly to nearly 66 million lb in 1963, then declined just as rapidly and has since been inconsequential since 1967. During the late 1960s and early 1970s, the Japanese and Russian fleets exploited shrimp stocks in the Gulf of Anadyr and in the north-central Bering Sea as well (Balsiger, 1981). At that time, humpy shrimp provided the major share of the catch from the Gulf of Anadyr and along the Koryak coast of the western Bering Sea (Balsiger, 1981).

Since 1967, shrimp stocks in the eastern Bering Sea have remained depressed, despite the lack of a directed fishery since 1967. Little is known about the stock of pandalids in the western Bering Sea.

Historically, most of the shrimp catch from Alaskan waters has come from the Gulf of Alaska, particularly around Kodiak Island and the Alaska Peninsula. The shrimp fishery in the Gulf of Alaska began in southeastern Alaska near Petersburg in 1915. The fishery principally targeted pink shrimp which were cooked, hand peeled, and frozen for special markets. The



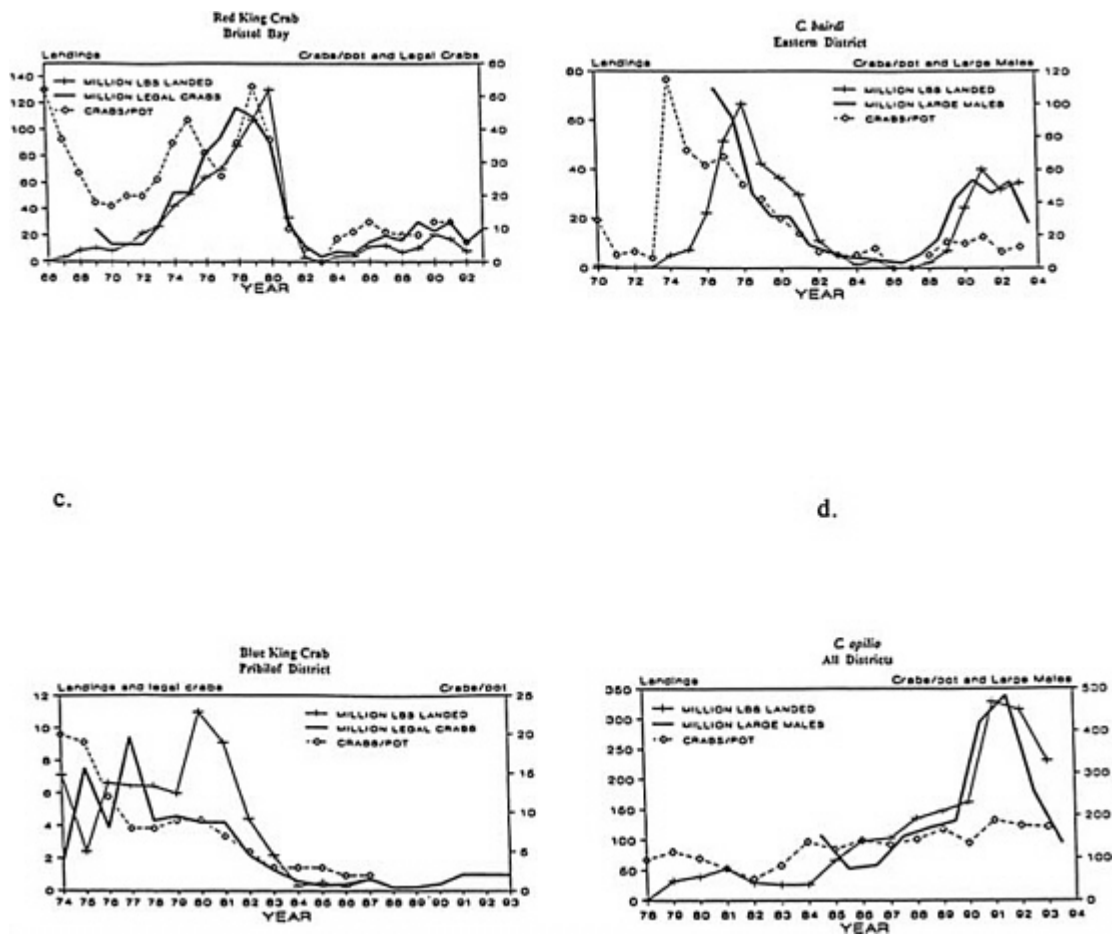


Figure 5.7a,b,c,d, U.S. crab landings in millions of pounds and abundances of legal or total crab, by species and region, 1966–93 (catch per unit effort as crabs per pot) (estimated from NMFS trawl surveys, AFSC Processed Report 93-14, report to industry on the 1993 eastern Bering Sea crab survey) (Stevens et al., 1993).

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fishery gradually expanded, and annual landings of 1.2 to 3.0 million lb occurred from 1945 to the mid-1950s (Gaffney, 1981). In 1957, the mechanical peeling machine was introduced in Wrangell, Alaska; and in 1958, a fishery developed using the mechanical peeling process to harvest the large stocks of shrimp located in lower Cook Inlet and Kodiak. The Gulf of Alaska fishery grew rapidly from 7.9 million lb in 1958 to 15.1 million lb in 1963. Growth slowed when shore plants and fishing vessels were badly damaged by the 1964 earthquake, but then grew rapidly to 128.8 million lb in 1976. Soon thereafter, however, populations in many historical production areas in western Alaska began showing signs of stress. By 1978 (the first year of precipitous decline in catches), catches had declined to 73.2 million lb. Gulf-wide totals dropped to 30 million lb in 1980, 4.6 million lb by 1986, and 2.0 million lb in 1989 (Savikko and Page, 1990). Since 1990, the Alaskan shrimp resource has been conservatively managed, with only limited catches being authorized. To date, however, there has been little evidence of stock recovery in either the Bering Sea or Gulf of Alaska.

### General Management Issues

A number of large-scale issues have influenced fisheries management and the fish populations in the eastern Bering Sea in a major way. For example, there has been a tremendous increase in fishing capacity (D. L. Anderson, personal communication), and that increased capacity (usually referred to as overcapitalization of the fleet) has affected fishing regulations and distribution of fishing effort in space and time. For example, the halibut fishery has become a so-called "derby fishery," in which many boats race to fish for a few hours during an abbreviated open season, no matter what the weather is like (Hoag et al., 1983; IPHC, 1982, 1983; NRC, 1994a). Other fisheries have been affected by similar factors, and those changes in the fisheries have biological effects as well, such as changes in population age structure and distribution.

Another problem complicating fishery management has been allocation problems, primarily questions concerning competition between inshore and offshore interests. Thus, Marasco and Aron (1991) described the explosive growth in both inshore and offshore capital investment—also related to the overcapitalization problem—and the "intense competition between these two segments of the industry for shares of the limited pollock catch." Huppert (1991) also discussed this problem, pointing out that there can be a tendency to favor Alaskan shore-based processors at the expense of factory trawlers and motherships because they provide direct employment and local economic benefits to Alaskans. As a result, state and federal interests do not always necessarily coincide.

### Western Bering Sea

Russian colonization of the Bering Sea region in the 1800s was followed by the growth of fishing and maritime hunting, including takings for commercial purposes (Alexeev, 1982). Nevertheless, until the 1950s, fishing in the western Bering Sea was small-scale and mostly a

coastal enterprise. The species targeted were salmon and herring of the northwestern Bering Sea and eastern Kamchatka (see [Figure 5.8](#) for locations mentioned in the text below).

Systematic research of Bering Sea biology by Soviet scientists began in the 1930s (History of Regional Research—, 1982). In 1932–33, oceanographic research and fish stock assessment studies were conducted in the western and northern Bering Sea by the Soviet Pacific Complex Expedition (Andriyashev, 1935; Investigations of the Seas, 1937; Stepanova, 1937). This expedition located spawning areas of cod and collected data on distribution of pollock and flatfish. However, no large fish populations that could serve as a basis for the deployment of a trawling fleet were discovered at the time. These studies assessed the eastern Bering Sea as more commercially promising than the western Bering Sea. As a result, Soviet research efforts since the mid-1930s and commercial fishing activities (which began in the 1960s) focused primarily on the eastern Bering Sea until access was restricted in the 1980s, with 10 to 12 Soviet research vessels working in the central and eastern Bering Sea and in the Gulf of Alaska (Ethnical History of the Northern People, 1982). Detailed data on the biology and distribution of flatfish, herring, Pacific Ocean perch, and commercial invertebrates was provided by the 1958–64 Bering Sea Fishery Expedition (Mesheryakova, 1964, 1970a; Neiman, 1963), the 1961–65 Bering Sea Herring Expedition (Mesheryakova, 1970b), and the 1969–72 Bering Sea trawling survey (Ethnical History of the Northern People, 1982). Beginning in the 1960s, Soviet academic science no longer participated in this research. Instead, research was shifted from studies of biological productivity and structure of fish populations to surveys of selected fish stocks, at the request of the Soviet commercial fishing industry.

The applied research effort was followed by the development of an ambitious program of Soviet high-seas fleet expansion. In the 1950s, the policy of the former Soviet Union was oriented to the rapid development of ocean activities and the economies in its border areas. The rate of budget investments for fisheries in the Far East exceeded that of other regional capital investments. Immense capital infusions were aimed at developing national ocean power of strategic importance. This period was characterized by a peak of research effort, mainly in the eastern Bering Sea, improved harvesting technologies, expansion of the distant water fishing/processing capacities and oceangoing auxiliary fleet, and later, an increase of joint-venture operations. For several years the expansion in Soviet landings and processing capacities was accompanied by a corresponding increase of catch from the eastern Bering Sea shelf and Gulf of Alaska. A large Soviet fleet entered the eastern Bering Sea in 1959 to catch slope rockfish (primarily Pacific Ocean perch complex fish), flounders, and king crabs. Trawling in the Gulf of Alaska began in 1962. Newly organized fishing on the eastern Bering Sea shelf and in the Gulf of Alaska provided 600,000 t of Pacific Ocean perch, yellowfin sole, herring, pollock, cod, crabs, and shrimps by the mid-1960s (Zilanov et al., 1989). After a few years, most of these species were overfished. Thus, the strategy of the Soviet fisheries was to expand the exploitation of a targeted species until it decreased, and then shift the effort to what appeared to be the next most abundant species.

Coastal resources of the Soviet Union/Russia (except for salmon, herring, and flatfish) were studied and exploited to only a limited extent. Landings in the western Bering Sea peaked for herring in 1966 at 118,300 t, for crabs (mainly the three king crab species mentioned earlier) in 1961 at 8,970 t, and for Pacific Ocean perch in 1965 at 6,970 t. However, by the end of the 1960s, fishing had caused significant depletion of these targeted fish and crab stocks, resulting

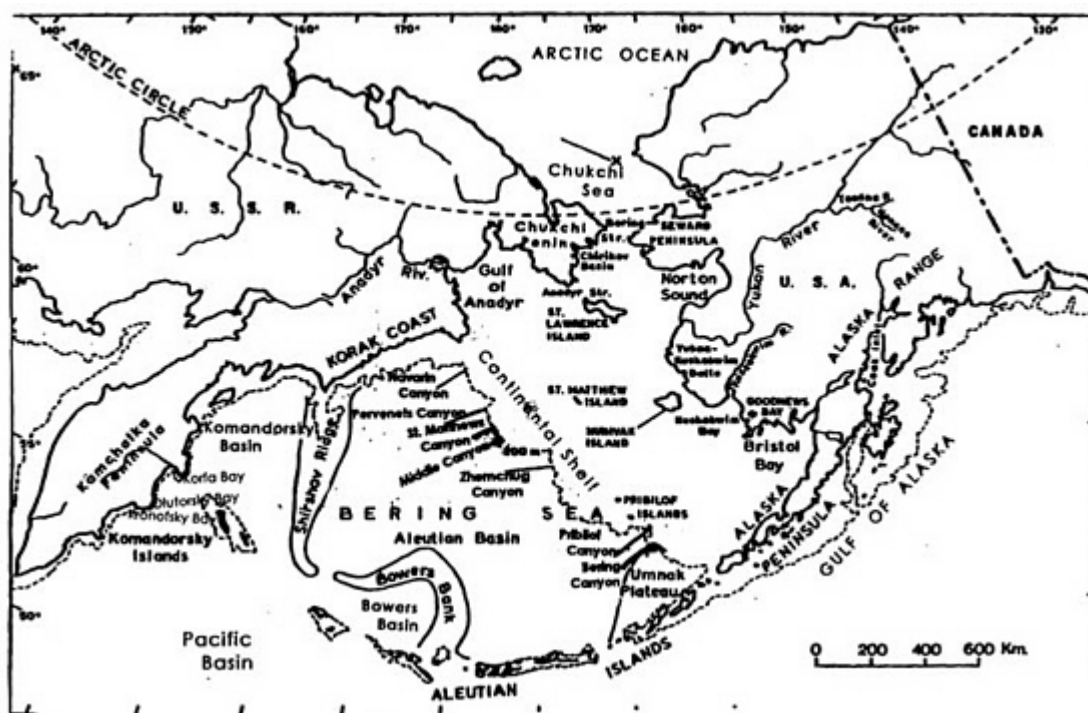


Figure 5.8 Locations of geographic features mentioned in the text (modified from Hood and Kelly, 1974).

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first in the total decline of regional landings, and then in substantial changes in the structure and composition of regional fish populations. Not all of this was a direct result of fishing, however. More than a twofold downward shift in the zooplankton biomass was observed in the western Bering Sea in the 1950s and 1960s (Naumenko et al., 1990), which was then followed by a change in the structure of macrofauna. Along with the decline in productivity of herring, capelin, saury, halibut, and Kamchatka and blue crabs (Shuntov and Dulepova, 1991), there was a considerable rise in the abundance of pollock, cod, flatfish, and Tanner crab. Dynamics of pollock in the western Bering Sea in the 1970s was literally described as an "explosion" (Fadeev, 1988). Since that time, pollock has been the mainstay of the Soviet/Russian fishing effort in the western Bering Sea.

The worldwide extension of fishery jurisdictions by expansion of economic zones severely affected the operations of the Soviet distant-water fleet. Almost immediately, Soviet fishers lost access to the resources of the U.S. exclusive economic zone, which resulted in a temporary decline in Soviet national catches. In addition, many Soviet/Russian fishing vessels, barred from other regions of the world, began fishing in the western Bering Sea, which nearly tripled the overall fishing effort in the area. With the change in the international regime of the oceans, the level of exploitation of the western Bering Sea rose substantially: from 359,010 t in 1975 to 1,685,390 t in 1988 (see Table 5.1). Since most of the Soviet vessels were constructed for large-scale high-seas fishing, their deployment in the western Bering Sea produced a dramatic increase in exploitation of the ecosystem.

In recent assessments by Russian scientists (which are based on observations over 50 years, and several models for the relationship between primary and fishery production), total potential fishery productivity of the Russian exclusive economic zone in the Bering Sea has been estimated at 3.8 to 4.8 million t, depending on pollock fluctuations (Markina and Khen, 1990) (Table 5.2).

Pelagic communities support two-thirds of the total fish production in the western Bering Sea. Composition, structure, and dynamics of these communities were not well known before the beginning of the western Bering Sea commercial industry. However, the exploitation methods described above indicate that the compositions of western Bering Sea pelagic communities have undergone radical changes.

## Finfish

**Salmon.** The most valuable species group in the region are salmon (*Oncorhynchus* spp.). Originating from the rivers of Kamchatka and Chukotka, these five salmon species<sup>1</sup> swim up to 2,000 miles through the central Bering Sea (Aleutian Basin) during their oceanic phase. Concentrations of high-seas salmonids in the central Bering Sea are explained by food abundance and favorable hydrology. As for the fish from the eastern Bering Sea, the oceanic phase is an extremely important part of the salmon's life cycle and uncontrolled fishing during this phase

<sup>1</sup> Pink (*O. gorbuscha*), chum (*O. keta*), sockeye (*O. nerka*), chinook (*O. tshawytscha*), and silver (*O. kisutch*).

Table 5.1 Catches in the western Bering Sea, by major species (in tons) (Official data of the Ministry of Fisheries, Moscow)

Species/ Years	Pollock	Herring	Pleuronectidae	POP(a)	Saffron Cod	Salmon	Cod	Halibut	Prawns	Crabs	Other	Total
1965	6,510	75,160	16,690	6,970	2,030	21,790	-	-	-	8,340	84,730	222,220
1966	-	118,290	23,450	2,030	1,160	13,610	-	-	-	8,790	116,813	284,143
1967	4,950	55,730	13,340	-	2,960	22,710	-	-	-	7,480	43,700	150,870
1968	2,680	12,870	3,600	-	-	8,910	-	-	-	-	67,050	95,110
1969	1,220	-	2,440	-	-	20,000	24,490	-	400	-	-	48,550
1970	34,680	-	29,140	-	6,784	14,230	8,970	-	199	7,238	3,480	104,721
1971	18,860	4,700	11,620	-	2,730	20,850	6,520	300	-	2,720	10,010	78,300
1972	422,100	300	17,500	-	9,500	9,000	10,500	-	-	3,127	115,600	587,627
1973	364,899	24	10,197	-	9,538	13,039	21,020	60	-	-	62,216	480,993
1974	426,957	-	9,938	-	13,358	17,742	17,435	-	-	-	66,138	551,568
1975	265,200	-	7,816	-	1,736	26,114	7,254	-	-	2,000	48,890	359,010
1976	551,649	-	6,023	260	1,490	18,857	9,790	-	-	-	193,431	781,500
1977	394,021	25,019	7,496	-	5,936	5,900	5,784	72	-	-	62,229	506,457
1978	481,635	8,900	17,443	178	13,866	18,725	6,979	3,243	-	-	26,202	577,171
1979	615,466	13,906	8,505	615	9,320	55,591	3,743	4,235	400	900	33,020	795,701
1980	928,008	12,800	20,814	1,200	14,021	14,770	14,181	301	300	800	40,835	1,048,030
1981	890,943	14,906	10,612	1,797	13,430	55,508	33,102	6,589	530	1,970	71,253	1,100,640
1982	1,019,120	12,880	12,010	540	12,870	18,800	62,160	2,940	-	2,990	68,510	1,212,820
1983	970,950	16,260	17,210	100	15,390	47,640	63,640	2,010	-	3,530	66,690	1,203,720
1984	785,890	17,440	8,000	60	16,120	29,360	97,460	2,640	-	3,220	26,960	987,150
1985	712,800	31,310	33,460	40	10,270	38,400	94,870	2,860	-	3,170	18,100	945,280
1986	936,690	20,980	39,900	20	8,890	24,120	117,650	5,030	90	4,800	15,120	1,173,290
1987	1,108,300	20,200	24,000	200	9,680	52,400	72,400	4,400	3,500	3,200	29,600	1,327,800
1988	1,291,700	15,340	27,900	980	10,480	21,750	70,340	2,520	-	5,810	238,570	1,685,390
1989	1,213,800	9,470	24,010	40	9,770	65,470	61,950	2,820	10	4,500	113,090	1,504,930
1990	928,400	16,270	26,760	50	15,220	16,500	89,180	2,980	-	4,290	84,790	1,184,440
1991	631,460	12,180	29,000	30	7,490	96,140	61,820	1,530	-	3,860	30,200	873,710
1992	702,710	2,370	25,450	30	13,520	29,880	110,000	1,380	-	0,570	26,790	912,700
1993	768,840	2,040	11,410	1,100	5,170	59,130	62,080	0,320	-	1,410	25,080	936,580

(a) Pacific Ocean Perch

Source: Official Data of the Ministry of Fisheries, Moscow.

Table 5.2 Assessment of Bering Sea productivity

Area <sup>a</sup>	Fish Production	Ichthyomass (million t) with Annual P/		Lower 2 Upper Limits of Fish Productivity (t/km <sup>2</sup> )
	(million t raw mass)	B Coefficients <sup>b</sup> of:—		
Shelf		0.5	0.4	
Up to 200 m	9.7 - 7.7	19.4 - 15.4	24.3 - 19.3	14.5 - 22.9
200-1000 m	0.5 - 0.4	1.0 - 0.8	1.3 - 1.0	7.0 - 11.5
More than 1,000 m	4.1 - 3.2	8.2 - 6.4	10.3 - 8.0	5.6 - 9.0
Russian EEZ shelf	3.1 - 2.5	6.2 - 5.0	7.8 - 6.3	18.0 - 28.0
Entire EEZ	4.8 - 3.8	9.6 - 7.6	12.0 - 9.5	10.0 - 17.1
American EEZ shelf	6.6 - 5.3	13.2 - 10.6	16.5 - 13.3	13.6 - 21.1
Entire EEZ	5.2 - 7.3	18.4 - 14.6	23.0 - 18.3	10.3 - 16.3
"Donut hole"	0.3 - 0.2	0.6 - 0.4	0.8 - 0.6	2.0 - 3.9
Bering Sea in general	14.3 - 11.4	28.6 - 22.8	35.8 - 28.5	9.8 - 15.5

<sup>a</sup> EEZ, exclusive economic zone

<sup>b</sup> P/B coefficient = summary production/total biomass

Source: Markina and Khen (1990).



(whether targeted or incidental) can greatly affect the overall population (Birman, 1985; Naske and Slotnick, 1987; see also NRC, 1996 for a discussion of salmon declines in the Pacific Northwest). The effects of removals outside the Bering Sea on the overall western Bering Sea populations are not known.

Soviet/Russian fishing for salmonids operates mainly in estuarine and coastal areas. There have been extensive fluctuations in annual catches of Russian salmon. Since 1965, these stocks have been depleted. In the 1980s, stocks of Russian salmon fell below 50 percent of the stock abundances measured 50 years ago; Kolmogorov and Sinelnikov (1984) also found that there appeared to be a shortage of male fish, the most valuable catch, at the spawning sites. Many small populations disappeared, whereas the structure of large populations has changed. Pink salmon now comprise more than 80 percent of the catch, while in the 1940s and 1950s half of the catch was chum salmon (Gritsenko, 1994). Rapid enhancement of salmon production at the more than 350 Japanese breeding hatcheries now probably affects the size of wild populations in the region (see NRC, 1996 for a discussion of hatchery effects on wild salmon populations).

There is considerable controversy on the roles of people and the environment in both short-term and long-term fluctuations of salmonids. One view regards the depression of Asian salmon stocks in the 1960s and 1970s as attributable to the Japanese high-seas fishery (Kolmogorov and Sinelnikov, 1984; Zilanov et al., 1989). It is also tempting to connect the most recent decline of Russian salmon to the extraordinary scale of poaching by both national and foreign fishermen. In Russian assessments, illegal catch of Asian salmon exceeds 20,000 t a year (Sovetsky Rybak, 1992). Another factor of growing importance is pollution of coastal waters by oil and chemical waste, and community sewage waste. In the Anadyr Bay, for instance, all communal wastes are discharged to the sea without any treatment (Report on the Environmental Situation..., 1993). Several years ago the Special Environmental Commission discovered that the oil pollution in Chayanskaya Bay exceeds the Russian government's total permissible concentration by 8 to 10 times (Klimenko, 1992). However, scientists from the Soviet/Russian Hydromet (hydrometeorological agency) assess the Bering Sea ecosystem in general as stable and pristine, that is, as comparatively clean, healthy, populated by active biota, and unaffected by direct anthropogenic pressure (Research in the Seas, 1990). The long-term dynamics of catches attests to cyclical variations in salmon abundance correlating with long-term trends in solar activities, climate changes, and changes in atmospheric circulation (Birman, 1985; Chigirinsky, 1993). Research by these specialists showed a primary correlation between salmon abundance and global and local environmental changes, and, secondarily, with fishing effort.

Currently, salmon stocks of the western Bering Sea are at average or depressed levels (State Report, 1994). According to TINRO (Tikhookeansky Nauchno-Issledovatel'sky Institute Rybnogo Khoziastvai Okeanographh [Pacific Ocean Institute of Scientific Research in Fisheries and Oceanography]) assessments, the total salmon biomass could support a maximum-sustained-yield catch of 95,400 t in 1991 and 37,600 t in 1993 (Shuntov, 1994a). If declines are related to the abundance of plankton, the current state of food resources for these species could promote their recovery (Klyashtorin and Smirnov, 1992). However, some Russian researchers have correlated declines of solar activity in the 1990s with a radical change of atmospheric and hydrological processes. They suggested that these large-scale environmental processes could cause declines in salmon abundance (Shuntov, 1986). A correlation between salmon abundance



in the eastern Bering Sea and climate change is mentioned earlier in this chapter, and the correlation is further analyzed in [Chapter 6](#).

**Herring.** Herring was the basis of Soviet regional fisheries in the 1950s and 1960s, when several populations were simultaneously targeted (in the southwest portion of the western Bering Sea, and the shelf of Olutorsky Bay, Korfa Bay, and adjacent area—along the northern part of the Kamchatka Peninsula). In the second half of the 1960s, up to 35 to 50 percent of the total herring population was taken annually by commercial fishing (Naumenko et al., 1990). In all cases, after a few years of fishing, the stocks were depleted. Since the 1970s, Korfa-Karagin area herring lost its commercial importance. During the 1970s and 1980s, even under a regime of stock conservation, average catches did not exceed 14,000 t. Exploitation of herring stocks, though at a lesser scale, was resumed in the mid-1970s, when the abundant year class of 1971 became available. In the 1980s, catches were stabilized at 25,000 to 30,000 t, while in the 1990s they declined abruptly. This decline of stocks resulted from the combined impact of the overfishing and change of natural spawning conditions (Naumenko et al., 1990). The status of Pacific herring is still very low (State Report, 1994). Although Russian experts expect a considerable increase of its biomass in the second half of the 1990s (Shuntov and Radchenko, 1994), the maximum sustainable yield for this species for 1994 was not even determined.

**Pollock.** Since the 1970s, the pelagic communities of the western Bering Sea have become dominated by pollock,<sup>2</sup> which make up 85 to 90 percent of the total biomass taken. According to ichthyoplankton surveys and virtual population models, western Bering Sea pollock production has averaged between 1.3 and 2.3 million t a year (assessments of P. Balykin, TINRO, personal communication). Different assessments by Soviet and Russian scientists on the dynamics of pollock and its role in the ocean ecosystem are explained by the absence of initial data on pollock abundance before the start of commercial fishing, as well as by inadequate knowledge of pollock biology. Russian scientists hold various views on the seasonal distribution of pollock. Some consider its life cycle adapted to the shelf and slope waters where this species is concentrated (Fadeev, 1988). Other research has shown that shelf and slope waters are inhabited only by juveniles, whereas large adults actively use food resources from the whole basin of the Bering and Okhotsk seas, forming concentrations even in deep water basins (Shuntov et al., 1988; Sobolevsky et al., 1989). Reproduction of pollock in the Russian exclusive economic zone takes place in Olutorsky Bay and adjacent areas of the northern half of the Kamchatka Peninsula. Older fish move to the Komandorsky Basin, where they are mixed with pollock of American origin, and in small quantities then migrate to open areas of the Bering Sea. After spawning, some pollock of American origin migrate into the Russian exclusive economic zone (see discussion of pollock population and stock structure in [Chapter 4](#)). Pollock-spawning in the Bogoslof Island area is widely distributed in the Aleutian (both east and west of 176°) and Komandorsky Basins. Pollock coming from the Pribilof-Unimak Island area migrate to the north

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<sup>2</sup> Pollock are usually considered to be groundfish, because they are often taken with bottom trawls. However, they are also caught in mid-water (pelagic) trawls because they occupy both pelagic and demersal communities.

and are found in the Navarin area. Russian scientists disagree about what part of the total Bering Sea pollock stock comes from Asian spawning aggregations. Some claim only 10 percent (Fadeev, 1991), while others consider it to be closer to 40 percent (Shuntov et al., 1990).

Russian commercial fishing for walleye pollock in the western Bering Sea is concentrated in the Navarin and Olutorsky areas, as well as in Ozerny and Korfa-Karaginsky bays. More than 60 percent of the harvest has been usually taken in the Navarin area adjacent to the U.S. exclusive economic zone (Fadeev, 1991). After peaking at 1,291,700 t in 1988, pollock catches in the Russian exclusive economic zone are reported to be in a steep decline. This trend is explained by a drop in the pollock biomass, which, in the opinion of Russian experts, is connected with reduced numbers of fish in the area (rather than smaller fish) and environmental changes (Shuntov and Dulepova, 1991; Shuntov and Radchenko, 1994).

**Forage Fish.** Although no specialized research has ever been done on capelin, this species seems to be present practically everywhere in the western Bering Sea, being especially abundant in Karagin, Olutorsky, and Anadyr bays and near-island groups (Naumenko, 1986). Specialized fishing for capelin has not been developed for several reasons, including low prices and the instability of populations, with huge interannual variations. However, with the development of appropriate technology, capelin might become a useful reserve for the Russian industry. Other potentially exploitable area resources include light-ray lantern fish, black smelts, argentine, and squid, which has a biomass assessed in excess of 6 million t (Ilinsky, 1990).

### Summary (Pelagic Fish Community).

The historical composition of the pelagic fish community of the western Bering Sea has been classified into three periods by Naumenko and others (1990):

1. The 1950s and early 1960s. Herring was the dominant species of the pelagic fish community at this time. Its biomass of 3.5 million t in 1953 may have been close to what the region could support. However, by the mid-1960s herring biomass dropped to 800,000 t. During this period, smelt biomass (100,000 t) was high, capelin biomass (80,000 t) was considered average, and pollock biomass (800,000 t) was low.
2. The transitional period, from the mid-1960s to 1973. There was no single dominant species in the pelagic community, and the status of herring was unstable. From 1968 to 1970, herring and pollock stocks appeared to be close to their historically minimum levels, while capelin biomass was suddenly and substantially boosted. In the beginning of the 1970s, the amounts of herring and pollock became equal, while biomass of pollock was more than twice that of herring. Meanwhile, stocks of smelt dropped to 40,000 t.
3. Most recent period. The period beginning in 1973 could probably be called the "pollock period." During this time, pollock comprised more than 85 percent of the commercial pelagic biomass. Stocks of this species had been on the rise until 1981, when it reached 3.5 million t. Since then, declines have set in. Numbers and biomass of herring, capelin, and smelt

have stabilized at the historically minimum levels of 319,000 t, 48,000 t, and 20,000 t, respectively.

These dynamics of western Bering Sea pelagic communities might be connected with both human-induced and climatic/oceanographic conditions. [Table 5.3](#) shows corresponding changes in temperature of water, surface, and other climatic parameters of the area, whereas [Table 5.4](#) shows average catches of the main commercial species for these periods. One can see that the first (herring) period was by most parameters the inverse of the third (pollock) period. The former was characterized by abnormally low water temperatures during spring and summer seasons, relatively mild winters, and cool summers, whereas the latter is characterized by the opposite conditions. During the second (transitional) phase, climatic and oceanographic conditions were close to average perennial parameters.

### Demersal Communities.

Demersal communities of the western Bering Sea are less abundant and less surveyed than those of the eastern part. A relatively complete range of observations exists only for the eastern Kamchatka shelf and several areas of the continental slope. Detailed surveys of demersal species composition in the western Bering have been conducted only since 1980s.

The numbers of demersal species in the area range from 40 species in Olutorsky and Karagin Bays to 16 species in the Bering Strait. In most cases, the number of dominant species does not exceed 4 to 9, which account for 70 to 90 percent of the biomass (Borets, 1989). Based on the species proportion in the total community biomass, polydominant communities (Kronotsky Bay, Bering Strait) and monodominant groundfish communities (in most of the bays and shelf areas) can be identified ([Table 5.5](#)).

In nearly all the areas of continuing demersal fisheries, the most significant species (by biomass) are cod (81.8 percent of the biomass on the Karagin-Olutorsky shelf, 68.8 percent of biomass at the Anadyr shelf) and flatfish. In the 1980s the demersal fish biomass of the western Bering Sea was assessed at 1.3 million t, including 1.1 million t of Pacific cod (Shuntov et al., 1990). Pacific cod is the second largest catch, by volume, of regional species. Its harvest started in 1969 at the shelf of the Olutorsky-Karagin area, later expanded all along the Kamchatka shelf. Catches peaked at 117,650 t in 1984 then after a few years of decline reached 110,000 t in 1992, before declining again. Although the population structure of the western Bering Sea cod is not well understood, the stocks are believed to be in good condition.

Flatfish are less abundant in the western Bering Sea than in the eastern part. Total biomass is assessed at 130,000 t (Shuntov et al., 1990). Flounders have been traditionally caught along the Olutorsky shelf and adjacent areas, as well as along the Kamchatka shelf at the depth of 150 to 400 m (Zilanov et al., 1989). Catches have varied considerably, from 8,000 t in 1984, to 39,900 t in 1986. Stock assessments for flounders and halibut are favorable. Russian experts expect relative growth in flounder abundance, a trend that has already been observed on the eastern Kamchatka shelf. [Table 5.5](#) shows that numbers of bycatch fish, such as sculpins (Cottidae), sea poachers (Agonidae), and eelpouts (Zoarcidae), are relatively high in areas where there has been no commercial fishing (Bering Strait).

Table 5.3 Dynamics of the main environmental parameters of the western Bering Sea

Period	Average Biomass of Zooplankton in Olutorsky Bay (mg/m <sup>2</sup> )	Average t° of water at the surface °C t° of air								Ice Surface in Western Bering, Jan.–May (thousand km <sup>2</sup> )
		Station Apuka		Station Ossora		Station Korf		3	4	
		1	2	1	2	1	2			
1951–65	660	4.59	6.78	3.51	7.85	5.83	7.81	2,136	1,255	704
Deviance from perennial	+123	-0.21	-0.17	+0.16	+0.03	-0.11	0.27	-14	-27	+65
1966–73	313	4.91	6.98	2.46	7.31	6.05	8.04	2,159	1,246	623
Deviance from perennial	-224	+0.11	+0.03	-0.89	-0.51	+0.11	-0.04	+9	-6	-16
1974–87	555	4.92	7.12	3.69	8.07	6.01	8.39	2,160	1,287	619
Deviance from perennial	+18	+0.12	+0.17	+0.34	+0.25	+0.07	+0.31	+10	+35	-20
Average perennial	537	4.80	6.95	3.35	7.82	5.94	8.08	2,150	1,252	639

Note:

1 - t° of water surface in May–June (spring).

2 - t° of water surface in July–Oct. (summer).

3 - a sum of degree-days of frost.

4 - a sum of degree-days of warm weather.

Source: Naumenko et al. (1990, p. 56).

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Table 5.4 Catches of the main commercial species in the western Bering Sea (thousand tons)

Species/Periods	1958–65	1966–73	1974–87	1988–93
Pollock	-	106.27	20.5	922.8
Herring	131.1	24.0	13.9	9.6
Cod	3.8	8.9	43.3	75.9
Saffron Cod	3.4	4.1	19.0	10.3
Flounder	8.1	13.9	15.9	24.1
Salmon	n/a <sup>a</sup>	15.3	30.3	48.1

<sup>a</sup> n/a, not available

Source: Calculated from the data of the VNIRO Department of Fishery Statistics.

Fish of the upper part of the continental slope (depths of 200 to 500 m) are usually not included in the Russian analysis of fish community changes. The relatively long history of observations in this region (since 1957), however, demands that these data be used in the analysis of Bering Sea ecosystem dynamics. Catches in different areas of the western Bering Sea slope are limited to a few species. During the last 25 years, the dynamics of catches and predominance of species in two main areas of the continental slope (the Navarin area and eastern Kamchatka) have been asynchronous. Thus, at the slope of the Navarin area, the 1960s' catch was based on sablefish, arrowtooth flounder, grenadier, and Pacific Ocean perch. Skates, cod, arrowtooth flounder, and Greenland turbot comprised 82.8 percent of the 1970s' harvest, whereas during the 1980s, 85 percent of the catch consisted of grenadiers and cod (Ilinsky, 1990). Along the slope of the eastern Kamchatka Peninsula, 76.9 percent of the 1960s' catch was made up skates, liparids, and rock and flathead sole; more than 80 percent of the 1970s' harvest consisted of rock sole, cod, and skates; and in the 1980s, 80 percent of the harvest was made up of cod and skates. Accompanying these asynchronous changes in different areas of the slope since the mid-1960s was a decrease in catches of sablefish, Pacific Ocean perch, and arrowtooth flounder in all regions. This phenomenon might be attributed to intensive fishing in the 1960s, a conclusion that is supported by fishery statistics (see Table 5.1) and data on the appearance of younger generations of targeted species in the catch. The change of dominant species has also been observed in areas not exposed to strong fishing pressure, however, such as along eastern Kamchatka. The impact of fishing on the slope communities of the western Bering Sea therefore does not appear to be substantially different from that attributed to the impact of environmental changes (Ilinsky, 1990).

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Table 5.5 Groundfish composition (percent) and biomass at the shelf of the western Bering Sea

Areas (years of Surveys)	Average biomass (tons/km <sup>2</sup> )	Skates (Rajidae)	Cods	Eelpouts (Zoarcidae) (percent)	Sculpins (Cottidae)	Sea Poachers (Agonidae)	Liparids (Liparidae)	Flatfish (Pleuronictidae)	Other	Total (thousand tons)
Shelf of the Eastern Kamchatka (1984, 1987)	7.70	1.3	54.4	0.3	19.5	0.3	0.2	23.7	0.3	152
Karagin-Olutorsky shelf (1983, 1985)	17.00	0.2	81.8	1.0	7.6	0.3	0.1	8.7	0.3	615
Koryak Shelf (1985)	2.30	0.9	82.9	+	6.0	+	0.3	9.8	0.1	228
Anadyr shelf (1985)	3.79	5.9	68.8	1.5	11.1	+	0.8	11.9	+	465
Bering Strait	4.78	3.0	50.5	2.4	11.1	0.7	1.8	28.4	2.1	380

Source: Based on Shuntov et al. (1990).

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Despite the inadequacy of knowledge on the state of stocks before their commercial exploitation, Russian experts still consider demersal communities of the western Bering Sea to be resistant to external impacts. The conclusion that its structure and normal functioning had been irreversibly damaged by fishing is not supported by the available data (Shuntov et al., 1990).

### **Invertebrates**

Until 1992, shellfish stocks (king crab, Tanner crab, and humpy shrimp) were considered stable in the western Bering Sea, with catches totaling 5,000 or 6,000 t. Russian crab fishing has traditionally been concentrated along the Kamchatka shelf, with the best results in the Olutorsky-Karagin area at 60 to 150 m depth (Zilanov et al., 1989). The most promising area for shrimp has been Anadyr Bay. In 1992, statistics reflected a crucial decline in the catch of crabs (although official statistics may not include the actual catch of crabs), and data for the landings of shrimp were not reported. Western crab-processing facilities have been installed recently in more than a dozen Russian vessels. By the late 1980s, construction was started on vessels especially designed for the catching shrimp, squid, and other nontraditional (for the Russian market) and underfished species. Overall, shellfish catches from the western Bering Sea may be increased in the near future by at least 1,000 t.

## **MARINE MAMMALS (AND BIRDS)**

### **Management Systems**

Hunting of marine mammals in the Bering Sea goes back thousands of years, to subsistence catches by the original indigenous populations. The commercial hunting of certain species dates to the eighteenth century. For about the first 150 years after the Russian discovery of Alaska, there was no government regulation of marine mammal catches. The result was serious depletion of many species. The first attempts at governmental regulations of fur seal hunting were undertaken on a unilateral basis by Russia (1799, 1886, and 1892), Japan (1884), and the United States (the Alaska Statute and 1870 Hutchinson Agreement) (Mirovitskaya et al., 1993). However, numerous unilateral and bilateral attempts to manage the fur seal herds proved inadequate to prevent the depletion of stocks, which by the early 1900s were reduced to a fraction of their initial abundance (Gay, 1987). After 20 years of negotiations, the first multilateral agreement, the Treaty for the Preservation and Protection of Fur Seals and Sea Otters, was signed in 1911 by Russia, Japan, Great Britain (for Canada), and the United States (Loughlin and Miller, 1989).

The convention was functionally limited to conservation and management of fur seal stocks at the maximum sustainable yield (the highest level of productivity that a resource can maintain indefinitely). The agreement prohibited pelagic sealing, granted Russia and the United States managerial authority over specific herds (including their exploitation), and established a mechanism for compensating other signatories (Japan and Canada) for their acceptance of the

ban. The treaty worked well, resulting in a steady increase in numbers of seals on the Pribilof Islands, while allowing for a moderate catch. This convention, characterized by unique environmental factors and relative simplicity of governmental regulations, not only functioned satisfactorily for all participants for over 70 years,<sup>3</sup> but also resulted in restoration of both Asian and American northern fur seal herds (Mirovitskaya et al., 1993). The Fur Seal Treaty is often cited as a most successful landmark in multinational scientific management of shared resources. However, in 1984 the U.S. Senate refused to extend the U.S. participation in the agreement, and the regime collapsed.

Another regional marine mammal, the polar bear, is protected in accordance with the 1973 multilateral Agreement on the Conservation of Polar Bears. This regime has been especially instrumental in managing these highly migratory animals: in the two decades of its existence, the stocks recovered, scientific knowledge about the species improved substantially, and a significant effort was applied to protect critical bear habitats (Stirling, 1988).

All species of pinnipeds occur in both the eastern and western Bering Sea, and as such are resources shared by the United States and Russia. Currently there are no international agreements that provide for joint conservation and management of shared stocks, even though the need for such agreements has long been recognized (e.g., Miller, 1984). For example, Fay et al. (1989) provide a detailed description of how the lack of coordinated management has allowed repeated depletions of the Pacific walrus population.

Whaling was first controlled in 1931 by the Convention for the Regulation of Whaling. This agreement was of limited effectiveness because it did not sufficiently restrict exploitation and did not include some of the major whaling nations (Japan, the Soviet Union, and Germany). Several international conferences concerning whaling were held during the following years, but it was not until 1946 that a comprehensive agreement was signed. In that year, all the major whaling nations of the world signed the International Convention for the Regulation of Whaling, which established the International Whaling Commission and a framework for the regulation of all whale hunting. Since then, the commission has dealt with a wide array of issues pertaining to the use and management of whale stocks (see review in Loughlin and Miller, 1989).

Bering Sea bird populations, which like fish and marine mammals are shared resources of the area, are also afforded protection through bilateral agreements. These include the 1916 Convention for the Protection of Migratory Birds (between Canada and the United States), the 1936 Convention for the Protection of Migratory Birds and Game Mammals (between the United States and Mexico), the 1972 Convention for the Protection of Migratory Birds and Birds in Danger of Extinction and Their Environment (between the former Soviet Union and Japan), and the 1976 Convention Concerning the Conservation of Migratory Birds and Their Environment (between the United States and the former Soviet Union).

These agreements are not limited to the Bering Sea region, but in combination they still form a multilateral regime under which migratory birds of the region that should be protected may be taken or traded. For instance, the 1976 USSR-U.S. agreement obliged parties to identify

<sup>3</sup> The treaty lapsed in 1941 and was replaced in 1957 by the Interim Convention on the Conservation of the North Pacific Fur Seals. The Interim Convention remained in effect through several renewals and extensions, but was disbanded in 1988 after the United States decided not to ratify the 1984 extension agreement.

and list especially important habitat areas within their territory to the fullest extent possible (Wallace, 1994).

Drift nets used in the salmon fishery were subject to regulation, and there were bilateral agreements between Japan and the Soviet Union and a parallel U.S.-Canada-Japan agreement. In 1992, bilateral arrangements were replaced with the Convention for the Conservation of Anadromous Stocks in the North Pacific, which also covers the central Bering Sea area. Drift net fishing is regulated by 1991 U.S. agreements with Japan, Korea, and Taiwan.

Relations between two coastal countries are regulated by a series of arrangements. The 1972 U.S.-USSR Agreement on Cooperation in the Field of Environmental Protection included sections on Protection of Nature and the Organization of Reserves (Area V, with special reference to marine mammals), Protection of the Marine Environment from Pollution (Area VI), Arctic and Subarctic Ecosystems (Area X), and Legal and Administrative Measures for the Protection of Environmental Quality (Area XI). The agreement was intended to promote cooperative, comprehensive research on the biotic resources of Beringia and the quality of the marine environment. Resulting from this framework agreement are the 1976 Convention on the Conservation of Migratory Birds and Their Environment, the 1989 Agreement Concerning Cooperation in Combatting Pollution in the Bering and Chukchi Seas in Emergency Situations, and several cooperative projects (the 1977 complex program "Research of the Bering Sea Biology," the 1981 complex expedition that initiated the program of long-term research and monitoring of the Bering Sea, and the 1984 and 1988 joint Soviet-American expeditions for the study of human-inflicted changes in the Bering Sea ecosystem). The 1988 U.S.-USSR Agreement on Mutual Fisheries Relations encouraged cooperation in mutual fishing as well as in many other matters, including protection of marine mammals, management of anadromous species, and scientific research.

However, many of the laws and agreements to protect fish, marine mammals, and seabirds in the North Pacific and Bering Sea have proved ineffective, particularly when viewed at the international level (Harrison et al., 1990) or from ecosystem perspectives. All of these agreements are limited functionally and in membership, and do not consider functional interactions within the food web, and thus are not able to mitigate perturbations to the Bering Sea ecosystem. Necessary changes might be brought about through the activities of two recently established institutions, the North Pacific Marine Science Organization (PICES) and the International Arctic Science Committee (IASC). PICES has a working group on the Bering Sea, established to promote and coordinate marine scientific research of the area and its living resources, to examine its uses and impacts from human activities, and to promote the collection and exchange of information and data related to marine scientific research (PICES fact sheet, undated). More recently, IASC has begun an effort to examine global change in the Bering Sea region as part of its science agenda (IASC, 1994).

A relatively recent occurrence in Alaska has been the development of management regimes by groups of indigenous people (Huntingdon, 1992). These regimes take a variety of forms and are in various stages of development. Perhaps the best developed and most successful is the Alaska Eskimo Whaling Commission, which since 1981 has managed virtually all aspects of bowhead subsistence whaling through a cooperative agreement with the National Oceanic and Atmospheric Administration. Other co-management and indigenous management efforts deal with Pacific walrus (the Eskimo Walrus Commission), polar bears (the Agreement on Polar Bear

Management in the Bering Sea), beluga whales (the Alaska Beluga Whale Committee), and geese (the Yukon-Kuskokwim Delta Goose Management Plan).

However, despite an impressive list of cooperative arrangements, thus far the Bering Sea does not have a regime that can guarantee the conservation of the regional interconnected ecosystems, or prevent depletion of common resources and associated stocks that are under the jurisdiction of coastal states. Regional management systems in place are based on a few species and are hampered by the inadequacy of the regional infrastructure. Although there is ample evidence of the interconnection of resource conflicts in the area, no serious attempt at complex regional regulation has yet been undertaken (Mirovitskaya and Haney, 1992).

Within the United States, the principal laws affecting marine mammals are the Marine Mammal Protection Act (MMPA) of 1972 and the Endangered Species Act (ESA) of 1973. The MMPA applies to all marine mammal species, and establishes a moratorium on all taking (harassment, injuring, or killing) and importation, with provisions for limited exemptions. The principal exemptions are subsistence use by Alaska natives, scientific research, public display, and incidental take in commercial fisheries. All but subsistence take require permits issued by the appropriate management agencies (National Marine Fisheries Service and the Fish and Wildlife Service). A provision of the MMPA requires that species or populations be designated as "depleted" if they are below their "optimum sustainable population range" (a range between the population size at environmental carrying capacity and the size at which the population achieves its "maximum net productivity level"), or if they are classified as "endangered" or "threatened" under provisions of the ESA. Management agencies are required to be more strict in allowing takings from depleted populations. The MMPA does not allow government agencies to restrict nonwasteful subsistence take of marine mammals by Alaska natives unless a population is declared depleted.

The ESA applies only to those marine mammal species that are listed as endangered (likely to become extinct within the foreseeable future) or threatened (likely to become endangered within the foreseeable future). The ESA limits federal actions (or federally permitted actions) that may affect listed species or their habitats. It requires the development and implementation of recovery plans, and provides a framework for programs to identify, mitigate, and monitor impacts of human activities on those species.

### INTERACTIONS OF INDIGENOUS POPULATIONS WITH MARINE ECOSYSTEMS

Native settlement in the Russian and American Bering Sea coastal regions dates back well over 10,000 years, marking what was the great migration of humans from the Asian to the American continents. This region, called Beringia, was the center of the world's most developed coastal cultures (Arutunov and Sergeev, 1975; Krupnik, 1989) and at least for the last two thousand years, these cultures were economically based on maritime hunting (Dikov, 1979). Archeological data attest to the fact that several ancient indigenous cultures emerged, flourished, and coexisted in this area. Currently, the Bering Sea coasts are home to approximately 65,000 Aleut, Koryak, Chukchi, Iñupiat, and Yupik people (I. Krupnik, personal communication).

Bering Sea marine mammals and seabirds have been used by indigenous peoples of Alaska and Russia as a subsistence resource for thousands of years (Loughlin and Miller, 1989).

In earlier years, meat and blubber were eaten, blubber served as fuel, and skins, bones, organs, ivory, and feathers were used to fashion a wide variety of clothing, tools, and other objects. Although imported materials have replaced marine mammal parts for some of these uses, in many coastal communities marine mammals are still an important source of food and products for handicrafts. These animals and their parts also provide a significant and central cultural and religious aspect to the lives of indigenous peoples. The bowhead whale, walrus, and ringed seal are particularly important animals to the coastal indigenous peoples and their cultures. Subsistence take and its importance were described in a recent report of the National Research Council (NRC, 1994b). In this section, we describe the effects of indigenous peoples on the marine ecosystem and the effects of ecosystem fluctuations—some clearly caused by overexploitation of marine resources—on them.

### Russia

The western part of Beringia is the homeland for several groups of native people. The most coastal-oriented culture is that of the Asian Eskimos, which extends from the Cape of Baranov at the west to Labrador on the east, and Kamchatka to the south (At the Meeting Point of Chukotka and Alaska, 1983). This culture, which is very similar to that of the Alaska Eskimos (Iñupiat and Yupik), reflects a high level of social adaptation to the arctic environment. The culture of the coastal Chukchis who shared (with precisely fixed boundaries) the Bering area with the Eskimos was a direct later succession of the Eskimo culture. The traditional way of life for these people was organized around maritime hunting (bowhead and gray whales, beluga, sea lion, walrus and various seals, and polar bear), fishing, and collecting other sea products. Aleuts (residents of the Aleutian Islands) are somewhat different from Eskimos in language and economics, but these two cultures have common elements of environmental behavior that probably can be attributed to long-standing ethno-cultural contacts (Taksami, 1988) and common knowledge acquired through constant interaction with similar environments.

In the permanent interaction of these coastal cultures, a comprehensive system of indigenous self-sustenance was created. The main components of this system have been well described by Russian experts (Vidovin, 1965, 1976; Volfson, 1987; Krupnik, 1984, 1989; Bogoslovskaya, et al., 1984; Pika et al., 1993). It consisted of two economic lifestyles: maritime hunting and nomadic stag breeding. The economy of the local communities was based on the productive and easily accessible resources of the sea and mainland at different trophic levels (marine mammals, shellfish, aquatic plants, fish, and seabirds). Having two cultural/economic traditions, the natives of Chukotka were able to survive through temporary resource degradation both at land and at sea. This was ensured by close contacts between local communities and their diversified character. Even in 1926, more than a third of the indigenous populations were engaged in a complex native economy that included both maritime hunting and stag breeding (Results of the 1926–1927 Census of Northern Borderlands of the Far-Eastern Area, 1929). Environmental changes that were unfavorable for one form of these two economies resulted in increased productivity in the other. Native villages have always been placed at locations with concentrations of at least three types of coastal resources (Krupnik, 1989). The harvesting pressure on the resources was divided by the indigenous populations



spatially and over time; this method allowed higher productivity of the food resources, while preventing its disastrous depletion (although localized shortages did occur).

Principle 22 of the Rio Declaration holds that "indigenous people and their communities have a vital role in environmental management and development because of their knowledge and traditional practices" (U.N. Conference on Environment and Development, 1992). Formation and development of traditional resource use by indigenous people in Beringia was the result of long-term adaptation to arctic conditions. Accordingly, understanding of the historic, economic and ethical validity of the northern native peoples' experience is by all means essential for sustainable development of the Bering Sea area (Rational Resources Use, 1987). In this regard a difference between the two main aspects of Beringia coastal cultures—their environmental knowledge and their practice of resource use—should be taken into account (Krupnik, 1984, 1989; Pika et al., 1993).

Environmental experience, also referred to as "traditional knowledge," is an aggregation of notions and natives' rational knowledge about the connection between humans and nature. This comprehensive wisdom is based on day-to-day empirical observations acquired by generations. Environmental experience is reflected in ethical principles of a community, its religion, and its traditional rituals. General ethical principles of Beringia dwellers as well as most northern natives exclude the senseless destruction of natural resources. Relating to nature as a "large habitation" has always been a characteristic of their personality (Taksami, 1988). The coastal cultures of Beringia incorporated a complex of animalistic perceptions, which were reflected in a number of protective cults and ritual traditions. An extremely careful (nearly sacred) attitude towards food is confirmed by ethnographic sources (Ethnographic materials, 1978; Bogoraz-Tan, 1934) and direct surveys of Russian scholars (Krupnik, 1989).

Environmental behavior, or the actual use of resources, does not necessarily reflect acquired environmental experience and sometimes is in serious contradiction to it. Popular belief that indigenous cultures existed in absolute harmony with nature does not have historical support from the western side of Beringia. Natural conditions of the area (climatic cycles, length of time for environmental restoration in cold conditions) can cause instability in the resource base. To counteract that feature, native communities had to adopt a mode of spatial expansion and active exploitation of food sources in order to provide a "reserve of stability" necessary for critical periods. Krupnik (1984, 1989) has shown that their exploitation of natural resources had negative impacts at times. Successful years, when food harvests were two or three times their needs, were often followed by poor hunting seasons with food shortages.

Native food supply was affected both by their own exploitation of these resources and by European exploitation. In the late 1700s and early 1800s, after Russian colonization of the area, sea otters and Steller sea lions were depleted and Steller sea cows were exterminated. As many as 35,000 sea otter pelts were traded by Russia between 1746 and 1763, and about 1,500,000 fur seals were killed on the Pribilof Islands in the five-year period from 1798 to 1803 (I. Krupnik, personal communication). Under certain conditions Eskimos and Chukchi communities were able to disturb the local ecosystem balance (see, for example, Simenstad et al., 1978 for an analysis of the population and community effects of prehistoric Aleut hunting of sea otters). In the 1700s and 1800s, both before and after the peak of American whaling, native maritime hunting affected the status of marine mammal populations. Hunters of Greenland whales, walrus, and other pinnipeds usually aimed at the most accessible



animals—pregnant or nursing females, and cubs. In the 1920s, for instance, hunting pressure of Chukotka natives on stocks of marine mammals reached a level at which populations were not being replaced, and by the 1930s had significantly exceeded these levels.

The history of Beringia shows that to survive under the extremely unstable environmental conditions, native communities had to use all available means of social and technological adaptation. The cultures of Asian Eskimos and coastal Chukchis were historically based upon active, comprehensive, symbiotic, and interchangeable systems of resource use. This system of resource use with specific modes of settlements and lifestyles was consistent, even after Russian colonization of Chukotka dating back to the eighteen century (Essays on the history ..., 1974), although natural fluctuations and overexploitation by the indigenous peoples created hardships at times. Substantial changes in the life of local communities were brought about later by the Soviet policy of "socialist reconstruction." In the 1930s, several governmental decrees on social and economic development of the area were adopted, and hundreds of millions of rubles were invested in the creation of industrial enterprises. Huge migrations of new settlers from central Russia and forced collectivization and resettlement of the indigenous populations were reflected in population dynamics, in lifestyle changes, and in a decay of traditional systems of resource use. (As described by Naske and Slotnick [1987], Western contact with indigenous Alaskans had somewhat similar effects.)

The Soviet socioeconomic policies brought indigenous people to the edge of depopulation. Once the main ethnic group (99 percent in 1926), Asian Eskimos and Chukchis became minorities in their homeland: in 1989, of 164,800 inhabitants of Chukotka, only 17,400 (10 percent) were native (Numbers and Composition of the Peoples of the North, 1990). Most Chukotka inhabitants are temporary laborers, and over 70 percent of the people live there less than 10 years. Under "socialist reconstruction", the pattern of settlement has been also radically changed. Previously the Russian coastal zone was densely populated and developed; the 1926 census identified 195 native settlements (Results of the 1926–1927 Census of Northern Borderlands of the Far-Eastern Area, 1929). Coastal villages and habitations were located within walking distance from each other, within easy reach of high concentrations of several types of subsistence fish and game. After the famous 1957 decree "On the measures of further development of economics and culture of the people of the North," most of the traditional settlements were liquidated. Natives were forcefully resettled into small towns and multinational settlements specializing in fur farming (Vidovin, 1965). The system of new settlements was not compatible with traditional activities, and the settlements were not in easy reach of bountiful subsistence animals or areas of their families historic traditions. There are few villages left at the coast of the Bering Sea along with several scientific monitoring stations (Krupnik, 1989). These settlements are at a distance of 100 to 150 km from each other and are no longer economically associated.

Maritime hunting reached its peak in the 1950s when an industrial basis was established. In accordance with state government plans, the annual production of marine mammal meat by local communities reached 30,000 to 40,000 t. But quite soon maritime hunting became a prerogative of the industrial sector. The use of specialized technology caused a depletion of stocks, and in less than a decade hunting by ships ended (Volfson, 1987). This extremely short period of industrialized maritime hunting negatively affected numbers of marine fauna in the Bering Sea (Pika et al., 1993). At the same time, indigenous people began losing their traditions

of hunting and fishing. The number of native maritime hunters diminished from 700 in the early 1960s to 200 in 1985 (History and Culture of Chukchis, 1987), and the numbers of species taken (especially seals) were reduced. Coastal whaling by natives ended in the 1950s. The whales needed by local communities are taken by vessel-factory "Zvezdnyi," while the indigenous people participate only in its transportation to the land.

### United States-Alaska

While the prehistory of Alaska shares many of the same traditions as the Russian native groups, three principal groups of Eskimos inhabit the Bering Sea coast of Alaska. Each may have developed independently over a long period of time from common ancestors. The people referred to as Inuit live on Alaskan lands northeast of the Aleutian Islands all the way up the coast to the North Slope, then across the northern coast to Canada. Based on linguistics, the Inuit who live north of Norton Sound on the Bering Sea belong to the Iñupiat, while the Yupik live to the south (Ivey and Duyan, 1991). The natives living along the Aleutian Island chain are known as Aleuts. The Aleut, Yupik, and Iñupiat have their own separate languages.

Historically, village locations were chosen by Alaska natives on the basis of seasonal food gathering (subsistence), the availability of seasonal foods, and trading routes. Western Iñupiat lived primarily on salmon and seals. Arctic coastal Iñupiat lived mostly on whale, seal, and walrus meat. Inland Iñupiat and Indians lived on caribou, birds, and small game. Other food items such as eggs, roots, greens, and berries were collected by all groups (Ivey & Duyan, 1991).

Contact with western culture and people first occurred in Alaska in the 1700s and 1800s when Russian explorers and traders came to Alaska. Although Bering's explorations did not establish Russian sovereignty, Siberian fur traders succeeded in eventually forcing their way eastward along the Aleutians to the mainland of Alaska. Hunting in the Aleutians had depleted fox and sea otter which caused expansion of trapping to Kodiak Island by 1762. In 1784, a Russian company was established on Kodiak to provide furs from the Alaskan Islands and mainland. The company, called the Russian-American Company, became a state monopoly in 1799 (Tikhmenev, 1863) and moved its headquarters to Sitka in 1800. Russian expeditions continued up the Alaskan coast to Norton Sound by 1819. Thus, by the middle of the nineteenth century, southwestern Alaska had been generally mapped, and the Alaska native population had become involved in the coastal fur trade. Russian Orthodox missionaries followed the traders and the Eskimo communities had become aware of Christianity through that influence.

After 1850 commercial whalers came to the region in large numbers each summer. The whalers traded with coastal natives and many were employed both on the vessels, and at coastal stations. Trade goods such as flour, crackers, tobacco, matches, firearms and molasses were a principal form of local payment. While the United States bought Alaska from the Russians in 1867, its influence on Alaskan life came primarily from interactions with natives due to whaling, mining, and salmon fishing and canning (after 1880). Modern American culture made significant inroads to Iñupiat and Aleut village culture after World War II.

In the Bering Sea, commercial exploitation of marine mammals began soon after the voyage of Vitus Bering in 1741. Hunting by Russians, Americans, and Europeans rapidly

resulted in the extinction of one species (the Steller sea cow) and the severe depletion of several others (sea otters, fur seals, walrus, and right, bowhead, and gray whales). More recently, some marine mammal species have also been harvested for commercial purposes (see review in Loughlin and Miller, 1989).

The effects of Euro-American overexploitation of marine resources were devastating to native populations. For example, according to Igor Krupnik (personal communication), "between 1845 and 1880, American commercial whalers killed some 10,000 bowhead whales in the North Bering Sea-Bering Strait area and the same amount of right whales in the Sea of Okhotsk and the adjacent areas of the Bering Sea." They severely depleted gray whales, and "as a result, the native people of the area [on both sides of the Bering Sea] suffered enormous hardship, with hundreds (if not thousands) perishing through starvation ... between 1878 and 1882." Naske and Slotnick (1987) wrote "Whalers, who had been present even during the Russian days, eventually decimated the whales." Euro-American hunters also hunted walruses, killing an estimated 200,000 of them between 1860 and 1880 (Naske and Slotnick, 1987), and encouraged the natives to take part. Eventually, "they discarded their age-old practice of killing only those animals needed for food. Their efficiency in slaughter was enhanced by the guns they obtained from the whites. Whole villages were threatened with starvation" (Naske and Slotnick, 1987). The overexploitation of salmon also affected the natives; according to Naske and Slotnick (1987), the annual production of salmon had risen to about 2.5 million cases each containing 48 1-lb cans by 1900, and averaged 4.8 million cases per year during the 1920s and just under 7 million in the mid-1930s. They reported that this intense exploitation resulted serious damage to the cultures of the indigenous peoples of the region, and resulted in many high-level meetings between officials in Washington, D.C. and Alaska on how to resolve the "salmon problem."

The most recent human take of marine mammals has been by commercial fishermen. Marine mammals may be caught incidentally in several types of commercial fishing gear (Young et al., 1993). Some have been killed intentionally by fishermen either because the mammals were used for bait or because they were perceived as damaging to fishing gear or stealing fish (Perez and Loughlin, 1991; Alverson, 1992).

### Accounts of Harvesting by Species and Species-Groups

#### Steller Sea Lion

Before 1959, virtually all taking of Steller sea lions was for subsistence. Midden records indicate that use was intense and that hunting pressure may have reduced sea lion numbers in some areas (Interagency Task Force, 1978). Until recently, however, subsistence catches were not systematically documented. Haynes and Mishler (1991) summarized the fragmentary data available at that time and estimated that the total annual catch of 25 communities was probably around 300 to 400 animals. A statewide monitoring program in Alaska, instituted in 1992, estimated the annual take at 548 animals (Wolfe, 1993). Most of these animals were taken in the Aleutian-Pribilof region.

Steller sea lions on the Pribilof Islands were apparently heavily exploited beginning in the late 1700s as a result of Russian occupation. Sparse records indicate that many thousands of animals were taken for meat and hides. The once large population was greatly depleted, and relatively few animals were taken after 1990. Small numbers of pups were taken at a rookery on St. Paul Island in 1949 and 1950 (Kenyon, 1962). In 1959, the U.S. Bureau of Commercial Fisheries took 616 animals, principally adult males, from rookeries between Kodiak Island and Unimak Island as part of an experimental harvest (Thorsteinson and Lensink, 1962). Between 1963 and 1972, a reported 45,178 pups were taken at several rookeries in this region (Merrick et al., 1987).

Significant takes of sea lions in commercial fisheries probably did not begin until after 1950, when the fisheries off Alaska began a period of explosive growth (Alverson, 1992). Records of the number of animals that may have been taken incidentally in fishing gear and intentionally shot are incomplete. Perez and Loughlin (1991) estimated that over 20,000 animals were incidentally caught in foreign and joint-venture trawl fisheries during 1966 to 1988. Matkin and Fay (1980) estimated that 305 sea lions were shot while interfering with fishing operations in the Copper River salmon gill net fishery in the spring of 1978. In recent years, the levels of both incidental and intentional taking have been considerably lower (Wynne, 1990; NMFS, unpublished data).

Alverson (1992) estimated that approximately 140,000 sea lions were killed by all human activities between 1960 and 1990. According to his estimates, most of these were from commercial fishery (45,178), incidental takes and shootings to protect gear in the trawl and salmon fisheries (43,976), and indiscriminate shootings associated with fisheries (34,000).

### Northern Fur Seal

The history of northern fur seal catch has been well documented (Figure 5.9; Lander, 1980; York, 1987). Subsequent to the discovery of the Pribilof Islands, Russians took an average of about 40,000 fur seals on the island rookeries each year using Aleut labor. The numbers taken dropped after 1820, but increased greatly after the purchase of Alaska by the United States in 1867. Unregulated catches resulted in nearly 250,000 fur seals being taken in 1868–69, after which regulations were passed that controlled the catch on the Pribilofs. From 1868 until 1911 over 600,000 animals were taken from the oceans. In 1911 the Treaty for the Preservation and Protection of Fur Seals and Sea Otters ended the pelagic catch and controlled the take on land. The convention was not renewed after it expired in 1984, and since 1985 the only catches have been by Pribilof Island residents for subsistence purposes. Annual catches since 1911 are shown in Table 5.6.

Considerable numbers of northern fur seals were incidentally caught in salmon and squid drift nets fished on the high seas beginning in the 1970s. Estimated catches in some years exceeded 2,000 animals (NMFS, 1993a). Fur seals have been caught only occasionally in trawl fisheries (Perez and Loughlin, 1991).

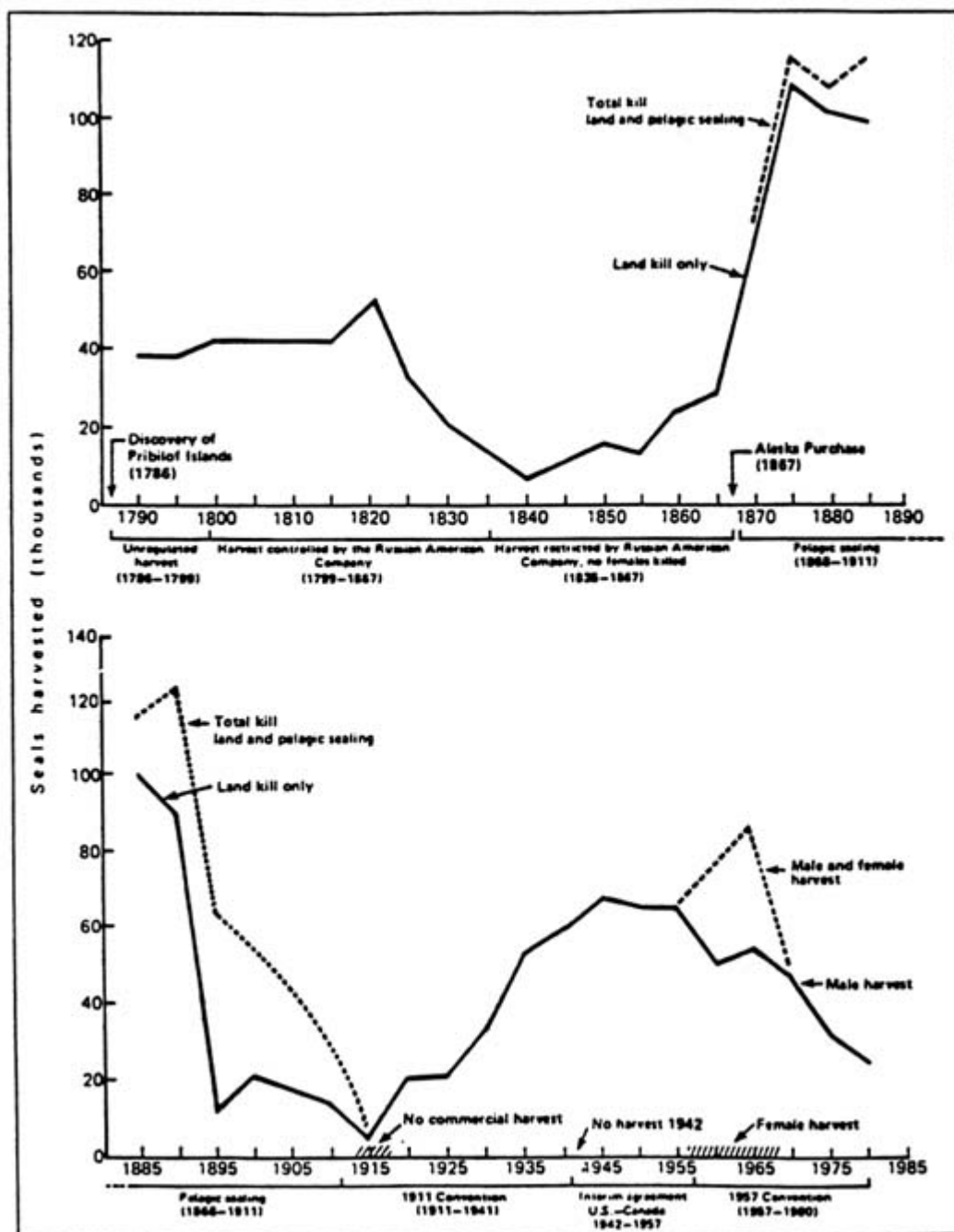


Figure 5.9 History of northern fur seal exploitation, Pribilof Islands, Alaska, 1786-79 (data are five-year averages) (York, 1987).

Table 5.6 Total number of fur seals taken annually on the Pribilof Islands, 1911–93

Year	Total Kill	Year	Total Kill
1911	11,899	1952	63,870
1912	3,169	1953	66,068
1913	2,406	1954	63,882
1914	2,735	1955	65,453
1915	3,947	1956	122,826
1916	6,466	1957	93,661
1917	8,169	1958	75,797
1918	34,890	1959	58,257
1919	27,790	1960	40,635
1920	26,648	1961	126,046
1921	23,656	1962	97,440
1922	31,152	1963	86,338
1923	15,854	1964	65,432
1924	17,189	1965	52,554
1925	19,839	1966	52,888
1926	22,088	1967	65,816
1927	24,916	1968	58,960
1928	31,061	1969	38,908
1929	40,068	1970	42,241
1930	42,497	1971	31,849
1931	49,516	1972	37,393
1932	49,329	1973	28,482
1933	54,550	1974	33,027
1934	53,468	1975	29,148
1935	57,296	1976	23,296
1936	52,446	1977	28,794
1937	55,180	1978	25,183
1938	58,364	1979	26,113
1939	60,473	1980	24,677
1940	64,856	1981	24,276
1941	95,013	1982	25,177
1942	150	1983	26,268
1943	117,164	1984	22,416
1944	47,652	1985	3,713
1945	76,964	1986	1,439
1946	64,523	1987	1,802
1947	61,447	1988	1,258
1948	70,142	1989	1,521
1949	70,890	1990	1,241
1950	60,090	1991	1,926
1951	60,689	1992	1,676
		1993	1,837

Source: NMFS, unpublished data.

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## Harbor Seal

From 1927 to 1967 U.S. federal and state governments paid a bounty on seals to encourage catches. Bounty records did not distinguish harbor seals from other species, but assuming that most of the seals submitted for bounty in the southeast and central/southwest Alaska districts were harbor seals, annual kills ranged from about 2,500 to 12,000 during 1927–52 (Wolfe, 1993). In the early 1960s, Alaskan harbor seal skins were sold on the European fur market and catches increased substantially. Estimated yearly catches climbed from between 6,000 and 10,000 before 1963 to over 50,000 in 1965 (Interagency Task Force, 1978). Many of these animals were pups taken at large haulouts such as Bristol Bay. Reduced prices for raw skins resulted in decreased catches (i.e., 8,000 to 10,000 per year). An additional 38,444 seals were reported killed on the Stikine, Taku, and Copper river deltas during 1951 to 1959, in a predator control program (Wolfe, 1993).

For the most part, subsistence catches of harbor seals have not been systematically monitored. Estimates of annual catches for the 1970s and early 1980s range from 500 to 2,500 (Hoover, 1988b). A detailed study reported that 2,867 seals were killed by subsistence hunters in Alaska during 1992 (Wolfe, 1993). Fifty-eight percent of the take occurred in southeast Alaska.

There is relatively little information on takes of harbor seals by commercial fisheries. Young and other (1993) cited reports of takes of 1,729 in 1978 and 2,800 in 1979, but kills of less than 100 in 1990 and 1991. Matkin and Fay (1980) estimated that about 500 harbor seals were killed or seriously injured in interactions with salmon drift net fisheries in Prince William Sound and the Copper River delta in 1978. Wynne (1990) reported that seal interactions with these fisheries were much less frequent in 1988 and 1989. Apparently harbor seals are only rarely caught in trawl fisheries (Sease, 1992).

## Ice-Associated Seals

In the United States, the only catches of ice-associated seals have been for subsistence purposes. Annual catches for all species through 1972 were estimated to range from about 15,000 to 21,000, consisting of about 65 percent ringed seals, 20 percent spotted seals, 15 percent bearded seals, and a few ribbon seals (Interagency Task Force, 1978). Catches generally declined after 1972. Kelly (1988a) considered that the annual take of ringed seals in Alaska during the mid-1980s probably exceeded 3,000. Burns (1981) estimated the average annual take of bearded seals in Alaska during 1966–77 as 1,784.

Soviet/Russian shore and ship-based hunters have taken substantial numbers of ice-associated seals. In the Bering Sea, ship-based fishing began in 1961. Catches of ringed seals in the 1970s and 1980s were generally 1,000 to 2,000 animals in each of the Bering and Chukchi seas (Kelly, 1988a). Shore-based hunters along Chukotka took about 1,000 bearded seals a year, whereas ship-based catches in the Bering and Chukchi seas ranged from about 1,000 to 7,000 per year (Kelly, 1988b). For ribbon seals, ship-based catches averaged 9,971 to 1961 to 1967 and then declined to an average of 2,933 during 1969 to 1982 (Kelly, 1988c). Ship-based catches of spotted seals in the Bering Sea ranged from 1,000 to 5,000 per year during 1969 to

1983 (Quakenbush, 1988). Ice-associated seals are seldom taken in commercial fisheries (Young et al., 1993).

### **Walrus**

Before the introduction of modern weapons and equipment, the subsistence catches of walrus by indigenous peoples of the Bering-Chukchi region were probably quite small. Commercial exploitation of the Pacific walrus population apparently began in the mid-seventeenth century and continued at a relatively low level through the mid-1980s (Fay et al., 1989). Fishing intensified after the purchase of Alaska from Russia, as American whalers pursued bowhead whales in the Bering and Chukchi seas, and averaged more than 12,000 animals per year during 1869–79. These figures do not include animals that were wounded or killed but not retrieved. Catches by whalers virtually ceased after 1880, probably because of scarcity of walrus and declining demand for walrus oil. Catches from 1880 through 1930 were largely unrecorded, although they may have been large enough to have some impact on the population (Fay et al., 1989).

Detailed records of Pacific walrus catches by the Soviet Union/Russia and the United States during 1931 to 1989 have been compiled by Fay and Bowlby (1994). The Alaskan take was generally less than 2,000 animals per year through 1974, and somewhat higher after that. The total annual Soviet/Russian catches have varied considerably, from less than 1,000 to over 8,000. However, some estimated 200,000 walruses were killed by Alaska native hunters off the Chukchi Peninsula between 1931 and 1961 (Krylov, 1968). These figures represent only the number retrieved and do not include animals killed but lost.

Pacific walrus are occasionally taken incidentally to commercial fishing, especially in bottom trawls (Young et al., 1993).

### **Sea Otter**

Indigenous people living around the North Pacific rim have taken sea otters for thousands of years. In at least some areas, fishing pressure was apparently great enough to cause local reductions in sea otter numbers and at least temporarily to restructure subtidal biological communities (Simenstad et al., 1978). Intense commercial exploitation of sea otters began in the mid-1700s and continued virtually unregulated until 1911. Records are incomplete, but it is likely that about 500,000 animals were taken over this period (Kenyon, 1969). In 1911, all hunting except that by Alaska natives was prohibited by the Treaty for the Preservation and Protection of Fur Seals and Sea Otters.

During 1962 to 1970, the State of Alaska conducted an experimental harvest program that took about 2,500 animals from densely populated islands in the Aleutians (Interagency Task Force, 1978). Since 1972, the only catches have been by Alaska natives for subsistence and production of handicrafts. Catches have increased somewhat in recent years, generally amounting to several hundred animals per year (U.S. Fish and Wildlife Service, unpublished data).

Alaskan sea otters are sometimes taken incidentally in commercial fisheries, especially gill net fisheries, but the number taken is relatively small (Young et al., 1993).

## Whales

Bowhead and gray and beluga whales have been hunted by aboriginal people of the Bering Sea region for at least the last 2,000 years (Krupnik, 1984; Stoker and Krupnik, 1993). Bowhead and beluga whales continue to be a valued subsistence resource for Alaska natives, with an average of 23 bowhead whales landed<sup>4</sup> each year between 1973 and 1994 at nine major whaling villages (Marine Mammal Commission, 1995). In the 1960s, the USSR began a government hunt of gray whales to provide food for coastal Siberian Eskimos, with an average take of about 165 per year; only a few gray whales are taken each year by Alaska natives (Wolman and Rice, 1979).

Commercial hunting of gray whales began in the bays and lagoons along the coast of Baja California in 1845–46 (Henderson, 1984). It is estimated that over 5,000 whales were killed in the lagoons in the 11 hunting seasons beginning in the winter of 1854–55. Because the hunting was conducted in calving areas, a large part of the catch was adult females (calves were not included in catch figures), and thus the population was rapidly depleted. The last significant catches were made in the early 1870s, by which time the major calving lagoons were essentially devoid of whales (Henderson, 1984). Relatively few gray whales were taken by pelagic whaling operations (Reeves, 1984).

Commercial exploitation of baleen whales in Alaska began in the mid-1800s, when American whalers discovered abundant stocks of bowheads in the northern Bering Sea, and right whales in the southeastern Bering Sea and western Gulf of Alaska (Bockstoce and Burns, 1993). Bowheads were depleted in the Bering Sea in the first 10 years after their discovery in 1848. By the end of the century, bowheads were greatly reduced in both Bering and Chukchi seas, and right whales were nearly extinct.

Limited whaling took place in Alaska during the first half of the twentieth century from a few shore-based stations in the eastern Aleutians and Gulf of Alaska. Following the end of World War II, however, Japanese and Russian pelagic whaling in the North Pacific expanded rapidly, targeting sperm and large baleen whales, particularly blue, fin, sei, and humpback whales. Intensive exploitation of baleen whales began in waters around Japan, spread north along the Kuril Islands to the southwestern Bering Sea, and then spread east along the Aleutians. Rich feeding grounds of whales were discovered in the Bering Sea and eastern Aleutians in the mid-1950s and in the Gulf of Alaska in the early 1960s (e.g., see [Figure 4.29](#)), and large catches of fin and sei whales were made (see [Figure 4.30](#)). Most whaling ended with international regulation imposed in 1975, by which time stocks of all large whales in the Bering Sea and Gulf of Alaska were severely depleted. Estimated total catches in the North Pacific during the 1950s

<sup>4</sup> Approximately 55 percent of bowheads struck during this period were landed; the proportion has increased in recent years to more than 70 percent. The quota has recently been raised from 52 animals struck and 41 landed per year to 68 struck and 55 landed in 1995; the landings quota will remain at 55 through 1998 but the strikes permitted will decrease to 65 in 1998 (Marine Mammal Commission, 1995).

to 1970s included 5,761 blue whales, more than 26,040 fin whales, 74,215 sei whales, and 30,143 humpback whales (NMFS, 1991b). The number, and particularly the biomass, of humpback and blue whales removed was not an insignificant proportion of the total for all baleen whales removed from the northern Gulf of Alaska, Aleutians, and Bering Sea.

In addition to baleen whales, sperm whales (*Physeter macrocephalus*) were heavily exploited in the North Pacific Ocean in the 1950s, 1960s, and 1970s. Between 1956 and 1976, more than 210,000 sperm whales were killed in the North Pacific, with many thousands of those killed in the Bering Sea (I. Krupnik, personal communication). Even those killed outside the Bering Sea (as is true with other whales) might have affected the Bering Sea ecosystem (including its human inhabitants) because they are migratory. The net result of this exploitation, which began in earnest in the eighteenth century, has been an enormous reduction in the numbers of whales in the Bering Sea.

## 6

# Causes and Effects in the Bering Sea Ecosystem

Population changes in some Bering Sea marine mammal, seabird, shellfish, and fish species over the last 30 years may indicate changes that could affect the long-term status of the Bering Sea ecosystem as a natural resource. The causes and significance of these changes are the key issues faced by the committee. The goals of this chapter are to broadly examine the effects of both environmental variation and patterns of human use on the Bering Sea ecosystem, and to develop a scenario for how they may have manifested themselves over the past three decades. The chapter is divided into three sections.

The first section attempts to answer the following questions: Is environmental variability a cause of changes in marine mammal, seabird, and fish assemblages in the Bering Sea ecosystem? If so, are the links direct (e.g., a direct population response to physical forcing) or indirect (e.g., bottom-up trophic interactions)?

The second section focuses on human effects by addressing the following questions: Is human activity a cause of change in marine mammal, seabird, and fish assemblages in the Bering Sea ecosystem? Has nonextractive resource use, such as waste disposal and pollution, had an effect on the ecosystem? Has extractive resource use—i.e., fishing—affected the Bering Sea ecosystem through removals causing short-term changes in density or distribution, or longer-term effects on population abundance, or through indirect impacts on nontarget species (e.g., bycatch)?

The third section presents a conceptual analysis of observed changes in marine mammal, seabird, and fish assemblages in the Bering Sea ecosystem over decadal periods. Some major changes in the Bering Sea ecosystem are known to be the direct result of human extractive use (e.g., the depletion of certain marine mammals and fish stocks of commercial importance), whereas other changes appear to be related to environmental factors. The proposed conceptual model recognizes that both anthropogenic and natural factors have had major influences on the Bering Sea ecosystem—the model suggests that the current Bering Sea ecosystem is a product of the complex interactions between human use and natural fluctuations caused by natural forcing. The analyses in this section build on the framework provided in [Chapter 2](#).

## ENVIRONMENTAL VARIABILITY

Much has been said about the regime shift that occurred in the North Pacific starting in the mid or late 1970s ([Chapter 3](#)). A relatively warm period was initiated in the northeastern part of the region, oceanic plankton productivity increased in the Gulf of Alaska, salmon production more than doubled throughout Alaska, and several fish populations experienced unusually strong recruitment and grew dramatically. At the same time, Steller sea lions, harbor seals, and some populations of seabirds in the Alaska region declined. Were such changes unique or had they occurred previously in this region or elsewhere in the world?

Appropriate data sets to answer this question are scarce. There are suggestions (see Francis and Hare, 1994; Beamish, 1993) that an earlier period of high productivity occurred in the North Pacific about 50 years ago. The apparent abundance of several stocks of sardines in the Pacific showed similar peaks, in the late 1930s and early 1940s and again after the mid-1970s (Kawasaki, 1991).

Steele and Henderson (1984) modeled long-term fluctuations in fish stock and showed that many pelagic fish stocks change rapidly in abundance, with intervening periods of about 50 years. In a later paper, Steele (1991) reviewed changes in several North Atlantic ecosystems, including the North Sea, where there had been dramatic herring declines and demersal fish increases, and concluded that large switches in marine communities can last several decades and that they can occur without human involvement, but can be increased in frequency or amplitude by human actions (see also [Chapter 2](#)).

While the major cause of such regime shifts appears to be changes in ocean climate of comparable frequency—that is, changes in circulation and mixing, and consequent alteration of surface layer temperature and other conditions—the mechanisms linking environmental and biotic changes are poorly understood. Conventional wisdom is that productivity at lower trophic levels is enhanced (or diminished), for example, by intensification (or diminution) of upwelling, with altered productivity then being felt at higher trophic levels. There may be other significant biotic consequences of climate changes, including:

- Changes in the community structure as recruitment of different species is differently affected by ambient conditions.
- Changes in distributions and migration patterns, especially of early life history stages, affecting survival of individuals of species and their availability to predators.

Many of the changes in the relative abundances of species in both fish and invertebrate communities observed in the 1960s in the Bering Sea appear to have been associated with the development of large commercial fisheries. This is perhaps most clearly illustrated in the overexploitation of groundfish assemblages (e.g., Pacific Ocean perch, yellowfin sole, and herring in the eastern Bering Sea and Gulf of Alaska). But low-frequency changes in ocean and atmospheric climate have also been documented in the Bering Sea and Gulf of Alaska over this



period. These environmental changes may have increased the productivity of some species while reducing the productivity of others.

### Natural Frequencies in the Environment

Over relatively short periods, changes in ocean climate will have the most pronounced impacts on the productivity of lower trophic levels. The response of top consumers to such changes may also be evident in the short-term (for example, seabird chick survival), but longer-term effects may also be expected.

One important issue in this study is whether the environment is influencing fish population and associated fishery changes. To address this question, it is necessary to first define what is meant by natural fluctuations in the environment and their effects on fish and fisheries in marine ecosystems. Some aspects of Bering Sea variability discussed in [Chapter 4](#) are then revisited in order to see how they may relate to environmental forcing.

There are many natural frequencies of variability in the northeast Pacific and Bering Sea. Those most studied by fisheries oceanographers are those that occur at the annual and decadal-scales. The sense of annual scale variability is critical for providing the stock assessments needed for annual fisheries management cycles. However, it is the decadal (and longer)-scale variability that seems to provide more insight into marine ecosystem processes, and such scales are rapidly becoming the focus of fisheries oceanography in both the North Pacific and North Atlantic. A fundamental question being asked is whether climate can cause rather rapid shifts in the organization of marine ecosystems, and if so, on what time and space scales these effects can be measured.

Hollowed and Wooster (1992) postulated that there are two mean state of winter atmospheric circulation in the North Pacific ([Figure 6.1](#)). These states are identified by the frequency of intense winter "Aleutian low pressure" events and the resulting ocean temperature and surface wind field responses. In a later paper, Hollowed and Wooster (1994) were able to show a link between years of anomalously low coastal ocean temperatures (caused by intense winter low-pressure events) and simultaneous strong year classes in groundfish species ranging from California to the Bering Sea ([Figure 6.2](#)). Fritz et al. (1993) provided evidence that pollock recruitment is positively correlated with temperature ([Figure 6.3](#)).

Francis and Hare (1994) have used the methods of time series analysis (autoregressive integrated moving average, and intervention models) to analyze or describe the spatial and temporal dimensions of the relationship between salmon production and atmosphere/ocean physics. They found very significant and coherent linkages between relatively sudden interdecadal shifts in the North Pacific atmosphere and ocean physics and marine biological responses as evidenced by indices of Alaska salmon production. [Figure 3.10](#) summarizes some of the results of these analyses. The top panel shows the time series of the North Pacific index (winter atmospheric pressure) during the twentieth century (Trenberth and Hurrell, 1994). The bottom two panels show actual fits of data and intervention analysis models to the index (1900–92) and western Alaska sockeye salmon catch time series (1925–92). Two points stand out from this analysis:

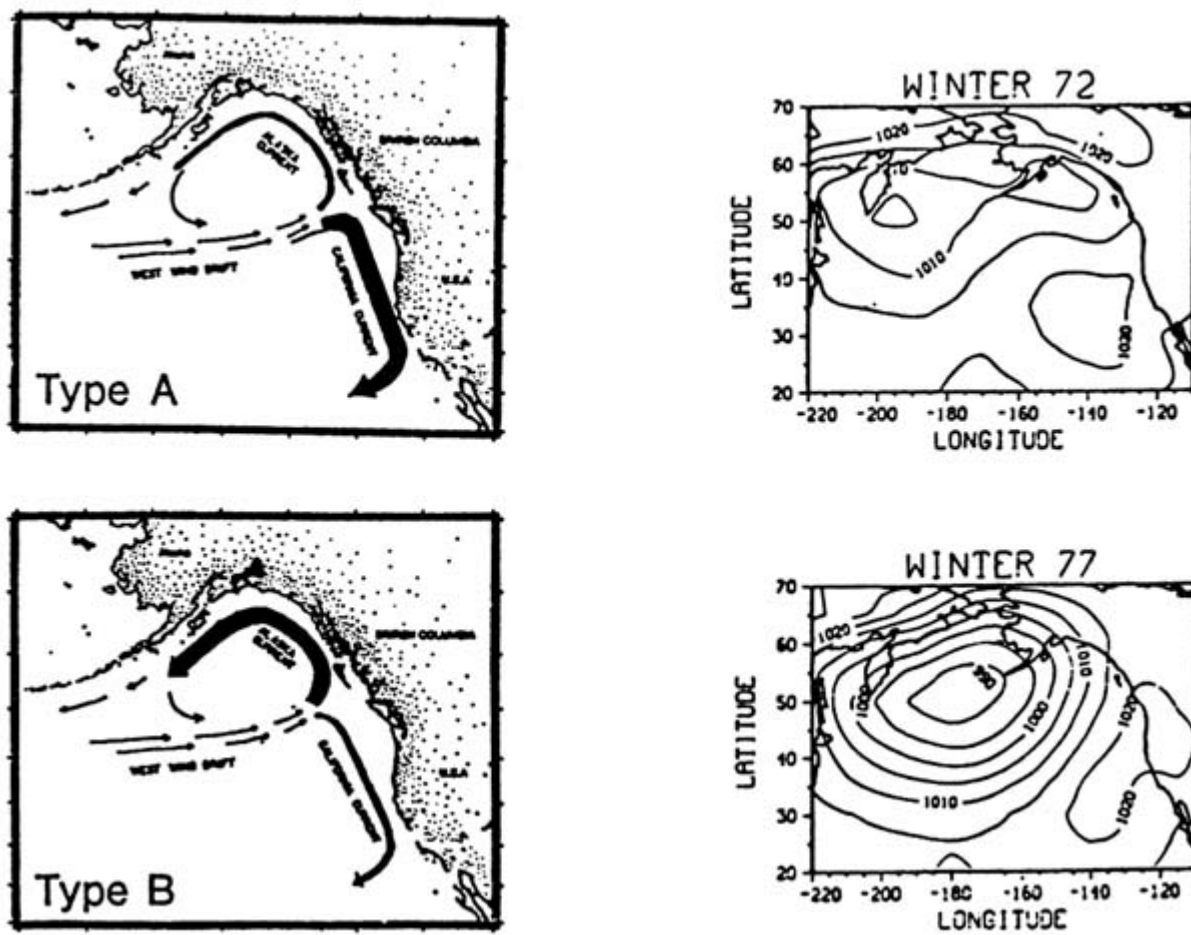


Figure 6.1 Two alternating patterns of atmospheric circulation postulated by Hollowed and Wooster (1992). An example of a winter sea level pressure pattern is illustrated for each circulation type (reproduced from Emery and Hamilton, 1985).

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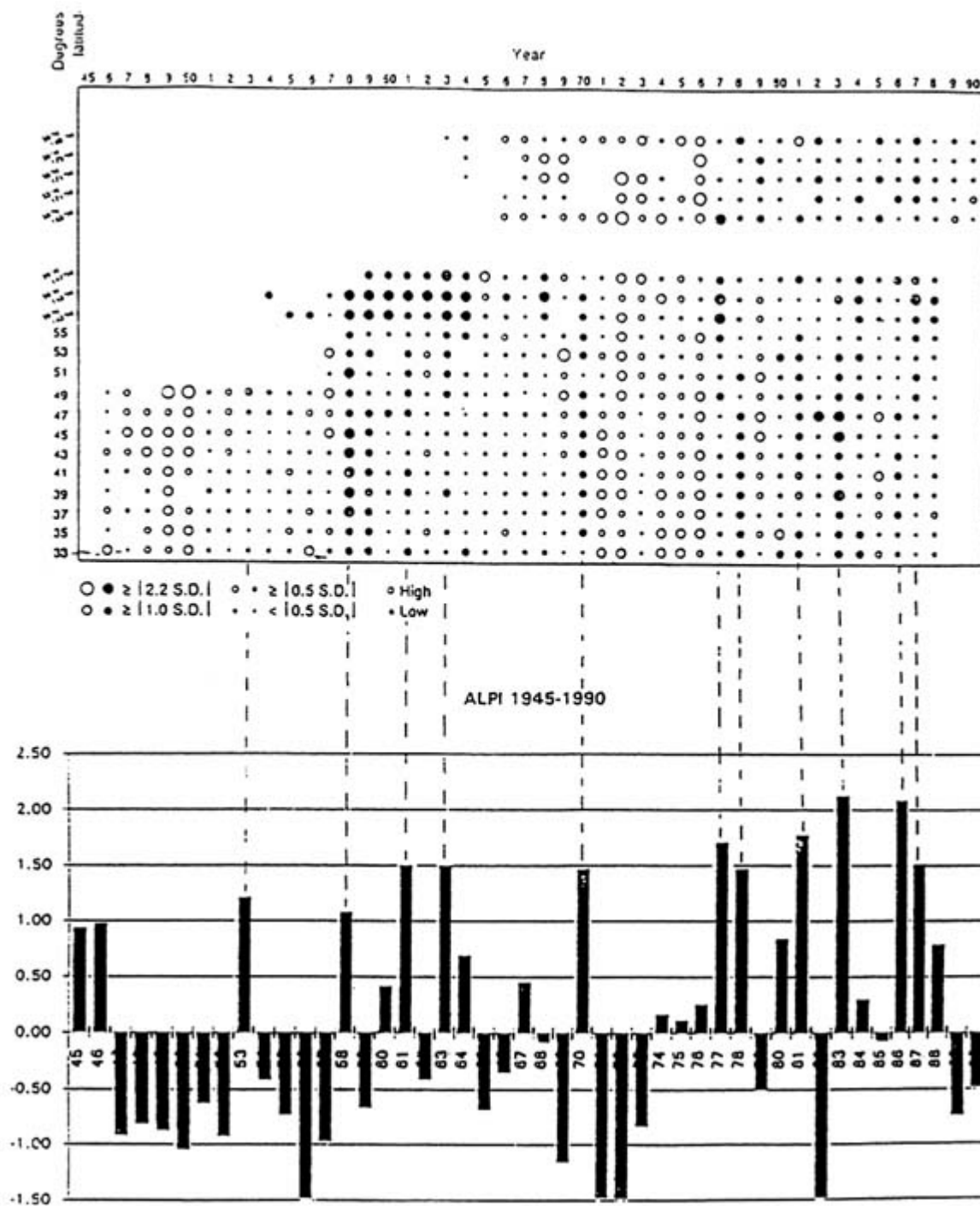


Figure 6.2 Relationship between sea surface temperature anomalies (upper) and proportion of northeast Pacific groundfish stocks with extreme year classes (lower) (W. Wooster, personal communication).

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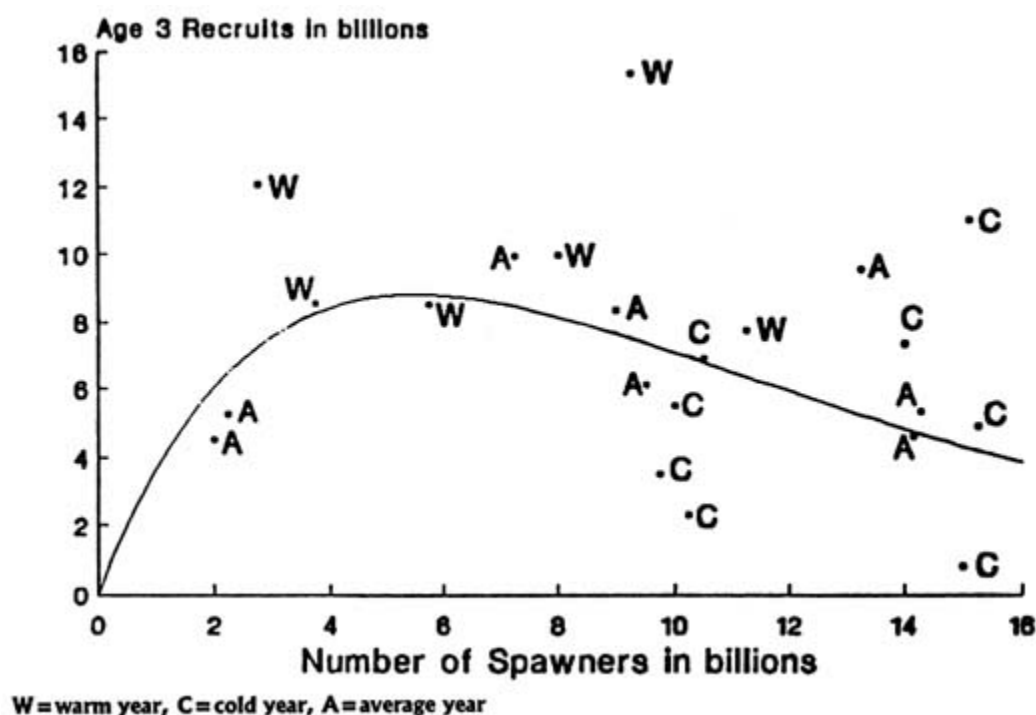


Figure 6.3 Bering Sea pollock spawner-recruit relationship and relative temperature during the first year of life for each year class. W = warm year, C = cold year, and A = average year (from Fritz et al., 1993a).

- Coherence is shown between physical and biological variables primarily at the decadal (regime) scale, and not the annual scale.
- During the twentieth century, there appear to have been four interdecadal regimes (Figure 3.10) in the North Pacific coupled atmosphere/ocean system: 1900 to 1924, 1925 to 1946, 1947 to 1976, and 1977 to the present.

Certainly the well-documented regime shift that occurred during the winter of 1976–77 had a profound impact on many components of North Pacific large marine ecosystems. Venrick and others (1987) show significant shifts in phytoplankton production (integrated chlorophyll-a) just north of Hawaii at about that time (Figure 3.16). Subsequent analysis reveals that the increase may be due to increased production of a deep species of phytoplankton in response to a shift in ocean mixing and a deepening of the mixed layer. Brodeur and Ware (1992) found a significant shift in the zooplankton biomass of the subarctic Pacific (Alaska Gyre), which corresponds to this recent regime shift (Figure 3.17). Later in this section, we point out possible relationships between this climatic regime shift and biological responses in the Bering Sea ecosystem.

Baumgartner et al. (1992) looked at natural frequencies in climate-driven fish production of the northeast Pacific over a much longer period. Through the analysis of fish scale deposition rates in anaerobic sediments in the Santa Barbara Basin off southern California, they developed a 1,750-year time series proxy of pelagic fish abundance in the California Current (Figure 6.4,



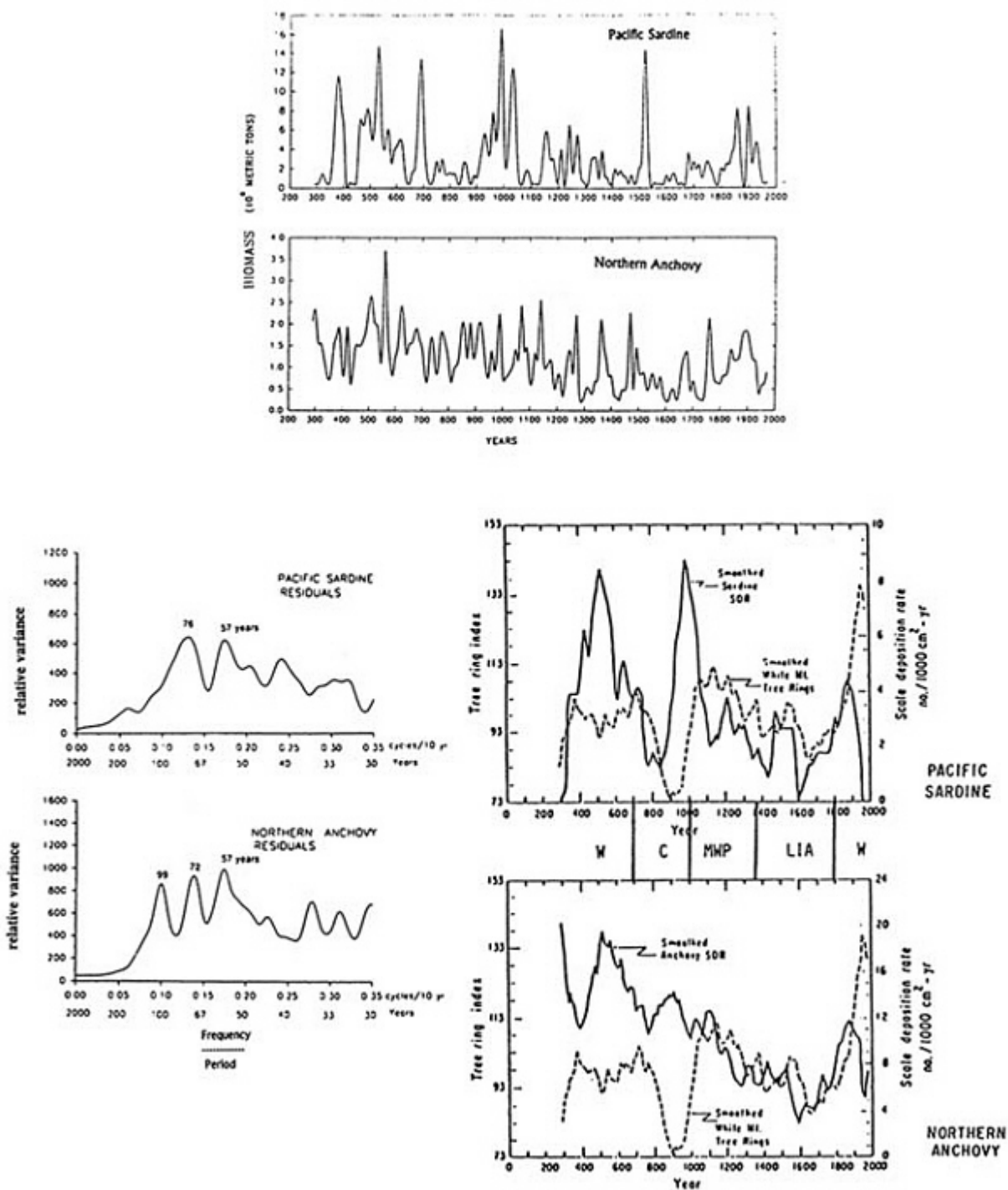


Figure 6.4 Proxy time series of pelagic fish abundance in the California Current (top), power spectra for high-frequency (< 150 year) variability (bottom left) and low-frequency (> 150 year) variability compared with tree ring widths (bottom right) (Baumgartner et al., 1992; t. Baumgartner, personal communication).

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top panels on Pacific sardine and northern anchovy). They partitioned this variability into low frequency (periods greater than 150 years) and high frequency (periods less than 150 years). The low-frequency variability reflects the centennial-scale climate epochs of the last 200 years (e.g., Medieval Warm Period and Little Ice Age), and relates very closely to bristlecone pine tree ring widths, which reflect prevailing atmospheric temperature regimes (Figure 6.4, bottom right panel). The high-frequency power spectra for both sardine and anchovies show peaks at around 60 and 75 years (Figure 6.4, lower left panel). During the twentieth century, pelagic fish populations of the California Current have tended to vary in response to atmospheric forcing similar to Alaska salmon (see Figure 3.14) (Ware and Thompson, 1991). This being the case, the kind of decadal-scale atmospheric forcing in the North Pacific seen during the twentieth century could have persisted for centuries.

As discussed in Chapter 3, Royer (1982) has identified possible relationships between regular variations in the production of a number of commercially important North Pacific marine species and the 18.6-year nodal tidal signal. For example, fluctuations in Bering Sea herring abundance since the early 1960s are noticeably similar to the pattern of sea surface temperature (Figure 6.5). Herring spawn inshore and feed in the coastal zone during the summer. Thus, year-class strength is probably related to the seasonal development of the coastal biological community, which is advanced and more prolific in warm years (Cooney, 1981; Springer et al., 1984, 1987). Likewise, the nodal tide signal has been associated with 60 percent of the variance of year class strength of halibut in the Gulf of Alaska (Parker et al., 1994). Of possible greater importance to the biota than the temperature contribution is the alteration of the relative amplitudes of diurnal and semidiurnal tidal components over this 18.6-year period. Organisms that are dependent on one of these tidal components might suffer under these changing conditions. Nodal tide variability might also affect the tidal mixing in the Bering Sea, as suggested by Loder and Garrett (1978) for the Labrador shelf.

The point of this discussion is that climate-driven variability in the large marine ecosystems of the North Pacific is significant, occurs at many different time scales, and affects many components of the ecosystems. It seems clear that climate does cause rather rapid shifts in the organization of these marine ecosystems and that the decadal-scale may be more important than the annual scale in its impact.

### Environmental Effects on Marine Mammals and Birds

Over relatively short periods, changes in productivity will likely have the most pronounced effects at lower trophic levels, but there may also be longer-term effects on top consumers. Lipps and Mitchell (1976) proposed a model linking the evolution of pelagic marine mammals to changes in the trophic structure of the oceans. They suggested that variations in primary productivity caused by upwelling may explain the invasion of the sea by mammals, and subsequent radiations and extinctions.

As large-bodied, long-lived, K-selected species, marine mammals would be expected to be relatively insensitive to many types of environmental fluctuations. As discussed in Chapter 4, most species that occur in the Bering Sea have relatively broad distributions in the North Pacific or Arctic Basin, and are therefore adapted to survival under a range of environmental



conditions. Conditions that exceed physiological limits and result in the deaths of individuals should occur infrequently, especially in the core of a species' range (e.g., Trites, 1990). However, it is clear that pinnipeds living in more southern regions may be affected by relatively severe climatic events such as El Niño (Trillmich and Ono, 1991).

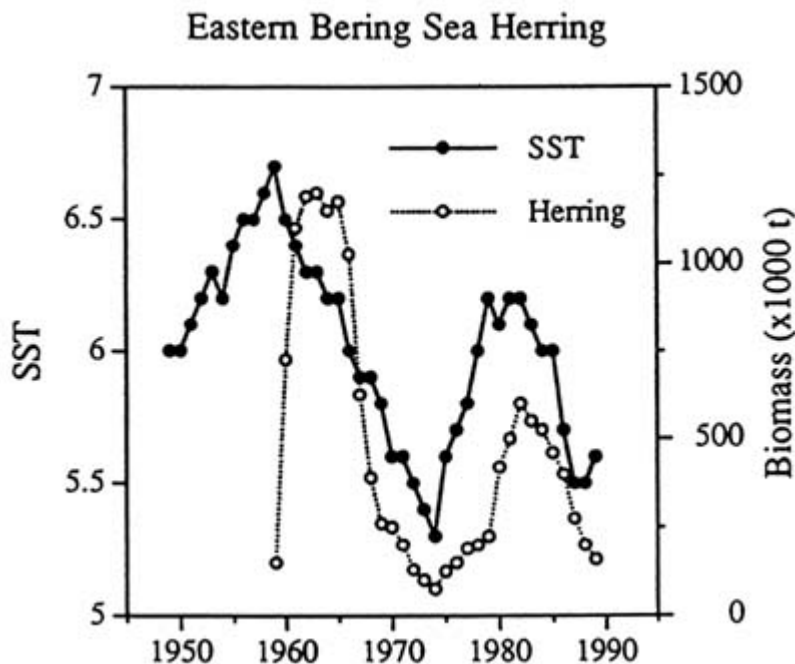


Figure 6.5 Bering Sea herring abundance and sea surface temperature (Wespestad, 1991).

Climate-caused physical changes in the environment can have significant effects on marine mammal habitats, and thereby on the abundance and distribution of species. In the Bering Sea, sea ice plays an important role in marine mammal ecology, providing important habitat for some species while excluding others (Fay, 1974). Year-to-year variations in the extent of sea-ice cover change species distributions, which may have a variety of biological effects. An example of ice-cover-dependent interspecific interaction is the relatively high rate of walrus predation on seals that occurred in the Bering Sea in 1979. This was a very light ice year, when the overlap in distributions of these species was greater than usual (Lowry and Fay, 1984).

Over a longer time frame, changes in sea-ice cover are related to changes in sea level. The two in combination may have a dramatic effect on marine mammal habitat availability (Davies, 1958). These events must have resulted in major shifts in the distributions of pinnipeds that use either land or ice for hauling out.

As discussed previously, the recent significant declines in fur seals, sea lions, and harbor seals probably have been environmentally influenced by climate-induced changes in the abundance and availability of food for juveniles during this critical phase of their life histories. More specifically, the problem probably has something to do with the relative availability of appropriately sized pollock and other forage fish (e.g., capelin, sand lance, and herring), and

would be a decadal (rather than annual)-scale effect. Environmental change, however, may not be the only cause of reductions in food for pinniped species.

### **Bering Sea Fish (Invertebrates) and Fisheries**

A number of the variations in Bering Sea fish populations described in [Chapter 4](#) appear to be related to environmental forcing. In general, there are two ways that this kind of forcing manifests itself. First, it can redistribute marine fish populations and their fisheries in space. The second and perhaps more important way is by affecting the absolute abundance of marine fish populations primarily through mechanisms controlling recruitment of new individuals. A considerable number of commercially important marine fish stocks of the Bering Sea (and Gulf of Alaska as well) and their fisheries are, at any time, supported by a relatively small number of very strong year classes or cohorts. Looking at a number of figures presented in [Chapter 4](#), one can certainly see evidence of this in the eastern Bering Sea and Gulf of Alaska (see [Figures 4.1, 4.2, and 4.3](#) on king and Tanner crab; [Figure 4.5](#), on walleye pollock; [Figure 4.13](#), on Pacific cod; [Figure 4.14](#), on Atka mackerel; [Figure 4.18](#), on flatfish; [Figure 4.21](#), on Pacific Ocean perch; and [Figures 4.24 and 4.25](#), on herring). Because fisheries tend to develop on stocks that are at high abundance (due primarily to strong recruitment), attempts to attribute cause generally focus on the causes of declines in these stocks rather than their increases even though the high stock levels may be anomalous events. The classic example of such a case in the northeast Pacific is that of pollock in Shelikof Strait (Gulf of Alaska).

**Groundfish.** A number of groundfish populations of the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska were significantly affected by the well-documented regime shift (general warming) that occurred in the winter of 1976–77 and subsequently manifested itself in the late 1970s and early 1980s. As pointed out by Hollwed and Wooster (1992), several strong year classes of groundfish occurred in 1977 and 1978 (eastern Bering Sea and Gulf of Alaska pollock in 1978, eastern Bering Sea cod in 1977, and Aleutian Islands Atka mackerel in 1977). In particular, these very strong year classes of pollock and cod supported significant expansions of Bering Sea fisheries. The 1978 year class of pollock essentially supported the expansion of the Bering Sea pollock fishery into the Aleutian Basin (Bogoslof and donut hole). In addition, the pollock fishery of the eastern Bering Sea shelf was redistributed to the southeast in the late 1970s in possible response to changes in ocean climate (see [Figures 4.8, 4.9, and 4.10](#)).

Although the year classes seem to be more difficult to pinpoint, significant increases in eastern Bering Sea shelf flatfish populations occurred in the late 1970s and early 1980s (yellowfin sole, rock sole, and Alaska plaice; see [Figure 4.18](#)). There was also a large increase in arrowtooth flounder in the Gulf of Alaska. At the same time, the one eastern Bering Sea flatfish species that tends to prefer colder water (Greenland turbot) declined significantly. Juvenile Greenland turbot were pushed to the northwest along the outer Bering Sea shelf as the ocean climate warmed ([Figures 4.15 and 4.16](#)).

**Forage Fish.** Pacific herring biomass in the eastern Bering Sea exhibits patterns similar to those of a number of other groundfish and invertebrate populations—decadal-scale surges in biomass supported by a small number of very strong year classes (Figures 4.24 and 4.25). As for a number of groundfish populations, the 1977 year class of eastern Bering Sea herring was extremely strong, possibly in response to the concurrent regime shift. It is interesting to note that the three largest year classes of herring (1957, 1958, and 1977) occurred at times of significant warming in the North Pacific (see Figure 6.5), and perhaps also in response to the 18.6-year nodal tidal signal.

In the western Gulf of Alaska, a 20-year record of trawl catches of important indicator species revealed that capelin virtually disappeared in the 1980s (Figure 4.27). Data on seabird diets and from fishery surveys in the Bering Sea also indicate that capelin and eulachon, another smelt, essentially disappeared there during the same time (Decker et al., 1995; Fritz et al., 1993; Figure 4.26). Both species were comparatively abundant in the 1970s, when the physical regime was much different than in the 1980s. Deposition rates of fish scales in Skan Bay on the Bering Sea side of Unalaska Island (eastern Aleutians) declined abruptly in the late 1970s after a period of relatively high abundance (R. Francis, personal communication). None of these short histories runs entirely parallel to that of herring, and all are difficult to evaluate in a decadal-scale context.

**Salmon.** The clear link between decadal-scale variations in Alaskan salmon abundance and regime-scale North Pacific climate fluctuations was discussed earlier in this section.

**Invertebrates.** As discussed in Chapter 4, fluctuations in eastern Bering Sea and Gulf of Alaska crab populations (king and Tanner; Figures 4.1, 4.2, and 4.3) and their fisheries occur in response to infrequent strong year classes or cohorts. The most dramatic of these fluctuations occurred in 1981 in Bristol Bay and 1982 in the Kodiak region of the Gulf of Alaska, when red king crab fisheries in both regions crashed. The Bristol Bay resource supported the largest king crab fishery in the world. Beginning in 1966, this fishery increased annually, to an all-time record catch of 58,938 t in 1980 (Figure 5.7). This increasing trend was mirrored in the biomass estimates from stock assessment surveys performed annually by the National Marine Fisheries Service. However, beginning in 1979, the survey began reporting a decline in overall biomass relative to the prior year's estimate. These pre-season forecasts were not readily accepted by the industry. Many people believed that the survey "missed the crab." In 1981, however, the catch dropped from almost 59,000 t to 15,876 t. Although such a decline in catch was predicted, the magnitude of the decline was shocking. In 1982, the catch fell to only 1,361 t, and in 1983 the number of reproducing male and female crabs was believed to be so low that no directed fishery was permitted.

Similar collapses were observed in all the other major crab fisheries in the Bering Sea (Figure 5.7). The next most valuable king crab was blue king crab, found most abundantly in the Pribilof Islands region. This fishery experienced similar declines in catch, from a high of 4,991 t in 1980, to 1,998 t in 1982, to only 318 t in 1987. Since then there has been no directed fishery for blue king crab in the Pribilof region. The largest of the Tanner crabs,

*Chionoecetes bairdi*, went from an all-time high in 1976–77 to no fishery by 1986. The smaller *C. opilio* crab became valuable only after the industry scrambled to develop alternative markets.

Once again, environmental forcing could have significantly affected all of these dynamics, by creating favorable conditions for those pulses of strong year classes that have supported many of the invertebrate (and finfish) fisheries of the North Pacific and Bering Sea. The declines, or in some cases crashes, were likely the results of disappearances due to mortality (natural and/or fishing) of those strong year classes, and were probably not environmentally driven.

## HUMAN EFFECTS

### Pollution

Persistent organics, heavy metals, and radioisotopes are major anthropogenic inputs from human industrialization that flow into marine systems. For example, acid rain drainage into the western Bering Sea from coal mining on the Kamchatka Peninsula and into the Gulf of Anadyr in the northern Bering Sea is of concern (National Geographic, 1994). The impact of such anthropogenic contaminants on high-latitude marine ecosystems, such as the Bering Sea, can be especially detrimental, because many biota are long-lived and slow growing, and thus are capable of accumulating pollutants over time. In addition, certain higher trophic animals (marine mammals, seabirds, and fish), which can accumulate these pollutants, are consumed by humans, and thus these contaminants are transferred to humans. Currently, the international Arctic Monitoring Assessment Program (AMAP, 1993), along with U.S. and Russian scientists involved in the program of Long-term Ecological Investigations of the Bering Sea and Other Pacific Ocean Ecosystems (BERPAC) (O'Connor et al., 1992), are focusing on these major contaminants. There is to date no hard evidence that these contaminants have significantly affected the Bering Sea ecosystem.

**Persistent Organics.** Persistent organics are transported primarily from low latitudes to the high latitudes via airborne transport. For example, polychlorinated biphenyls (PCBs), DDT, dioxins, hexachlorocyclohexane (HCH), dibenzofurans, chlordane, and toxaphene have been found in arctic air, surface water, snow, suspended sediments, fish, marine mammals, seabirds, terrestrial animals and humans (Barrie et al., 1992; Lockhart et al., 1992; Muir et al., 1992; O'Connor et al., 1992; Thomas et al., 1992). Long-range transport can occur via rivers and ocean currents as well as the atmosphere (carrying pollutants from industrialized and agricultural areas, including those in Asia, Europe, and North and Central America). Although many of these organic compounds have been banned in many countries, they are still produced and used in many other countries around the world.

Persistent organic compounds are preferentially volatilized in warm regions of the world and transported to cold regions, such as the Bering Sea and the Arctic Ocean (Otto, 1981). This process is known as "cold trapping" (Muir et al., 1992). Persistent organic compounds preferentially accumulate in the fatty tissues of organisms. This is especially important in cold northern regions where lipid-rich wildlife is consumed by native populations, thus providing

a direct pathway of these pollutants to humans (Kinloch et al., 1992; Muir et al., 1992). Concentrations of HCHs and toxaphene are greater in surface waters of the Arctic than in waters of the temperate or north Atlantic waters (Muir et al., 1992; O'Connor et al., 1992). Dioxins and dibenzofurans have higher concentrations in ringed seals and polar bears in the Canadian high Arctic than mammals further south (Norstrom et al., 1990). Elevated concentrations of PCBs have been found in both planktonic and benthic fauna and sediments in the Bering and Chukchi seas (Chernyak et al., 1992; Rice et al., 1992), and elevated concentrations of PCBs have been found in the breast milk of native Inuit women (Dewailly et al., 1989). However, no population-level effects have been observed to date.

**Heavy Metals.** Heavy metals are also of concern and have both local and long-range transport mechanisms. The cold Arctic is a sink for heavy metals, and marine mammals are known to contain elevated concentrations of heavy metals, especially mercury and cadmium (AMAP, 1993). Low concentrations of heavy metals have been found in organisms and sediments of the Bering and Chukchi seas (Kolobova et al., 1992; Krynitsky et al., 1992). Other anthropogenic compounds of concern are those influencing acidification and arctic haze in the atmosphere, climate change (e.g., global warming), and depletion of stratospheric ozone.

**Radionuclide Contamination.** Radionuclide releases, both from atmospheric testing fallout and from dumping into the marine environment, are of special concern. The revelations of large-scale disposal of radioactive materials in the North Pacific Ocean (e.g., off Kamchatka Peninsula in the western Bering Sea) and the Arctic Ocean by the former Soviet Union (Yablokov et al., 1993) have led to new interest in the study of how these ecosystems respond to environmental stress and global change. Recent information on the extent of Russian radioisotope contamination in the North Pacific and Arctic oceans is of interest to this study. Although current concentrations in the Bering Sea do not indicate a widespread threat, there is a need for national surveys and monitoring networks to establish baselines for specific radioisotopes in the atmosphere) and in aquatic and terrestrial environments (AMAP, 1993).

An example of a radioactive isotope used to study long-term transport of released materials is plutonium (with a half-life of 24,000 years). Plutonium isotopes ( $^{240}\text{Pu}$  and  $^{239}\text{Pu}$ ) from fuel reprocessing have a specific ratio different from the ratios in bomb fallout. Data presented by T. Beasley (personal communication) at the 1993 Interagency Research Policy Committee Workshop on Arctic Contamination in Anchorage showed that low concentrations of plutonium in surface sediments in the Canada Basin of the Arctic Ocean off Alaska are unequivocally derived from weapons-grade material ( $^{240}\text{Pu}/^{239}\text{Pu} = 0.06$ ), most likely discharged from plutonium reprocessing plants on the Ob and Yenesei rivers in Siberia. At the same time, the plutonium isotope composition of shallow sediments in the Bering and Chukchi seas is consistent with bomb fallout sources ( $^{240}\text{Pu}/^{239}\text{Pu} = 0.20$ ), even though the still low inventories of plutonium are an order of magnitude higher than in the deep arctic sediments.

Cesium-137, a particle-reactive radioisotope, is an anthropogenic product of nuclear testing (half-life of 30.2 years) that was introduced into the biosphere at around 1953, as a result of bomb fallout deposition. The distribution in marine sediments is influenced not only by



atmospheric fallout but also by oceanographic currents, bioturbation, and greater cation exchange and solubility in seawater, as well as by additional sources derived from nuclear material disposal, particularly in the former Soviet Union. Recent data indicate only low-level contamination of marine sediments (Figure 6.6; Cooper et al., 1995; Grebmeier et al., 1993). The highest radiocesium concentration (12.9 Bq kg dw<sup>-1</sup>) occurred in a sheltered embayment (Port Clarence, Alaska) subject to significant freshwater runoff, which would provide a source of terrestrially deposited <sup>137</sup>Cs, irreversibly bound to clay minerals. Some radiocesium accumulation has been detected in Bering and Chukchi Sea benthic organisms (J.H. Grebmeier, L. Cooper, and I.L. Larsen, unpublished data, 1994). Low concentrations of dissolved or waterborne <sup>137</sup>Cs have also been detected in the water column, and the inventory integrated over depth at various sites in the Bering and Chukchi seas ranged from 8.1 to 12.6 mBq cm<sup>-2</sup> in 1988 (Medinets et al., 1992); consequently most of the radiocesium is deposited within sediments. A comparison with marine sediments more heavily by anthropogenic contamination, such as Russian waters of the Black Sea, indicate a combined surface sediment concentration of 17.3 Bq kg dw<sup>-1</sup> for <sup>137</sup>Cs, with total <sup>137</sup>Cs inventories of 536 mBq cm<sup>-2</sup> (J. Grebmeier, L. Cooper, and I. L. Larsen, unpublished data, cited in Cooper et al., 1995); therefore typical cesium concentrations and inventories in Alaskan marine sediments of the Bering and Chukchi seas are an order of magnitude less than in Black Sea sediments. Ongoing studies as part of the Office of Naval Research, U.S. Fish and Wildlife Service and Arctic Monitoring Assessment Program will provide additional data to develop long-term monitoring and assessment programs.

### Offshore Oil and Gas Development

Although Alaska is estimated to contain large petroleum resources on its outer continental shelf (OCS) and in state waters (i.e., within three miles of shore) (NRC, 1994b), the only oil produced from Alaska's OCS to date has come from Cook Inlet south of Anchorage. There has been considerable industry interest in the OCS off Alaska's Beaufort and Chukchi seas, north of the Bering Sea, and a great deal of production from state waters and onshore around Prudhoe Bay. Because the oil is piped from the North Slope to Alaska's south-central coast, there has been little or no direct effect of North Slope oil production on the Bering Sea. Industry interest in the Bering Sea has been relatively low and has declined recently (NRC, 1994b), although leases have been sold there and exploration has occurred in the past (Lewbel, 1983; MMS, 1992). For example, a lease in the Navarin Basin (part of the Bering Sea OCS) planned for 1992 was canceled because of lack of industry interest and deferred for further review until 1996 (MMS, 1992). Thus, the likelihood of offshore oil and gas production in the eastern Bering Sea within the next 10 years is close to zero, because it takes at least that long after a lease sale to begin producing oil and gas, and there is little or no exploration taking place in the eastern Bering Sea at present. There is no possibility in the foreseeable future of the kind of extensive oil and gas activities that characterize the OCS of the central Gulf of Mexico. Little or no OCS oil and gas activity is occurring or likely to occur soon in the Russian area of the Bering Sea (West, 1994). It is therefore safe to conclude that OCS oil and gas activities in the Bering Sea have not significantly affected the Bering Sea ecosystem.



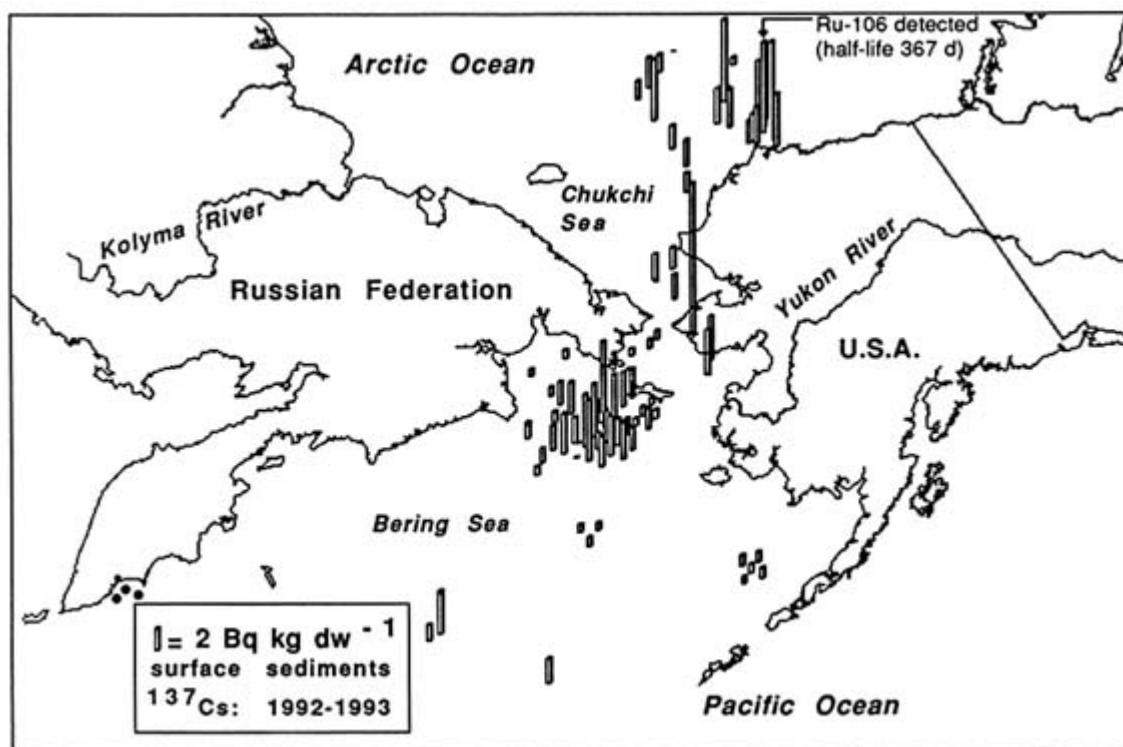


Figure 6.6 Surface sediment cesium-137 distributions during 1992 and 1993 (Cooper et al., 1995). The black dots indicate radioactive dump sites (Yablokov et al., 1993).

The actual effects of offshore oil and gas activities have been described in recent reports by the National Research Council (most recently with respect to Alaska [NRC, 1994b]) and by the Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP, 1992). The 1994 National Research Council report considered potential effects of oil and gas activities in Alaskan waters, especially the Beaufort and Chukchi seas.

The most likely adverse effects of these activities—for the Bering Sea as well as for the Beaufort and Chukchi seas—would occur on shorelines (NRC, 1994b), because there is unlikely to be enough development to affect more than small, localized areas in the open sea. Even a major oil spill at sea would probably have the most serious consequences on shorelines reached by the spilled oil. Two major potential sources of adverse effects—in both the western and eastern Bering Sea—would be onshore developments that were related to offshore oil and gas activities, including exploration, development, production, and operation of terminals (possible onshore developments could be related to staging, fabrication, and pipeline terminals, harbors, and housing for workers) and oil spills (from accidents involving development and production wells, and transportation accidents). Particularly sensitive areas onshore include estuaries, lagoons, haulout areas for marine mammals, marine bird colonies, and other places where organisms gather to feed, overwinter, or reproduce. Areas of human habitation and activities would also be particularly sensitive.

### Direct Effects of Extractive Resource Use

Chapters 4 and 5 showed that a number of changes in animal populations observed in the Bering Sea are due simply to direct and intentional removals by humans. It is important to recognize these explainable changes, as distinct from the unexplained population declines that are now of major concern.

**Marine Mammals.** Hunting has clearly had a major impact on populations of Bering Sea marine mammals. Over the past 200 years, nearly all species have been harvested for commercial and/or subsistence purposes. The Steller sea cow was hunted to extinction, and the northern right whale nearly so. Gray whales, bowhead whales, fur seals, walruses, and sea otters were severely reduced, but their populations have recovered to various degrees. Blue whales, fin whales, humpback whales, sperm whales, and sei whales were not heavily hunted until relatively recently, so it is unclear what their long-term recovery will be. Species of relatively low commercial value (e.g., Steller sea lions, ringed seals, bearded seals, spotted seals, and harbor seals) generally have not been severely depleted by hunting, though they are consistently hunted for their subsistence use and because they have important cultural and traditional values for the native populations. However, it is quite possible that hunting was partially responsible for the initial decline of sea lions, harbor seals, and fur seals in some parts of their range.

**Fish.** Fishing has clearly had significant influence on the dynamics of fish populations in the Bering Sea. The effects have been most clearly seen in the K-selected slope rockfish species (in particular, Pacific Ocean perch) harvested in the 1960s from the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska. As was mentioned in Chapter 5, these populations were essentially mined out of the region and, with a few exceptions, have shown little indication of recovery. Most slope rockfish are long-lived (as long as 90 years for the Pacific Ocean perch [Bakkala, 1993]) and have very low rates of production. This natural history suggests that these populations are adapted to capitalize on infrequent environmental conditions that support strong year classes. With populations at such low levels from the heavy fishing of the 1960s, the chance of taking advantage of these rare conditions when they occur could be significantly reduced.

The other group of groundfish species that showed similar responses to the heavy and uncontrolled exploitation of the late 1950s and 1960s were the eastern Bering Sea shelf flatfishes, and in particular, yellowfin sole (Figure 4.15). Unlike Pacific Ocean perch, perhaps because of its more r-selected nature, the yellowfin sole population grew in the late 1970s and early 1980s to previous biomass levels.

It is clear that fishing has affected the populations of many groundfish, forage fish, and invertebrates of the Bering Sea and Gulf of Alaska. These fisheries grew rapidly in response to large year classes that boosted populations to high levels of abundance, and in later years of lower recruitment, the fisheries accelerated the declines by removing the biomass that had been created by strong recruitment. This certainly seems to be the case for pollock and cod in both

the Bering Sea and Gulf of Alaska, Atka mackerel in the Aleutian Islands, herring in the eastern Bering Sea, and king and Tanner crab in the eastern Bering Sea and western Gulf of Alaska.

Recalling the discussions in [Chapter 2](#) of ecosystem structure and self-organizing capacities, perhaps the most serious effects of fishing are long-term impacts on ecosystem organization by the rapid removals of large biomasses of long-lived species (Apollonio, 1994). Removals create tension or disequilibrium at the system level, which, because of the low rates of production of the harvested species, will not be relieved by recoveries to previous conditions. As a result, something else fills the energy niche. And so, according to Allen (1985), this tension within an ecosystem can set the stage for rapid reorganization—the greater the tension, the greater the potential for rapid reorganization. Systems under great tension can then be triggered, perhaps by rather subtle environmental shifts, into rapid and significant flips from one state to another, with drastic alterations in system structure. In this way, the history of fishing and hunting can play a vital role in determining the nature of marine ecosystem order. This is clearly true for the Bering Sea ecosystem, as is discussed further in this report.

### Indirect Effects of Extractive Resource Use

Each year commercial fisheries remove large quantities of biomass from the eastern Bering Sea and Gulf of Alaska. (Substantial quantities of biomass are also removed from the western Bering Sea, but—as described in [Chapter 5](#)—reliable quantitative information on those removals is not available.) Although this is an obvious feature of fishing, the actual particular impacts of such removals on other species and on the ecosystem as a whole are largely unknown. Management of marine fish harvests is largely based on assumptions of maximum sustainable yield models. It is assumed that fishing will reduce the standing stock of fish such that there is a density-dependent increase in productivity, resulting in a harvestable surplus. Under the sustainable yield model, the annual biomass increment that is removed by fishing will be replaced the following year as a result of the growth of surviving fishes and the recruitment of new individuals to the population. It is also assumed that changes in the abundance of the target fish population as a result of fishing have no impact on the abundance of competitors in the system. That is, it is assumed that the dynamics of the target population are decoupled from the system. This is not likely to be a reasonable assumption in most situations, and is not an ecosystem-based approach as described in [Chapter 2](#).

There are several ways in which removals of fish by fisheries may have effects on other ecosystem components. One may be the effect of fishing on competitive interactions, such that the reduction in density of fishes due to fishing results in reduced food availability for fish-eating predators. The amount of fish caught each year depends on a number of factors. In the Bering Sea, annual catch rates for pollock, herring, and yellowfin sole have ranged from less than 10 percent to more than 60 percent of the exploitable biomass removed (Fritz et al., 1993b). Clearly, industrial fisheries, like that for pollock in the Bering Sea, remove massive amounts of fish biomass from the ocean (the Bering Sea total pollock harvest was almost 4 million t in 1988; [Figure 4.6](#)). According to fishery managers, pollock stocks in the Bering Sea, Aleutian Islands, and Gulf of Alaska have not been "overfished" in recent years. Nonetheless, several regions

where pollock were once abundant (e.g., Shelikof Strait, the Bogoslof Island area, and the donut hole) have been heavily exploited, and pollock stocks are now very low in those areas.

The most dramatic example of possible local overexploitation occurred in Shelikof Strait. A large spawning concentration of pollock was "discovered" in this region in the late 1970s, and an intensive fishery rapidly developed. As a result, pollock catches in the Gulf of Alaska increased from less than 100,000 t to more than 300,000 t and remained high even during the mid-1980s, when it was apparent that there had been poor recruitment and stock abundance was declining (Megrey and Wespestad, 1990). During this period, annual combined removals from fishing and sea lion predation were estimated to be as much as 30 to 50 percent of the total exploitable biomass (Lowry et al., 1989). According to one estimate (Nunnallee and Williamson, 1988), exploitable biomass of pollock in the Gulf of Alaska fell from greater than 3 million t in 1981 to less than t in 1993 (NPFMC, 1993). During this same period of time, sea lion numbers on nearby rookeries showed a dramatic decline, and animals began to show signs of reduced growth rate (Calkins and Goodwin, 1988; Lowry et al., 1989). However, before 1962–71, models suggest that pollock population sizes and year-class strengths were very low, yet there is no evidence that the sea lion population was in decline. It would be of interest to know what the principal fish in their diet were at that time.

The effect of fishery removals on competitive interactions will depend not only on the amount of biomass removed, but also, and perhaps more importantly, on the spatial and temporal pattern of fishing. We might expect that fisheries that operate on a broad temporal and spatial scale would have a lesser effect on local density of fishes than those that are compressed in space and time. The development of sophisticated, highly capitalized fishing fleets has in many cases resulted in harvesting that is very intense. For example, during the winter of 1994 the Bering Sea trawl fleet caught approximately 600,000 t of pollock in a six-week period. At its peak, the fleet was harvesting at a rate of 30,000 t per day. The actual effects of fishing on local densities of fish and the effects of changes in local fish density on marine mammal predators are currently unknown.

Another way in which fishing may indirectly affect marine ecosystems is through effects on community structure. In the eastern Bering Sea, large harvests of both whales and fishes, coupled with favorable environmental conditions, could have led to the large increase in pollock abundance that is thought to have occurred in the late 1960s and early 1970s (see [Chapter 4](#)). This pollock-dominated pelagic system has probably had significant effects on the abundance of other species of fish, which in turn may have affected seabirds and pinnipeds. Similar major shifts in the dominance of the fish community on Georges Bank in the western North Atlantic (from gadoids to elasmobranchs and pelagic species) have recently been attributed to excessive fishing (NOAA, 1993). Numerous detailed studies have shown a direct correlation between die-offs of seabirds related to deprivation of fish; several examples are cited in Croxall (1987) and Nettleship et al. (1984). One example from the Arctic was presented by Lid (1981), who showed that there was a drastic decline in the breeding success of Atlantic puffins, common guillemots, and razorbills in the Norwegian sector of the North Sea as a result of a reduction in local herring through overfishing. Harvests of herring dropped from 10 million t in 1958 to 0.5 million t in 1969. As discussed in [Chapter 4](#), the major die-offs of seabirds in the Bering Sea and Gulf of Alaska, particularly in the vicinity of the Pribilofs, have been associated with increased fishing and reduction in prey for the birds.

Probably the most intriguing relationship between trawling and ecosystem patterns is the time-space correlation between intense trawl fishing and the declines in two marine mammal species, the Steller sea lion and the harbor seal. Declines in these two species coincide with the period of tremendous concentration of trawling effort in time and space that accompanied the Americanization of the fishery after establishment of the 200-mile exclusive economic zone (Fritz, 1993a, 1993b). Yet the observed declines in the populations of both Steller sea lions and harbor seals are not uniform across the ranges of the species in the North Pacific. Populations have not declined in the region from southeast Alaska southward. This line coincides with the demarcation between the geographic region where trawl fisheries operate to the north and where trawling is light or absent to the south. The existence of such a correlation is consistent with some effect of trawling on the populations of these two species of marine mammals. On a smaller scale, attempts to correlate the amounts of pollock caught with changes in sea lion numbers have yielded equivocal results. Loughlin and Merrick (1989) compared fish removals from blocks around seven rookeries with the trend in sea lion counts at those rookeries and found significant negative correlations in some cases, but no relationship or positive correlations in other instances.

The likely impacts of fishing on the nutritional status of consumers will depend on a number of factors, including the areas and times fished, the size distribution of the catch, the feeding preferences and population sizes of the predators, and the availability of alternate prey. Steller sea lions consume a wide range of sizes of pollock, including those targeted in the commercial catch (Frost and Lowry 1986). Much of this catch has been taken from areas in the Bering Sea, Aleutian Islands, and Gulf of Alaska that are near major Steller sea lion rookeries and haulouts (Fritz et al., 1993a, 1993b). These fisheries are very much pulsed in nature, and they might therefore have a major impact on the local abundance of pollock (and perhaps other nontarget species) in areas that are intensively fished. More information is needed on this matter.

The National Marine Fisheries Service has identified the areas within 20 nautical miles of most rookeries and haulouts, and three at-sea zones (eastern Bering Sea near Bogoslof Island, Seguam Pass, and Shelikof Strait) as critical feeding habitat for Steller sea lions. Fritz (1993a) compiled the records of pollock catches within these areas during 1977–92. In the Bering Sea the catch in critical feeding habitat increased from 100,000 to 300,000 t during 1977–86, to 500,000 to 600,000 t during 1987–91. Most of the latter catch was from the Bogoslof fishery, targeting spawning female pollock in the eastern Bering Sea critical feeding habitat. For the Gulf of Alaska, the percentage of the catch from critical feeding habitats increased from less than 5 percent in 1977 to more than 80 percent in 1985, and has fluctuated between 55 percent and 93 percent during 1986–92. Research on the effects of this fishing on sea lions is needed.

Relatively small pollock appear to be important foods for several marine mammal species (Frost and Lowry, 1986; Figure 6.7), and they may be particularly significant in the diets of Pribilof fur seals and young Steller sea lions (Merrick and Calkins, in press; Sinclair et al., 1994). Pollock stocks in both the Gulf of Alaska and Bering Sea have shown variable recruitment since the early 1960s, and occasional strong year classes have supported the commercial fishery (Fritz et al., 1993b). If reductions of pollock spawning stocks from fishing affect the abundance of small pollock (either the size of recruitment within a year or the frequency of relatively strong recruitment events), this could have an impact on the growth,



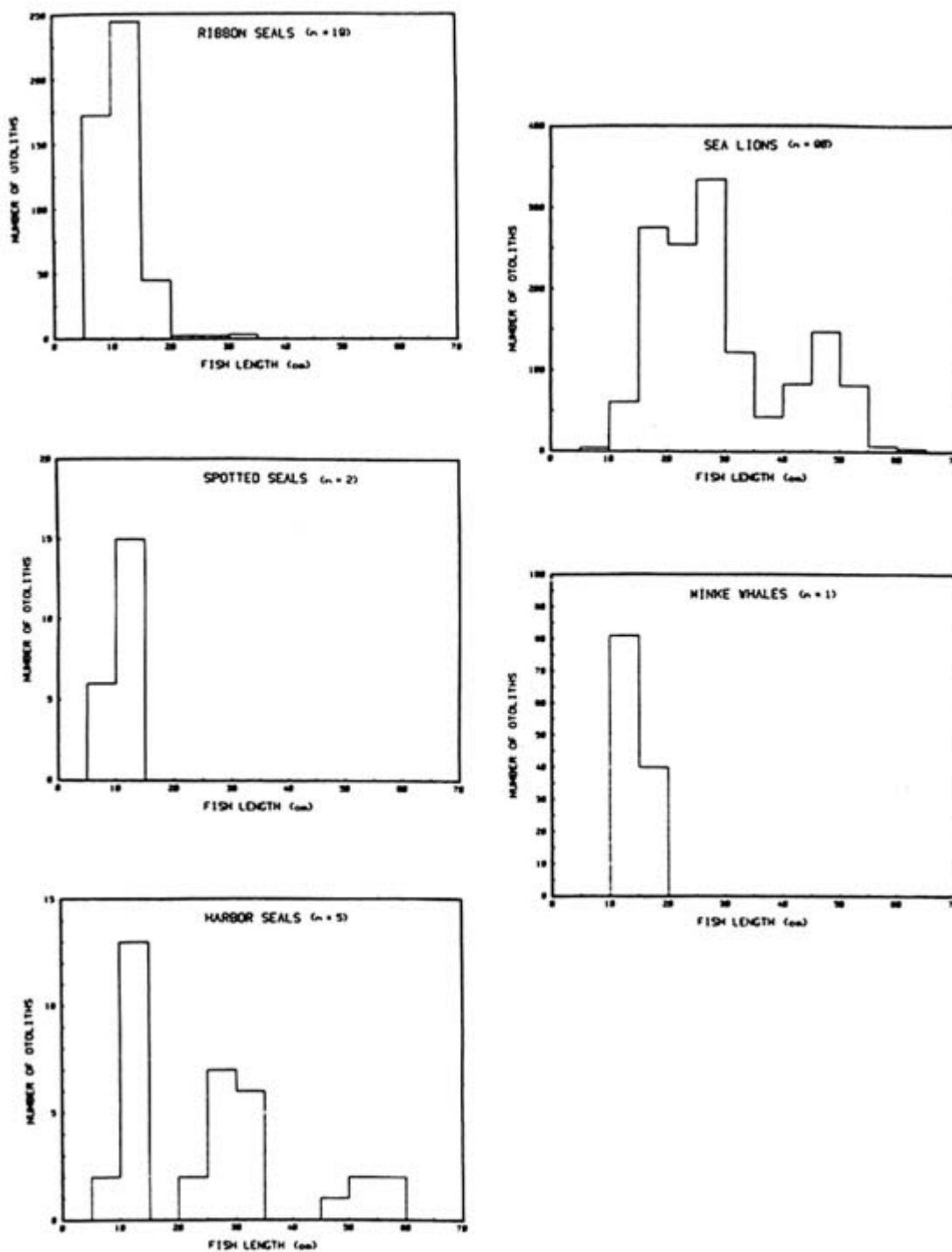


Figure 6.7 Size distributions of walleye pollock eaten by five species of marine mammals collected in the Bering Sea, 1975–81 (from Frost and Lowry, 1986).

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reproductive output, and survival of species dependent on small pollock for their nutrition (Anonymous, 1993).

**Trawl Effects on Bottom.** Wherever trawling is intensive, there is concern about its possible side effects on ecosystem structure and dynamics. Two major issues are often raised: the effects of bottom disturbance, and the effects of bycatch mortality. Bottom disturbance has the potential to alter the benthic invertebrate community, which itself directly or indirectly provides the prey for most demersal fish and crustacean species. Important bottom habitats, such as biogenic or physical structures, may also be affected by trawling. Bottom disturbance can also alter geochemical fluxes of nutrients and materials from the sediments to the water column, thereby influencing water column production. Mortality of individuals caught as bycatch and discarded can be separated into two cases, losses of juveniles of commercially or recreationally important species, and losses of species without direct importance as targets of human fishing. This distinction is meaningful, because for exploited species, bycatch mortality can be estimated and factored into harvest quotas, whereas for other species there is no accounting by managers and there are no models for the ecosystem consequences of the exploitation, except in the special cases where a bycatch species is endangered or threatened, as for sea turtles (NRC, 1990).

Bottom trawling is generally confined to regions characterized by soft sediments, because trawl gear snags and tears on rocks. Because soft sediments are inhabited largely by infaunal, buried invertebrates, rather than epifauna, most of the research on direct impacts of trawling on the benthos has focused on the infauna. These studies do reveal substantial impacts of trawls, especially beam trawls, and dredges on benthic infauna. Mortalities vary with species, but range from 15 to 55 percent (ICES, 1992). The subsequent impact of trawling on benthic communities will depend on the rate of the recolonization process of secondary succession on the seafloor. This involves colonization by more opportunistic species, with rapid growth rates, high reproductive rates, and generally short life spans. Despite some level of confidence in predicting the general effect of physical disturbance on infaunal communities, the longer-term implications of such changes induced by trawl disturbance of the seafloor are not at all obvious. For example, three months after disturbance, Peterson and others (1987) could detect no substantial differences in the macroinfauna of estuarine seafloor in areas that had been intensively disturbed by a clam dredging process. For any given ecosystem, such as the Bering Sea, this question would need to be evaluated empirically by designing fishing regulations as an experiment and evaluating the ecosystem consequences subsequently. This has not been done.

The effects of disturbance from bottom trawls on habitat are likely to be greater when the habitat is biogenic rather than physically created. There are reports of trawls moving rocks (Caddy, 1973; Fowler, 1987), and so physically created habitat is not immune to the trawl. However, rocky bottoms are generally avoided by trawlers because of the risk of damage to the gear. In addition, biogenic habitats are more fragile and susceptible to major disruption by trawls. For example, reefs of the tube-building polychaete *Sabellaria* have been destroyed in regions of the German Wadden Sea, where shrimp trawling is intense (Riesen and Reise, 1982). It is reasonable to expect other biogenic structures produced by benthic animals, namely, burrows, mounds, pits, tubes, and so forth, to be similarly disrupted by bottom trawling. This effect is probably transitory, i.e., the animal architects themselves survive to rebuild the

features, but relatively long-lasting where the trawl causes widespread mortality of the habitat-providing species, as in the case of *Sabellaria*. If recolonization and recovery rates of the habitat provider are slow relative to the frequency of trawling, alteration of the biogenic habitat could persist indefinitely until trawling operations cease. In the Bering Sea, there is no information on the importance of biogenic habitat to various demersal species and no basis on which to evaluate the possible ecosystem significance of trawl damage to bottom habitat.

Bottom trawling also creates sediment excavation and resuspension to some extent, depending on trawl design, transit, and bottom type. This physical disturbance of the seabed can enhance the turbidity of the overlying water column, facilitate erosion and transport of fine sediments (thereby changing the grain sizes on the seabed), and alter rates of important biogeochemical processes, such as nutrient releases. Churchill (1989) concluded from study of the trawling on the northeast coast of the United States that trawling could contribute substantially to sediment transport where storm-induced bottom stresses were weak, but that no clear short-term impacts of trawling could be detected on erosion rates of outer shelf sediments. The turbidity induced by passage of trawls is obvious near the bottom but may not be of much direct biological significance except in shallow waters where shading may inhibit primary producers in the photic zone. The immediate effect of the passage of a trawl over the seafloor is to create a pulse of released nutrients. This is then followed by reduced rates of nutrient release to the water column, as biochemical gradients within the sediments are reestablished. The net effect of these initial enhancements and subsequent depressions is probably not large (Krost, 1990). Nevertheless, it is possible that primary production could be enhanced by the greater oxygenation of buried sediments and the resulting faster decomposition of organic matter in the seabed. Furthermore, wherever buried pollutants, such as heavy metals or organic contaminants, are concentrated in the upper sediments of the seafloor, trawling could act to remobilize those contaminants and reinject them into food chains. No study of the Bering Sea explicitly addresses the importance of trawling on these sedimentary processes. Because wind-generated waves during storms cause substantial physical disturbance of bottom sediments, to a depth of even 85 m (Cacchione et al., 1987), it seems reasonable to assume that in the stormy Bering Sea the physical impacts of sediment disturbance by trawls are of relatively little added significance in shallow shelf environments.

**Bycatch, Discards, and Waste.** Fisheries that produce substantial bycatch discards or that kill or even excavate and expose large numbers of marine invertebrates by the disturbance of the trawl seem likely to benefit populations of scavengers that can utilize these food resources. The large growth in populations of scavenging seabirds in the North Sea has been attributed to exactly this process (Cramp et al., 1974; Fisher, 1953; Lloyd et al., 1991). The provision of discards to scavenging seabirds can alter seabird communities by favoring not only those species that scavenge but also the most aggressive of those scavengers. Furness et al. (1988) documented the exclusion of smaller birds, such as herring gulls and kittiwakes, by larger species, such as gannets, in feeding around fishing boats in the North Sea. Such enhanced feeding opportunities for the more aggressive scavengers seem likely to explain, at least in part, the observed increases in their populations. However, increased populations of these larger, dominant scavengers may subsequently have negative impacts on other, less aggressive seabirds

through interference competition, nest predation, or resource competition. In the North Sea, declines in herring gulls, lesser black-backed gulls, and kittiwakes may reflect such indirect effects of subsidizing scavenger food chains by trawler discards. Enhanced provision of dead, injured, or exposed animals on the seafloor may likewise be expected to benefit populations of certain demersal scavengers and predators, including various crabs, large scavenging amphipods, and some demersal fishes. To our knowledge, no study has attempted to evaluate this influence of bottom trawling for any fishery.

The direct effects on those species caught incidentally as bycatch during bottom trawling operations must vary tremendously among fisheries and species of bycatch. As a rule, marine mammals and seabirds are more subject to bycatch in fixed gears such as gill nets than in trawls (ICES, 1992). However, the bycatch mortality of Steller sea lions taken by trawlers in the U.S. exclusive economic zone was estimated as approximately 989 animals per year by the foreign and joint-venture trawl fishery between 1966 and 1988 (Perez and Loughlin, 1991). The kill was especially high in the early 1980s Shelikof Strait joint-venture pollock fishery. Estimated takes were 958 to 1,436 in 1982, 216 to 324 in 1983, and 237 to 355 in 1984 (Loughlin and Nelson, 1986). Most of the animals caught were sexually mature females, which would increase the likely effect of this mortality on the dynamics of local sea lion rookeries. Trawl fisheries of the Bering Sea may also have had some significant effect on marine mammals through direct capture in the nets. While the Bering Sea pollock fishery is reported to be among the "cleanest" of all trawl fisheries—with very low bycatch relative to targeted catch (Alverson et al., 1994)—there is bycatch nonetheless. Depending on species, some fraction of discarded bycatch survives, but death is the more common fate. No systematic assessment of the composition and potential ecosystem consequences of bycatch has been conducted for the Bering Sea trawl fisheries. This assessment may be particularly important for forage fishes, such as capelin and sand lance, which are important foods of both fishes and pinnipeds.

### THE "CASCADE HYPOTHESIS" AND THE BERING SEA ECOSYSTEM

No matter how ecosystems are defined, it seems clear that they are hierarchical products of complex and dynamic interactions between organisms and their physical environments, and that these interactions evolve over time and space as described in [Chapter 2](#). To the extent that these characterizations are accurate, then the current state of an ecosystem is also a product of its history. And this history may affect the future evolution of the system's structure and function. We conclude that significant changes in the Bering Sea over the past 50 years can be attributed in part to the history of human exploitation of living resources in this region, and in part to environmental changes. Both human exploitation and changes in the physical environment have occurred at different spatial and temporal scales, confounding our current best attempts to understand the relative importance of each.

The upper trophic levels of the eastern Bering Sea and Gulf of Alaska area have undergone significant changes in the past 100 to 150 years, at least partly due to commercial exploitation of mammals, fish, and invertebrates. [Figure 6.8](#) provides a schematic representation of historical trends in the dominant marine mammal, seabird, fish, and crab populations in the Bering Sea. Although initial population sizes are uncertain, there is general agreement that

populations of blue, sei, fin, and humpback whales were severely reduced by the end of whaling in about 1975. These species fed primarily on zooplankton and small, pelagic, schooling fishes. At about the same time (i.e., beginning in 1954), large-scale international fisheries for groundfish developed rapidly, and since 1960 groundfish resources have been exploited intensively (Bakkala, 1993) and have dominated the biomass of living resources removed from the eastern Bering and Gulf of Alaska. Large, mobile trawler fleets exerted intensive fishing efforts on localized fishing grounds for a few years, and then moved on to other species when depletions of target populations became unprofitable (Megrey and Weststad, 1990).

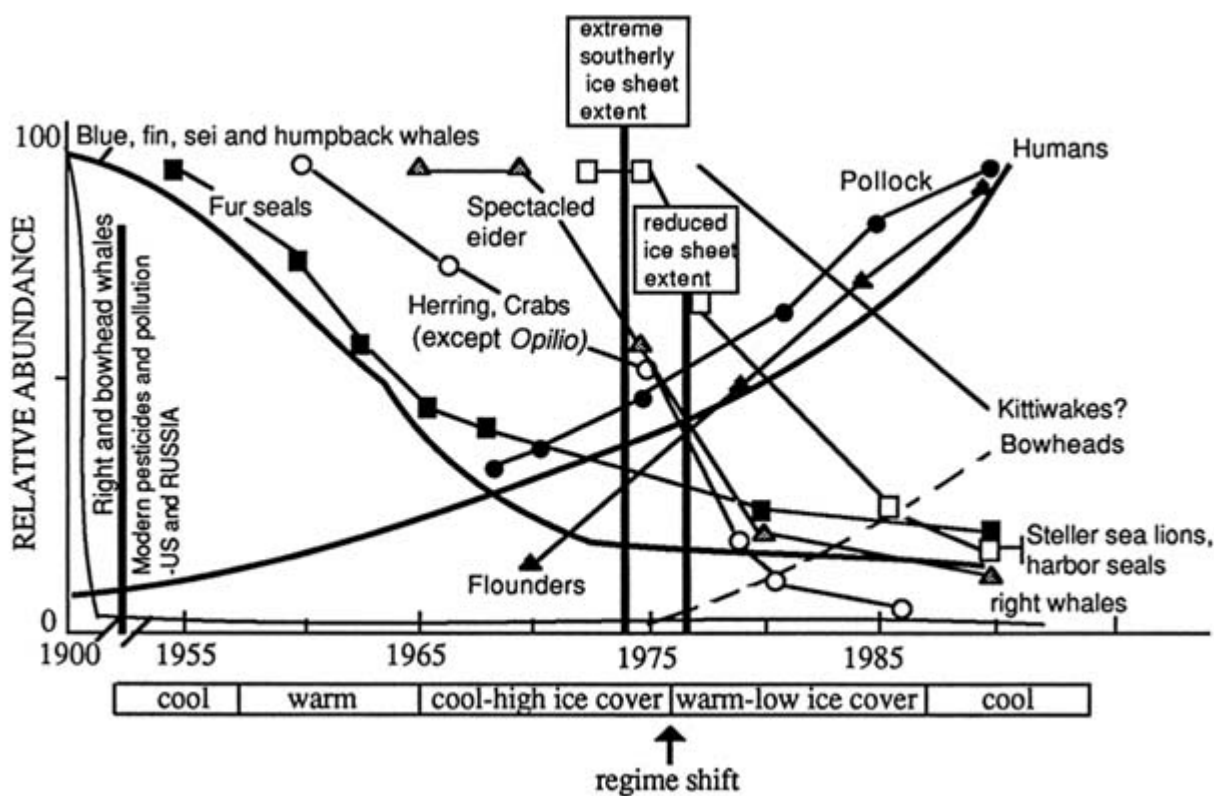


Figure 6.8 Schematic temporal change in relative abundance of certain marine mammals, seabirds, fish, and shellfish in the Bering Sea. Lower bar indicative of changes in sea surface temperature (Committee on the Bering Sea Ecosystem).

Coincident with the final decline in baleen whales during the late 1950s, 1960s and 1970s, Pacific Ocean perch was also overfished throughout the region and populations declined dramatically (Figure 4.20). Yellowfin sole, pandalid shrimp, herring, and crabs (except *C. opilio*) declined dramatically during the 1960s and 1970s. Fur seal populations in the Pribilof Islands started declining beginning in the 1950s, stabilized in the mid-1960s, declined again from the late 1960s to the mid-1980s, and appeared to have stabilized since then. Steller sea lions and some harbor seal populations began to decline in the 1970s, but the decline increased during the

1980s. This was mirrored to some extent by declines in murre and kittiwake in the Pribilof and Gulf of Alaska. On the other hand, pollock abundance increased dramatically in the Bering Sea during the late 1960s and early 1970s, and again during the early 1980s, along with a number of other groundfish species (e.g., Pacific cod and flounders). Although many of the Bering Sea biological resources were directly depleted by human use, the effects of overfishing on the spatial distribution of these species outside the fishing area, yet still within the Bering Sea ecosystem, are unknown.

The following conceptual analysis elaborates on this history and discusses changes in abundance and spatial distribution of four major groups of biota in the Bering Sea over the past 30 years, in relation to environmental or human-induced causation. The four groups are marine mammals (great whales, Steller sea lions, fur seals, and harbor seals), fish-eating seabirds, fish and invertebrates (including Pacific Ocean perch, yellowfin sole, pollock, herring, and capelin), and crab (king and Tanner).

### Marine Mammals

The large baleen whales were commercially harvested in the Bering Sea starting in the mid-1800s. Whaling for the balaenopterids (blue, fin, sei, and humpback whales) and sperm whales was intense from the 1950s through the mid-1970s and resulted in major stock depletions. Whale removals occurred over large spatial areas of the Gulf of Alaska, Aleutian Islands, and Bering Sea as far north as Cape Navarin (Figure 6.9). Within the Bering Sea, whale harvesting was intensive in the middle and outer shelf regions, especially along the shelf break in the region of the green belt (Figure 3.15).

As noted earlier, over the last 15 to 20 years, sea lion, harbor seal, and fur seal populations have declined or stabilized in several areas of the Gulf of Alaska and Bering Sea; the exception is southeast Alaska and British Columbia, where both sea lion and harbor seal populations have increased (Figure 6.10). Given the detailed analysis of Chapter 4, what can be concluded about the causes of these recent declines? In the case of Pribilof fur seals, it appears that for a period beginning in the late 1960s, intentional harvests of adult females and reduced juvenile survival account for the observed trend in pup production. Concerning the cause of reduced juvenile survival, it seems most likely that entanglement in debris and reduced food availability (due to climate effects) in the North Pacific Ocean were both significant factors. It does not appear that environmental conditions in the eastern Bering Sea have played a large role in the population decline. Furthermore, it appears that the population decline stopped in the 1980s, at least at St. Paul Island.

One of the most striking features of the pattern of decline in sea lion numbers is the fact that the most severe declines have occurred in the core of the species' range from the central Gulf of Alaska through the Aleutian Islands. Although sea lions have been hunted, direct human exploitation is not sufficient to explain the decline that has occurred in their numbers in the Gulf of Alaska and Bering Sea since 1960. Commercial harvesting ended in 1972, and although commercial harvest and incidental takes of sea lions would have contributed to the declines in some regions through the 1980s, they cannot account for the magnitude of the observed declines during these years. Subsistence takes have been relatively small and localized. Incidental takes



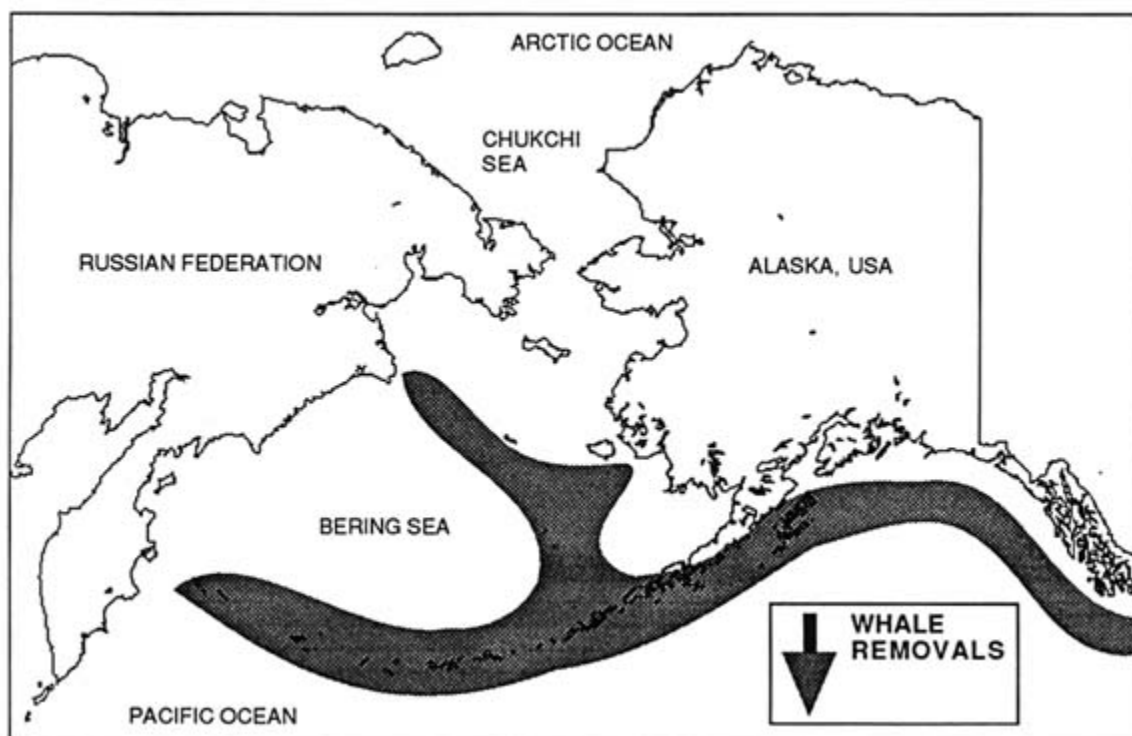


Figure 6.9 Schematic distribution of great whale declines (Committee on the Bering Sea Ecosystem).

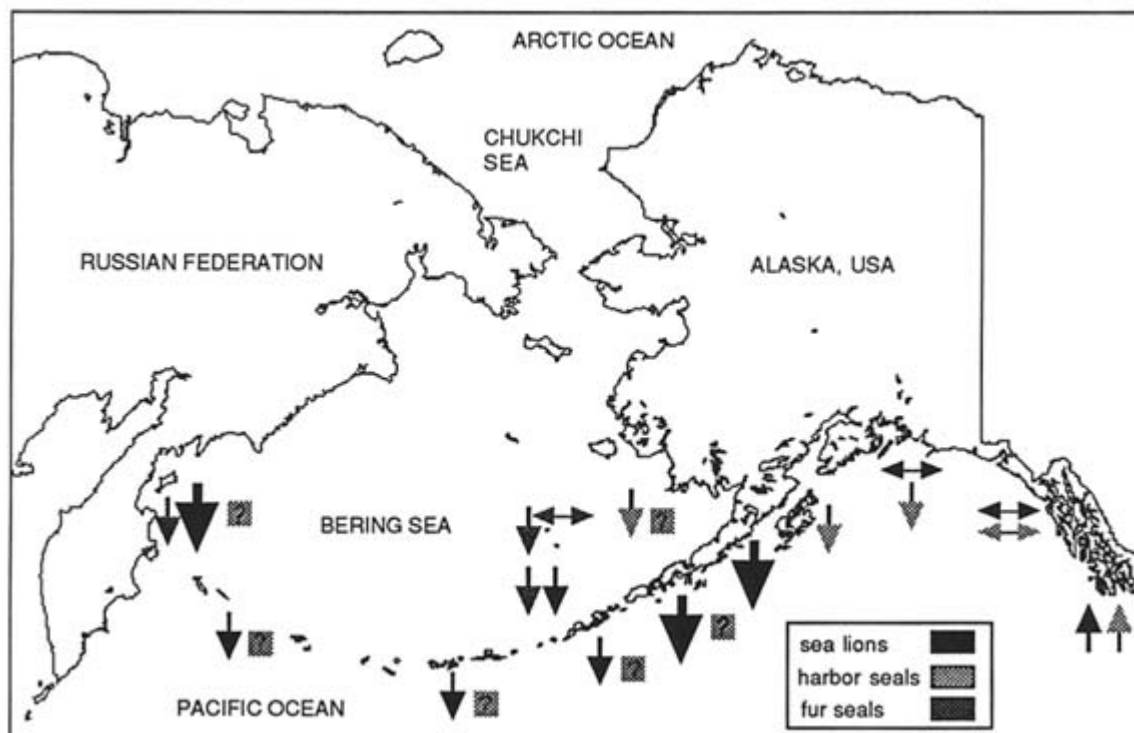


Figure 6.10 Schematic distribution of pinniped increases and declines (Committee on the Bering Sea Ecosystem).

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in fisheries have at times been substantial, but they can account for only a relatively small part of the decrease in numbers. Pollution, disease, and predation do not appear to have been important factors. Available data, though limited, do suggest that food availability may have declined at a faster rate than the number of sea lions, and resulted in reduced condition and reduced survival, particularly of juveniles (Anonymous, 1993). Small walleye pollock were important prey items for juvenile Steller sea lions in the 1970s and 1980s, and reduced abundance of juvenile pollock and other forage in the Gulf of Alaska in recent years could have influenced sea lion feeding. Changes in abundance of other small forage fishes, such as capelin, herring, and sand lance, may also have affected sea lion nutrition. Changes in these fish populations may have been brought about through the trophic effects of significantly reorganized ecosystems in response to historical patterns of exploitation and/or climate-induced environmental effects. For the most part, we do not have the data to assess the relative importance of fishery effects (both direct and indirect) and environmental effects on food availability, but both have likely been involved in the decline of sea lion numbers over the several decades.

Finally, there is very little understanding of what factors may be causing the number of harbor seals to decline in parts of Alaska. However, there are some similarities with the Steller sea lion situation in the timing of the declines and the areas affected, suggesting that a decrease in food availability may somehow be involved here as well.

### Seabirds

Adult survival of most seabirds is high, reproductive output is low, and sexual maturity is delayed. Thus, seabirds, like marine mammals, have life history attributes that in the long-term tend to make populations resistant to environmental variability and dampen fluctuations in population size (Furness and Monaghan, 1987).

In the short-term, however, populations do vary considerably—in Alaska, there are numerous examples of growing and shrinking colonies of a variety of species (Figure 6.11). In fact, most populations for which we have a history of information spanning at least 10 to 20 years have shown remarkable changes in abundance. Change appears to be common rather than exceptional. The question, then, is "Are the changes natural?" That is, should we be concerned that any of the changes, such as the broadly based declines on the Pribilofs, are related to factors other than "natural" change in the physical and biological environment of the southeastern Bering Sea? The term *natural* in this sense excludes human-induced changes, such as, through commercial fishing, oil spills, or other involvement. Or are we seeing evidence of the variability in productivity and abundance of birds that is shaped by changes in weather and climate, but because of our short historical time scale, we cannot yet recognize it as such? If so, what is the evidence?

Seabirds in Alaska appear to respond to changes in the environment at interannual, decadal, and perhaps even longer time scales. At the interannual scale, there are many cases of nesting failures of seabirds in particular years, for example, that were clearly caused by shortages of prey during periods of anomalous physical oceanographic conditions (e.g., Springer et al., 1984, 1987). At the longer scale, the overall abundance and distribution of red-legged

kittiwakes apparently have declined during this century. They are now absent from the western Aleutians (where they were abundant nesters and apparently outnumbered black-legged kittiwakes in the late 1800s), and from Akutan Island in the eastern Aleutians and Sanak Island in the western Gulf of Alaska (where they also once were common) (Byrd, 1978; Turner, 1885). Another example of long-term change is the decline of least auklets on St. George Island, which now are perhaps at only one-tenth of their abundance of 100 years ago. A long, gradual decline has been attributed to the encroachment of soil and vegetation into the limited talus areas of the island, and the resulting loss of important nesting space (Roby and Brink, 1986). Although there are no clear physical environmental correlates to these changes, it seems likely that they might exist.

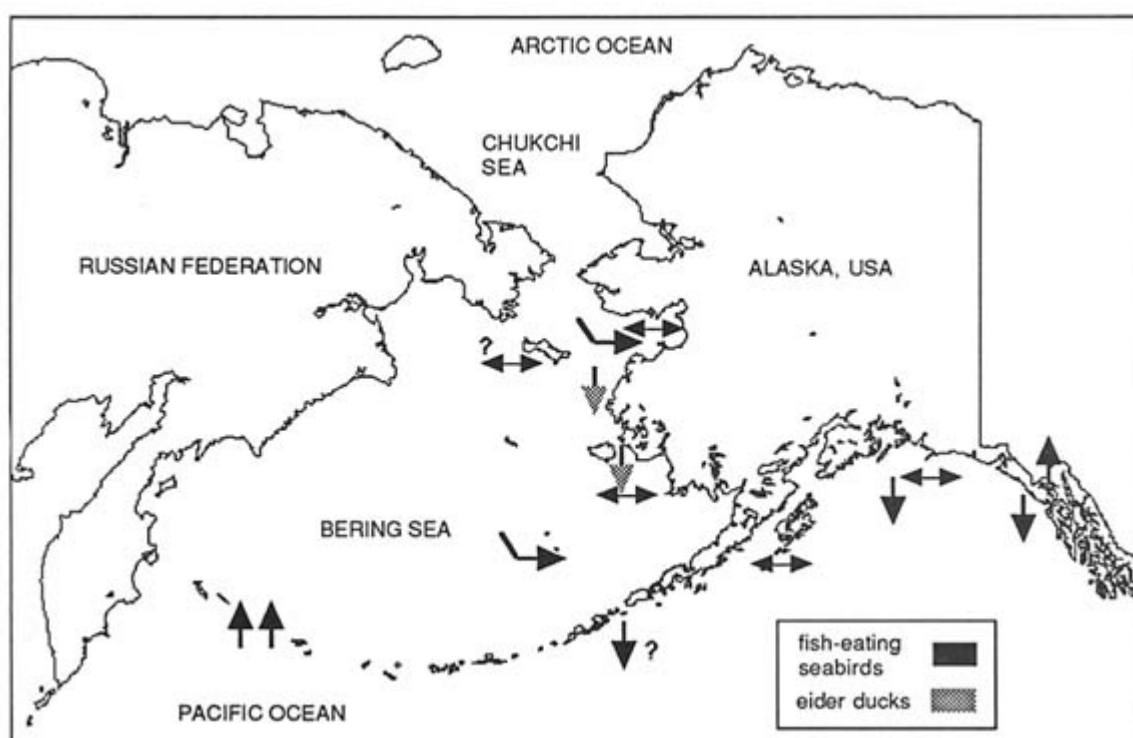


Figure 6.11 Schematic distribution of fish-eating seabird increases and declines (Committee on the Bering Sea Ecosystem).

There are now enough years with information on seabird biology and the physical environment in Alaska that we can see what appear to be coupled decadal-scale trends at several locations. Perhaps the most compelling relationship is between kittiwake productivity and water temperature in the eastern Chukchi Sea (Figure 6.12). The coastal food web that supports the birds in summer is very temperature-dependent, and prey populations tend to grow in proportion to the seasonal rise in water temperature (Neimark, 1979; Springer et al., 1984, 1989). In cold years, when warming is delayed, prey production generally is not sufficient to support high productivity of kittiwakes.

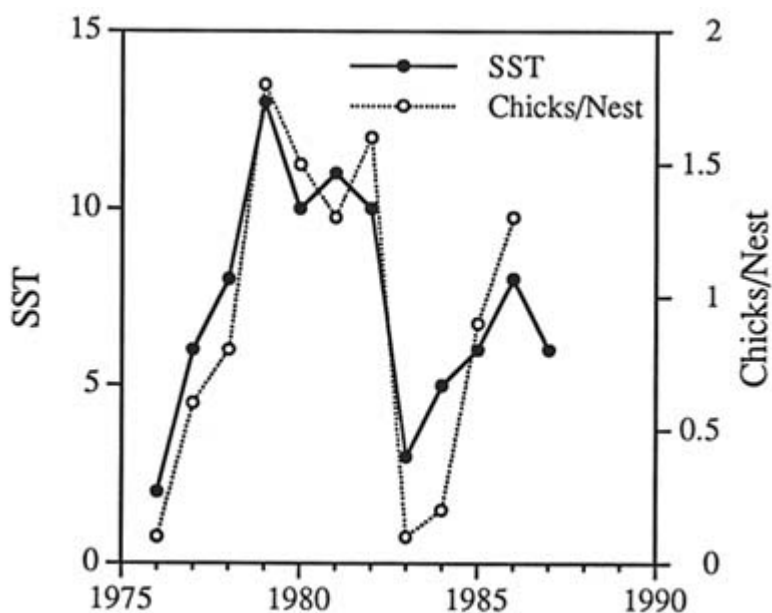


Figure 6.12 Productivity of black-legged kittiwakes and sea-surface temperature in the eastern Chukchi Sea (Springer, 1991; reproduced with permission of the Minister of Supply and Services, Canada, 1995).

Just the opposite relationship exists on the Pribilofs—kittiwake productivity was highest in the mid-1970s, declined through the early 1980s, and recovered by the early 1990s (Figure 6.13). The same pattern is apparent, but less pronounced, for murre. In this case, productivity is inversely correlated with water temperature, and it seems likely that changes in productivity are also mediated by changes in the food web, although the mechanism in that outer continental shelf community is not obvious. In this case, temperature might only be a proxy for other changes in the physical environment that are responsible for fluctuations in prey availability.

The abundance of kittiwakes and murre on the Pribilofs is variable, but the trends are downward in all but one case (Figure 6.14). The "official" time series does not begin until 1976, when the first census was taken, but the decline was first noticed in about 1973 (L. Merculieff, personal communication). For kittiwakes on St. George Island (for which the data are most complete), it appears as if kittiwake numbers and ecosystem productivity might be related, with lag times corresponding to life history characteristics of the two species (Figure 6.15). The longer apparent lag between change in productivity and change in numbers of red-legged kittiwakes compared to black-legged kittiwakes is consistent with other life history characteristics of the two species, which indicate that the former are somewhat more K-selected than the latter.

In the western Aleutian Islands, numbers of murre and kittiwakes increased between the mid-1970s and mid-1980s at rates that were similar to the rates of decline on the Pribilofs during

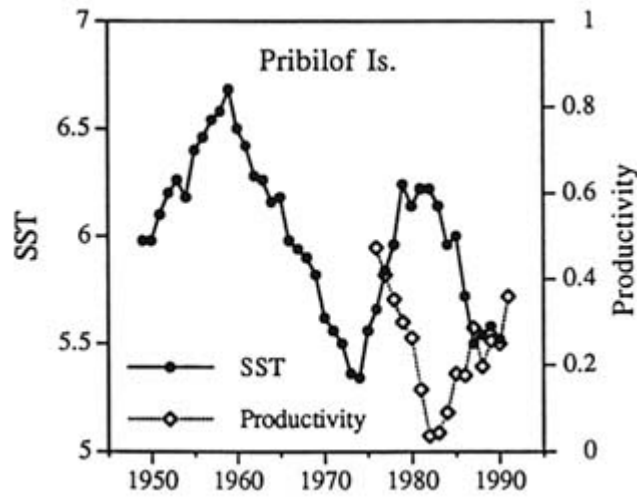


Figure 6.13 Kittiwake productivity on the Pribilof Islands and sea surface temperature in the southeastern Bering Sea (three-year running mean of kittiwake productivity, and five-year running mean of sea surface temperature) (Anonymous, 1993).

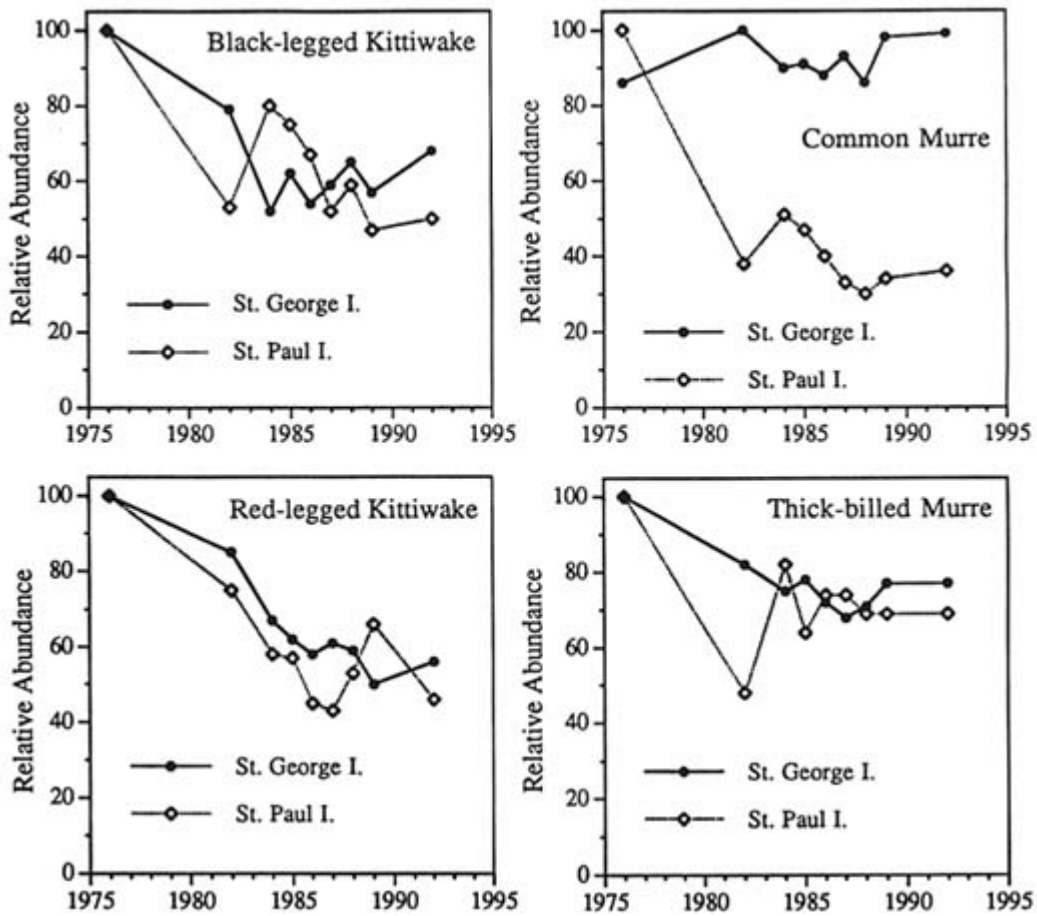


Figure 6.14 Trends in abundance of murre and kittiwakes on the Pribilof Islands (Dragoo and Dragoo, 1994; Climo, 1993).

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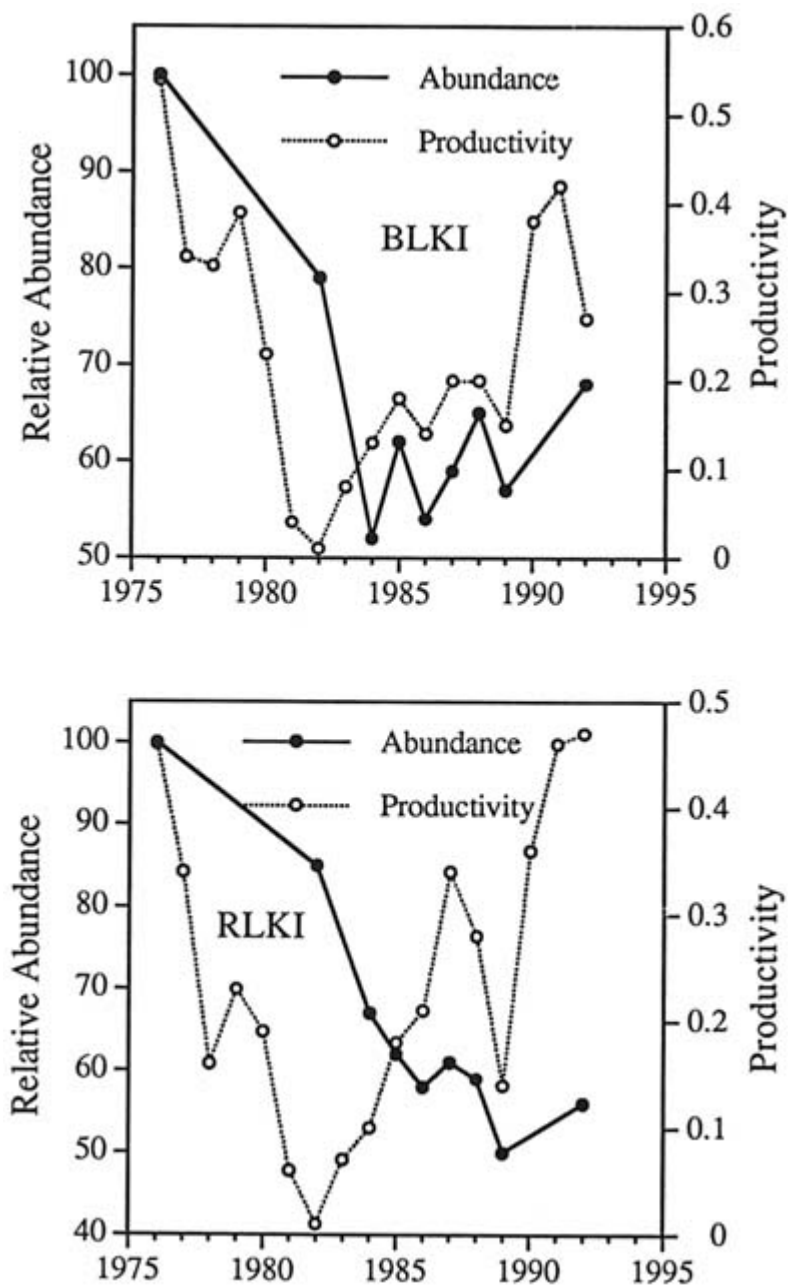


Figure 6.15 Trends in productivity and abundance of black-legged (BLKI) and red-legged (RLKI) kittiwakes on St. George Island (Springer, 1993).

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the same time (Figure 6.16). In both regions, inflection points in the trends apparently occurred in the mid-1970s and the mid-late 1980s. Contrasting with both is the apparent stability in numbers of murre and kittiwakes at Cape Peirce, a coastal colony in Bristol Bay (Figure 6.17). Productivity of kittiwakes at Buldir cannot be readily assessed, because it has been determined only since 1988. At Cape Peirce, information on kittiwake productivity is fragmentary from 1970 to 1984 but continuous since, and it shows features similar to the Pribilofs case—productivity is comparatively high now after recovering from a low period during the early to mid-1980s.

Kittiwake productivity at offshore colonies in the Gulf of Alaska declined to very low levels in the early 1980s, as water temperature rose (Figure 6.18). However, it did not subsequently recover (as at the Pribilofs and Cape Peirce), but has continued to be generally poor, perhaps because water temperature in the gulf has remained warm (unlike the Bering Sea, which has been cooling). Murres in the gulf have also suffered poor productivity in recent years, and declines have occurred both within and outside of the area oiled by the *Exxon Valdez* spill and were apparent before the spill (Piatt, 1994).

The seabird decline in the gulf occurred at the same time as a shift in pathways of energy flow through food webs there. Capelin was the dominant prey of several species of seabirds during the 1970s but was absent, or nearly so, in diets in the 1980s (Figure 6.19). The shift corresponded with the other indicators of a widespread decline of capelin in the Gulf of Alaska and Bering Sea. Capelin was replaced in seabird diets primarily by pollock and sand lance. It is not known if the absence of capelin by itself has been responsible for the poor productivity of some seabirds or is simply indicative of generally poor prey availability. The declines in the abundance of an important forage species coincided with changes in the physical environment of the gulf (as measured by water temperature), trends that together provide support for the hypothesis that some recent dynamics of seabirds, and perhaps other species at higher trophic levels, may be related to physical changes in the ecosystem.

### Fish and Invertebrates

The main target of the developing international fishery in the late 1950s was yellowfin sole, a benthopelagic continental shelf species (see Chapter 4). During a brief period from 1959 to 1961, catches averaged over 400,000 t annually. After 1962, the yellowfin sole population and catches rapidly declined to low levels as a result of heavy exploitation. With the crash of the yellowfin sole population, trawl fisheries began to harvest eastern Bering Sea Pacific halibut, Pacific Ocean perch, and sablefish—all long-lived continental-slope species. With the rapid overexploitation of these species and herring (eastern Bering Sea herring biomass decreased to one-sixth of its former levels during the 1960s, as shown in Figure 4.24), foreign trawl fleets moved into the Aleutian Islands and Gulf of Alaska to target slope rockfish and, in particular, Pacific Ocean perch. The latter species was subsequently "mined out" of these regions during the 1960s (see Figure 4.20 for stock biomass trajectories). During the 1960s, as stocks of Pacific Ocean perch declined, foreign trawl fleets shifted to walleye pollock (Alton 1981). Reported catches of pollock in the eastern Bering Sea increased rapidly from 175,000 t in 1964



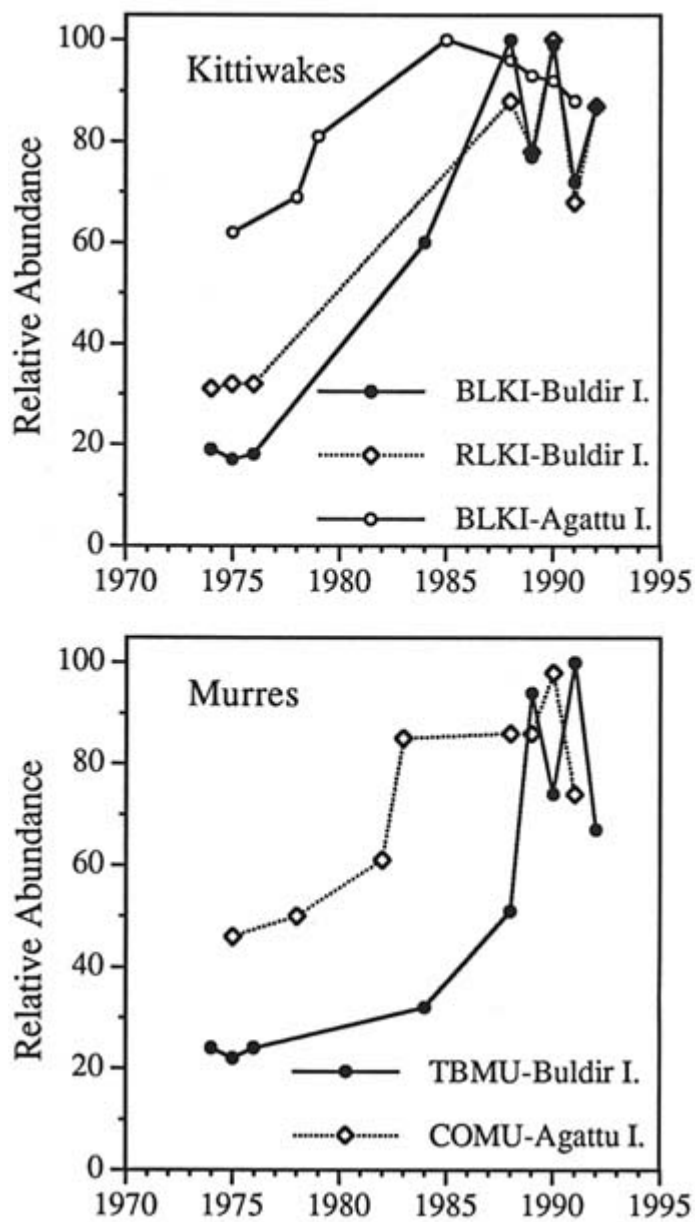


Figure 6.16 Trends in abundance of thick-billed (TBMU) and common (COMU) murres and black-legged (BLKI) and red-legged (RLKI) kittiwakes at Buldir Island (Williams and Byrd, 1992; J.C. Williams, unpublished data).

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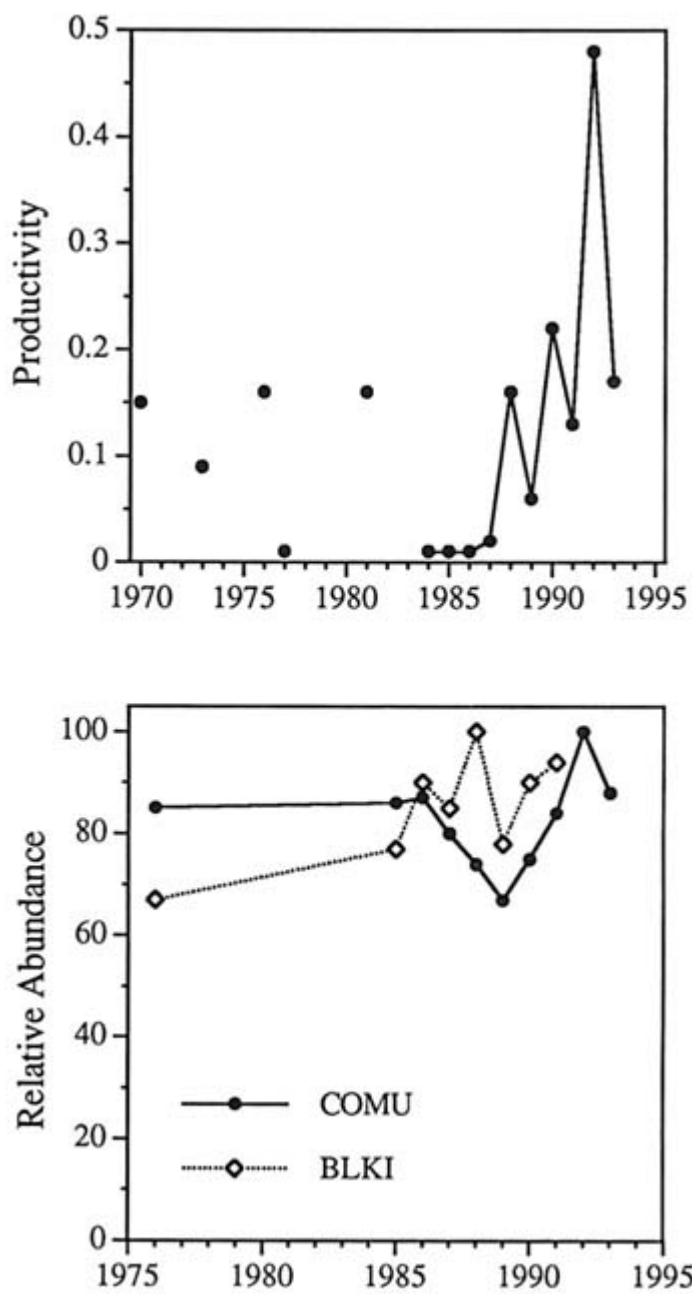


Figure 6.17 Trends in productivity and abundance of common (COMU) murre and black-legged (BLKI) kittiwakes at Cape Peirce (Hagbloom, 1994).

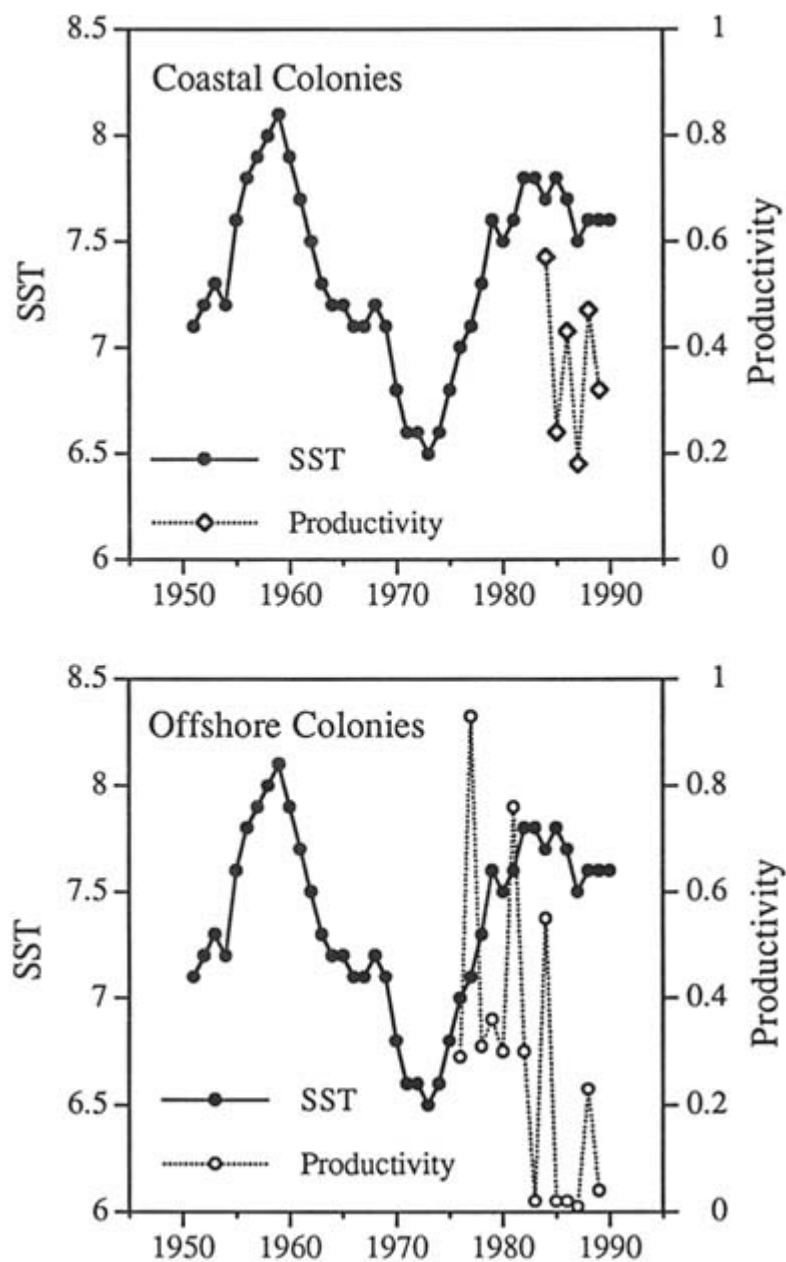


Figure 6.18 Productivity of black-legged kittiwakes in the Gulf of Alaska (three-year running mean of kittiwake productivity and five-year running mean of sea surface temperature) (Hatch et al., 1993; reproduced with permission of the Minister of Supply and Services, Canada, 1995).

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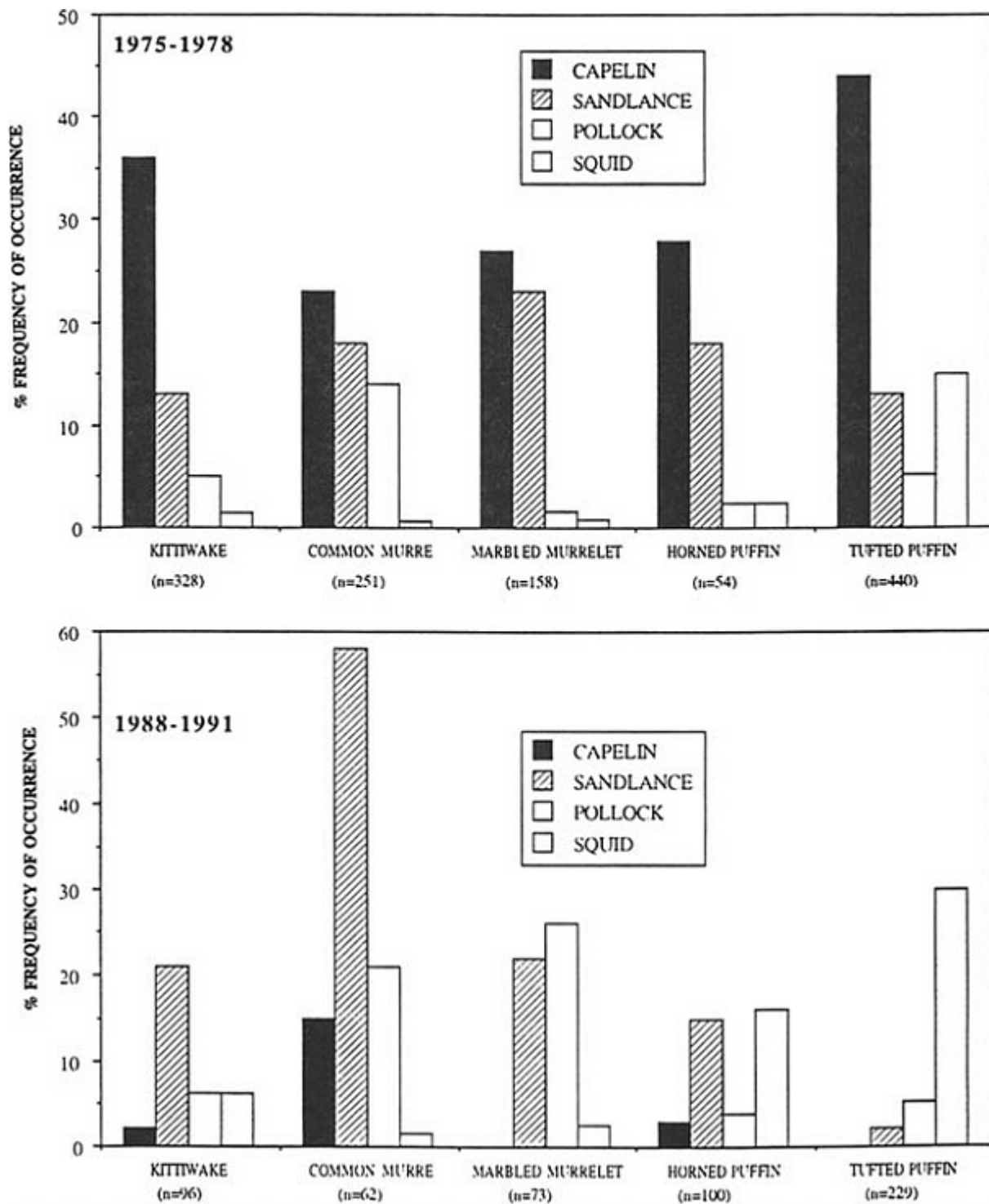


Figure 6.19 Diets of seabirds in the Gulf of Alaska, 1975–78 and 1988–91 (Piatt and Anderson, in press).

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to 1.9 million t in 1972. Much of this shift was due to the more than six-fold increase in eastern Bering Sea pollock biomass between 1964 and 1971 (Bakkala, 1993). Pollock catches in the Gulf of Alaska increased in the early 1980s, to a peak of around 300,000 t in 1984 (due to a more than three-fold increase in biomass between 1974 and 1982), and then fell to near 60,000 t in 1988 as the strong year classes responsible for the surge in the fishery disappeared.

Between the late 1970s and mid-1980s, a number of eastern Bering Sea (EBS)/ Aleutian Island (AI) groundfish and pelagic stocks showed rapid increases in biomass (EBS pollock, 2.6 times; EBS cod, 3.1 times; AI Atka mackerel, 4.4 times; EBS herring, 3 times; EBS arrowtooth flounder, 4.7 times; EBS yellowfin sole, 1.6 times; EBS rock sole, 1.9 times; and other EBS flatfishes, 3.8 times) (NPFMC, 1993). The estimated adult biomass of these species combined increased from around 10 million t in the late 1970s to 25 million t in the mid 1980s. Fisheries on these stocks increased accordingly. At the same time, a number of forage fishes, in particular capelin around the Pribilof Islands and Kodiak Island, declined significantly.

King crab populations and their associated fisheries, which had declined in the eastern Bering Sea and around Kodiak Island in the early 1960s, grew very rapidly in the eastern Bering Sea in the 1970s and then crashed in both the eastern Bering Sea and Kodiak region in the early 1980s (Figures 4.1, 4.2, and 4.3). Both *C. opilio* and *C. bairdi* populations in the eastern Bering Sea declined in the 1970s; *C. opilio* populations and landings increased significantly in the late 1980s (Figure 4.1).

## DISCUSSION

The Bering Sea ecosystem, like all ecosystems, has undergone natural environmental changes for a very long time. It has also been significantly affected by human activities for hundreds of years, more significantly in the past 200 years (Chapter 5). Therefore, the changes of the past several decades that have been discussed in some detail in this report cannot be interpreted as perturbations to a "pristine" ecosystem, and they are not unique in many ways. However, until recent decades, good information on many of the major species in the Bering Sea was lacking. Thus the "cascade" changes that began in the 1950s described below probably are only the most recent in a series beginning no later than the nineteenth century.

To recapitulate our understanding of the most recent set of changes, from the mid-1950s to the early 1970s, large populations of both fish and mammals (particularly the large whales) were dramatically reduced. This reduction in biomass likely increased the amount of food (zooplankton and small fish) available to other vertebrate predators. Unfortunately, there is not sufficient information available on a time series basis for this period to examine the abundances and distributions of such organisms to verify this. However, it seems reasonable to suggest that the dramatic increase in the abundance of pollock, which apparently occurred during the late 1960s in the eastern Bering Sea, may have been in some way linked to overexploitation and reduction of these other populations. In fact, there is little doubt that the eastern Bering Sea fish assemblage switched to a pollock-dominated system in the late 1960s and early 1970s, and that this domination of pollock biomass has persisted since then.

What other changes might have been associated with the concentration of resources into pollock biomass? One effect might have been reduced abundance of forage fish species, such

as capelin and sand lance, which compete with young pollock for zooplankton. Unfortunately, it is not possible to evaluate this hypothesis, even in a general way, because we have few data on trends in the abundance of these fishes and other forage species. A major climate regime shift occurred in the North Pacific in the late 1970s. Combined with the historical restructuring of parts of the large oceanic ecosystems of the region, this climate shift could have set the stage for the rapid changes in top-level predator populations that seem to have accelerated in the last 15 to 20 years. There is persuasive evidence of very large increases in piscivorous fish populations resulting from the synchronous strong year classes that occurred in the late 1970s, just after the regime shift.

Merrick (1995) proposed a very similar hypothesis to explain the recent declines in the Steller sea lion population of the northeast Pacific and eastern Bering Sea. He suggested that there had been a major shift in the trophic structure of the Bering Sea (and probably the Gulf of Alaska) beginning in the mid-1960s, "a decade prior to the initiation of the current fishery management regime." He argued that if there was an actual cause-effect relationship, it lay in the dietary overlap between whales, fish, and some pinnipeds. The significant increase in pollock biomass of the 1960s (eastern Bering Sea) and early 1970s (Gulf of Alaska) (see [Figure 4.4](#)) could then have resulted from the release of euphausiid and calanoid copepod prey (preferred prey for juvenile pollock) due to the fishery removal of whales (fin, sei, and humpback), Pacific Ocean perch, and herring, and the reduction of juvenile pollock predators due to the significant harvest of northern fur seals. Merrick estimated that "the reduction of fin whales, Pacific herring and Pacific Ocean perch in the Bering Sea and Aleutian Islands could have released 1.36 to 2.81 million mt of zooplankton prey a year...which would be sufficient to feed 4.3 to 8.9 billion age-1 pollock for a year." In addition, he estimated that the reduction in fur seals could remove predation on 2.8 billion age-1 pollock. He concluded that the released zooplankton and reduced predation pressure could have supported pollock abundance at the high levels resulting from recent high recruitments. He also reported that around the time of the 1976–77 climate regime shift, preferred prey (forage fish such as capelin and sand lance) began to disappear in a serial fashion as a number of adult groundfish populations, in particular Pacific cod and a number of flatfish species, grew significantly. In summary, Merrick concluded that the combination of favorable ocean conditions, continued zooplankton release, and low predation in the late 1970s and early 1980s resulted in a series of strong pollock year classes. As a result, adult (but not juvenile) biomass again increased and remained high in the eastern Bering Sea (perhaps due to an effective fisheries management regime using light exploitation rates), and predatory Pacific cod and flatfish populations also increased. These fishes reduced the populations of small fish prey such as capelin and sculpins. The reduced biomasses of forage fishes and juvenile pollock abundance were insufficient to meet the dietary needs of Steller sea lions.

One piece of this scenario that is not fully understood is why juvenile pollock have been less abundant recently. One possibility is cannibalism, as well as predation by Pacific cod and flatfishes. Another possibility is that although recent environmental conditions have favored pollock recruitment, there have been a few large year classes (especially 1978), rather than a steady supply of juveniles, and the lack of other forage fishes has made the variable supply of juvenile pollock more of a limitation for marine mammals and birds than it normally would have been. Indeed, the year-class strength of pollock has declined recently. What does seem likely



is that a combination of cascading trophic interactions and a significant climate shift has caused major—and perhaps irreversible—restructurings of the oceanic ecosystem of the eastern Bering Sea, Aleutian Islands, and Gulf of Alaska.

There are several important questions to consider when analyzing the pattern of declining and changing marine mammal, seabird, and fish populations in the Bering Sea:

1. Can we expect species to recover from a perturbation (either human-caused or environmental) in a changing ecosystem? For example, consider the large-scale removal of whales and predatory fishes from the Bering Sea. This removal may have resulted in an explosion of one or more prey species (e.g., walleye pollock), as well as an increase in other predators or increased concentration on pollock by predators that feed on these prey, including humans. The resulting reordering of the competitive food web would likely be characterized by an increase or decrease of many of their other components (e.g., crab, sea lions, and seabirds). As a result of this complex reorganization, whales may encounter new competitors for their prey base (e.g., factory trawlers with sophisticated electronics and huge nets) that limit their recovery notwithstanding direct regulatory protection.
2. Time lags and different time scales can produce nonlinear relationships that make it very difficult to explain the changes that occur at any one time. For example, are we still seeing changes in the Bering Sea ecosystem caused by baleen whale removals in the 1960s and 1970s? Was the large pollock year class of 1978 a result of prey release or competitive interactions at lower trophic levels that enabled pollock populations to explode? Or was it a response to warming seawater temperatures after the 1976 regime shift, allowing an increase in water column production and juvenile success? Were both factors partly responsible? Is the current organization of the ecosystem stable or is it likely to shift again, either to its previous condition or to some other condition?
3. At any one time the system may be controlled (limited) by a few key factors (Berryman, 1993). Because these key factors are generally unknown, it is not often possible to know a priori when humans influence one of them, setting off a series of unexpected, cascading changes throughout the ecosystem. This "cascade hypothesis" (described in [Chapter 2](#)) might explain some of the rapid and then persistent changes observed in crab, pandalid shrimps, demersal fish, seabird, and marine mammal populations and assemblages. The key question is how this knowledge can be used to manage human actions in order to reduce our impact on the ecosystem.

## CONCLUSIONS

As a general conclusion, the most likely explanation of events in the Bering Sea ecosystem is that a combination of a decadal or regime shift in the physical environment acted in concert with human exploitation of predators (whales, other fish) to cause pollock to dominate the ecosystem and other predatory fish populations to greatly increase in abundance. As a result, some forage fishes that have higher nutritional value than pollock became less available to some marine mammals and birds, leading to their decline. The increase of adult pollock and other predatory fishes in the past 20 years might also be responsible for keeping the forage fishes

relatively scarce. This food shortage might have been exacerbated by pulse fishing of pollock, which might have removed them from some areas for long enough to cause difficulties to marine mammals and birds, especially juveniles. There is no evidence that any human activity other than fishing (including whaling) has had a significant effect on the Bering Sea ecosystem, although better information on various pollutants would be of interest. We emphasize that although this is the most likely explanation or description of events over the past 50 years, it is not one in which there can be a high degree of confidence at present, and it might well be partly but not completely correct. Indeed, until we know more about exploitation rates in the western Bering Sea, we can probably never be very confident of any scenario. Nonetheless, it is worth exploring this scenario in a little more detail.

Physical changes have occurred in the Bering Sea ecosystem over the past 50 years. In addition to interannual variations, decadal or regime shifts have occurred; these have included changes in sea surface temperature, the mean extent of ice cover, and atmospheric and oceanic circulation patterns. It is most likely that these changes have altered the distributions and abundances of many members of the ecosystem, especially short-lived species. One of the largest such changes occurred in the winter of 1976–77; since then, the eastern Bering Sea has had warmer surface temperatures and less ice cover on average than in the period before 1976. The brief period of warmer sea temperatures in the 1960s (Figure 6.5) could also have contributed.

Human impacts were also being felt by the Bering Sea ecosystem during the past 50 years—indeed, for the past 200 years at least, and probably much longer (Chapter 5). Intensive hunting of whales continued, along with a significant harvest of fur seals. Heavy exploitation of yellowfin sole caused rapid declines in the population in the early 1960s; other long-lived slope species, such as halibut, Pacific Ocean perch, and sablefish, along with herring in the eastern Bering Sea, also suffered population declines as a result of exploitation.

It is extremely plausible that the removal of whales and various fish species that were predators on or competitors with pollock combined with a decadal regime shift to cause a large increase in pollock recruitment. As result, pollock populations increased (as did populations of Pacific cod and some predatory flatfishes, especially arrowtooth flounder), and they came to dominate the ecosystem. It is also plausible—but completely untested—that increased competition from young pollock for zooplankton or increased predation by growing populations of piscivorous fishes led to the decline of important forage species such as capelin, sand lance, and squid.

There is persuasive although not conclusive evidence indicating that some marine mammals—especially Steller sea lions in the eastern Bering Sea—have and some seabirds—especially murrelets and kittiwakes, particularly around the Pribilof Islands—have suffered from food shortages, probably affecting juveniles more severely than adults. Indeed, it seems that some populations have decreased as pollock biomass has increased. It thus appears that the declines were not caused by declines in total abundance of pollock (which have not declined), or even in total abundance of all prey species, although declines in total abundances of capelin, sand lance, squid, and perhaps of juvenile pollock might have contributed to their difficulties.

But, especially since the late 1970s, fishing for pollock has been concentrated at some times in some places. This would imply that pollock are effectively removed from some areas at some times, and the local populations would probably take at least days or weeks to be rebuilt

by in-migration from elsewhere. It is thus possible that food shortages for some mammals and birds—perhaps at crucial times and places for juveniles—have been exacerbated by this intense pulse fishing. Even if a general increase in pollock has caused a decrease in some other, perhaps more valuable, forage species, it is almost certain that removing pollock from an area could not result in a rebound in the populations of those other species in only a few weeks. As long as overall pollock biomass remains high, it is plausible that the biomass of those other species will remain low.

In any event, the above scenario—the most plausible that the committee could identify—does not lead to the conclusion that pollock have been subjected to ecosystem overfishing. In other words, it is hard to see how the total rate of exploitation of pollock over the past 25 years is directly (or even indirectly) responsible for the decline of mammals and birds. If this is true, it is then impossible to see how reduction of the total rate of exploitation of pollock would be helpful in the short-term; it is even possible, although highly speculative, that some mammals and birds would be helped by a temporary increase in the exploitation of pollock. It is more likely that marine mammals and birds have been affected by the distribution in space and time of fishing effort on pollock, and thus that they would be helped by a broader distribution of fishing effort in space and time, especially in areas where they are known to feed. We caution that it is by no means certain that this would be effective enough to reverse or even halt their population declines.

It is also hard to predict the effects of protecting other marine mammals. Many whale species have been recovering outside the Bering Sea since whaling ceased or was reduced, and some of those are the ones whose declines might have encouraged pollock increases. It is not clear why recoveries of those species in the Bering Sea have not been observed (Chapter 4), but recoveries are possible. Perhaps if they increase and human exploitation continues, the dominance of pollock in the ecosystem will be reduced, particularly if environmental conditions do not favor their recruitment. Perhaps some of the shorter-lived forage species such as capelin and sand lance would increase quickly enough under those circumstances to provide a significant food source for mammals and birds. At least we can say that it seems extremely unlikely that the production of the Bering Sea ecosystem can sustain current rates of human exploitation of the ecosystem and the populations of all marine mammal and bird species that we believe existed before human exploitation—especially modern exploitation—began. Over the long-term, fishing competes to some degree with at least some top-level predators; therefore, if the goal of management is to have as many top-level predators as possible (not a common management goal), then it seems that ultimately fishing will have to be reduced. We note that "fishing" includes commercial, subsistence, and recreational fishing, all of which can compete among each other as well as with marine mammals, birds, and predatory fishes. Even commercial fishing can be divided into various sectors. Allocating effort among these competing groups remains a major challenge to managers.

Finally, we emphasize how difficult it will be for human management to cause a large, complex marine ecosystem to achieve and maintain a desirable balance. If the above scenario is even partly correct, it is clear that many significant factors have influenced the Bering Sea ecosystem over the past 200 years, only some of which have been under human influence (let alone control) and only some of which have been adequately documented. Some of the changes that have occurred might be irreversible over normal human time frames (say 100 years or less).

This difficulty does emphasize the need for an adaptive approach to management and the need for good, long-term data on physical and biological phenomena.

7

## Implications for Management Policy and Institutional Arrangements

As demonstrated in the previous chapters, the Bering Sea ecosystem, like all such systems around the globe, is very complex. It consists of physical, chemical, and biological components that interact in ways not completely understood. It is thus difficult to fully describe the ecosystem at any point in time or to make predictions about how it will change over time, with or without human input. Although measurements of some ecosystem components are possible and historical records for some are available (for example, the composition and relative sizes of various populations), our understanding of the Bering Sea ecosystem is necessarily incomplete.

These uncertainties pose a significant challenge to any effort to develop policies and institutions to manage the Bering Sea ecosystem. Given the uncertainties in ecosystem structure and dynamics, what is the best approach for ecosystem management? It is important to recognize that the lack of complete understanding does not preclude effective ecosystem management. Management efforts must be based on what is known about ecosystem components and their interrelationships, as well as the likely effects of private and public human activities on the ecosystem. At the same time, however, management institutions should also provide a framework for improving the scientific understanding of the ecosystem through ongoing research and data collection activities. As understanding of the ecosystem improves, management policies must change accordingly.

One of the most problematic aspects of ecosystem management is the selection of criteria by which the relative success of various management programs can be evaluated. Because of the political, economic, distributional, and cultural aspects of the issue, the committee thought that it would be presumptuous to select a specific set of criteria. The committee instead chose to describe a framework based on environmental economics that will provide a basis to evaluate different management programs.

This framework views the Bering Sea ecosystem as an economic asset that can be used to provide a flow of goods and services over time. Treating environmental systems in this way is an established approach in environmental economics (see for example, Herfindahl and Kneese, 1974; Krutilla and Fisher, 1975; Pearce and Turner, 1990; Tietenberg, 1992). In this approach, the "goods and services" include resources such as the scientific value of the ecosystem as a natural laboratory; the value of future catches; societal benefits resulting from the production of cultural, social, and aesthetic amenities; and the value of the ecosystem as a transportation

agent, as well as more traditional resources of the ecosystem, such as yearly fishery catches (NRC, 1994c). The basic idea of this approach is to list all possible resources (current and future), assign to each resource a monetary value and quantify all costs (direct and indirect) associated with its production, and then develop a management policy that maximizes the overall value of all resources in the ecosystem. Assigning an economic value to environmental resources is controversial and involves complex analysis of many factors, including the sustainability of production, the availability of substitute resources, the irreversibility of the production process, and intergenerational equity issues (NRC, 1994c). Even so, such a framework is useful because it explicitly considers the complex interdependencies of natural ecosystems and the large-scale, long-term effects of policy decisions.

### THE BERING SEA ECOSYSTEM AS AN ASSET

The Bering Sea ecosystem can be viewed as an asset capable of producing a wide range of goods and services for humankind. Wise use of the asset can be defined in terms of the size, composition (types and relative amounts), and distribution (who gets what) of the flow of goods and services over time. The production of most of the goods and services requires the input of other resources (e.g., it takes labor and boat days to produce fish). Wise use must also consider the flow of goods and services these other inputs could produce if used elsewhere.

The range of goods and services should be defined as broadly as possible. It includes, among other things, fish for food and recreation, transportation, waste assimilation, the reduction of cultural, social, and aesthetic amenities, a natural laboratory for scientific research, and provision for the maintenance of certain species (e.g., through the Marine Mammal Protection Act). Some are produced and sold on the market, some are not. In some instances units of measure for production inputs of production and output levels are readily available, in other cases they are not. These differences make comparisons of goods and services flows problematic, and is another problem that must be faced explicitly when selecting success criteria for management.

The basket of goods and services produced by the ecological asset during any given period depends on the combination of productive inputs<sup>1</sup> applied and on the state of the ecosystem.<sup>2</sup> The state of the ecosystem, however, is itself affected by the various inputs and outputs to the system. The flow of total good and services through time is therefore a function of the flow of the combinations of inputs through time. In other words, what society does today to obtain outputs affects the ecosystem, which will affect what society can get in the future.

<sup>1</sup> The word input is used in the economic anthropocentric sense. It refers to hours of fishing, or ton/miles of transport, or labor and capital applied to oil production. It does not refer to inputs in the ecological sense, such as inputs of energy from the sun.

<sup>2</sup> The state of the ecosystem is multidimensional, including physical, biological, and chemical aspects. The problems of description and measurement and of predicting changes over time have been noted in previous chapters.



One important attribute of an ecological system is that it changes over time, and therefore the same combination of inputs will not always produce the same basket of outputs. In addition, system responses are not always immediate. Some responses may take years or decades to manifest themselves. Moreover, current knowledge is not sufficient to predict how the system will change on its own or as a result of the application of various input combinations, or how the basket of outputs will change with changes in the ecosystem.

It is useful to think of combinations of inputs and baskets of outputs because it makes the interdependencies explicit. There is no independent relationship between the input for one particular service and the level of output produced. For example, fishing for one species at a specific place and time can affect future catches of other species throughout the ecosystem. The equipment used to produce oil can affect the amounts and types of fishing activities as well as the routes vessels must take. The harvest of fish for commercial use will reduce the amount available for traditional use.

The production of any of the goods and services from the ecological asset comes at a cost. There is the opportunity cost of the inputs and, potentially, the externality cost of lost production of other goods and services from the ecological asset now or in the future. This is a critical point for management and policy analysis. A particular service may be valued or desired, but often it can be obtained only by giving up another service. Good policy analysis requires that the choice be acknowledged.

The composition of the inputs used at any point in time is the result of human choice. Much of it is determined by private choice, when profit or utility-maximizing individuals or firms make decisions. Private choice is constrained and motivated by various rules and institutions established by government. For example, gear restrictions affect how fishermen operate, and tax laws and depreciation schedules affect investments in capital used to produce annual inputs to the ecological system. Some of the inputs result from collective choice, as when governments take direct actions such as military operations or pollution cleanup.

### **Management Policy and Wise Use of the Ecological Asset**

Simply put, wise use of the ecological asset and the inputs used to exploit it requires that the flow of the combination of inputs used over time be structured such that the most desirable flow of output baskets over time is achieved. If the current flow is not the most desirable, management policy should attempt to change the combination of inputs used through indirect control of private choice and through collective choices such that the most desirable output flow is achieved.

One major part of policy, therefore, is the design, implementation, and enforcement of rules and regulations that affect private choice and also lead to direct collective action. Knowledge is an important input in private and collective decision making, and yet because it

is a public good, knowledge is likely underproduced.<sup>3</sup> Therefore, another relevant role for policy is to provide knowledge that can be used in making private and public decisions.

The criteria for success of the management system must include ways to compare different flows to output baskets through time, which is a very difficult task. Different flows can vary in the composition of output at any point in time, and in the size and composition of output over time. Thus, to compare goods and services flows, it is necessary to place relative values on both present (yearly fishing catch, scientific research) and future (sustainable fishing yields) outputs.

Many criteria can be used in ranking different flows of goods and services, including economic efficiency, distribution, and religious and cultural beliefs. On efficiency grounds, output flows would be ranked according to their net present value. This is part of current policy, in that many laws and regulations call for an efficiency analysis of policy actions (e.g., the "602" regulations implementing the National Standards in the Magnuson Act and Executive Order 12291).

In addition to the net value of an output, the distribution of the output (both in any one period and over time) will affect how individuals rank alternatives. Societies frequently and knowingly make decisions that decrease the size of the pie on the basis that what is produced is distributed more fairly. It is sometimes possible, and potentially very useful, to separate distribution issues from issues dealing with the size and composition of the pie. Taxes and transfer payments, and other government programs, can affect how output is distributed across time, geographic areas, income classes, and various interest groups. However, the separation can never be complete for general reasons. First, redistribution programs can change the incentives facing private and collective decision makers, which can alter the input combinations used, and hence affect the outputs produced. Second, the composition of inputs has implicit distributional impacts. Therefore, policy that is presumably focused only on the nature of the outputs will affect distribution. For example, a policy to close fishing in a spawning or nursery ground for a particular fish stock in order to increase long-term production can have direct effects on the ability of various groups with different types of equipment or fishing schedules to access the stock. This policy characteristic clearly can have repercussions on the ability to discuss policy options, because the discussants may be focusing on different issues.

Religion, culture, and perceptions of right and wrong are also important factors in ranking the composition and timing of output flows. The fact that different individuals have different views means that deciding how these issues are factored into the ranking process can be a contentious procedure. It will take action at all levels of government to find compromises that will address these differences.

As difficult as determining an appropriate ranking system may be, there are other issues that further complicate ecosystem management. There are a variety of legal and cultural constraints on the ways government can control private choice (e.g., constitutional guarantees against "takings" and for equal protection and freedom of religion) and on the types of activities it can undertake on its own (e.g., its reluctance to enter production activities in direct

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<sup>3</sup> For the most part, private entities will not undertake research or experimentation activities if the expected costs are more than their own potential returns. However, since others may benefit as well from the research results, knowledge will be underproduced if that research is not undertaken.

competition with private enterprise). In addition, the development of policy to achieve the most efficient use of an ecosystem is difficult because of the uncertain relationships between changes in inputs and changes in outputs.

An extra layer of complexity is added by international management. International management occurs in the context of international law, which is much more loosely structured than national law and less able to produce effective change. Additionally, different countries have different views about the composition and distribution of a particular output flow. There can be different valuations of the same good or service and different views about the trade-offs between goods in the present versus these goods in the future. These differences can be cultural or represent different economic circumstances. Distributional conflicts can be especially harsh, because of a reduced willingness to admit that individuals in the other country have any legitimate claims at all. Differences over composition and distribution can also lead to strategic behavior in the interpretation of science. For example, countries that assign higher value to present day fish relative to future fish may be tempted to emphasize uncertainties about potential future decreases in productivity as a justification to increase current catch.

### IMPLICATIONS FOR MANAGEMENT

The above framework stresses several important points. What we get out of the system depends on what inputs we apply. Directly or indirectly, government rules, laws, and actions affect the nature of the inputs and hence the nature and distribution of the outputs over time. It does not make sense to talk about conservation of the ecosystem in and of itself. It is difficult to define what the Bering Sea ecosystem is and to find ways of measuring various facets of it. It is extremely difficult to define conservation of a system that is constantly changing—sometimes incrementally, sometimes abruptly, but never in ways that we will ever completely understand or be able to predict in operational terms. Conservation is wise use over time, discussed most simply, in terms of the flow of services that the system can produce.

A review of the domestic, bilateral, and multinational agreements and institutions that currently govern various aspects of the Bering Sea ecosystem (see [Chapter 5](#)) illustrates that most management policies have not been developed within such a broad framework. U.S. domestic laws oversee Bering Sea fisheries (Magnuson Fishery Conservation and Management Act, 1977; Fishery Conservation Amendments, 1990) and protect marine mammals (Marine Mammal Protection Act, 1972) and other endangered species (Endangered Species Act, 1973). Management regimes developed by indigenous peoples of Alaska also govern specific animals of the region (Alaska Eskimo Whaling Commission, Eskimo Walrus Commission, Alaska Beluga Whale Committee, Yukon-Kuskokwim Delta Goose Management Plan). Bilateral agreements among the United States, Canada, Russia, Japan, Mexico, and Australia regulate fishing methods (e.g., drift net mesh sizes), specific fisheries (e.g., halibut, salmon), and a variety of migratory birds. Multinational agreements regulate fishing methods (U.N. General Assembly resolution placing global moratorium on drift nets, 1989), protect specific species (Treaty for the Preservation and Protection of Fur Seals and Sea Otters, 1911; Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea, 1994), and provide an

international framework for the conservation of marine resources (Convention for the Conservation of Anadromous Stocks in the North Pacific Ocean, 1992).

Nearly all of these regulations and institutions have been designed to govern a specific subset of the entire Bering Sea ecosystem. There has been no attempt to develop a consistent ranking procedure for the various resources of the ecosystem, and as a result, choices on the relative value of different resources have been made largely by default. For example, in decisions about the size of commercial fishing levels, the focus may have been on employment and current resource utilization and allocation patterns, whereas little attention may have been directed at the effects of current fishing levels on future productivity. Or similarly, when the Marine Mammal Protection Act was passed, the effects of its regulations on commercial fishing may not have been fully considered. The point here is not to argue against commercial fishing or marine mammal protection, but to emphasize that the full effects of a policy decision should be explicitly considered if appropriate decision are to be made.

Based on the discussion in previous chapters and the above framework, the basic problems that need to be solved to achieve proper management of the Bering Sea ecosystem can be summarized as follows:

1. Lack of knowledge and inherent limitations on understanding and predictability.
2. Incomplete specification of the management objectives.
3. Lack of appropriate U.S. and international institutional structure in which to make and implement *coordinated* management decisions.
4. Inability to coordinate domestic management with users and management agencies of other nations.

These problems are related and, as defined, are not mutually exclusive. However, they are listed separately to focus the discussion. An important factor contributing to problem 1 has been the lack of a coherent research strategy among fishery and wildlife scientists to understand the workings of the Bering Sea ecosystem. Problem 2 refers to the lack of objective criteria for comparing different output flows for the use of the ecosystem. Problems 3 and 4 relate to the inability to ensure that all effects of management decisions are considered and that they are compared against consistent standards when choices about ecosystem use are made. Fisheries and wildlife scientists must ensure that new developments in ecosystem science, concepts and implications, are passed on to decision makers. It should be noted that the problems mentioned apply to ecosystem management in other parts of the nation and the world. It follows therefore, that recommendations presented below thus apply to national policy as well as policy specifically for the Bering Sea ecosystem.

The committee concludes that the following measures are necessary to address these problems. The first is a general recommendation to evaluate the various institutional structures that oversee resource use in the Bering Sea. The other recommendations focus on improving the coordination of policy objectives, policy implementation efforts, and research activities within the Bering Sea ecosystem.

**1. Improve coordination within the complete web of institutional structures that make management decisions concerning resource use in the Bering Sea ecosystem area.**

Management decisions concerning use of the Bering Sea resources are currently made by myriad agencies, councils, committees, and commissions at the tribal, city, county, state, regional, federal, and international levels. These governing bodies have various mandates, authorities over particular areas and resources, and standard operating procedures. The effectiveness of these institutions and the degree of coordination and communication between them vary widely. In addition, there appear to be many cases of overlapping authority and conflicts of interest among institutions. As a result, the committee recommends that a detailed study of all management organizations in the area be conducted. At a minimum, this study should compile the following information for each organization:

- the geographic area under its jurisdiction;
- the resources or activities under its jurisdiction;
- the basis for its authority;
- the legislative mandate and/or other operational objectives;
- its basic operational procedure;
- its funding levels and sources; and
- implicit or explicit links in research, planning, or operation to other organization.

These data will allow an evaluation of the overall institutional structure governing resource use in the Bering Sea ecosystem. This evaluation should focus on several key issues: (1) Do the existing management institutions address the important resources of the ecosystem? (2) Are there areas or resources that are covered by more than one governing body, and if so, are there adequate means of coordination between institutions? (3) Are there conflicts in mandates or operational objectives among institutions that have overlapping jurisdictions? And, most importantly, (4) How can the current institutional structure be improved to develop a coordinated management regime that adequately considers the scientific, cultural, and commercial values of the ecosystem?

**2. Coordination of the philosophy and objectives of the major U.S. acts dealing with resource use in the Bering Sea ecosystem.**

Many federal laws affect the use of the Bering Sea ecosystem, and not all of them are consistent in their mandates or even their philosophies. To the degree possible, any coherent approach to management of the Bering Sea ecosystem needs careful analysis of these laws and a conscious attempt to coordinate management actions by the various agencies that are responsible for implementing them. At a minimum, the acts that should be coordinated include the Magnuson Fishery Conservation and Management Act, the Marine Mammal Protection Act, the Endangered Species Act, the Coastal Zone Management Act, the National Environmental Policy Act, the Outer Continental Shelf Lands Act, and the Clean Water Act. It may be wise to consider those acts dealing with shipping, pollution, and marine minerals as well. To help

full specification of management objectives, this coordinating action should outline the preferences of the affected publics with respect to ecosystem use and, where possible, express their trade-off valuations between various uses in time and over time.

Currently, parts of various U.S. federal laws have many points of conflict at the operational level. The Magnuson Act and Marine Mammals Protection Act are good examples. As discussed in NRC (1994a), the Magnuson Act defines optimum yield for fisheries in such a broad way that "it can be used to justify almost any quantity of catch," and often results in overfishing. Yet conflicts exist between this act and provisions of the Marine Mammal Protection Act—which is administered by the same agency (National Marine Fisheries Service)—and is designed to protect marine mammals from becoming depleted or endangered by the same industry competing with the mammals for fish. To improve management, it will be necessary to identify the specific places and issues where conflicts exist and eliminate them through the development of explicit standards, objectives, guidelines, and mechanisms of coordination and cooperation.

**3. Improved processes and institutions are needed to coordinate the implementation of major federal acts relating to resource use in the ecosystem, and federal-state and international management.**

Developing the explicit standards, objectives, and guidelines for comprehensive management of the Bering Sea ecosystem is only the first step toward coordinated multiple use. It is also necessary to set up an institution that has the obligation and ability to consider the full effects of all actions. This institution could take several possible forms. At one extreme, it could be an "ecosystem" agency that would have direct responsibility for activities by all persons and organizations within the ecosystem. The other extreme would be some sort of coordinating committee for the various public and private agencies and organizations. The advantage of a single agency is that more of the interrelationships between uses would be made explicit. However, there are institutional limits on the amount of coordination that can be achieved within a single agency. Although some degree of coordination is essential, an option closer to independent management may be preferable. This would allow for more clearly defined agency goals, if potentially at the expense of coordination.

Human cultures and institutions change much faster and, generally, at a smaller spatial scale than the ecological systems they are related to. As Norton (1992) points out, *resource management* generally operates at an annual cycle of production whereas *environmental management* (governed by constraints necessary to protect the self-organizing and self-regulatory system that provides the resource) must operate on much longer time scales. For ecosystem management to be effective, institutions must be structured to take this into account.

An informative example from this point of view is that of the Great Barrier Reef Marine Park Authority (R. Francis, personal communication).

The authority, consisting of a three-person board reporting directly to the federal parliament, attempts to balance the many activities and resource uses in ways which provide for the reef's protection and minimize adverse



impacts on essential ecological processes. One way to manage an area this size which will permit multiple use while preserving an ecological balance is to create zones of activity. Every five years, the authority reviews the activities within these zones to ensure that they meet park goals and standards. Comprehensive scientific research has become a critical function because the authority bases its zoning plans and permissible activities on the findings of those research studies. While it works closely with the state of Queensland in managing the park on a daily basis, the authority maintains absolute control over regulations, zoning, policy matters, and conflict resolution. On balance, however, we must conclude that the authority's supervision of the Great Barrier Reef's ecosystem appears to be effective from both scientific and management standpoints. To a large extent, the success of reef management is due to the solid support of the Australian public, which has insisted that the ecosystem be protected and preserved as a national treasure without suffering undue adverse human impacts from multiple-use activities. Some of the authority's success also is due to its having overriding jurisdiction of the reef and the power to enforce its edicts. Furthermore, an effective balance and smooth communications exist between management and science, each of which thrives on the other's presence. Finally, some reason for success in managing the reef is due to the decision to plan and integrate human activities by zone. The Great Barrier Reef, while large and complex an area, is a continuum representing one distinct ecosystem, and the authority has integrated and managed it as such.

Again, the time and space scales at which ecosystem management operates are critical. In the case of the barrier reef, one umbrella agency operates at the scale of what Norton calls environmental management—large blocks or zones of the sea and on a five-year time scale.

One possible structure for oversight of the Bering Sea ecosystem would be to develop a management council that has management and conservation authority over all living resources. Management plans would then be forced to take a more general ecosystem approach and would be judged by the expanded set of standards and guidelines mentioned above. In addition, it would be necessary to set up a coordinating committee to ensure that the plans were in conformance with acts dealing with shipping, pollution, and marine minerals management. The coordinating committee would also be responsible for ensuring that actions with respect to these uses were in conformance with living resource management plans.

In addition, the council should work with state and tribal governments to facilitate joint management where appropriate. Alternatively, the federal government could institute a carrot-and-stick approach similar to that used in the Inter-Jurisdictional Fishery Act to deal with East Coast fisheries. The federal government could fund joint research and planning activities, which would allow for joint management by councils, state, and tribal governments. If joint management plans that meet the standards are not developed in a timely manner, the federal government could assume management authority.

Finally, there would need to be formal provision for coordination between the management council and the State Department as the latter negotiates and implements treaties

concerned with international management issues. Where possible, the treaties should allow for direct relationships between the council and comparable entities in other countries. The council would then have the ability to produce plans for domestic use that directly consider actions to be taken by other countries.

The goal of the above structure should be to focus authority and responsibility in a single entity (the council and the cabinet department that oversees it and approves its actions), while at the same time allowing for necessary coordination with other entities that will continue to have a role in management given the realities of a federalist government with international obligations. This will require the checks and balances of a plan and approval process that considers whether the standards are met and whether the plans are in conformance with other existing laws. It is important, however, to ensure that the process does not become a bureaucratic nightmare that ultimately obstructs good management. Provisions must be made that allow for emergency actions to be taken in a timely manner, actions that can remain in effect for 180 days to a year while permanent management actions are considered.

Because there will always be uncertainties about the current state of the ecosystem and the effects of various combined inputs, a coordinated management agency will not be able to wait for perfect information. It must face the fact that decisions will have to be made on the basis of the best information available. The agency should formally introduce into the policy institutional structure concepts from the literature on decision making under risk and uncertainty and on game theory. Such concepts as confidence intervals and expected values can help decision makers explicitly face what cannot be known for certain. Efforts like the Fisheries-Oceanography Coordinated Investigations of the National Oceanic and Atmospheric Administration Pacific Marine Environmental Laboratory and Alaska Fisheries Science Center would be quite effective if they focused on the impacts of fishing on the ecosystem.

Similarly, because of the uncertainties about the effects of current inputs on the ability of the ecosystem to produce future outputs, if the management goal is to reduce the risk of ecological surprises and to avoid significant population declines in top-level predators, the coordinated agency should adopt a risk-averse position when making policy decisions. Because the negative effects could be substantial and long lasting, the council should assess outcomes conservatively. It should err on the high side when estimating likely costs in terms of forgone future production, and it should take reversible actions to the degree possible, so that mistakes can be undone when the opportunity costs prove higher than originally estimated. For example, it seems that the heavy exploitation of several long-lived (K-selected) species in the Bering Sea in the 1950s through the 1970s helped to create the current conditions there, conditions that are undesirable and perhaps not reversible through short-term management actions. The management agency should also structure its management actions such that it can learn more about the ecosystem (see recommendation 4 below).

One of the reasons private decisions regarding inputs will not always generate the appropriate flow of outputs is that, given the current property rights structure, private decision makers are not forced to bear all of the costs of their actions nor are they able to gain all of the benefits. Different kinds of production in the ecosystem are interrelated, but current property rights do not consider this. One way to address this is to adjust the property rights structure. Creating new property rights is one possibility. Individual transferable quotas (ITQs) in fisheries management are an example. Co-management with tribal governments or fisheries cooperatives

may also be worth considering when these entities have appropriate internal governance abilities. The coordinating agencies should also consider further implementations of ITOs, co-management, or other changes in the property rights structure that would change the incentives of private decision makers so they will more fully consider the effects of their actions.

**4. A research program to increase understanding of the Bering Sea ecosystem should be designed (keeping international issues and cooperation in mind), to fulfill the research needs outlined in the following chapter to help future policy makers solve both short-term management issues and longer-term ecological issues.**

Although it will never be possible to know everything about the workings of the Bering Sea ecosystem, much more can still be learned. The more we know, the better we will be able to make decisions to ensure proper resource use. To obtain new information, a research program is needed to examine the problems of the Bering Sea ecosystem. The effort should address both the short-term management issues of today and the major ecological issues that will later affect policy decisions. Because the main policy issue is the choice of appropriate outputs, research should focus on this broad picture. To give a simple example, while it may be important to understand how a change in prey will affect foraging behavior and the relative population size of a particular stock, the research is not complete until this is interpreted in terms of inputs and outputs over time. Further, while parts of the research program may need to focus on specific aspects of the ecosystem, it is vitally important that the research program as a whole emphasize the patterns and interconnections of the system in a way that supports coordinated management.

The research program should be an integral part of the institutional structure of management. There must be appropriate channels of communication such that the types of problems facing management organizations and the kind of information they need to make better decisions are directly considered when choosing the kinds and amount of research to be done.

It is also important for the current state of knowledge, however imperfect, to be tied to the rule-making of the institutional structure. Basically, this means that there must be mandated channels and proscribed formats for research results to be received in a timely manner and presented in ways that can be directly useful; it is most important for the research to include indigenous as well as Western knowledge and participants.

At a more fundamental level, however, there must be procedures to ensure that all relevant information is considered when making decisions. As a simple example, consider a decision to set a total allowable catch in a fishery. In such cases, stakeholders often have differing views and interests concerning how much should be taken in the short-term and how much should be left to ensure future value. Depending on the balance of interests in the institutional structure, quotas might be set a higher level than can be justified by scientific information, although the different views often are expressed in terms of what the information does justify (see NRC, 1994a for a discussion of related topics). To reduce such possibilities, reviews that mandate consistency with the best available scientific information (with redress if such consistency is not maintained) should be built into the overall institutional structure. In cases where such reviews already are incorporated, steps could be taken to broaden the scientific

basis of the reviews to ensure that they include ecosystem and socioeconomic perspectives. Similar considerations led a recent National Research Council committee on anadromous salmonids to recommend the establishment of an independent science advisory board to help bring an unbiased scientific component to decision making in the Pacific Northwest (NRC, 1996).

Although much of the research necessary to improve management may be conducted in the traditional manner in government and academic research labs and vessels, it will be wise to consider other venues as well. Joint research projects with the commercial fishing industry, tribal governments, environmental groups, and other nations that have interests in the region, perhaps through organizations such as the North Pacific Marine Science Organization (PICES), are needed, in terms of both research design and implementation or funding. Cooperative decision making is much easier if both parties agree on the science. At the minimum, planning meetings are necessary to ensure that common calibration and research methodologies are used.

The instability in former Soviet Union countries poses a serious threat to the amount and types of research that will be done in the Bering Sea. The United States should be very cooperative in assisting research that, under normal situations, might be considered the obligation of another country. Understanding events in Russian waters will be important to the overall management of the Bering Sea. If the appropriate amounts and types of research are not likely to be forthcoming, it may be in the interest of the United States to do more of this research and to help these countries with funding. In addition, a study should be initiated to evaluate and possibly retrieve data on the Bering Sea ecosystem that are scattered in publications, files, and archives of former Soviet Union agencies (Soviet Ministry of Fisheries, Naval Hydrographic Service, Ministry of Geology, State Committee on Hydrometeorology and Environmental Control, and the Soviet Academy of Sciences). Such a study should focus on evaluating both the significance and the accuracy of the data in order to determine whether a data rescue effort should be actively pursued.

A final research issue is the ability to learn from management decisions. Following Walters and Hilborn (1986), it is wise to implement policies that allow for learning. If it is unclear how different intensities of exploitation affect stock size, exploitation rates can deliberately be manipulated to learn what will happen. The implications of such approaches on other outputs (i.e., other populations and species of organisms and various ecosystem characteristics, including effects on humans) must be considered, however. More knowledge may be beneficial, but the potential gains in knowledge must be balanced against the effects of abrupt changes in the output of fish or other components of the system. While this is a controversial issue, the rules for determining what management actions are appropriate should not be so strict as to preclude learning by doing.

## 8

# Gaps in Knowledge and Recommendations

Both the gaps in our knowledge about the Bering Sea ecosystem and the research required to fill those gaps are so extensive that a detailed elaboration could be a report in itself. However, characterizing the general shortcomings of our past perspectives that contribute to our present lack of understanding and specifying a list of priority research needs could help address some of the most pressing issues concerning the Bering Sea ecosystem.

The biggest single impediment to understanding the causes of change in the Bering Sea ecosystem (as well as in many other ecosystems) is the absence of an ecosystem viewpoint in research and scientific analysis. Previous research has typically focused on individual species populations, small subsets of the ecosystem, or short time periods. Such approaches have reflected the narrow ecological and temporal focus and responsibilities of the individual management agencies responsible for specific subsets of resources in this ecosystem. Such partitioning of an ecosystem into separate species, or subsets of species, does not allow the broad synthesis of information across all interacting and interdependent components of the ecosystem. Such synthesis is required to properly interpret the dynamics of the system. The most significant research recommendation that emerges from this study is to adopt a broader ecosystem perspective in both science and management of the natural resources of the Bering Sea. Such an approach makes sense scientifically and holds the greatest promise for improved management and understanding.

Even with adoption of an ecosystem perspective to synthesize information, ecological science will never achieve complete understanding of what controls the dynamics of distributions and abundances of species in any ecosystem. Gaps in knowledge will always be present and unexpected phenomena will continue to arise. Such changes, if deemed important, will stimulate demand for additional research, enhancing our understanding of causation and consequences. The challenge to management and stewardship of ecosystems is therefore how best to manage human activities given substantial uncertainty in the scientific understanding of the causes of dynamic change in those ecosystems.

In part because of undersampling of marine ecosystems, there is probably greater uncertainty about the causes of dynamic changes in ecosystems in the ocean than on land. The vastness, isolation from human habitation, and large, three-dimensional domain of the open oceans create an overwhelming problem in simply knowing the abundances and distributions of species in the ecosystem. Although physical oceanographers have the technological capacity to

characterize ocean currents in three dimensions by use of acoustic Doppler current profilers, for example, the development of analogous biological samplers (even those exploiting the same acoustical principles) is in its infancy.

Nonetheless, despite substantial gaps in our understanding of the dynamics of marine ecosystems, there is compelling evidence that changes in both the physical climate of the sea and fishing have had large influences on the composition and dynamics of many marine ecosystems (e.g., Sherman, 1991; [Chapter 6](#)). Again, distinguishing between effects of physical changes and those of fishing (more broadly, exploitation of natural resources) was the central issue in our evaluation of the causes of recent declines in certain marine mammals (Steller sea lions, harbor seals, and fur seals) and seabirds (red- and black-legged kittiwakes, sea ducks, and murre) over various expanses of the Bering Sea and adjacent regions.

A critical difference exists between these two kinds of potential causes of change in the Bering Sea ecosystem. Changes in the physical climate of the sea occur largely, although not completely, independent of human control, whereas exploitation of natural resources is directly carried out by humans and theoretically can be controlled (in practice, control often is extremely difficult). This difference potentially allows fisheries to be managed with attention to evaluating rigorously the consequences of the exploitation (e.g., Peterson, 1993). This has been called adaptive management (McAllister and Peterson, 1992; Walters and Hilborn, 1986). Under well-designed fishing regulations (based on hypotheses about ecological causation), adaptive management of fisheries can become an extremely powerful tool for improving our understanding, not only of the impacts of fishing but also of the basic functioning of marine ecosystems (Holling, 1993). Clearly, the potential for adaptive management of the Bering Sea fisheries has not been adequately applied to develop the necessary understanding of the role of fishing in contributing to ecosystem changes. These would especially include disturbing declines in many important marine mammals and seabirds.

Much of the research on the Bering Sea ecosystem to date has followed the traditional reductionist path of trying to understand the mechanisms that drive the dynamics of this ecosystem on various spatial and temporal scales. Such an approach has obvious value. Elucidating fundamental interactions among components of the physical and biological environment appeals to a large majority of scientists and promises the capacity to understand and perhaps predict. Such research on basic processes should continue, but it should be complemented by assessments of the effects of manipulating the system through fisheries-management practices.

This effort must include the provision of resources sufficient for research to follow up with evaluations of how variations in fishing affected the functioning of the system. It also must examine the ecosystem's ability to sustain populations of key component species. For example, the recent establishment of no-fishing buffers around important colonies of seabirds and marine-mammal haulouts provides opportunities for exactly the sort of experimental adaptive management that is required. However, there has been no experiment or dedicated research to assess the role of fishing in declines of certain important marine mammals and seabirds. The U.S. National Marine Fisheries Service (NMFS) regulations of fishing were not designed with experiment in mind, and little research support was provided to evaluate the effects of these



changes in fishing practices. This is a wasted opportunity to realize an important aspect of adaptive management; learning through rigorous evaluation of the consequences of management interventions. These oversights must be corrected to achieve confident stewardship and sustainable use of the living resources of this ecosystem.

To be effective, the adaptive management actions and research goals to be addressed through intervention in fishing practices must be jointly planned by fisheries scientists, bird and wildlife biologists, oceanographers, fisheries managers, and the users of the natural resources on both sides of the Bering Sea. In using adaptive management to evaluate the role of fishing in the ongoing declines of valued marine mammals and seabirds, any changes in regulation and management of fishing must be carefully crafted. They should include tests of specific hypotheses that relate to critical aspects of the species' ecology in the proper physical context. For example, while average abundance of important forage fishes such as pollock may remain high even with intense fishing when considered over the complete Bering Sea basin, dramatic depletion of certain size (age) classes at certain times and in certain places is likely to occur as a result of commercial fishing in this system. The creation, evolution, movement, and transformation of those depleted patches will depend on both physical and biological processes. Those local depletions may correspond with the seasons and locations where food limits one or more important consumers of these forage fishes. For example, the need for abundant food of high nutritive value around rookeries or other important foraging areas to nourish parents or independent young may well present a conflict between fishing and sustained production of some marine mammals and seabirds.

Design of adaptive fisheries management to test the relationship of local fishing to successful passage through potentially critical life history stages must be achieved through collaboration. The collaboration should take place among scientists of several disciplines and fisheries managers, so that the management actions taken match the relevant biological time and space scales. Thus experts on marine mammals and seabirds must participate early in the design of the management plan, and agree that the plan is an appropriate test of the most important hypotheses. The study plan developed must recognize relevant physical transport and mixing processes as well. One set of adaptive management actions may not suffice to test all the important hypotheses; several management interventions may be needed. Some disruption of historical patterns of commercial fishing will necessarily occur in this process, but adaptive management is the most rigorous, efficient, and effective means of evaluating the effects of these fisheries on the broader ecosystem. Other indirect methods of testing for the effects of various fishing practices will perpetuate the piecemeal efforts of the past, and will not dramatically improve our understanding of the relationships until a great deal more money has been spent and critical time for restoration has passed. Manipulation of the fisheries using a well-crafted design, together with funding for ecological evaluation of impacts, represents the best way to address these unanswered questions. It is important to keep in mind that fishing includes commercial, subsistence, and recreational fishing, and that all of them to varying degrees affect each other and the exploited organisms.

There are several additional research needs of high priority. One is the need for a better, more complete retrospective analysis of the Bering Sea ecosystem and certain of its key components. This analysis is especially critical for pollock, because of continuing uncertainty over whether its present high abundance is a relatively recent phenomenon, or whether the

absence of pollock fishing before about 20 years ago gives a false impression of relatively low pollock biomass in earlier years. The relationship between adult and juvenile pollock abundances also needs to be understood better. Resolution of these and similar unanswered problems related to the historical composition of the Bering Sea ecosystem is critical to understanding the relationship of top predators to prey resources and questions concerning natural versus human-caused fluctuations in species abundance.

The present monitoring of the Bering Sea ecosystem is inadequate to understand, let alone predict, biological changes within it. In fact, there is no ecosystem monitoring. Only a few components of the system are monitored at all, with insufficient attention to the broader context of the ecosystem. We have little or no quantitative information on such critically important prey species as capelin, sand lance, smelts, squids, and myctophids. Understanding and managing an ecosystem without basic knowledge of the prey base on which the predator species depend is virtually impossible.

Both conceptual and mathematical models of the structure and function of the Bering Sea ecosystem must be developed and verified by comparison with field data to advance understanding of the ecosystem, to focus further research on the most sensitive issues, and to guide adaptive management decisions. Such models are also necessary to design proper ecosystem monitoring, which cannot be so extensive as to provide information on all elements of the system. A sensible ecosystem monitoring strategy must be model-driven. For example, a selection of specific seabirds and marine mammals may serve well as indicators of the forage prey base of the entire ecosystem in a much more cost-efficient and biologically meaningful way than direct monitoring of all prey populations. Monitoring a shallow-diving seabird such as a kittiwake and a deep-diving seabird such as a murre might be one tool, for example, to monitor offshore pelagic forage fish. Such suggestions need to be more completely developed to cover the most important aspects of the ecosystem.

At present, there is no archive of information about the various databases that do exist on certain aspects of the Bering Sea ecosystem. The sources and contact people for each database need to be identified and compiled in a fashion that permits potential users to access data. This is not to suggest that vast resources be spent in the creation of a comprehensive database on the Bering Sea. In the modern era of distributed computing and information highways, such an effort is not necessary. Ultimately, the use of geographic information system technologies to achieve integration through data overlays on various scales of time and space should be encouraged to move closer to the integration required for an ecosystem perspective.

Long-term monitoring of important physical and biological components of the Bering Sea ecosystem must be established to permit analyses of observed changes in the system and their causes. The short-term perspective of almost all available data sets contrasts sharply with what is known about the longer-term nature of many important climate changes and the population dynamics of many long-lived organisms. Instead of initiating necessary long-term monitoring, some of the most important long-term records are being abandoned, with grave implications for understanding and management of the system as a whole. For example, a long-term (30-year) program of monitoring juvenile fur seal survivorship was abandoned in 1988 and should be reinitiated. Other long-term monitoring programs need to be established through reference to good conceptual models of the ecosystem.

A major field research program is required to develop the necessary basic understanding of how the physical conditions of the Bering Sea interact with the biological system to drive changes in ecosystem dynamics. There has been a substantial research commitment to achieving an oceanographic, process-based understanding of the eastern boundary current systems of upwelling. In other ecosystems, these upwelling systems are critical to production of important ecosystem goods and services. However, mechanistic understanding of the roles of climate and physical oceanographic forcing relative to the predominantly buoyancy-driven currents of the critical green belt of the Bering Sea is incomplete. This basic oceanographic research is central to developing the conceptual and mathematical models for focusing research, monitoring, and managing of this system.

A data rescue and archiving project should be initiated immediately to preserve endangered ecological information that has been collected by individuals and institutions within the borders of the former Soviet Union. The breakdown of institutional structures within Russia and the republics threatens the loss of valuable information on components of the Bering Sea ecosystem along the Asian coast. In this region of the Bering Sea, there has been virtually no research by U.S. scientists. Furthermore, many data records that complement U.S. information are also known to be in files within the former Soviet Union, often in such forms as hand-written notes.

Further basic research on ecosystem dynamics is needed to address convincingly whether ecological science can predict or even explain how a perturbation to an ecosystem cascades through that system. The characteristics of an ecological system that will allow confident prediction or explanation of cascading impacts should be identified. These questions need to be addressed in marine pelagic ecosystems, where little, if any, research has ever taken a broad perspective involving the dynamics of complete ecosystems.

Research is also needed to integrate traditional knowledge of indigenous peoples into the body of scientific knowledge on the Bering Sea, to achieve both better scientific understanding and better resource management. The traditional knowledge of native communities and the acquired knowledge of fishermen and hunters represent valuable sources of information and understanding.

Ecological research on the meaning of sustainability is necessary to address the question of how to define sustainability under conditions of dynamic natural change in ecosystems. This is an especially challenging question in ecosystems undergoing substantial changes in response to major climate shifts, which force biological responses.

Management decisions concerning the Bering Sea ecosystem that affect many stakeholders both within the region and in other parts of the world are made by local, state, regional, tribal, national, and international entities. Good institutional structures should be designed to coordinate the activities of these entities such that the views of all stakeholders can be heard, the likely effects of alternative actions can be made known, and decisions can be reached. In addition, research is necessary to design specific management regimes and regulatory tools (such as area management, co-management, or individual transferable quotas) that are acceptable to the stakeholders, enforceable, and capable of changing individual behavior such that the intended objectives for resource use can be achieved. Improved knowledge of the ecosystem will have little effect on resource use unless there are overall management structures that can implement effective policies and overall communication structures that can facilitate exchange of knowledge

and understanding among different stakeholders. These considerations led the committee to make the following recommendations.

## RECOMMENDATIONS

### Research

#### Adaptive Management

One research recommendation includes and influences all the others, and that is the first one on adaptive management and monitoring. Humans have exploited the Bering Sea ecosystem for hundreds of years, at least, but because of environmental variability and the lack of adaptive (experimental) approaches to management, our understanding of the system remains meager. This problem is not unique to the Bering Sea; it is common to many if not all problems of natural resource management (see, for example, NRC, 1996 for a discussion of this problem with respect to salmon in the Pacific Northwest.)

- **An adaptive or experimental approach should be taken to all management actions concerning the Bering Sea ecosystem.** Despite the committee's conclusions that the cascade hypothesis is a plausible explanation for at least some of the changes observed in the Bering Sea over the past 50 years and that the only significant human activity that could have affected the Bering Sea ecosystem is fishing, much remains unknown about the ecosystem and its functioning. Regulated human activities such as fishing provide some of the best possible vehicles for experimentation and improving understanding, as do protective activities mandated by the Endangered Species Act and the Marine Mammal Protection Act. It is therefore of critical importance that such activities and related regulations be designed such that information can be gained from them wherever possible. In addition to information already required, such as catch statistics, regulations should be implemented on an adaptive basis wherever possible. For example, no-fishing zones have been established adjacent to 43 sea lion rookeries, but some people, including members of this committee, believe that they are too small. Therefore, the National Marine Fisheries Service should reexamine the size of the no-fishing zones based on actual foraging ranges and habits of juveniles. In particular, no-fishing zones of various sizes should be implemented in a controlled way. As another example, the committee suggests that experimental fishing (and perhaps even overfishing in some carefully selected and limited areas) would be of value. Thus, in a few selected areas, one might set catch limits on pollock and some flatfish species above the level estimated to be sustainable, with carefully designed experimental monitoring of a variety of ecological factors, including those mentioned in the recommendations that follow.

## Research to Improve Understanding of the Ecosystem

Two of the most important questions about the functioning of the Bering Sea ecosystem concern pollock, which appears to be an important (keystone) species in the ecosystem (Bakkala, 1993; chapters 4 and 6), and the effects of sea ice, which has a major influence on the oceanography of the eastern Bering Sea shelf (Coachman, 1986; Ohtani and Azumaya, 1994; Chapter 3), and hence on the life of bottom-dwelling and near shore species such as crabs, flatfishes, and herring. Research on the more general questions about the ecosystem should keep these two questions in mind. The committee recommends research on the following questions.

- **What are the nature and causes of the dynamics of pollock in the northeastern Pacific and Bering Sea over the past 50 years?** Understanding this broad question can be approached by asking a number of more specific questions:
  - a. Is the cascade hypothesis a plausible scenario for ecosystem dynamics? To answer this question, models would be useful. Is it possible to model energetics and energy transfers to arrive at a result that is consistent with the cascade hypothesis, with experience in other ecosystems, and with the available data? What is the effect of releasing zooplankton from predation? To what degree are alternative states of ecosystem organization stable? How likely is the organization to return to its previous state or to some other state?
  - b. What are the short- and long-term effects of commercial fishing on the structure and dynamics of the Bering Sea ecosystem? Short-term effects might be investigated through adaptive management of the fishery, as described in the first research recommendation. Longer-term effects could be investigated through modeling and through comparisons with other large ecosystems, in addition to the continued, controlled collection of relevant data about fishing and its effects. Important questions include the effects of removing commercial species on their predators, their competitors, and their prey. In each case, information about substitutability is important, e.g., would their predators switch to other food sources and would their prey be eaten by their competitors? How does fishing affect the distributions of various species? How wide-ranging are its effects, e.g., how does fishing off Attu Island affect distributions and abundances of species in Norton Sound?
  - c. What are the roles of top-down and bottom-up forcing in the Bering Sea ecosystem? Do commercial, subsistence, and recreational fishery effects tend to be top-down and environmental effects bottom-up? How do such effects manifest themselves?
  - d. What are the relationships between juvenile pollock and other forage species (e.g., capelin and Pacific sand lance) in the ecosystem? How do they organize the time and space dynamics of the top-level predators such as birds and marine mammals (and human fishers)? Answering this question would require studies of at-sea ecology of marine mammals and birds. More information is needed on the foraging locations and diets of marine mammals, especially pinnipeds. Long-term information on the distribution and abundance of seabirds at sea would be valuable to help understand foraging patterns and their relationships to oceanic productivity and the distribution and abundance of plankton and small fish. Finally, focused time series studies of the geographic and spatial distributions (and variability) of macrozooplankton are needed. This information is needed to study and understand the behavior of larger invertebrates,

and the vertebrates (including pollock) that rely on them and on zooplankton as a significant part of their diet.

- **What is the role of ice in structuring the Bering Sea ecosystem?** This general question encompasses many questions about the eastern Bering Sea shelf resources, in particular those concerning crabs, flatfishes, and herring, and their population dynamics. They are all influenced by bottom temperatures, which in turn are influenced by sea ice. More specific questions include the following:
  - a. What are the habitat requirements of various commercial invertebrates (especially crab species) and demersal finfishes (especially flatfishes and herring)? It would be valuable to know the habitat preferences and requirements (if any) of these species, and the relationship of fishing activities to their occupation of various habitats. A habitat and distribution atlas would be helpful.
  - b. How did the seasonal and interannual dynamics of ice affect the collapse of the eastern Bering Sea king crab fishery? Would it have been possible to manage the fishery so as to avoid the collapse?
- **What are the periodicities of ecosystem changes?** Much of this information can be obtained by analysis of existing data and by extrapolation from other related systems, but most will require long-term study. In some cases, the information is already being collected, and financial and administrative support is needed for continued study. Information is needed on the periods of physical changes such as the position of the Aleutian Low, ocean circulation changes, and sea surface temperatures. Better and longer-term information is needed on the distribution and abundance of marine mammals, seabirds, fish, benthic invertebrates, and plankton.
- **How do lower trophic levels of the ecosystem interact?** Better understanding of the lower-levels of food webs is needed, especially trophic roles and dynamics. Planktivorous birds (and fishes, if their place and time of collection are carefully documented) can be used to monitor at least the surface distribution and abundance of various planktonic species.
- **What are the structure and functioning of the "green belt?"** It is important to understand the green belt better, to know the degree to which it supports productivity of various parts of the Bering Sea ecosystem, and to know more about the physical and biological features that make it more productive than other parts of the Bering Sea. Does it serve as an important source of biological production for the eastern, central, and western Bering Sea? Does it provide a connection between those areas; i.e., do changes in the green belt affect the various areas in a related way?
- **How well are the management and institutions of the Bering Sea structured to address problems and provide appropriate management solutions?** The committee recommends detailed study of these institutions (for the reasons described in more detail in [Chapter 7](#)); the important questions to ask about each institution would include:



- the geographic area under its purview;
- the resources and activities under its purview;
- the basis for its authority;
- the legislative mandate or other operational objectives;
- its basic operational procedures;
- its source and level funding; and
- any implicit or explicit links between it and other organizations in research, planning, or operations.

This information would help to develop understanding of the areas and types of regulation. Answers to these questions could help answer other questions, such as whether the North Pacific Fishery Management Council should be given more or less centralized authority or whether it should be restructured, and whether the Magnuson Fishery Conservation and Management Act, the Marine Mammal Protection Act, and the Endangered Species Act are compatible with a program of research and management with an ecosystem perspective.

## Management and Institutional Recommendations

### Institutions

The committee identified four basic problems that need to be solved to achieve proper management of the Bering Sea ecosystem: the lack of knowledge and inherent limitations on understanding and predictability, incomplete specification of management objectives, lack of appropriate domestic institutional structures through which to make and implement coordinated management decisions on either side of the Bering Sea, and the limited ability to coordinate domestic management with users and management agencies of other nations. The committee recommends the following steps to address these problems (described in detail in [Chapter 7](#)):

- **Improve the coordination of the complete web of institutional structures that make management decisions concerning resource use in the Bering Sea.**
- **Coordinate the philosophy and objectives of laws dealing with management in the Bering Sea ecosystem.**
- **Improve processes and institutions to coordinate the implementation of major federal acts relating to resource use in the ecosystem, and federal-state and international management.**
- **Develop a research program to increase understanding of the Bering Sea ecosystem (keeping international issues and cooperation in mind), to fulfill the research needs identified by the committee to help future policy makers solve both short-term management and longer-term ecological problems.**

### **Specific Action to Reverse Declines in Marine Mammals and Birds**

To reverse declines in marine mammals and birds, broaden the distribution of fishing effort in space and time, especially for pollock. As described in [Chapter 6](#), there is a significant likelihood that concentrated fishing for pollock in some places at some times can have an adverse effect on availability of food for marine mammals and birds, especially juveniles. Therefore, fishing over wider areas and over longer periods is likely to improve the food supply for these animals, and is extremely unlikely to have adverse effects. The intent of this recommendation is not to increase total catches, and some areas should probably still be closed to fishing for conservation of fish, bird, and mammal populations. As with all management actions, if this one is adopted, it should be done on an adaptive basis.

### **THE FUTURE**

The Bering Sea ecosystem, like all ecosystems, has been affected by natural fluctuations since time immemorial. Like most ecosystems, it has been affected by human activities since prehistory, but especially within the past 200 years as commercial exploitation developed. Thus, the recent changes that we see today should not be thought of as perturbations of a "pristine" ecosystem, but as part of a pattern of change affected by a complex array of natural and human influences.

The complexity of the influences on the ecosystem makes understanding and management difficult, but some things are clear. First, environmental change will continue to occur in the future. Second, significant human exploitation of a single species can affect not only that species but many other species as well. In other words, there are connections among ecosystem components. Finally, the total productivity of the ecosystem has a limit, which means that human use of living resources will affect the ecosystem to some degree. Those three conclusions imply that unexpected events will continue in the future and that they will be larger as living resources are more heavily exploited. It also follows that actions with respect to single species will have complex consequences that will be hard to predict. Simply changing exploitation rates on a single species—pollock, for example—is unlikely to have easily predictable effects on other ecosystem components—marine mammals, for example.

To operate successfully within this complex system, management strategies must be based on long-term data on physical and biological phenomena and must be adapted as we learn more about the structure and functioning of the ecosystem. A better understanding of institutional and socioeconomic factors will also be needed. Finding a balance between human uses of the region's many resources and maintaining other desired aspects of the ecosystem, such as high productivity of marine mammals or a particular composition of fish communities, will be an ongoing challenge.

## References

- ADF&G (Alaska Department of Fish and Game). 1993. Preliminary forecasts of catch and stock abundance for 1993 Alaska herring fisheries, F. Funk, ed. Regional Information Rep. No. 5J93-06. 92pp.
- Aebischer, N. J., J. C. Coulson, and J. M. Colebrook. 1990. Parallel long-term trends across four marine trophic levels weather. *Nature* 347:753–755.
- Agreement on Mutual Fisheries Relations, 31 May 1988, United States-Soviet Union.
- Ainley, D. G., A. R. DeGange, L. L. Jones, and R. J. Beach. 1981. Mortality of seabirds in high-seas salmon gillnets. *Fish. Bull.* 19:800–806.
- Ainley, D. G., R. P. Henderson, H. R. Huber, R. J. Boekelheide, S. G. Allen, and T. L. McElroy. 1985. Dynamics of white shark/pinniped interactions in the Gulf of the Farallones. *Mem. South. Calif. Acad. of Sci.* 9:109–122.
- 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. *Stud. Avian Biol.* 15:119–133.
- Alaska Geographic. 1976. Alaska's Volcanoes: Northern Link in the Ring of Fire. *Alaska Geographic*, vol. 4, number 1. Anchorage: Alaska Geographic Society.
- Alexeev, A. I. 1982. Russian Discovery of the Far East and Russian America. Moscow: Nauka. [In Russian].
- Allen, P. M. 1985. Ecology, thermodynamics, and self-organization: Towards a new understanding of complexity. *Can. Bull. Fish. Aquat. Sci.* 213:3–26.
- Allen, T. F. H., and T. B. Starr. 1982. *Hierarchy: Perspectives for Ecological Complexity*. Chicago. University of Chicago Press.
- Allen, T. F. H., and T. W. Hoekstra. 1992. *Towards a Unified Ecology*. New York. Columbia University Press. 384 p.
- Alton, M. S., R. G. Bakkala, G. E. Walter, and P. T. Munro. 1988. Greenland Turbot (*Reinhardtius hippoglossoides*) of the Eastern Bering Sea and Aleutian Islands Region. U. S. Department Commerce, NOAA Tech. Rep. NMFS 71.
- Alverson, D. L. 1992. A review of commercial fisheries and the Steller sea lion (*Eumetopias jubatus*): The conflict arena. *Rev. Aquat. Sci.* 6:203–256.
- Alverson, D. L., M. H. Freeberg, S. A. Murawski, and J. G. Pope. 1994. A Global Assessment of Fisheries Bycatch and Discards. FAO Fish. Tech. Paper 339. 233 pp.

- AMAP. 1993. (Arctic Monitoring and Assessment Program) A report from the AMAP Task Force: Update on Issues of Concerns to the Arctic Environment, Including Recommendations for Action. pp. 1–56.
- American Association of Petroleum Geologists, Pacific Section, Los Angeles. Pp. F1–F28.
- Anderson, P. J. 1978. Growth and mortality estimates for a population of pink shrimp *Pandalus borealis* from the western Gulf of Alaska. Unpublished.
- Andriyashev, A. P. 1954. Fishes of the Northern Seas of the USSR. Moscow: AN SSSR. [In Russian].
- Andriyashev, A. 1935. Geographical distribution of marine commercial fishes of the Bering Sea and related issues. Issled. Morei SSSR. 22:135–145. [In Russian].
- Anonymous. 1992. Report of the Study Group on Ecosystem Effects of Fishing Activities. International Council for the Exploration of the Sea. Unpub. document C. M. 1992, G:11, 144 pp.
- Anonymous. 1993. Is It Food? Addressing Marine Mammal and Seabird Declines, Workshop Summary. p. 41 in Distribution and Abundance Trends of Forage Fishes in the Bering Sea and Gulf of Alaska, L. W. Fritz, ed. University of Alaska Sea Grant Rep. 93–01. Fairbanks: University of Alaska.
- Apollonio, S. 1994. The use of ecosystem characteristics in fisheries management. Rev. Fish. Sci. 2(2):157–180.
- Apollonio, S. 1993. Fisheries ecosystem research program. Pp. 170–173 in The System in the Sea—Applying Ecosystem Principles to Marine Fisheries, D. D. Platt ed. Rockland, Maine: Island Institute.
- Armstrong, D. A., J. L. Armstrong, R. Palacios, G. Williams, G. C. Jensen, and W. Person. 1985. Early life history of juvenile blue king crab, *Paralithodes platypus*, around the Pribilof Islands. Pp. 211–227 in Proceedings of the International Crab Symposium, Anchorage, Alaska.
- Arsen'ev, V. S. 1967. Currents and water masses of the Bering Sea Moscow: Izd. Nauka. [In Russian, English summary]. (Transl., 1968, NMFS, Northwest Fish. Center, Seattle, Wash.) 135 pp.
- Aruntunov, S., and D. Sergeev. 1975. Problems of the Ethnical History of A Beringia. Ekwen Tomb-stones. Moscow: Nauka.
- Ashmole, N. P. 1971. Sea bird ecology in the marine environment. Pp. 223–286 in Avian Biology, Vol.1, in D. S. Farner, and J. R. King eds. New York: Academic Press.
- At the Meeting Point of Chukotka and Alaska. 1983. Moscow: Nauka.
- Bailey, E. P., and J. L. Trapp. 1986. A Reconnaissance of Breeding Marine Birds and Mammals in the East-Central Aleutian Islands—Kasatochi to the Islands of Four Mountains—Summer 1982, with Notes on Other Species. Homer, Alaska: U.S. Fish and Wildlife Service.
- Bailey, E. P. 1990. Fox Introductions on Aleutian Islands—History, Impacts on Avifauna, and Eradication. Homer, Alaska: U.S. Fish and Wildlife Service.

- Bailey, E. P., and G. H. Davenport. 1972. Die-off of common murrelets 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. Pp. 218–226 in *Status and Ecology of Temperate North Pacific Seabirds*. K. Vermeer, K. T. Briggs, and D. Siegel-Causey eds. Ottawa: Canadian Wildlife Service.
- Bailey, K. M., and D. G. Ainley. 1982. The dynamics of California sea lion predation on Pacific hake. *Fish. Res.* 1:163–176.
- Bak, P., and K. Chen. 1991. Self-organized criticality. *Sci. Am. Jan.*:46–53.
- Baker, J. D., and C. W. Fowler. 1992. Pup weight and survival of northern fur seals *Callorhinus ursinus*. *J. Zool. (Lond.)* 227:231–238.
- Bakkala, R. G. 1981. Population characteristics and ecology of yellowfin sole. Pp. 553–574 in *The Eastern Bering Sea Shelf: Oceanography and Resources*, vol. 1, D. W. Hood, and J. A. Calder, eds. Seattle: University of Washington Press.
- Bakkala, R. G. 1993. Structure and historical changes in the groundfish complex of the eastern Bering Sea. U.S. Department of Commerce, NOAA Tech. Rep. NMFS 114. 91 Pp.
- Bakkala, R. G., and G. B. Smith. 1978. Demersal Fish Resources of the Eastern Bering Sea: Spring 1976. Progress Report. Seattle: NOAA, NMFS, MWAFC. 534 Pp.
- Balsiger, J. W. 1981. A review of pandalid shrimp fisheries in the Northern Hemisphere. In *Proceedings of the International Pandalid Shrimp Symposium*, February 13–15, 1979, Kodiak, Alaska, T. Frady ed. University of Alaska Sea Grant Rep. 81–3. Fairbanks: University of Alaska.
- Bang, I. 1991. Numerical Modeling Study of the Circulation in the Gulf of Alaska. Ph.D. thesis, University of Alaska, Fairbanks. 146 pp.
- Barr, L., and R. McBride. 1967. Surface-to-bottom pot fishing for pandalid shrimp. *Spec. Sci. Rep. Fish. No. 560*. Homer, Alaska: U.S. Fish and Wildlife Service.
- Barrie, L. A., D. Gregor, B. Hargrave, R. Lake, D. Muir, R. Shearer, B. Tracey, and T. Bidleman. 1992. Arctic contaminants: sources, occurrence and pathways. *Sci. Total Environ.* 122:1–74.
- Bartholomew, G. A. 1970. A model for the evolution of pinniped polygyny. *Evolution* 24:546–559.
- Barton, L. H., and V. G. Wespestad. 1980. Distribution and stock assessment of Western Alaska herring. In *Proceedings of the Alaska Herring Symposium*, V. G. Wespestad, and B. R. Melteff eds. University of Alaska Sea Grant Rep. 80–4. 31 Pp.
- Barton, L. H., and V. G. Wespestad. 1991. Distribution, biology and stock assessment of western Alaska herring stocks. In *Proceedings of the Alaska Herring Symposium*. V. G. Wespestad, and B. R. Melteff eds. University of Alaska Sea Grant Rep. 80–4.
- Baskakov, V. 1993. Stock-holding—an important stage of transition to market relations. *Rybn. Khoz.* 3:8–12. [In Russian].
- Baumgartner, T. R., A. Soutar, and V. Ferreira-Bartrina. 1992. Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millenia from sediments of the Santa Barbara basin, California. *CalCOFI Rep.* 33:24–40.
- Beamish, R. J. 1993. Climate and exceptional fish production off the west coast of North America. *CJFAS* 50:22070–2291.

- Beliaev, G. 1960. Quantitative distribution of benthic fauna in the north-western part of the Bering Sea. Trudy IO AN SSSR 34: 85–103. [In Russian].
- Berg, L. 1956. Ancient Data on the Far North of Siberia. Selected writings. Moscow.
- Beringia Conservation Program: Progress Report. 1992. National Audubon Society, Alaska-Hawaii Regional Office.
- Berryman, A. A. 1993. Food web connectance and feedback dominance, or does everything really depend on everything else? *Oikos* 68 (1):183–185.
- Bertram, D. F. 1989. The status of ancient murrelets breeding on Langara Island, British Columbia, in 1989. Can. Wildl. Serv. Tech. Rep. Ser. No. 59. 67 pp.
- Best, P. B. 1993. Increase rates in severely depleted stocks of baleen whales. *ICES J. of Mar. Sci.* 50:169–186.
- Beverton, R. J. H., and S. J. Holt. 1957. On the Dynamics of Exploited Fish Populations. Fish. Invest. Serv. II. XIX, Her Majesty's Stationery Office, UK. Facsimile reprint 1993, Chapman and Hall, London. Distributed in the United States by the American Fisheries Society, Bethesda, MD.
- Bickham, J. W., J. C. Patton, and T. R. Loughlin. In press. High variability for control-region sequences in a marine mammal: implications for conservation and maternal phylogeny of Steller sea lions (*Eumetopias jubatus*). *Conserv. Biol.*
- Bigg, M. A. 1985. Status of the Steller sea lion (*Eumetopias jubatus*) and the California sea lion (*Zalophus californianus*) in British Columbia. Can. Spec. Pub. Fish. Aquat. Sci. No. 77. 20 pp.
- Biological Resources of the Pacific Ocean. 1986. Moscow: Nauka. [In Russian]
- Birman, I. B. 1985. Ocean Period of Life and Issues of Dynamics of the Far Eastern Salmon. Moscow: Agropromizdat. [In Russian].
- Bjerknes, J., 1969. Atmospheric teleconnections from the equatorial Pacific. *Mon. Weather Rev.* 97: 162–172.
- Blau, S. F. 1986. Recent declines of red king crab (*Paralithodes camtschatica*) populations and reproductive conditions around the Kodiak Archipelago, Alaska. Pp. 360–369 in North Pacific Workshop on Stock Assessment and Management of Invertebrates, G. S. Jamieson, and N. Bourne, eds. Can. Spec. Publ. Fish. Aquat. Sci. No. 92.
- Bockstoce, J. R., and J. J. Burns. 1993. Commercial whaling in the North Pacific sector. Pp. 563–577 in *The Bowhead Whale*, J. J. Burns, J. J. Montague, and C. J. Cowles eds. Society for Marine Mammalogy Spec. Publ. No. 2.
- Bogdanov, N. A., and Yu. P. Neprochnov. 1984. Geology of the deep sea basins of the Bering Sea. Pp. 4–11. In *Istoriya i proiskhozhdeniye okrainnykh i vnutrennykh morey (History and Origin of Marginal and Interior Seas)*. 27th International Geol. Cong. Symposium, S. 06.2.3: Reports, vol. 6, Pt. 2). Moscow: Nauka Press.
- Bogdanovich, K. 1901. Essays of the Chukotka Peninsula. Sankt-Petersburg.
- Bogoraz-Tan, 1934. V. Chukchis, vol. 1, pp. 106–112. Leningrad.
- Bogoslovskaya, L., L. Votrogov, and I. Krupnik. 1984. Greenland whale in Chukotka waters. History and current status of population. in *Marine Mammals*. Moscow: VNIRO.
- Boness, D. J., W. D. Bowen, and O. T. Oftedal. 1994. Evidence of a maternal foraging cycle resembling that of otariid seals in a small phocid, the harbor seal. *Behav. Ecol. Sociobiol.* 34:95–104.



- Bonner, W. N. 1984. Lactation strategies in pinnipeds: Problems for a marine mammalian group. *Symp. Zool. Soc. Lond.* 51:253–272.
- Borets, L. A. 1989. Composition and biomass of demersal fishes at the shelf of the Western Bering Sea. In *Vop. Ichtiol.* 29(5): 740–45. [In Russian].
- Bossart G. D., and L. A. Dierauf. 1990. Marine mammal clinical laboratory medicine. Pp. 1–52 in *CRC Handbook of Marine Mammal Medicine: Disease and Rehabilitation*, L.A. Dierauf ed. Boca Raton, Fla: CRC Press
- Botkin, D. B. 1990. *Discordant Harmonies*. New York: Oxford University Press.
- Boveng, P. 1988a. Status of the California Sea Lion Population of the U.S. West Coast. Administrative Rep. LJ-88-07. La Jolla: NMFS Southwest Fisheries Science Center. 26 Pp.
- Boveng, P. 1988b. Status of the Pacific Harbor Seal Population of the U.S. West Coast. Administrative Rep. LJ-88-06. La Jolla: NMFS Southwest Fisheries Science Center. 43 Pp.
- Bowen, W. D. 1991. Behavioural ecology of pinniped neonates. Pp. 66–127 in *Behaviour of Pinnipeds*, D. Renouf, ed. Cambridge: Chapman and Hall and Cambridge University Press.
- Bowen, W. D., J. W. Lawson, and B. Beck. 1993. Seasonal and geographic variation in the species composition and size of prey consumed by grey seals (*Halichoerus grypus*) on the Scotian shelf. *Can. J. Fish. Aquat. Sci.* 50:1768–1778.
- Bowen, W. D., O. T. Oftedal, and D. J. Boness. 1992. Mass and energy transfer during lactation in a small phocid, the harbor seal (*Phoca vitulina*). *Physiol. Zool.* 65:844–866.
- Braham, H. W., R. D. Everitt, and D. J. Rugh. 1980. Northern sea lion decline in the eastern Aleutian Islands. *J. Wildl. Manage.* 44:25–33.
- Breuer, E. M., R. H. Ernst, R. J. Hofmeister, J. Hentschke, G. Molle, and H. Ludwig. 1988. First report of canine-distemper-like disease and lesions in harbor seals: pathologic-histologic findings and virus isolation. *Angew. Zool.* 2: 129–138.
- Brodeur, R. D., and D. M. Ware. 1992. Interannual and interdecadal changes in zooplankton biomass in the subarctic Pacific Ocean. *Fisheries Oceanogr.* 1:32–38.
- Brodie, P. F., and B. Beck. 1983. Predation by sharks on the grey seal (*Halichoerus grypus*) in eastern Canada. *Can. J. Fish. Aquat. Sci.* 40:267–271.
- Brueggeman, J. J., R. A. Grotefendt, and A. W. Erickson. 1984. Endangered whale abundance and distribution in the Navarin Basin of the Bering Sea during the ice-free period. Pages 201–236 in *Proceedings of the Workshop on Biological Interactions among Marine Mammals and Commercial Fisheries in the Southeastern Bering Sea*. University of Alaska Sea Grant Rep.84-1.
- Bryan, K., and M. J. Spelman. 1985. The ocean's response to a CO<sub>2</sub> induced warming. *J. Geophys. Res.* 90:11679–11688.
- Buck, E., et al. 1975. *Kadyak: A Background for Living*. Resource Utilization, Shellfish, Shrimp. Anchorage, Alaska: Arctic Environmental Information and Data Center.
- Buckland, S. T., J. M. Breiwick, K. L. Cattnach, and J. L. Lake. 1993. Estimated population size of the California gray whale. *Mar. Mammal Sci.* 9:235–249.

- Burns, J. J. 1981. Bearded seal-(*Erignathus barbatus*). Pp. 145–170 in Handbook of Marine Mammals, vol 2. Seals, S. H. Ridgway and R. J. Harrison, eds London: Academic Press.
- Burns, J. J., and V. N. Gol'tsev. 1984. Comparative biology of harbor seals, *Phoca vitulina* Linnaeus, 1758, of the Commander, Aleutian, and Pribilof Islands. Pages 17–24 in F. H. Fay, and G. A. Fedoseev eds. Soviet American Cooperative Research on Marine Mammals. Vol. 1-Pinnipeds. U.S. Dep. Commerce NOAA Tech. Rep. NMFS 12.
- Butler, T. H. 1964. Growth, reproduction and distribution of pandalid shrimp in British Columbia. J. Fish. Res. Bd. Can. 21(6):1403–1452.
- Butterworth, D. S., and P. A. Wickens. 1990. Annex 2. Modeling the dynamics of the South African fur seal population in Report of the subcommittee appointed at the request of the Minister of Environment Affairs and of water affairs, to advise the Minister on scientific aspects of sealing. Cape Town: Ministry of National Education and Environmental Affairs.
- Byrd, G. V. 1978. Red-legged kittiwake colonies in the Aleutian Islands, Alaska. Condor 80: 250.
- Byrd, G. V. 1989a. Seabirds on the Pribilof Islands, Alaska: Trends and Monitoring Methods. M.S. thesis, University of Idaho, Moscow.
- Byrd, G. V. 1989b. Observations of northern Sea Lions in the Western Aleutian Islands, Alaska in 1989. Unpublished Report, U.S. Fish and Wildlife Service, Alaska Maritime National Wildlife Refuge, Adak.
- Byrd, G. V. 1994. Status report on Red-legged Kittiwake (*Rissa brevirostris*), a Candidate Species. Homer, Alaska: U.S. Fish and Wildlife Service.
- Byrd, G. V., J. C. Williams, and R. Walder. 1992. Status and Biology of the Tufted Puffin in the Aleutian Islands, Alaska after a Ban on Salmon Driftnets. Adak, Alaska: U.S. Fish and Wildlife Service. 20 pp.
- Cacchione, D. A., W. D. Grant, D. E. Drake, and S. M. Glenn. 1987. Storm-dominated boundary layer dynamics on the northern California shelf: measurements and predictions. Jour. Geophys. Res. 92:1817–1827.
- Caddy, J. F. 1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. J. Fish. Res. Bd. Can. 30:173–180.
- Caddy, J. F. 1989. A perspective on the population dynamics and assessment of scallop fisheries, with special reference to the sea scallop, *Placopecten magellanicus* Gmelin. Pp. 559–589 in Whales, Dolphins, and Porpoises. K. S. Norris ed. Berkeley: University of California Press. Berkeley.
- Calkins, D. G. 1986. Marine mammals. Pp. 527–558 in The Gulf of Alaska: physical environment and biological resources. D. W. Hood, and S. T. Zimmerman, eds. Anchorage, Alaska: NOAA Ocean Assessment Division.
- 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. 76 pp.

- Calkins, D. G., and K. W. Pitcher. 1982. Population assessment, ecology, and trophic relationships of Steller sea lions in the Gulf of Alaska. U.S. Department of Commerce, Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators 19:447–546.
- Carlson, P. R., and H. A. Karl, 1988. Development of large submarine canyons in the Bering Sea, indicated by morphologic, seismic and sedimentologic characteristics. *Geol. Soc. Am. Bull.* 100:1594–1615.
- Carlton, J. T., and J. B. Geller. 1993. Ecological roulette: The global transport of nonindigenous marine organisms. *Science* 261:78–82.
- Carpenter, S. R., and J. F. Kitchell. 1988. Consumer control of lake productivity. *BioScience* 38(11):764–769.
- Carpenter, S. R., J. F. Kitchell, and J. R. Hodgson. 1985. Cascading trophic interactions and lake productivity. *BioScience* 35:634–639.
- Castellini, M. A., R. W. Davis, T. R. Loughlin, and T. M. Williams. 1993. Blood chemistries and body condition of Steller sea lion pups at Marmot Island, Alaska. *Mar. Mammal Sci.* 9:202–208.
- Caswell, H. 1978. Predator-mediated co-existence: A non-equilibrium model. *Am. Nat.* 112:127–154.
- Census of Northern Borderlands of the Far-Eastern Area. 1929. [In Russian].
- Chapman, D. G. 1961. Population dynamics of the Alaska fur seal herd. *Trans. North Am. Nat. Resource Conf.* 26:356–369.
- Chernyak, S. M., V. M. Vronskaya, and T. P. Kolobova. 1992. Migratory and bioaccumulative peculiarities in the biogeochemical cycling of chlorinated hydrocarbons. Pp. 279–284 in *Results of the Third Joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC)*, P. A. Nagel, ed. U.S. Fish and Wildlife Service. Biol. Rep.
- Chigirinsky, A. I. 1993. Global environmental factors, catches and abundance of Pacific salmon. *Rybn. Khoz.* 2:8–12. [In Russian].
- Chorny, E. 1994. Soviet Secrets of Whaling. *Izvestiia.* 02.03 [In Russian].
- Churchill, J. H. 1989. The effect of commercial trawling on sediment resuspension and transport over the middle Atlantic Bight continental shelf. *Cont. Shelf Res.* 9:841–864.
- Churkin, M. 1972. Western boundary of the North American continental plate in Asia. *Geol. Soc. Am. Bull.* 83:1027–1036.
- Climo, L. 1993. The Status of Cliff-Nesting Seabirds at St. Paul Island, Alaska in 1992. Homer, Alaska: U.S. Fish and Wildlife Service.
- Coachman, L. K. 1986. Circulation, water masses, and fluxes on the southeastern Bering Sea shelf. *Cont. Shelf Res.* 5:23–108.
- Coachman, L. K. 1993. On the flow field in the Chirikov Basin. *Cont. Shelf Res.* 13:481–508.
- Coachman, L. K., and K. Aagaard, 1988. Transports through the Bering Strait: Annual and interannual variability. *J. Geophys. Res.* 93:15535–15539.
- Coachman, L. K., and R. L. Charnell. 1979. On lateral water mass interaction—a case study, Bristol Bay, Alaska. *J. Phys. Oceanogr.* 9:278–297.
- Coachman, L. K., and J. J. Walsh. 1981. A diffusion model of cross-shelf exchange of nutrients in the Bering Sea. *Deep-Sea Res.* 28:819–837.

- Coachman, L. K., K. Aagaard, and R. B. Tripp. 1975. Bering Strait: Regional Physical Oceanography. Seattle: University of Washington Press.
- Cobb, J. N. 1927. Pp 385–499. Pacific cod fisheries. Rep. U.S. Comm. Fish. for 1929. App. VII, Doc. No. 1014
- Connell, J. H. 1972. Community interactions on marine rocky intertidal shores. *Ann. Rev. Ecol. Syst.* 3:169–192.
- Conservation Biology of Thick-billed Murres in the Northwest Atlantic, pp. 52–61. Ottawa: Canadian Wildlife Service, Ottawa.
- Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea. February 11, 1994. In the Materials of the Tenth Conference on the Conservation and Management of the Living Marine Resources of the Central Bering Sea.
- Cooney, R. T. 1981. Bering Sea zooplankton and micronekton communities with emphasis on annual production. Pp. 947–974 in *The eastern Bering Sea Shelf: Oceanography and Resources*, vol.2, D. W. Hood and J. A. Calder, ed. Seattle: University of Washington Press, Seattle.
- Cooney, R. T. 1986. The seasonal occurrence of (*Neocalanus cristatus*), (*Neocalanus plumchrus*), and (*Eucalanus bungii*) over the shelf of the northern Gulf of Alaska. *Cont. Shelf Res.* 5:541–553.
- Cooney, R. T., and K. O. Coyle. 1982. Trophic implications of cross-shelf copepod distributions in the southeastern Bering Sea. *Mar. Biol.* 70:187–196.
- Cooper, C. F., and B. S. Stewart. 1983. Demography of northern elephant seals, 1911–1982. *Science* 219:969–971.
- Cooper, A. K., M. S. Marlow, and D. W. Scholl. 1987a. Structural framework, sedimentary sequences, and hydrocarbon potential of the Aleutian and Bowers Basins, Bering Sea. In *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins-Beaufort Sea to Baja California*. D. W. Scholl, A. Grantz, and J.G. Vedder, compilers and eds. Houston: Circum Pacific Council for Energy and Mineral Resources.
- Cooper, A. K., M. S. Marlow, and D. W. Scholl. 1987b. Geologic framework of the Bering Sea Crust. In *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins-Beaufort Sea to Baja California*. D. W. Scholl, A. Grantz, and J. G. Vedder, compilers and eds. Houston: Circum Pacific Council for Energy and Mineral Resources.
- Cooper, L. W., J. M. Grebmeier, and T. E. Whitedge. 1991. Oxygen-18 used to trace sources of nutrients to the Arctic Ocean through the Bering Strait (abstract), *EOS. Trans., AGU.* 72. 218 pp.
- Cooper, L. W., J. M. Grebmeier, I. L. Larsen, C. Solis, and C. R. Olsen. 1995. Evidence for re-distribution of cesium-137 in Alaskan tundra, lake and marine sediments. *Sci. Total Environ.* 160/161: 295–306.
- Costa, D. P. 1991. Reproductive and foraging energetics of high latitued penguins, albatrosses and pinnipeds: Implications for life history patterns. *Am. Zool.* 31:111–130.
- Costa, D. P., J. P. Croxall, and C. Duck. 1989. Foraging energetics of Antarctic fur seals (*Arctocephalus gazella*), in relation to changes in prey availability. *Ecology* 70:596–606.

- Costa, D. P., F. Trillmich, and J. P. Croxall. 1988. Intraspecific allometry of neonatal size in the Antarctic fur seal (*Arctocephalus galapagoensis*). *Behav. Ecol. Sociobiol.* 22:361–364.
- Costanza, R. 1992. Toward an operational definition of ecosystem health. In *Ecosystem Health*, R. Costanza, B. G. Norton, and B.D. Haskell eds. Washington, D.C.: Island Press. 269 pp.
- Coyle, K. O., and R. T. Cooney. 1988. Estimating carbon flux to pelagic grazers in the ice-edge zone of the eastern Bering Sea. *Mar. Biol.* 98:299–306.
- Coyle, K. O., and R. C. Highsmith. 1994. Benthic amphipod community in the northern Bering Sea: Analysis of potential structuring mechanisms. *Mar. Ecol. Prog. Ser.*
- Crawford, R. J. M., L. G. Underhill, C. M. Raubenheimer, B. M. Dyer, and J. Martin. 1992. Top predators in the Benguela ecosystem—implications of their trophic position. *S. Afr. J. mar. Sci.* 12:675–687.
- Croxall, J. P. ed. 1987. *Seabirds: feeding ecology and role in marine ecosystems*. Cambridge: University Press. 408 pp.
- Croxall, J. P., and R. L. Gentry eds. 1987. *Status, Biology, and Ecology of Fur Seals*. NOAA Tech. Rep. NMFS 51. 212 pp.
- Dahlstrom, W. A. 1970. Synopsis of biological data on ocean shrimp *Pandalus jordani* Rathbun. *FAO Fish. Rep.* 57:1377–1416.
- David, J. H. M. 1989. Seals. Pp. 288–302 in *Oceans of Life off Southern Africa*, A. I. L. Paine, and R. J. M. Crawford eds. Cape Town: Vlaeberg.
- Davies, J. L. 1958. Pleistocene geography and the distribution of northern pinnipeds. *Ecology* 39:97–113.
- Davis, R. W., E. A. A. Brandon, S. Kanatous, T. Adams, D. W. Brandon, T. M. Williams, M. A. Castellini, T. R. Loughlin, D. Calkins, and J. Sease. 1993. Female reproductive effort and pup growth in Steller sea lions. Galveston: Abs. Tenth Biennial Conf. on the Biology of Mar. Mamm. Nov. 11–15.
- Dawson, P. 1994. *The Stock Structure of Bering Sea Pollock*. MS thesis, School of Fisheries, University of Washington.
- Day, R. H. 1980. *The occurrence and characteristics of plastic pollution in Alaska's marine birds*. M.Sc. thesis, University of Alaska, Fairbanks.
- Day, R. H., and D. G. Shaw. 1987. Patterns in the abundance of pelagic plastic and tar in the North Pacific Ocean, 1976–1985. *Mar. Pollut. Bull.* 18:311–316.
- Day, R. H., D. S. Wehle, and F. C. Coleman. 1985. Ingestion of plastic pollutants by marine birds. Pp. 344–386. In *Proceedings of the workshop on the fate and impact of marine debris*, R. S. Shomura and H. O. Yoshida eds. NOAA Tech. Memo. NOAA-TM-NMFS-SWFC-54.
- Day, R. H., D. G. Shaw, and S. E. Ignell. 1990. The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1985–88. Pp. 247–266. In *Proceedings of the Second International Conference on Marine Debris*, R. S. Shomura and M. L. Godfrey eds. NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-154.

- Decker, M. D., G. L. Hunt, Jr., and G. V. Byrd, Jr. 1995. The relationship between sea-surface temperatures, the abundance of juvenile walleye pollock (*Theragra chalcogramma*), and the reproductive performance and diets of seabirds at the Pribilof islands in the southeastern Bering Sea. *Can. Spec. Publ. Fish. Aquat. Sci.* 121:425–437.
- DeGange, A. R., and T. C. Newby. 1980. Mortality of seabirds and fish in a lost salmon driftnet. *Mar. Pollut. Bull.* 11:322–323.
- DeGange, A. R., and R. H. Day. 1991. Mortality of seabirds in the Japanese land-based gillnet fishery for salmon. *Condor* 93:251–258.
- DeGange, A. R., D. J. Forsell, and L. L. Jones. 1985. Mortality of seabirds in the high-seas Japanese salmon mothership fishery 1981–1984. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- DeGange, A. R., D. J. Forsell, and L. L. Jones. 1992. Mortality of seabirds in the high-seas Japanese salmon mothership fishery 1981–1984. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- DeGange, A. R., R. H. Day, J. E. Takekawa, and V. M. Mendenhall. 1993. Losses of seabirds in gillnets in the North Pacific. Pp. 204–211 in *Status and Ecology of Temperate North Pacific Seabirds*, K. Vermeer ed. Ottawa: Canadian Wildlife Service.
- Dellinger, T., and F. Trillmich. 1988. Estimating diet composition from scat analysis in otariid seals (Otariidae): Is it reliable? *Can. J. Zool.* 66:1865–1870.
- DeLong, R. L., G. A. Antonelis, C. W. Oliver, B. S. Stewart, M. C. Lowry, and P. K. Yochem. 1991. Effects of the 1982–83 El Niño on several population parameters and diet of California sea lions on the California Channel Islands. Pp. 166–172 in *Pinnipeds and El Niño: Responses to Environmental Stress*, F. Trillmich and K. Ono eds. New York: Springer-Verlag.
- Denman, K. L., and T. W. Powell. 1984. Effects of physical processes on planktonic ecosystems in the coastal ocean. *Oceanogr. Mar. Biol. Annu. Rev.* 22:125–168.
- Dewailly, E., F. Meyer, A. Nantel, and J. P. Weber. 1989. High levels of PCBs in breast milk of women from Arctic Quebec. *Bull. Environ. Contam. Toxicol.* 43:641–646.
- Dick, M. H., and L. S. Dick. 1971. The natural history of Cape Pierce and Nanvak Bay, Cape Newenham National Wildlife Refuge, Alaska. Bethel, Alaska: Final Rep. Bureau of Sport Fisheries and Wildlife.
- Dikov, N. 1979. Ancient cultures of the North-Eastern Asia. In *Asia at the Meeting Point with America in Ancient Times*. Moscow: Nauka.
- Dodimead, A. J., F. Favorite, and T. Hirano. 1963. Salmon of the North Pacific Ocean, Part 2, Review of Oceanography of the Subarctic Pacific region. *Bull. Int. North Pac. Fish. Comm.* 13. 195 pp.
- Dragoo, D. E., and B. K. Bain. 1990. Changes in colony size reproductive success of seabirds at the Semidi Islands, Alaska, 1977–1989. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- Dragoo, D. E., and B. K. Dragoo. 1994. Results of Productivity Monitoring of Kittiwakes and Murres at St. George Island, Alaska in 1994. U.S. Fish and Wildlife Service Rep. AMNWR 95/01. Homer, Alaska: U.S. Fish and Wildlife Service. 77 Pp.



- Dragoo, B. K., and K. Sundseth. 1993. The Status of Northern Fulmars, Kittiwakes, and Murres at St. George Island, Alaska, in 1992. U.S. Fish and Wildlife Service Rep. AMNRW 93/10. Homer, Alaska: U.S. Fish and Wildlife Service. 92 Pp.
- Dunlop, H. A., F. H. Bell, R. J. Myhre, W. H. Hardman, and G. M. Southward. 1964. Investigation, Utilization and Regulation of Halibut in Southeastern Bering Sea. Int. Pac. Hal. Comm. Rep. 35. 72 pp. Seattle: International Pacific Halibut Commission.
- Ebbesmeyer, C. C., D. R. Cayan, D. R. McClain, F. H. Nichols, D. H. Peterson and K. T. Redmond. 1991. 1976 step in the Pacific climate: Forty environmental changes between 1968–1975 and 1977–1984. Pp. 115–126 in Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop. J. L. Betancourt, and V. L. Tharp eds. Tech. Rep. 26, Calif. Department of Water Resources.
- Eberhardt, L. L. 1981. Population dynamics of the Pribilof fur seals. Pp. 197–220 in Dynamics of large mammal populations. C. W. Fowler, ed. New York: John Wiley & Sons.
- Eckel, E. B. 1970. The Alaska Earthquake, March 1964: Lessons and Conclusions. U.S. Geological Survey Professional Paper 546. Washington, D.C.: Government Printing Office.
- Ecological Society of America. In press. Report of the Ad Hoc Committee on Ecosystem Management. Ecological Applications.
- Emery, W. J., and K. Hamilton. 1985. Atmospheric forcing of interannual variability in the northeast Pacific Ocean: Connections with El Nin. *J. Geophys. Res.* 90 (C1):857–868.
- Enfield, D. B., and J. S. Allen. 1980. On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America, *J. Phys. Oceanogr.* 10: 557–588.
- Epley, R. W., and B. J. Peterson. 1979. Particulate organic matter flux and planktonic new production in the deep ocean. *Nature* 282:677–680.
- Essays on the History of Chukotka from the Ancient Times till Nowadays. 1974. Novosibirsk, Nauka, 1974.
- Estes, J. A. 1979. Exploitation of marine mammals: r-selection of K-strategists? *J. Fish. Res. Brd. Can.* 36:1009–1017.
- Estes, J. A., and J. E. Palmisano. 1974. Sea otters: Their role in structuring near shore communities. *Science* 185:1058–1060.
- Ethnical History of the Northern People. 1982. Moscow: Nauka.
- Fadeev, N. S. 1986. Bering Sea In Biological Resources of the Pacific Ocean. Moscow: Nauka [In Russian].
- Fadeev, N. S. 1988. Distribution and migrations of pollock in the Bering sea. *Rybn. Khoz.* 7:46–47. [In Russian].
- Fadeev, N. S. 1991. Distribution and migrations of pollock in the Bering Sea. Moscow: VNIRO. [In Russian].
- Favorite, F. 1974. Flow into the Bering Sea through Aleutian island passes. Pp. 3–37. In *Oceanography of the Bering Sea*. D. W. Hood, and E. J. Kelley eds. University of Alaska, Fairbanks: Institute of Marine Science.
- Favorite, F. A., J. Dodimead, and K. Nasu. 1976. Oceanography of the Subarctic Pacific Region, 1960–1971. *International North Pacific Fisheries Commission Bulletin* 33.

- Fay, F. H. 1974. The role of ice in the ecology of marine mammals of the Bering Sea. Pp. 383–399. In *Oceanography of the Bering Sea*. D. W. Hood, and E. J. Kelley eds. Univ. Alaska Inst. Mar. Sci. Occas. Publ. No. 2.
- Fay, F. H., and C. E. Bowlby. 1994. Harvests of Pacific Walrus, 1931–1989. U.S. Fish and Wildlife Service Tech. Rep. MMM-94-XX.
- Fay, F. H., B. P. Kelly, and J. L. Sease. 1989. Managing the exploitation of Pacific walrus: A tragedy of delayed response and poor communication. *Mar. Mammal Sci.* 5:1–16.
- Feder, H. M., R. H. Day, S. C. Jewett, K. McCumby, S. McGee, and S. V. Schonberg. 1985. Infauna of the Northeastern Bering and Southeastern Chukchi Sea, Outer Continental Shelf Environmental Assessment Program. Final Reports of Principal Investigators, 32. Washington, D.C.: U.S. Department of Commerce, NOAA.
- Feder, H. M., A. S. Naidu, S. C. Jewett, J. M. Hameedi, W. R. Johnson, and T. E. Whittedge. 1994. The Chukchi Sea continental shelf: Benthos environmental interactions. *Mar. Ecol. Prog. Ser.* 111: 171–190.
- Ferrians, O. J., Jr., R. Kachadoorian, and G. W. Green. 1969. Permafrost and Related Engineering Problems in Alaska. U.S. Geological Survey Professional Paper 678. Washington, D.C.: U.S. Geological Survey.
- Fiscus, C. H., and G. A. Baines. 1966. Food and feeding behavior of Steller and California sea lions. *J. Mammal.* 47:218–223.
- Fishery Conservation and Management Act of 1976 (MFCMA). U.S.C. section 1801–1882, 1976, 1982.
- Forsell, D. J. and P. J. Gould. 1981. Distribution and Abundance of Marine Birds and Mammals Wintering in the Kodiak Area of Alaska. FWS/OBS-81/13; RU 4568. Anchorage: U.S. DOI Minerals Management Service Alaska Region.
- Foster, N. R. 1991. Intertidal bivalves: A guide to the common marine bivalves of Alaska Fairbanks: University of Alaska Press.
- Fowler, C. 1985. An evaluation of the role of entanglement in the population dynamics of northern fur seals on the Pribilof Islands. Pgs 291–307. In *Proceedings of the Workshop on the Fate and Impact of Marine Debris*, 26–29 November, Honolulu, Hawaii, R. S. Shomura and H. O. Yoshida, eds. U.S. Dept. of Commerce, NOAA Tech. Memo NMFS SWFC-54.
- Fowler, C. 1987. Marine debris and fur seals: A case study. *Mar. Pollut. Bull.* 18:326–345.
- Fowler, C. W. 1990. Density dependence in northern fur seals (*Callorhinus ursinus*). *Mar. Mammal Sci.* 6:171–195.
- Fowler, C. W., and T. D. Smith. 1981. Dynamics of large mammal populations. New York: John Wiley & Sons.
- Fox, W. W. 1972. Dynamics of exploited pandalid shrimps and an evaluation of management models. Ph.D. thesis, University of Washington, Seattle.
- Fox, C. A., and R. Leben. 1993. Observations of circulation variability in the Bering Sea using Geosat altimetry data. (Abstract). In abstracts of the PICES, Second Annual Meeting, Seattle, October 25–30.

- Francis, R. C. 1993. Climate change and salmonid production in the North Pacific Ocean. Pp. 33–43 in Proceedings of the Ninth Annual Pacific Climate (PACLIM) Workshop, K. T. Redmond and V. L. Tharp ed. Calif. Dept. Water Res., Interagency Ecol. Studies Prog., Tech. Rep. 34.
- Francis, R. C., and K. M. Bailey. 1983. Factors affecting recruitment of selected gadoids in the northeast Pacific and east Bering Sea. Pp. 35–60 in From Year to Year, W. S. Wooster ed. Washington Sea Grant Publ. WSG-WO-83-3.
- Francis, J. M., and D. J. Boness. 1991. The effect of thermoregulatory behaviour on the mating system of the Juan Fernandez fur seal (*Arctocephalus philippii*). Behaviour 119:104–126.
- Francis, R. C., and S. R. Hare. 1994. Decadal-scale regime shifts in the large maine ecosystem of the northeast Pacific: A case for historical science. Fish. Oceanogr. 3:279–291.
- French, D. P., M. Reed, J. Calambokidis, and J. C. Cabbage. 1989. A simulation model of seasonal migration and daily movements of the northern fur seal. Ecol. Modeling. 48:193–219.
- Fritz, L. W. 1993a. Trawl Locations of Walleye Pollock and Atka Mackerel Fisheries in the Bering Sea, Aleutian Islands and Gulf of Alaska from 1977–92. NOAA NMFS AFSC Processed Rep. 93-08. 62 Pp.
- Fritz, L. W. 1993b. Estimated Catches of Walleye Pollock, Atka Mackerel, and Pacific Within Critical Habitat of the Steller Sea Lion in the Bering Sea, Aleutian Islands and Gulf of Alaska from 1977–92. NOAA NMFS AFSC Processed Rep. 93-13. 66 Pp.
- Fritz, L. W. In press. Juvenile walleye pollock (*Theragra chalcogramma*) bycatch in commercial groundfish fisheries in Alaskan water. In Importance of Pre-Recruit Walleye Pollock to the Bering Sea and North Pacific Ecosystem. R. Brodeur, A. Hollowed, P. Livingston, and T. Loughlin eds. U.S. Department of Commerce, NOAA Tech. Rep.
- Fritz, L. W., V. G. Wespestad, and J. S. Collie. 1993. Distribution and abundance trends of forage fishes in the Bering Sea and Gulf of Alaska. Pages 30–44 in: Is it food? University of Alaska Sea Grant Report No. 93-01.
- Frost, B. 1987. Grazing control of phytoplankton stocks in the open subarctic Pacific Ocean: A model assessing the role of mesozooplankton, particularly the large calanoid copepods, *Neocalanus* spp. Mar. Ecol. Prog. Ser. 39: 49–68.
- Frost, K. J., and L. F. Lowry. 1981a. Foods and trophic relationships of cetaceans in the Bering Sea. Pp 611–625 In The Eastern Bering Sea Shelf: Oceanography and Resources, Volume 1. D. W. Wood and J. A. Calder eds. Washington, D.C.: U.S. Government Printing Office.
- Frost, K. J., and L. F. Lowry. 1981b. Trophic importance of some marine gadoids in northern Alaska and their body-otolith size relationships. Fish. Bull. 79(1):187–192.
- Frost, K. J., and L. F. Lowry. 1986. Sizes of walleye pollock, (*Theragra chalcogramma*), consumed by marine mammals in the Bering Sea. Fish. Bull. U.S. 84:192–197.
- Frost, K. J., and L. F. Lowry. 1994. Assessment of injury to harbor seals in Prince William Sound, Alaska, and adjacent areas following the Exxon Valdez oil spill. Final Rep. Marine Mammal Study No. 5, State-Federal Resource Damage Assessment. 154 pp.
- Frost, K. J., L. F. Lowry, and J. J. Burns. 1983. Distribution of marine mammals in the coastal zone of the Bering Sea during summer and autumn. U.S. Dept. Commerce, NOAA, OCSEAP Final. Rep. 20:365–562.

- Frost, K. J., R. B. Russell, and L. F. Lowry. 1992. Killer whales, (*Orcinus orca*), in the southeastern Bering Sea: Recent sightings and predation on other marine mammals. *Mar. Mammal Sci.* 8:110–119.
- Frost, K. J., L. F. Lowry, E. Sinclair, J. Ver Hoef, and D.C. McAllister. In press. Impacts on distribution, abundance, and productivity of harbor seals. *Marine Mammals and the Exxon Valdez*. New York: Academic Press.
- Fukuchi, M., H. Sasaki, H. Hattori, O. Matsuda, A. Tonimura, N. Handa, and C.P. McRoy. 1993. Temporal variability of particulate flux in the northern Bering Sea, Cont. *Shelf Res.* 13:693–704.
- Furness, R. W., and P. Monaghan. 1987. *New York: Seabird Ecology* Chapman and Hall.
- Furness, R. W., A. V. Hudson, and K. Ensor. 1988. Interactions between scavenging seabirds and commercial fisheries around the British Isles. In *Seabirds and other marine vertebrates: competition, predation, and other interactions*. J. Burger, ed. New York: Columbia University.
- Gaffney, F. 1981. History of research and management of Alaskan shrimp. In *Proceedings of the International Pandalid Shrimp Symposium, February 13–15, 1979, Kodiak, Alaska*, T. Frady, ed. University of Alaska Sea Grant Rep. 81-3. Fairbanks: University of Alaska.
- Gause, G. F. 1934. *The Struggle for Existence*. New York: Hafner. 163 pp.
- Gay, J. 1987. *American Fur Seal Diplomacy. The Alaska Fur Seal Controversy*. New York: Peter Lang.
- Gentry, R. L. 1973. Thermoregulatory behaviour of eared seals. *Behaviour* 46:73–93.
- Geological Survey. Open File Report, p. 26.
- Germanovich, D., A. Elizarov, and V. Sapojnikov. 1900. *Biological Productivity of the Oceans*. Moscow: VNIRO. [In Russian].
- GESAMP (Group of Experts on the Scientific Aspects of Marine Pollution). 1992. *Review of Potentially Harmful Substances: Oil, and Other Chemicals Used in Offshore Exploration and Exploitation*. London: International Maritime Organization.
- Goni, R., H. Hartmann, and K. Mathews. 1993. *Groundfish Fisheries and Dynamics of the Northeastern Pacific Ecosystems*. El Cerrito: Greenpeace, 57 pp.
- Gotshall, D. W. 1969. The use of predator food habits in estimating relative abundance of the ocean shrimp, *Pandalus jordani*. *FAO Fish. Rept.* 57(3):667–686.
- Goudie, R. I., S. Brault, B. Conant, A. V. Kondratyev, M. R. Petersen, and K. Vermeer. 1994. *The status of sea ducks in the North Pacific Rim: Toward their conservation and management*.
- Gould, P. J., B. Roberts, D. R. Nysewander, and K. Omura. 1984. *Reproductive Ecology of Seabirds at Middleton Island, Alaska, Summer 1984*. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- Gould, S. J. 1989. *Wonderful Life: The Burgess Shale and the Nature of History*. New York: W. W. Norton & Co.
- Graham, N. E. 1994. Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: Observations and model results. *Climate Dyn.* 10:135–162.

- Grantz, W. A., L. Breslav, T. Johnson, and W. Hanna. 1970a. Chukchi Sea, Seismic Reflection and Magnetic Profiles—1969, Between Northern Alaska and International Date Line. U.S.
- Grantz, W. A., L. Breslav, T. Johnson, and W. Hanna. 1970b. Reconnaissance Geology of the Chukchi Sea as Determined by Acoustic and Magnetic Profiling. In Proceedings of Geologic Seminar on North Slope of Alaska. W.L. Adkinson and W.W. Brosge, eds.
- Grebmeier, J. M., C. P. McRoy, and H. M. Feder. 1988. Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. I. Food supply source and benthic biomass. *Mar. Ecol. Prog. Ser.* 48:57–67.
- Grebmeier, J. M., H. M. Feder, and C. P. McRoy. 1989. Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. II. Benthic community structure. *Mar. Ecol. Prog. Ser.* 51:253–268.
- Grebmeier, J. M., and C. P. McRoy. 1989. Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. III. Benthic food supply and carbon cycling. *Mar. Ecol. Prog. Ser.* 53:253–268, 1989.
- Grebmeier, J. M. 1993. Studies of pelagic-benthic coupling extended onto the Soviet continental shelf in the northern Bering and Chukchi Seas. *Cont. Shelf Res.* 13:653–668.
- Grebmeier, J. M., and J. Barry. 1991. The influence of oceanographic processes on pelagic-benthic coupling in polar regions: A benthic perspective. *J. Mar. Syst.* 2:495–518.
- Grebmeier, J. M., and L. W. Cooper. 1995. Influence of the St. Lawrence Island polynya upon the Bering Sea benthos. *J. Geophys. Res.* 100:4439–4460.
- Grebmeier, J. M., L. W. Cooper, I. L. Larsen, C. Solis, and C. R. Olsen. 1993. Cesium-137 inventories in Alaskan tundra, lake and marine sediments: An indicator of recent organic material transport Pp. 147–159 in Applications of Isotope Techniques in Studying Past and Current Environmental Changes in the Hydrosphere and the Atmosphere. Vienna: SM-329/21. International Atomic Energy Agency.
- Grebmeier, J. M., W. O. Smith, Jr., and R. J. Conover. 1995. Biological Processes on Arctic Continental Shelves: Ice-Ocean-Biotic Interactions. Pp. 231–261. in Arctic Oceanography: Marginal Ice Zones and Continental Shelves. W. O. Smith, Jr., and J.M. Grebmeier, eds Washington, D.C.: American Geophysical Union.
- Gritsenko, O. F. 1994. Salmon of the Far East. *Ryb. Khoz.* 2:28–30. [In Russian].
- Groot, C., and L. Margolis, eds. 1991. Pacific Salmon Life Histories. Vancouver, B.C.: UBC Press.
- Gusey, W. F. 1979. The Fish and Wildlife Resources of the Bering Sea Region. Houston: Environ. Affairs Dept., Shell Oil Company. Houston, Texas.
- Hacker, E. S., and G. A. Antonelis, Jr. 1986. Pelagic food habits of northern fur seals. Pp. 5–30 in Summary of Joint Research on the diets of Northern Fur Seals and Fish in the Bering Sea during 1985, T. R. Loughlin and P. A. Livingston, eds. U.S. Dept. Commerce, NMFS/NOAA/AFSC Proc. Rep. 86-19.
- Haflinger, K. A. survey of benthic infaunal communities in the southeastern Bering Sea shelf, Pp. 1091–1103 in The Eastern Bering Sea Shelf: Oceanography and Resources, vol. 2, D.W. Hood and J.A. Calder, ed. Seattle: University of Washington Press. 1981.

- Hagbloom, L. 1994. The Status of Kittiwakes, Murres, and Cormorants at Cape Pierce and Cape Newenham, Bristol Bay, Alaska, Summer 1992. Dillingham: Alaska. U.S. Fish and Wildlife Service.
- Hameedi, M. J. 1978. Aspects of water column primary productivity in the Chukchi Sea during summer. *Mar. Biol.* 48:37-46.
- Hansell, D. A., T. A. Whitedge, and J. J. Goering. 1993. Patterns of nitrate utilization and new production over the Bering-Chukchi shelf. *Cont. Shelf Res.* 13:601-627.
- Hare, S. R., and R. C. Francis. 1995. Climate change and salmon production in the N.E. Pacific ocean. Pps. 357-372. In *Climate change and Northern fish populations*. Canadian Special Publications. Fisheries and Aquatic Sciences. R.J. Beamish ed. Vol. 121.
- Harris, M. P. 1991. Population changes in British Common Murres and Atlantic Puffins, 1969-88. Pp. 52-61. In *Studies of High-Latitude Seabirds. 2. Conservation Biology of Thick-billed Murres in the Northwest Atlantic*, A. J. Gaston and R. D. Elliot ed. Ottawa: Canadian Wildlife Service.
- Harrison, C. M., K. S. Choe, H. Fen-qi, N. Litvinenko, and Y. Shibaev. 1990. A Summary of Laws and treaties of Canada, China, Japan, Korea, USA, USSR that protect seabirds at land and sea. Abstract of the paper presented at Pacific Seabird Group Annual Meeting, 22-25 February, Victoria, Canada.
- Hart, J. L. 1973. Pacific fishes of Canada. *Fish. Res. Bd. Can. Bull.* 180.
- Hartmann, D. L., 1974. Time spectral analysis of mid-latitude disturbances. *Mon. Weather Rev.* 102:348-362.
- Harvey, J. T. 1989. Assessment of errors associated with harbour seal (*Phoca vitulina*) faecal sampling. *J. Zool. (Lond.)* 219:101-111.
- Harwood, J., and A. Hall. 1990. Mass mortality in marine mammals: Its implications for population dynamics and genetics. *TREE* 5:254-257.
- Hatch, S. A. 1984. Nestling diet and feeding rates of Rhinoceros auklets in Alaska. Pp. 106-115. *Marine Birds: Their Feeding Ecology, and Commercial Fisheries Relationships*. D. N. Nettleship, G. A. Sanger, and P. F. Springer, eds. Ottawa: Canadian Wildlife Service, Ottawa.
- Hatch, S. A. 1993. Ecology and population status of northern fulmars (*Fulmarus glacialis*) of the North Pacific. Pp. 82-92 In *Status, Ecology, and Conservation of Marine Birds of the North Pacific*, K. Vermeer, K. T. Briggs, K. H. Morgan, et al. eds. Special Publication. Ottawa: Canadian Wildlife Service.
- Hatch, S. A., and G. A. Sanger. 1992. Puffins as samplers of juvenile pollock and other forage fish in the Gulf of Alaska. *Mar. Ecol. Prog. Ser.* 80:1-14.
- Hatch, S. A., G. V. Byrd, D. B. Irons, and G. L. Hunt, Jr. 1993. Status and ecology of kittiwakes (*Rissa tridactyla* and *R. brevirostris*) in the North Pacific. Pp. 140-153 In *Status, Ecology, and Conservation of Marine Birds of the North Pacific*, K. Vermeer, K.T. Briggs, K.H. Morgan, et al., eds. Special Publication. Ottawa: Canadian Wildlife Service.
- Hayes, M. L. 1983. Variation in abundance of crab and shrimp with some hypotheses on its relationship to environmental causes. Pp. 86-101 in *From Year to Year*, W.S. Wooster, ed. Washington Sea Grant Pub. WSG-WO 83-3.



- Haynes, T. L., and C. Mishler. 1991. The subsistence harvest and use of Steller sea lions in Alaska. Tech. Paper No. 198. Juneau: Alaska Dept. of Fish and Game, Division of Subsistence. 45 pp.
- Haynes, E. B., and R. L. Wigley. 1969. Biology of the northern shrimp *Pandalus borealis* in the Gulf of Maine. Trans. Am. Fish. Soc. 98 (1):60-76.
- Hearst, D. and P. Brown. 1994a. Soviet whaling lies revealed. The Guardian, Feb. 12, P. 1.
- Hearst, D. and P. Brown. 1994b. Whaling scandal. The Guardian, Feb. 12, p. 12.
- Heath, C. B. 1989. Behavioural ecology of the California sea lion (*Zalophus californianus*). Ph.D. thesis, University of California, Santa Cruz.
- Heide-Jorgensen, M.P., T. Harkonen, R. Dietz, and P.M. Thompson. 1992. Retrospective of the 1988 European seal epizootic. Dis. Aquat. Org. 13:37-62.
- Hela, I., and T. Laevastu. 1962. Fisheries Hydrography. London: Fishing News. 137 pp.
- Henderson, D. A. 1984. Nineteenth century gray whaling: Grounds, catches and kills, practices and depletion of the whale population. Pp. 159-186 In The Gray Whale. M.L. Jones, S.L. Swartz, and S. Leatherwood eds. Academic Press: New York.
- Hennick, D. P. 1973. Sea Scallop, *Patinopecten Caurinus*, investigations in Alaska. Alaska Department of Fish and Game, Division Comm. Fish, Completion Rep. 5-23-R.
- Herfindahl, O. C., and Kneese, A. 1974. Economic Theory of Natural Resources. Merrill Publishing. Columbus: N.Y.
- Highsmith, R. C., and K. O. Coyle. 1990. High productivity of northern Bering Sea amphipods, Nature 344:862-864.
- Highsmith, R. C., and K. O. Coyle. 1991. Amphipod life histories: Community structure, impact of temperature on decoupled growth and maturation rates, productivity and P:B ratios. Am. Zool. 31:861-873.
- Highsmith, R. C., and K. O. Coyle. 1992. Productivity of arctic amphipods relative to gray whale energy requirements. Mar. Ecol. Prog. Ser. 83:141-150.
- Hinckley, S. 1987. The reproductive biology of walleye pollock (*Theragra chalcogramma*) in the Bering Sea, with reference to spawning stock structure. M.c.S thesis, School of Fisheries, University of Washington, Seattle. 103 Pp.
- Hinckley, D. A., T. F. Bidleman, and C. P. Rice. 1992. Long-range transport of atmospheric organochlorine pollutants and air-sea exchange of hexachlorocyclohexane. Pp. 267-278 in Results of the Third Joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC), P.A. Nagel, ed. U.S. Fish and Wildlife Service, Biol. Rep.
- Hindell, M. A., and H. R. Burton. 1987. Past and present status of the southern elephant seal (*Mirounga leonina*) at Macquarie Island. J. Zool. (Lond.) 213: 365-380.
- History and Culture of Chukchis. 1987. Leningrad, Nauka.
- History of regional research of the biological resources of the ocean and its utilization. 1982. 1982. Moscow: Nauka [In Russian].
- Hoag, S. H., R. J. Myhre, G. St-Pierre, and D. A. McCaughran. 1983. The Pacific Halibut Resource and Fishery in Regulatory Area 2. I. Management and Biology. Seattle: IPHC. Seattle.
- Hodges, J. I., J. G. King, B. Conant, and H. A. Hansen. 1994. Water bird population trends in Alaska: The last half of the twentieth century. Trans. North Am. Wildl. Nat. Resource. Conf.

- Holling, C. S. 1993. Investing in research for sustainability. *Ecol. Appl.* 3:552–555.
- Hollowed, A. B., and W. S. Wooster. 1992. Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. *ICES Mar. Sci. Symp.* 195:443–444.
- Hollowed, A. B., and W. S. Wooster. 1994. Decadal-Scale Variations in the Eastern Subarctic Pacific. B. Response of Northeast Pacific Fish Stocks. *Can. Spec. Publ. Fish. Aquat. Sci.*
- Hollowed, A. B., K. M. Bailey, and W. S. Wooster. 1987. Patterns in recruitment of marine fishes in the northeast Pacific Ocean. *Biol. Oceanogr.* 5:99–131.
- Hood, D. W., and J. A. Calder eds. 1981. *The Eastern Bering Sea Shelf: Oceanography and Resources*. U.S. Dept. of Commerce, U.S. Dept. of the Interior, U.S. Bur. Land Mgmt., NOAA 1,339 pp.
- Hood, D. W., and E. J. Kelley, eds. 1974. *Oceanography of the Bering Sea with emphasis on renewable resources*, Occasional Publ. No. 2. Fairbanks: Institute of Marine Science, University of Alaska. 623 pp.
- Hood, D. W., and Y. Takenouti, eds. 1975. *Bering Sea Oceanography: An Update, 1972–1974*. IMS Pubs. Rep. 75-2. Fairbanks: University of Alaska. 292 pp.
- Hood, D. W., and S. T. Zimmerman, eds. 1986. *The Gulf of Alaska; Physical Environment and Biological Resources*, U.S. Departments of Commerce and the Interior, Minerals Management Service Publ. OCS Study MMS 86-0095. 655 pp.
- Hood, W. R., K. A. Ono, and L. V. Higgins. 1993. Effects of El Niño on maternal attendance patterns and pup behavior in a declining population of Steller sea lions (Abstract). Paper presented at the Tenth Biennial Conference on the Biology of Marine Mammals, November 11–15, Galveston, Tex.
- Hoover, A. 1988a. Steller sea lion, (*Eumetopias jubatus*). Pp. 161–193 In *Selected Marine Mammals of Alaska. Species Accounts with Research and Management Recommendations*, J. W. Lentfer ed. Marine Mammal Commission. Washington, D.C.: U.S.
- Hoover, A. 1988b. Harbor seal. Pp. 125–157 In *Selected Marine Mammals of Alaska*, J. W. Lentfer, ed. Washington, D.C.: U.S. Marine Mammal Commission.
- Hughes, P. 1965. The temperature and salinity of the surface waters of the Irish Sea for period 1947–61. *Geophys. J.* 10:(4)421–435.
- Hunt, G. L., Jr., B. Burgesson, and G. A. Sanger. 1981a. Feeding ecology of seabirds of the eastern Bering Sea. Pp. 629–648 in D. W. Hood, and J. A. Calder eds. *The Eastern Bering Sea Shelf: Oceanography and Resources*, Vol. 2. Juneau: NOAA.
- Hunt, G. L., Jr., B. Burgesson, and R. Squibb. 1981b. Reproductive ecology, foods and foraging areas of seabirds nesting on the Pribilof Islands, 1975–1979. Pp. 1–158. In *Environ. Assess. Alaskan Contin. Shelf, Final Rep.* vol. 12, Biological Studies, Boulder, Colo.: NOAA, and Bur. Land Mgmt., Outer Contin. Shelf Environ. Assess. Program.
- Hunt, G. L., Jr., M. B. Decker, and A. Kitaysky. 1981c. Fluctuations in the Bering Sea ecosystem as reflected in the reproductive ecology and diets of kittiwakes on the Pribilof Islands, 1975 to 1990.
- Huntingdon, H. P. 1992a. *Wildlife Management and Subsistence in Alaska*. Polar Research Series. London: Belhaven Press. 177 pp.

- Huntingdon, H. P. 1992b. The Alaska Eskimo Whaling Commission and other cooperative marine mammal management organizations in northern Alaska. *Polar Rec.* 28:119–126.
- Huppert, D. 1991. Managing the groundfish fisheries of Alaska: History and prospects. *Rev. Aquat. Sci.* 4:339–373.
- ICES, 1992. Report of the study group on ecosystem effects of fishing activities, Copenhagen ICES C.M. 1992/G:11
- Ilinisky, E. N. 1990. Long-term changes in the composition of the prevailing fish species of the continental slope of the Far-Eastern Seas. In *The Results of the Ecosystem Research on Biological resources of the Far-eastern Seas*. Shuntov V.P., ed. Vladivostok: TINRO. [In Russian].
- Imler, R. H., and H. R. Sarber. 1947. Harbor seals and sea lions in Alaska. U.S. Fish and Wildlife Service Special Scientific Report No. 28.
- INPFC (International North Pacific Fisheries Commission). 1979. Historical catch statistics for salmon of the North Pacific Ocean. *Int. North Pac. Fish. Comm. Bull.* 39. 166 pp.
- Interagency Task Force. 1978. Final Environmental Impact Statement. Consideration of a Waiver of the Moratorium and Return of Management of Certain Marine Mammals to the State of Alaska. Washington, D.C.: Interagency Task Group, NMFS, and U.S. Fish and Wildlife Services.
- International Arctic Science Committee. 1994. A Regional Research Programme in the Arctic on Global Change. Proceedings of Workshop at Reykjavik, Iceland, April 22–25, 1992. Washington, D.C.: National Academy Press.
- IPHC (International Pacific Halibut Commission). 1982a. Annual Report 1983. Seattle: IPAL. Seattle.
- IPHC. 1982b. The Pacific Halibut: Biology, Fishery, and Management. IPHC Techn. Rep. 16. Seattle: IPHC.
- IPHC. 1994. Report of Assessment and Research Activities 1993. International Pacific Halibut Commission, Seattle, Wash.
- Iverson, R. L., L. K. Coachman, R. T. Cooney, T. S. English, J. J. Goering, J. L. J. Hunt, M. C. Macauley, C. P. McRoy, W. S. Reeburg, and T. E. Whitledge. 1979a. Pp. 437–466. Ecological significance of fronts in the southeastern Bering Sea. In *Ecological processes in coastal and marine systems*, R.J. Livingston ed. New York: Plenum Press.
- Iverson, R. L., T. E. Whitledge, and J. J. Goering. 1979b. Chlorophyll and nitrate fine structure in the southeastern Bering Sea shelf break front. *Nature* 281:664–666.
- Ivey, G. H., K. R. Duyan. 1991. Alaska Area Native Health Service: Improving the Health Status of the Native People of Alaska. Arctic Medical Research (Finland), Suppl. p.66–69.
- Jacobs, G. A., H. E. Hurlbert, J. C. Kindle, E. J. Metzger, J. L. Mitchell, W. J. Teague, and A. J. Wallcraft. 1994. A warm anomaly stemming from the 1982–3 El Nino spans the northern Pacific in 1993. *Science*.
- Jewett, S. C., and H. M. Feder. 1980. Autumn food of adult starry flounder (*Platichthys stellatus*) from the NE Bering Sea and SE Chukchi Sea. *J. Cons. Int. Explor. Mer.* 39:7–14.

- Jewett, S. C., and H. M. Feder. 1981. Epifaunal invertebrates of the continental shelf of the eastern Bering and Chukchi seas. Pp. 1131-1115 in *The Eastern Bering Sea Shelf: Oceanography and Resources*, vol. 2, D. W. Hood, and J. A. Calder, eds. Seattle: University of Washington Press.
- Jin, F. F., J. D. Neelin, M. Ghil. 1994. El Niño on the devils staircase: annual subharmonic steps to chaos. *Science* 264:70-72.
- Jobling, M. 1987. Marine mammal faecal samples as indicators of prey importance—a source of effort in bioenergetics studies. *Sarsia* 72:255-260.
- Jobling, M., and A. Breiby. 1986. The use and abuse of fish otoliths in studies of feeding habits of marine piscivores. *Sarsia* 72:265-274.
- Johnson, K. R., and C. H. Nelson. 1984. Side-scan sonar assessment of gray whale feeding in the Bering Sea. *Science* 225:1150-1152.
- Johnson, W. R., T. C. Royer, and J. L. Luick. 1988. On the seasonal variability of the Alaska Coastal Current. *J. Geophys. Res.* 93:12423-12437.
- Jones, L. L., and A. R. DeGange. 1988. Interactions between seabirds and fisheries in the North Pacific Ocean. Pp. 269-291 in *Seabirds and Other Marine Vertebrates: Competition, Predation, and Other Interactions*, J. Burger ed. New York: Columbia University Press.
- Kareiva, P. M., and M. Anderson. 1988. Spatial aspects of species interactions: The wedding of models and experiments. Pp. 35-50 in *Community Ecology*, A. Hastings ed. Lecture Notes in Biomathematics 77. Springer-Verlag, Berlin.
- Karl, H. A., and P. R. Carlson. 1987. Surface current patterns suggested by suspended sediment distribution over the outer continental margin, Bering Sea. *Mar. Geol.* 74:301-308.
- Kasuya, T. 1991. Density dependent growth in North Pacific sperm whales. *Mar. Mammal. Sci.* 7:230-257.
- Kawasaki, T. 1991. Long-term variability in the pelagic fish populations. Pp. 47-60 in T. Kawasaki, S. Tanaka, Y. Toba, and A. Taganuchi, eds. *Long-term Variability of Pelagic Fish Populations and their Environment*. Oxford: Pergamon Press.
- Kelleher, G., and R. Kenchington. 1992. Guidelines for Establishing Marine Protected Areas. Gland, Switzerland: IUCN, The World Conservation Union.
- Kelley, J. J., L. L. Longerich, and D. W. Hood. 1971. Effect of upwelling, mixing, and high primary productivity on CO<sub>2</sub> concentrations in surface waters of the Bering Sea. *J. Geophys. Res.* 76:8687-8693.
- Kelly, B. P. 1988a. Ringed Seal. Pp. 57-75 in *Selected marine mammals of Alaska*, J. W. Lentfer, ed. Washington, D.C.: U.S. Marine Mammal Commission.
- Kelly, B. P. 1988b. Bearded seal. Pp. 77-94 in *Selected marine mammals of Alaska*, J. W. Lentfer, ed. Washington, D.C.: Marine Mammal Commission.
- Kelly, B. P. 1988c. Ribbon seal. Pp. 95-106 in *Selected Marine Mammals of Alaska*, J. W. Lentfer, ed. Washington, D.C.: U.S. Marine Mammal Commission.
- Kennedy, S., J. A. Smyth, S. J. McCullough, G. M. Allen, F. McNeilly, and S. McQuaid. 1988. Confirmation of cause of recent seal deaths. *Nature* 336:404.
- Kenney, R. D., M. A. M. Hyman, R. E. Owen, G. P. Scott, and H. E. Winn. 1986. Estimation of prey densities required by western North Atlantic right whales. *Mar. Mammal Sci.* 2:1-13.

- Kenyon, K. W. 1962. History of the Steller sea lion at the Pribilof Islands, Alaska. *J. Mammal.* 43:68–75.
- Kenyon, K. W. 1965. Food of harbor seals at Amchitka Island, Alaska. *J. Mammal.* 46:103–104.
- Kenyon, K. W. 1969. The Sea Otter in the Eastern Pacific Ocean. U.S. Fish and Wildlife Service North American Fauna 68. 352 pp.
- Kenyon, K. W., and D. W. Rice. 1961. Abundance and distribution of the Steller sea lion. *J. of Mammal.* 42:223–234.
- Kenyon, K. W., V. B. Scheffer, and D. G. Chapman. 1954. A Population Study of the Alaska Fur Seal Herd. U.S. Dept. of the Interior, U.S. Fish and Wildlife Service Special Sci. Rep., Wildlife. No. 12. 77 pp.
- Kerr, R. A. 1992. Unmasking a shifty climate system, *Science* 253:1508–1510.
- Kertell, K. 1991. Disappearance of the Steller's eider from the Yukon-Kuskokwim Delta, Alaska. *Arctic* 44:177–187.
- Kessel, B., and D. D. Gibson. 1978. Status and distribution of Alaska birds. *Stud. Avian Biol.* 1:1–100.
- Kinder, T. H., and L. K. Coachman. 1978. The front overlying the continental slope in the eastern Bering Sea. *J. Geophys. Res.* 83:4551–4559.
- Kinder, T. H., L. K. Coachman, and J. A. Galt. 1975. The Bering Slope Current, *J. Phys. Oceanogr.* 5:231–244.
- Kinder, T. H., J. D. Schumacher, and D. V. Hansen. 1980. Observation of a baroclinic eddy: an example of mesoscale variability in the Bering Sea. *J. Phys. Oceanogr.* 10:1228–1245.
- Kinder, T. H., D. C. Chapman, and J. A. Whithead, Jr. 1986. Westward intensification of the mean circulation on the Bering Sea shelf. *J. Phys. Oceanogr.* 16:1217–1229.
- King, W. B., R. G. B. Brown, and G. A. Sanger. 1979. Mortality to marine birds through commercial fishing. Pp. 195–219 in *Conservation of Marine Birds of Northern North America*, J. C. Bartonek and D. N. Nettleship, eds. Wildlife Res. Rep. 11. Washington, D.C.: U.S. Department of the Interior.
- Kinloch, D., H. Kuhnlein, and D. C. G. Muir. 1992. Inuit foods and diet: A preliminary assessment of benefits and risks. *Science Total Environ.* 122:247–278.
- Klimenko, A. 1992. Tub of tar will not spoil Kamchatka. *Sov. Rybak* 7:5. [In Russian].
- Klyashtorin, L. B., and Smirnov B. P. 1992. North Pacific salmon stocks dynamics and some aspects of salmon breeding. VNIERKH Review Information Series: Aquaculture, 2. Moscow: VNIERKH. [In Russian].
- Koike, I., K. Furuya, H. Otake, T. Nakai, T. Nemoto, and A. Hattori 1982. Horizontal distributions of surface chlorophyll *a*, and nitrogenous nutrients near Bering Strait and Unimak Pass. *Deep-Sea Res.* 29:149–155.
- Kolmogorov, D. and I. Sinelnikov. 1984. Regulations of Pacific salmon. *Ryb. Khoz.* 1984. 4:69–73. [In Russian].
- Kolobova, T. P., and L. G. Manyakhina. 1992. Heavy metals in water and sediment. Pp. 317–318 in *Results of the Third joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC)*. P.A. Nagel, ed., U.S. Fish and Wildlife Service Biol. Rep.
- Korelsky, V. 1993. Main directions and modes of changes in the fisheries of Russia. *Rybn. Khoz.* 3:3–7. [In Russian].

- Kravanja, M., and E. Shapiro. 1993. World Fishing Fleets, vol 5. National Marine Fisheries Service.
- Krost, P. 1990. The impact of otter-trawl fishery on nutrient release from the sediment and macrofauna of Kieler Bucht (Western Baltic). Ber. Inst. für Meereskunde Nr. 200. 167 pp.
- Krupnik, I. I. 1984. Gray whales and the aborigines of the Pacific Northwest: The history of aboriginal whaling. Pp. 103–120 in the gray whale M. L. Jones, S. L. Swartz, and S. Leatherwood eds. New York: Academic Press.
- Krupnik, I. I. 1989. Arctic Ethno-ecology. Model of Traditional Use of Nature of Marine Hunters and Deer-Hunters of Northern Eurasia. Moscow: Nauka.
- Krupnik, I. I. 1993. Arctic Adaptions: Native Whalers and Reindeer herders of Northern Eurasia. Hanover: University Press of New England. 355 pp.
- Krutilla, J. V., and Fisher, A. C. 1975. The Economics of Natural Environments. Published for Resources for the Future by Johns Hopkins University Press, Baltimore.
- Krylov, V. I. 1968. Modern status of the Pacific walrus stock and some perspectives of its rational utilization. Pp 189–215 in the Pinnipeds of the North Pacific - Proceedings of the VNIRO Institute, 68. Moscow. [In Russian].
- Krynitsky, A., C. P. Rice, and P. Roscigno. 1992. Baseline levels of certain trace metals in sediment and biota. Pp 319–323 in Results of the Third Joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC), P. A. Nagel, ed. U.S. Fish and Wildlife Service, Biol. Rep.
- Lagerloef, G. S. E. 1994. Interdecadal variations in the Alaska gyre. EOS Trans. Am. Geophys. Union 75:205.
- Lander, R. H. 1979. Role of land and ocean mortality in yield of male Alaskan fur seal herd. (*Callorhinus ursinus*). Fish. Bull. 77:311–314.
- Lander, R. H., ed. 1980. Summary of Northern Fur Seal Data and Collection Procedures, vol. 1. Land Data of the United States and the Soviet Union. NOAA Tech. Memo. NMFS F/NWC-3. 315 pp.
- Lander, R. H., and H. Kajimura. 1982. Status of the northern fur seals. In Mammals of the Sea. FAO Fish. Serv. No. 5. 4:319–345.
- Larsen, M., H. Nelson, and D. Thor. 1980. Geological, Geochemical, and Geotechnical Observations on the Bering Shelf, Alaska. U.S. Geological Survey Open File Report 80–979.
- Latif, M., and T. P. Barnett. 1994. Causes of decadal climate variability over the North Pacific and North America. Science 266:634–637.
- LeBoeuf, B. J., and R.S. Condit. 1983. The high cost of living on the beach. Pacific Discovery July–Sept: 12–14.
- Levin, S. A. 1992. Pattern and scale in ecology. Ecology 73:1943–1967.
- Lewbel, G. S. ed. 1983. Bering Sea Biology: An Evaluation of the Environmental Data Base Related to Bering Sea Oil and Gas Exploration and Development. Anchorage, Alaska: LGL Alaska Research Associates, Inc., Anchorage, Alaska, and SOHIO Alaska Petroleum Co. 180 pp.
- Lid, G. 1981. Reproduction of puffins on Rost in the lofoten islands in 1964–1980. Fauna Norv. Serv. C. Cinclus 4:30–39.



- Lie, H. J., and M. Endoh. 1991. Seasonal and interannual variability in temperature of the upper layer of the Northwest Pacific, 1964–1983. *J. Phys. Oceanogr.* 21:385–397.
- Limberger, D., F. Trillmich, H. Biebach, and R.D. Stevenson. 1986. Temperature regulation and microhabitat choice by free-ranging Galapagos fur seal pups (*Arctocephalus galapagoensis*). *Oecologia* 69:53–59.
- Lipps, J. H., and E. Mitchell. 1976. Trophic model for the adaptive radiations and extinctions of pelagic marine mammals. *Paleobiology* 2:147–155.
- Lisitsyn, A. 1966. Recent Sedimentation in the Bering Sea. Translated by Israel Program for Scientific Translation, Jerusalem. Washington, D.C.: U.S. Department of Commerce, National Science Foundation.
- Lloyd, D. S., C. P. McRoy, and R. H. Day. 1981. Discovery of northern fur seals (*Callorhinus ursinus*) breeding on Bogoslof Island, Southeastern Bering Sea. *Arctic* 34:318–320.
- Lloyd, C., M. L. Tasker, and K. Partridge. 1991. The Status of Seabirds in Britain and Ireland. T. and A. D. Poyser eds. London.
- Lockhart, W. L., R. Wagemann, B. Tracey, D. Sutherland, and D. J. Thomas. 1992. Presence and implications of chemical contaminants in the freshwaters of the Canadian Arctic. *Sci. Total Environ.* 122:165–245.
- Loder, J. W., and C. Garrett. 1978. The 18.6-year cycle of sea surface temperature in shallow seas due to tidal mixing. *J. Geophys. Res.* 83:1967–1970.
- Lotka, A. J. 1925. *Elements of Mathematical Biology*. New York: Dover reprint 1956. 465 pp.
- Loughlin, T. R. 1987. Report of the Workshop on the Status of Northern Sea Lions in Alaska. NOAA NMFS Processed Rep. 87-04. 49 Pp.
- Loughlin, T. R. 1994. Abundance and distribution of harbor seals (*Phoca vitulina richardsi*) in southeastern Alaska during 1993. NMFS Population Assessment Program, Annual Report. 30 pp.
- Loughlin, T. R., and R. L. Merrick. 1989. Comparison of commercial harvest of walleye pollock and northern sea lion abundance in the Bering Sea and Gulf of Alaska. Pp. 679–700 in *Proceedings of the International Symposium on the Biology and Management of Walleye Pollock*. University of Alaska Sea Grant Rep. 89-1.
- Loughlin, T. R., and R. V. Miller. 1989. Marine mammals. Pp. 261–296 in *Fisheries harvesting life from water*. F. G. Johnson and R. R. Stickney, eds. Dubuque, Iowa: Kendall/Hunt Publishing Company.
- Loughlin, T. R., and R. Nelson, Jr. 1986. Incidental mortality of northern sea lions in Shelikof Strait, Alaska. *Mar. Mammal Sci.* 2:14–33.
- Loughlin, T. R., D. J. Rugh, and C. H. Fiscus. 1984. Northern sea lion distribution and abundance: 1956–80. *J. Wildl. Manage.* 48:729–740.
- Loughlin, T. R., P. J. Gearin, R. L. DeLong, and R. L. Merrick. 1986. Assessment of Net Entanglement on Northern Sea Lions in the Aleutian Islands, 25 June-15 July 1985. NOAA/NMFS NWAFC Processed Rep. 86-02. 50 pp.
- Loughlin, T. R., J. L. Bengston, and R. L. Merrick. 1987. Characteristics of feeding trips of female northern fur seals. *Can. J. Zool.* 65:2079–2084.

- Loughlin, T. R., A. S. Perlov, and V. V. Vladimirov. 1990. Survey of Northern Sea Lions (*Eumetopias jubatus*) in the Gulf of Alaska and Aleutian Islands during June 1989. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS F/NWC-176. 20 pp.
- Loughlin, T. R., A. S. Perlov, and V. V. Vladimirov. 1992. Range-wide survey and estimation of total number of Steller sea lions in 1989. *Mar. Mammal Sci.* 8:220–239.
- Lowry, L. F. 1993. Foods and feeding ecology. Pp. 201–238 in *The Bowhead Whale*, J. J. Burns, J. J. Montague, and C. J. Cowles eds. Society for Marine Mammalogy, Spec. Publ. No. 2.
- Lowry, L. F., and F. H. Fay. 1984. Seal eating by walrus in the Bering and Chukchi Seas. *Polar Biol.* 3:11–18.
- Lowry, L. F., and K. J. Frost. 1985. Biological interactions between marine mammals and commercial fisheries in the Bering Sea. Pp. 42–61 in *Marine mammals and fisheries*. J. R. Beddington, R. J. H. Beverton, and D. M. Lavigne eds. London: George Allen & Unwin.
- Lowry, L. F., and K. J. Frost, and J. J. Burns. 1979. Potential Resources Competition in the Southeastern Bering Sea: Fisheries and Phocid Seals. In *Proc. 29th Alaska Science Conference, American Assoc. for the Advancement of Science, Sea Grant Report 79-6 RU 0232*.
- Lowry, L. F., K. J. Frost, D. G. Calkins, G. L. Swartzman, and S. Hills. 1982. Feeding habits, food requirements, and status of Bering Sea marine mammals. North Pacific Fishery Management Council, Anchorage, Alaska, Document Nos. 19 and 19A. 574 pp.
- 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. Pp. 701–726 in *Proceedings of the International Symposium on the Biology and Management of Walleye Pollock*. University of Alaska Sea Grant Rep. 89-1
- Lucas, F. A. 1899. The causes of mortality among seals. Pp. 75–98 in *The Fur Seals and Fur-Seal Islands of the North Pacific Ocean*, Part 3. Washington, D.C: U.S. Treasury Department.
- Ludwig, D. and C. J. Walters. 1985. Are age-structured models appropriate for catch-effort data? *Can. J. Fish. Aquat. Sci.* 42:1066–1072.
- Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: Lessons from history. *Science* 260: 17, 36.
- Lyman, R. L. 1988. Zoogeography of Oregon coast marine mammals: The last 3,000 years in *Mar. Mammal Sci.* 4:247–264.
- Magnuson, J. J. 1990. Long-term ecological research and the invisible present. *BioScience* 40(7):495–501.
- Majluf, P., and J. C. Reyes. 1989. The marine mammals of Peru: A review. Pp. 344–463 in Pauly et al., eds.
- Maksimov, I. V., and N. P. Smirnov. 1965. A contribution to the study of the causes of long-term variations in the activity of the Gulf Stream. *Oceanology* 5:15–24.
- Mann, K. H. 1988. Towards predictive models for coastal ecosystems. Chapter 15: Concepts of Ecosystem Ecology, L.R. Pomeroy and J.J. Alberts eds. New York: Springer-Verlag.
- Mann, K. H., and J. R. N. Lazier. 1991. *Dynamics of Marine Ecosystems: Biological-Physical Interactions in the Oceans*. Boston: Blackwell Scientific Publications.

- Manak, D. K., and L. A. Mysak. 1987. Climatic atlas of arctic sea ice extent and anomalies 1953–1984. Climate Research Group Rep. 87-8.
- Marasco, R., and W. Aron. 1991. Explosive evolution—the changing Alaska groundfish fishery. *Rev. Aquat. Sci.* 4:299–315.
- Margalef, R. 1986. Recent successions and suspected chaos in models of marine populations. In *Proc. Int. Symp. Long-Term Change Mar. Fish. Pop., Vigo, Spain*.
- Marine Mammal Commission. 1995. Annual Report to Congress, 1994. Washington, D.C.: Marine Mammal Commission.
- Marine Mammals of the Pacific Ocean. 1969. *Trudy VNIRO*, vol. 68 [In Russian].
- Markina N. P., and G. V. Khen. 1990. Main elements of functioning of the pelagic communities of the Bering sea. *Izvestiia TINRO*, vol. III, pp. 79–93.
- Marlow, M. Scholl, D. Cooper, A., and E. Buffington. 1976. Structure and evolution of Bering Sea shelf south of St. Lawrence Island. *Am. Assoc. Pet. Geol. Bull.* 60(2), p. 161.
- Mathisen, O. 1991. Trophic Interactions of the Bering Sea Ecosystem. Juneau Center for Fisheries and Ocean Sciences, University of Alaska, Fairbanks, mss. rep. 32 pp.
- Matkin, C. O., and F. H. Fay. 1980. Marine Mammal-Fishery Interactions on the Copper River and in Prince William Sound, Alaska, 1978. Final report contract MMC-78/07 to U.S. Marine Mammal Commission, Washington, D.C.
- May, R. 1937. Stability and complexity in model ecosystems. *Monographs in Population Biology*. Princeton University Press, Princeton, N.J. Press. 235 pp.
- Mayo, C. A., and M. K. Marx. 1990. Surface foraging behaviour of the North Atlantic right whale, (*Eubalaena glacialis*), and associated zooplankton characteristics. *Can. J. Zool.* 68:2214–20.
- McAllister, M. R., and R. M. Peterson. 1992. Experimental design in the management of fisheries: A review. *North Am. J. Fish. Manag.* 12:1–18.
- McCaffery, B. J. 1989. Results of the Nunivak Island Seabird Inventory 1988. Bethel, Alaska. U.S. Fish and Wildlife Service.
- McFarlane, G. A., and R. J. Beamish. 1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*, *Can. J. Fish. Aquat. Sci.* 49:743–753.
- McRoy, C. P. 1993. ISHTAR, the project: An overview of Inner Shelf Transfer and Recycling in the Bering and Chukchi seas. *Cont. Shelf Res.* 13:473–479.
- McRoy, C. P., and J. J. Goering. 1974. The influence of ice on the primary productivity on the Bering Sea. pp. 403–21. *Oceanography of the Bering Sea*, D. W. Hood and E. J. Kelley, eds., Occasional Publ. No. 2. Fairbanks, Alaska: Institute of Marine Science.
- McRoy, C. P., J. J. Goering, and W. S. Shiels. 1972. Studies of primary production in the eastern Bering Sea. *Motoda Commem.* 3:199–216.
- McRoy, C. P., D. W. Hood, L. K. Coachman, J. J. Walsh, and J. J. Goering. 1986. Processes and resources of the Bering Sea shelf (PROBES): The development and accomplishments of the project. *Cont. Shelf Res.* 5:5–22.
- Medinets, V., V. G. Soloviev, and B. V. Glebov. 1992. Investigation of cesium137 distribution in seawater. Pp. 327-9. Results of the Third Joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC), P. A. Nagel, ed. U.S. Fish and Wildlife Service Biol. Rep.

- Megrey, G. A. and V. G. Wespestad. 1990. Alaskan groundfish resources: 10 years of management under the Magnuson Fishery Conservation and Management Act. *North Am. J. Fish. Manage.* 10:125–143.
- Merrick, R. L., and T. R. Loughlin. 1993. Foraging behavior of adult female and young-of-the-year Steller sea lions in Alaskan waters. Galveston: Abs. Tenth Biennial Conf. Biol. Mar. Mamma., Nov 11–15.
- Merrick, R. L. 1995. The Relationship of the Foraging Ecology of Steller Sea Lions (*Eumetopias jubatus*) to Their Population Decline in Alaska. Ph.D. thesis, University of Washington, Seattle.
- Merrick, R. L. and D. G. Calkins. In press. Importance of juvenile walleye pollock in the diet of Gulf of Alaska sea lions. Report of the Workshop on the Importance of Prerecruit Walleye Pollock to the Bering Sea and North Pacific Ecosystems. October 28–30, 1993, Seattle.
- 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. *Fish. Bull. U.S.* 85:351–365.
- Merrick, R. L., D. G. Calkins, and D. C. McAllister. 1992. Aerial and Ship-Based surveys of Steller Sea Lions (*Eumetopias jubatus*) in Southeast Alaska, the Gulf of Alaska, and Aleutian Islands during June and July 1991. NOAA Tech. Memo. NMFS-AFSC-1. 41 pp.
- Mesheryakova, I. 1964. Quantitative distribution of plankton in the south-eastern Bering Sea in summer 1958–59. *Izvestiia TINRO*, 51:141–150. [In Russian].
- Mesheryakova, I. 1970a. Plankton of the eastern Bering Sea in spring and autumn hydrological seasons. *Trudy VNIRO* 70:98–114. [In Russian].
- Mesheryakova, I. 1970b. Winter-spring plankton of the south-western Bering Sea. *Trudy VNIRO* 70:114–121. [In Russian].
- Miller, R. V. 1984. The US-USSR project. Pp. 1–4 in *Soviet-American cooperative research on marine mammals*. vol. 1. Pinnipeds, F. H. Fay and G. A. Fedoseev, eds. NOAA Tech. Rep. NMFS 12.
- Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham, and J. M. Obertuber. 1994. The 1976–1977 climate shift of the Pacific Ocean. *Oceanography* 7:21–26.
- Mirovitskaya, N., and C. Haney. 1992. Fisheries Exploitation as a Threat for International Environmental Security. In *Marine Policy*, July.
- Mirovitskaya, N., M. Clark, and R. Purver. 1993. North Pacific fur seals: Regime formation as a means of resolving conflict. In *Polar Politics: Creating International Environmental Regimes*, O. Young and G. Osherenko, eds. Ithaca: Cornell University Press.
- Mistakidis, M. N. 1957. The biology of *Pandalus montagui* Leach. *Fishery Invest.*, London, Ser. 2. 21(4).
- MMS (Mineral Management Service). 1992. Chukchi Sea Oil and Gas Lease Sale 126. Final Environmental Impact Statement. OCS EIS/EA, MMS 90–0095. Anchorage, Alaska: Alaska Region, Minerals Management Service, U.S. Department of the Interior. 2 vols.
- Morphology, Structure of Populations and Rational Exploitation of Salmonidae. 1983. Leningrad: Nauka. [In Russian].
- Moskaltsov, Yu. Presentation at the Pacific Rim Fisheries Conference, Beijing, March 1994. Provided by Milan Kravanja, NMFS.

- Muck, P. 1989. Major trends in the pelagic ecosystem off Peru and their implications for management. Pp. 386–403. In Pauly et al., eds.
- Muir, D. C. G., R. Wagemann, T. B. Hargrave, D. J. Thomas, D. B. Peakall, and J. R. Norstrom. 1992. Arctic marine ecosystem contamination. *Sci. Total Environ.* 122:75–134.
- Murie, O. J. 1959. Fauna of the Aleutian Islands and Alaska Peninsula. *North Am. Fauna* 61:406.
- Murie, D. J., and D. M. Lavigne. 1985. Interpretation of otoliths in stomach content analyses of phocid seals: Quantifying fish consumption. *Can. J. Zool.* 64:1152–1157.
- Murphy, E. C., A. M. Springer, and D. G. Roseneau. 1986. Population status of Common Guillemots (*Uria aalge*) at a colony in western Alaska: Results and simulations. *Ibis* 128:348–363.
- 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. *J. Anim. Ecol.* 60:515–534.
- Musgrave, D. L., T. J. Weingartner, T. C. Royer. 1992. Circulation and hydrography in the northwestern Gulf of Alaska. *Deep-Sea Res.* 39:1499–1519.
- Namias, J., X. Yuan, and D. R. Cayan. 1988. Persistence of North Pacific sea surface temperature and atmospheric flow patterns. *J. Clim.* 1:682–703.
- Naske, C. M., and H. Slotnick. 1987. Alaska: History of the 49th State, 2nd ed. Norman: University of Oklahoma Press.
- National Geographic. 1994. Kamchatka: Russian Land of Fire and Ice. Pp. 36–67. Vol. 185:4
- Naumenko, E. A. 1986. Evaluation of fishery resources and recruitment of capelin from the Anadyr Bay. Pp. 93–99. Dynamics of Numbers of Commercial Species of the Far-Eastern Seas. Vladivostok: TINRO. [In Russian].
- Naumenko, N. I., P. A. Balykin, E. A. Naumenko, and E. R. Shaginian. 1990. Long-standing changes in the pelagic ichthyofauna of the western Bering Sea. In *The Results of the Ecosystem Research on Biological Resources of the Far-Eastern Seas*. V.P. Shuntov, ed.
- Neiman, A. 1963. Quantitative distribution of benthos in the eastern Bering Sea. *Zool. J.* 39 (9):1281–1292. [In Russian].
- Neimark, L. M. 1979. Zooplankton ecology of Norton Sound, Alaska, M.Sc. thesis, University of Alaska Fairbanks. 93 pp.
- Nelson, J. W., and A. L. SOWLS. 1985. Breeding Seabird Survey of Chamisso Island and Southern Kotzebue Sound, 8–20 August 1981. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- Nemoto, T. 1963. Some aspects of the distribution of (*Calanus cristatus* and *C. plumchrus*) in the Bering and its neighboring waters, with reference to the feeding of baleen whales. *Sci. Rep. Whales Res. Inst.* 17:157–170.
- Nettleship, D. N., G. A. Sanger, and P. F. Springer, eds. 1984. *Marine Birds: Their Feeding Ecology and Commercial Fisheries Relationships*. Canadian Wildlife Service Spec. Pub. 220 pp.
- New England Fishery Management Council. 1982. Fishery Management Plan, Final Environmental Impact Statement, Regulatory Impact Review for Atlantic Sea Scallops (*Placopecten magellanicus*). Saugus, Mass: New England Fishery Management Council.

- Nicolis, G., and I. Prigogine. 1977. *Self-Organization in Non-Equilibrium Systems*. New York: John Wiley & Sons.
- Niebauer, H. J., and V. Alexander. 1985. Oceanographic frontal structure and biological production at an ice edge. *Cont. Shelf Res.* 4:367–388.
- Niebauer, H. J., and R. H. Day. 1989. Causes of interannual variability in the sea ice cover of the eastern Bering Sea. *Geojournal* 18:1, 45–59.
- Niebauer, H. J. and D. M. Schell. 1993. Physical Environment of the Bering Sea Population, Pp. 23–43. *The Bowhead Whale*. Society for Marine Mammalogy. Spec. Publ. No. 2.
- Niebauer, H. J., V. Alexander, and S. Henrichs. 1990. Physical and biological interaction in the spring bloom at the Bering sea marginal ice edge zone. *J. Geophys. Res.* 95:22229–22241.
- Nieman, A. A. 1963. Quantitative distribution of benthos on the shelf and upper continental slope in the eastern part of the Bering Sea. Pp. 143–217. *Soviet Fisheries Investigations in the Northeast Pacific, Part 1*, P.A. Moiseev, ed. (Israel Program for Scientific Translations, 1968).
- NMFS (National Marine Fisheries Service). 1991a. Conservation Plan for the Northern Fur Seal, (*Callorhinus ursinus*). Silver Spring, Md: National Marine Fisheries Service. 74 pp.
- NMFS. 1991b. Endangered Whales: Status Update. Silver Spring MD: National Marine Fisheries Service. 52 pp.
- NMFS. 1992. Our Living Oceans. Report on the Status of U.S. Living Resources, 1992. NOAA Tech. Memo. NMFS-F/SPO-2.
- NMFS. 1993a. Final Conservation Plan for the Northern Fur Seal (*Callorhinus ursinus*). Prepared by the NMFS/Alaska Fisheries Science Center/National Marine Mammal Laboratory, Seattle, Wash. and the NMFS/Office of Protected Resources, Silver Spring, Md. 80 pp.
- NMFS. 1993b. Final Recovery Plan for the Steller Sea Lion, (*Eumetopias jubatus*). Prepared by the Steller Sea Lion Recovery Team for the National Marine Fisheries Service, Silver Spring, Md. 92 pp.
- NOAA (National Oceanic and Atmospheric Administration). 1993. Status of Fishery Resources of the Northeastern United States for 1993. NOAA Tech. Memo. NMFS-F/NEC-101.
- Norse, E. A., ed. 1993. *Global Marine Biological Diversity Strategy: Building Conservation into Decision Making*. Washington, D.C.: Center for Marine Conservation 383 pp.
- Norton, B. G. 1992. A new paradigm for environmental management. Pp. 23–41 in *Toward an Operational Definition of Ecosystem Health*. R. Costanza, ed. Ecosystem Health. R. Costanza, B. G. Norton, and B.D. Haskell eds. Washington, D.C.: Island Press. 269 pp.
- NPFMC (North Pacific Fishery Management Council). 1993. Plan Team for Groundfish Fisheries of the Bering Sea and Aleutian Islands, The (Compilers). Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands Regions as projected for 1994. Unpublished Report, North Pacific Fishery Management Council, Anchorage, Alaska.
- NRC (National Research Council). 1990. *Decline of the Sea Turtles: Causes and Prevention*. Washington, D.C.: National Academy Press.



- NRC (National Research Council) 1994a. Improving the Management of the U.S. Marine Fisheries. Washington, D.C.: National Academy Press. 62 pp.
- NRC (National Research Council). 1994b. Environmental Information for Outer Continental Shelf Oil and Gas Decisions in Alaska. Washington, D.C.: National Academy Press.
- NRC (National Research Council). 1994c. Assigning Economic Value to Natural Resources. Washington, D.C.: National Academy Press.
- NRC (National Research Council). 1995. Science and the Endangered Species Act. Washington, D.C.: National Academy Press.
- NRC (National Research Council). 1996. Upstream: Salmon and Society in the Pacific Northwest. Washington, D.C.: National Academy Press.
- Numbers and Composition of the Peoples of the North. 1990. Moscow: CSU RSFSR.
- Nunnallee, E. P., and N. J. Williamson. 1988. Results of Acoustic/Mid-water Trawl Surveys of Walleye Pollock in Shelikof Strait, Alaska. Unpublished manuscript.
- Nur, N., and D. G. Ainley, 1992. Comprehensive Review and Critical Synthesis of the Literature on Recovery of Marine Bird Populations from Environmental Perturbations. Stinson Beach, Calif. Point Reyes Bird Observatory.
- Nysewander, D., and C. Dipple. 1992. Population Surveys of Seabird Nesting Colonies in Prince William Sound, the Outside Coast of the Kenai Peninsula, Barren Islands, and other Nearby Colonies, with Emphasis on Changes of Numbers and Reproduction of Murres. Homer, Alaska: U.S. Fish and Wildlife Service.
- Nysewander, D. R. and J. L. Trapp. 1984. Widespread Mortality of Adult Seabirds in Alaska, August-September 1983. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- O'Brannon, B. K., ed. 1994. Fisheries of the United States, 1993. Silver Spring: NOAA, U.S. Department of Commerce. 121 pp.
- O'Connor, H. J., Y. A. Izrael, A. V. Tsyban, T. E. Whitledge, C. P. McRoy, and L. K. Coachman. 1992. 1.1 Program on Long-term Ecological Investigations of the Bering Sea and Other Pacific Ocean Ecosystems (BERPAC Program). Pp. 3-6 in Results of the Third Joint US-USSR Bering and Chukchi Seas Expedition (BERPAC), Summer 1988. P. A. Nagel, ed. Washington, D.C.: U.S. Fish and Wildlife Service.
- O'Daniel, D. H., H. Knechtel, and J. Schneeweis. 1990. Seabird Monitoring at Aiktak Island, Aleutian Islands, Alaska in 1990. Adak, Alaska: U.S. Fish and Wildlife Service.
- O'Neill, R. V., D. L. DeAngelis, J. B. Waide, and, T. F. H. Allen. 1986. A Hierarchical Concept of Ecosystems. Princeton, N.J.: Princeton University Press.
- Oftedal, O. T., D. J. Boness, and R. A. Tedman. 1987. The behavior, physiology, and anatomy of lactation in the pinnipedia. *Curr. Mammal.* 1:175-245.
- Ohtani, K., and T. Azumaya. 1995. Influence of interannual changes in ocean conditions on the abundance of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea. Pp. 87-95 in North Pacific Workshop on Stock Assessment and Management of Invertebrates, R.J. Beamish ed. *Can. Spec. Publ. Fish. Aquat. Sci.* 92.
- Okkonen, S. 1993. Circulation Variability in the Bering Sea. Ph.D. thesis, University of Alaska, Fairbanks. 127 pp.
- Olesiuk, P. F., M. A. Bigg, and G.M. Ellis. 1990. Recent trends in the abundance of harbour seals, (*Phoca vitulina*) in British Columbia. *Can. J. Fish. Aquat. Sci.* 47:992-1003.

- On the Protection of Natural Resources of the Territorial Waters, Continental Shelf and Economic Zone of the Russian Federation. 1992. *Vedomosti S'ezda*. 19:1379–1380.
- Osherenko, G., and O. Young. 1989. *The Age of the Arctic: Hot Conflicts and Cold Realities*. Cambridge: Cambridge University Press.
- Osterhaus, A. D. M. E., and E. J. Vedder. 1988. Identification of virus causing recent seal deaths. *Nature* 335:20.
- Otto, R. S. 1981. Eastern Bering Sea crab fisheries. Pp. 1037–1077 in *The Eastern Bering Sea Shelf: Oceanography and Resources*, vol. 2, D.W. Hood and J.A. Calder eds. Seattle: University of Washington Press.
- Otto, R. S. 1986. Management and assessment of eastern Bering Sea king crab stocks. Pp 83–106 in G. S. Jamieson and N. Bourne, eds. *North Pacific Workshop on Stock Assessment and Management of Invertebrates*. Can. Spec. Publ. Fish. Aquat. Sci. 92.
- Otto, R. S. 1990. An overview of eastern Bering Sea king and Tanner crab fisheries. Pp. 9–26 in *Proceeding of the International Symposium on King and Tanner Crabs*. Anchorage, Alaska, USA, November 28–30, 1989. Eighth Lowell Wakefield Fisheries Symposium. Alaska Sea Grant Report 90-4. Fairbanks: University of Alaska.
- Overland, J. E. 1981. Marine climatology of the Bering Sea. Pp. 15–22 in *The Eastern Bering Sea shelf: Oceanography and Resources*. vol. 1, D. W. Hood and J. A. Calder, eds. Seattle: University of Washington Press.
- Overland, J. E., and C. H. Pease. 1982. Cyclone climatology of the Bering Sea and its relation to sea ice extent. *Mon. Weather Rev.* 110:5–13.
- Overland, J. E., M. C. Spillane, H. E. Hurlbert, and A. J. Wallcraft. 1994. A numerical study of the Bering Sea Basin and exchange with the North Pacific. *J. Phys. Oceanogr.* 24(4):736–758.
- Paine, R. T. 1980. Food webs: Linkage, interaction strength and community infrastructure. *J. Anim. Ecol.* 49:667–685.
- Paluszkiewicz, T., and H. J. Niebauer, 1984. Satellite observations of circulation in the eastern Bering Sea. *J. Geophys. Res.* 89:3663–3678.
- Park, P. K., L. I. Gordon, and S. Alvarez-Borrego. 1973. The carbon dioxide system of the Bering Sea. Pp. 107–147 in *Oceanography of the Bering Sea*, D.W. Hood and E. J. Kelley eds. Fairbanks: Institute of Marine Science, University of Alaska.
- Parker, K. S., T. C. Royer, and R. B. Deriso. 1994. High latitude climate forcing by the 18.6 year lunar nodal cycle and historical recruitment trends in Pacific halibut. *Can. J. Fish. Aquat. Sci.*
- Parkinson, C. L., J. C. Comiso, H. J. Zwally, D. J. Cavalieri, P. Gloersen, and W. J. Campbell. 1987. *Arctic Sea Ice, 1973–1976: Satellite Passive-Microwave Observations*, NASA Spec. Publ. 489. 296 pp.
- Parrish, D. M. 1987. *An Estimate of Annual Primary Production in the Alaska Arctic Ocean*. M.S. thesis, University of Alaska, Fairbanks. 166 pp.
- Parsons, T. R. 1992. The removal of marine predators by fisheries and the impact of trophic structure. *Mar. Pollut. Bull.* 25:51–53.
- Parsons, T. R., and G. M. Lalli. 1988. Comparative oceanic ecology of the plankton communities of the subarctic Atlantic and Pacific Oceans. *Oceanogr. Mar. Annu. Rev.* 26:317–359.

- Pascual, M. A., and M. D. Adkinson. 1994. The decline of the Steller sea lion in the northeast Pacific: Demography, harvest or environment. *Ecol. Appl.* 4:393–403.
- Pauly, D., P. Muck, J. Mendo, and I. Tsukayama eds. 1989. *The Peruvian Upwelling Ecosystem: Dynamics and Interactions*. Callao, Peru: IMARPE. 438 pp.
- Pearce, D. W., and R. K. Turner. 1990. *Economics of Natural Resources and the Environment*. Baltimore: Johns Hopkins University Press.
- Pereyra, W. T., J. E. Reeves, and R. G. Bakkala. 1976. Demersal Fish and Shellfish Resources of the Eastern Bering Sea in the Baseline Year 1975. *Prog. Rep. OSCEAP RU No. 175*, October. NOAA, U.S. Dept. of Commerce and Bur. Land Mgmt., U.S. Dept. of the Interior. Northwest and Alaska Fish Center. 619 pp.
- Perez, M. A., and M. A. Bigg. 1986. Diet of northern fur seals, *Callorhinus Ursinus*, off western North America. *Fish. Bull.* 84:957–971.
- Perez, M. A., and T. R. Loughlin. 1986. Relationships among marine mammals and gadoid fishes: a comparison between the Bering Sea and the North Sea. NMFS Northwest and Alaska Fisheries Center, Seattle. Pp. 357–391 in *Proceedings of the Workshop on Comparative Biology, Assessment, and Management of Gadoids from the North Pacific and Atlantic Oceans*, vol. I.
- Perez, M. A., and T. R. Loughlin. 1991. Incidental Catch of Marine Mammals by Foreign-Directed and Joint-Venture Fishing Vessels in the U.S. EEZ of the North Pacific, 1973–1988. NOAA Tech. Rep. NMFS 104. 57 pp.
- Perlov, A. S. 1991. Present abundance of Steller sea lions (*Eumetopias jubatus*) in the U.S.S.R. NMFS Alaska Fisheries Science Center Processed Rep. 91-14. 17 pp.
- Peterson, C.H. 1993. Improvement of environmental impact analysis by application of principles derived from manipulative ecology; lessons from coastal marine case histories. *Aust. J. Ecol.* 18:21–52.
- Petersen, G. H., and M. A. Curtis. 1980. Differences in energy flow through major components of subarctic, temperate and tropical marine shelf ecosystems. *Dana* 1:53–64.
- Peterson, C. H., H. S. Summerson, and S. R. Fegley. 1987. Ecological consequences of mechanical harvesting of clams. *Fish. Bull.* 85:281–298.
- Pfannkuche, O., and H. Thiel. 1987. Meiobenthic stocks and benthic activity on the NE Svalbard shelf and in the Nansen Basin. *Polar Biol.* 7:253–266.
- Philander, S. G. H. 1990. *El Nino, La Nina, and the southern oscillation*. San Diego: Academic Press. 293 pp.
- Piatt, J. F. 1994. Response of murre (*Uria* spp.) to the Exxon Valdez oil spill and changes in the Gulf of Alaska marine ecosystem. Exxon Valdez Oil Spill Symposium Proceedings
- Piatt, J. F., and P. Anderson (in press) Response of common murre to the Exxon Valdez oil spill and long-term changes in the Gulf of Alaska marine ecosystem. In Rice et al., (eds) Exxon Valdez Oil Spill Symposium Proceedings. AFSC Symp. No. 18.
- Piatt, J. F., and T. I. Van Pelt. 1993. A wreck of Common Murre (*Uria aalge*) in the Northern Gulf of Alaska during February and March of 1993. Anchorage, Alaska: U.S. Fish and Wildlife Service.
- Piatt, J. F., S. A. Hatch, B. D. Roberts, W. W. Lidster, J. L. Wells, and C. J. Haney. 1988. Populations, productivity, and feeding habits of seabirds on St. Lawrence Island, Alaska. Anchorage, Alaska: U.S. Fish and Wildlife Service.

- Piatt, J. F., C. J. Lensink, W. Butler, M. Kendziorek, and D. R. Nysewander. 1990. Immediate impact of the 'Exxon-Valdez' oil spill on marine birds. *Auk* 107:387-397.
- Pika, A., L. Terentieva, and D. Bogoyavlensky. 1993. Providence Area of the Chukotka: Historical and Ethnographical Description. vol. 2. Moscow: Center of Demography and Human Ecology.
- Pitcher, K. W. 1980. Food of the harbor seal, (*Phoca vitulina richardsi*), in the Gulf of Alaska. *Fish. Bull.* 78:544-549.
- Pitcher, K. W. 1984. The harbor seal (*Phoca vitulina richardsi*). Pp. 65-70 in Raine mammals species accounts. J. J. Burns, K. J. Frost, and L. F. Lowry, eds. Alaska Dept. of Fish and Game, Game Tech. Bull. 7.
- Pitcher, K. W. 1990. Major decline in number of harbor seals, (*Phoca vitulina richardsi*), on Tugidak Island, Gulf of Alaska. *Mari. Mammal Sci.* 6:121-134.
- Pitcher, K. W., and D. G. Calkins. 1978. Pp 80-98 in Environmental Assessment of the Alaskan Continental Shelf Annual Reports of Principal Investigators for the year ending March 1978. vol.1. Boulder: U.S. Environmental Research Laboratories. Outer Continental Shelf Environmental Assessment Program.
- Pomeroy, R., E. C. Hargrove, and J. J. Alberts. 1988. The ecosystem perspective. Chapter 1 in Concepts of Ecosystem Ecology. L. R. Pomeroy, and J. J. Alberts, eds. New York: Springer-Verlag.
- Presidential Decree from 05.05.1992 "Ob okhrane prirodnykh resursov territorial'nykh vod, continental'nogo shel'fa i ekonomicheskoy zony Rossiiskoy Federacii" (On the conservation of natural resources of the territorial waters, continental shelf and economic zone of the Russian Federation). 1992. *Vedomosti S'ezda.* 19:1379-1380 [In Russian].
- Prigogine, I. 1980. From Being to Becoming: Time and Complexity in the Physical Sciences. New York: W. H. Freeman and Co.
- Quakenbush, L. T. 1988. Spotted seal. Pp. 107-124 in Selected Marine Mammals of Alaska, J.W. Lentfer, ed. Washington, D.C.: U.S. Marine Mammal Commission.
- Quakenbush, L., and J. Cochrane. 1993. Report on the Conservation Status of the Steller's Eider (*Polysticta stelleri*), a Candidate Threatened and Endangered Species. Fairbanks, Alaska: U.S. Fish and Wildlife Service. 25 pp.
- Qui, B., and T. M. Joyce. 1992. Interannual variability in the mid-and low latitude western North Pacific. *J. Phys. Oceanogr.* 22:1062-1079.
- Ragen, T. J., G. A. Antonelis, and M. Kyota. 1993. Early phase of northern fur seal pup migration from St. Paul Island, Alaska. (Abstract) P.88 in 10th Biennial Conference on the Biology of Marine Mammals, 11-15 November, Galveston, Tex.
- Rampino, M. R., S. Self and R. W. Fairbridge. 1979. Can climate change cause volcanic eruptions? *Science* 206:826-829.
- Rasmussen, B. 1969. Variations in protandric hermaphroditism of *Pandalus borealis*. *FAO Fish. Rep.* 57(3).
- Rational Resources-Use at the Commander Island. 1987. Moscow: MGU.
- Raveling, D. G. 1984. Geese and hunters of Alaska's Yukon Delta: Management problems and political dilemmas. *Trans. North Am. Wildl. Nat. Resour. Conf.* 49:555-575.

- Reeburgh, W. S., and G. W. Kipphut. 1986. Chemical distributions and signals in the Gulf of Alaska, its coastal margins and estuaries. Pp. 77–91 in *The Gulf of Alaska, Physical Environment and Biological Resources*, D. W. Hood and S. T. Zimmerman, eds. MMS/NOAA, Alaska Office, Anchorage, OCS Study MMS 86-0095.
- Reed, R. K. 1990. A year-long observation of water exchange between the North Pacific and the Bering Sea. *Limnol. Oceanogr.* 35:1604–1609.
- Reed, R. K. and J. D. Schumacher. 1986. Physical oceanography. Pp. 57–75 in *The Gulf of Alaska: Physical Environment and Biological Resources*, D. W. Hood and S. T. Zimmerman, eds. MMS/NOAA OCS study, MMS 86-0095.
- Reed, R. K., and P. J. Stabeno. 1990. Flow trajectories in the Bering Sea: Evidence for chaos. *Geophys. Res. Lett.* 17:2141–2144.
- Reed, R. K., G. V. Khen, P. J. Stabeno, and A. V. Verkhunov. 1993. Water properties and flow over the deep Bering Sea basin, summer 1991. *Deep-Sea Res.* 40:2325–2334.
- Reeves, R. R. 1984. Modern commercial pelagic whaling for gray whales. Pp. 187–200 in *The Gray Whale*. M. L. Jones, S. L. Swartz, and S. Leatherwood (eds). New York: Academic Press.
- Reijnders, P. J. H. 1986. Reproductive failure in common seals feeding on fish from polluted coastal waters. *Nature* 324:456–457.
- Reijnders, P. J. H., S. Brasseur, J. Van der Toorn, P. Van der Wolf, I. Boyd, J. Harwood, D. Lavigne, and L. Lowry. 1993. Seals, Fur Seals, Sea Lions, and Walrus. IUCN/Seal Specialist Group. Gland, Switzerland. IUCN.
- Reilly, S. B., and J. Barlow. 1986. Rates of increase in dolphin population size. *Fish. Bull.* 84:527–533.
- Reimann, B., and E. Hoffmann, 1991. Ecological consequences of dredging and bottom trawling in the Limfjord, Denmark. *Mar. Ecol. Prog. Ser.* 69:171–178.
- Repenning, C. A. 1976. Adaptive evolution of sea lions and walruses. *Syst. Zool.* 25:375–390.
- Report on the Environmental Situation at the Seas of the Russian Federation and Some Ocean Areas in 1991. 1992. Moscow: Roskomhydromet. [In Russian].
- Report on the Environmental Situation at the Seas of the Russian Federation and Some Ocean Areas in 1992. 1993. Moscow: Roskomhydromet. [In Russian].
- Research in the seas of the USSR. 1937. J. 113:208–226. [In Russian].
- Research in the seas of the USSR. 1990. J. 113:208–226. [In Russian].
- Results of the 1926–1927 Census of the Northern Borderlands of the Far-Eastern Area. Blagoveshensk. CSU RSFSR, 1929. [In Russian].
- Rice, C. P., A. Krynitsky, and P. F. Roscigno. 1992. Organochlorine contamination of sediments, fish, and invertebrates. Pp. 285–289 in *Results of the Third joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC)*, P.A. Nagel, ed. U.S. Fish and Wildlife Service Biol. Rep.
- Rice, D. W., and A. A. Wolman. 1982. Whale census in the Gulf of Alaska, June to August 1980. *Rep. Int. Whaling Comm.* 32:491–497.
- Ricker, W. E. 1958. Handbook of computation for biological statistics of fish populations. *Fish. Res. Bd. Can. Bull.* 119:1–300.
- Ricker, W. E. 1994. Stock and recruitment. *J. Fish. Res. Bd. Can.* 11:559–623.

- Riedmann, M. 1990. *The Pinnipeds. Seals, Sea Lions, and Walruses*. Berkeley: University of California Press. 439 pp.
- Riemann, B., and E. Hoffmann. 1991. Ecological consequences of dredging and bottom trawling in the Limfjord, Denmark. *Mar. Ecol. Prog. Ser.* 69:171–178.
- Riesen, W., and K. Reise. 1982. Macrobenthos of the subtidal Wadden Sea: Revisited after 55 years. *Helgoländer Meeresunters.* 35:409–429.
- Rinaldo, R. G. 1976. *Pandalus borealis* Management Modeling. Completion Report Project 3-189-R. Augusta: Maine Department of Marine Resources.
- Robert, G., and G. S. Jamieson. 1986. Commercial fishery data isopleths and their use in offshore sea scallop (*Placopecten magellanicus*) stock evaluations. Pp. 76–82 in *North Pacific Workshop on Stock Assessment and Management of Invertebrates*. G. S. Jamieson and N. Bourne, Eds., *Can. Spec. Publ. Fish. Aquat. Sci.* 92.
- Roberts, W. O., and R. H. Olson. 1973. Geomagnetic storms and wintertime 300 mb trough development in the North Pacific and North American area. *J. Atmos. Sci.* 30:135–140.
- Roby, D. D., and K. L. Brink. 1986. Decline of breeding least auklets on St. George Island, Alaska. *J. Field Ornithol.* 57:57–59.
- Rodin, V. E. 1989. Population biology of the king crab and parathithics camtschatecu tilesius in the North Pacific ocean. Pp. 133–144 in *proc. Tint Symp. King and Tanner Crabs*, November, Anchorage, Alaska.
- Rodin, V. E., and V. I. Myasoyedov. 1982. Biological characteristics of the red king crab population in the northwest Okhotsk Sea. *Izv. TINRO* 106:3–10.
- Rogers, D. E. 1992. False Pass Chum Salmon. Fisheries Research Inst. Publ. FRI-UW-9404.
- Rosenberg, A. A., ed. 1992. *Defining Overfishing—Defining Stock Rebuilding*. U.S. Dept. of Commerce NOAA Tech. Memo. NMFS-F/SPO-8 68 pp.
- Rosenberg, A. A., M. J. Fogarty, M. P. Sissenwine, J. R. Beddington, and J. G. Shepherd. 1993. Achieving sustainable use of renewable resources. *Science* 262:828–829.
- Roseneau, D. G., M. I. Springer, E. C. Murphy, and A. M. Springer. 1985. Population and trophics studies of seabirds in the northern Bering and eastern Chukchi seas, 1981. U.S. Dept. of Commerce, NOAA, OCSEAP Final Rep. 30:1–58.
- Rowe, G. T., and W. C. Phoel. 1991. Nutrient regeneration and oxygen demand in Bering Sea continental shelf sediments. *Cont. Shelf Res.* 12:439–449.
- Royer, T. C. 1982. Baroclinic transport in the Gulf of Alaska. Part I. Seasonal variations of the Alaska Current. *J. Mar. Res.* 39:251–266.
- Royer, T. C. 1989. Upper ocean temperature variability in the northeast Pacific Ocean: Is it an indicator of global warming? *J. Geophys. Res.* 94:18175–18183.
- Royer, T. C. 1992. Coastal fresh water discharge in the Northeast Pacific. *J. Geophys. Res.* 87:2017–2021.
- Royer, T. C. 1993. High-latitude oceanic variability associated with the 18.6-year nodal tide. *J. Geophys. Res.* 98:4639–4644.
- Royer, T. C. 1994. Interdecadal changes in temperature and salinity in the northern North Pacific. *EOS Trans.* 75.
- Royer, T. C. and W. J. Emery. 1984. Circulation in the Bering Sea, 1982–83, based on satellite-tracked drifter observations. *J. Phys. Oceanogr.* 14:1914–1920.



- Sabolevsky E. I., V. P. Shuntov, and A. F. Volkov. 1989. The composition and the present state of pelagic fish communities in the Western Bering Sea. Pp. 231–245 in Proceedings of the International Scientific Symposium on Bering Sea Fisheries, Seattle.
- Saetersdal, G., and H. Loeng. 1987. Ecological adaptation of reproduction in northeast Arctic Cod. Fish. Res. 5:253–270.
- Saino, T., K. Miyata, and A. Hattori. 1979. Primary production in the Bering and Chukchi seas and in the northern North Pacific in 1978 summer. Bull. Plankton Soc. Jpn. 26:96–103.
- Salmon, D. K. 1992. On interannual variability and climate change in the North Pacific. Ph.D. thesis, University of Alaska, Fairbanks. 219 pp.
- Sambrotto, R. N. 1985. The dependence of phytoplankton nutrient utilization on physical processes in the eastern Bering Sea. In El Nino North; Nino Effects in the Eastern Subarctic Pacific Ocean, W. S. Wooster, and D. L. Fluharty, eds. Washington Sea Grant Publ. WSG-WO 85-3. Seattle: University of Washington. 312 pp.
- Sambrotto, R. N., and J. J. Goering. 1983. Interannual variability of phytoplankton and zooplankton production on the southeast Bering Sea shelf. In From Year to Year W.S. Wooster ed., pp. 161–177. Washington Sea Grant. Seattle: University of Washington.
- Sambrotto, R. N., J. J. Goering, and C. P. McRoy. 1984. Large yearly production of phytoplankton in the western Bering Strait. Science 225:1147–1150.
- Sambrotto, R. N., H. J. Niebauer, J. J. Goering, and R. L. Iverson. 1986. Relationships among vertical mixing, nitrate uptake, and phytoplankton growth during the spring bloom in the southeast Bering Sea middle shelf. Cont. Shelf Res. 5:161–198.
- Sambrotto, R. N., G. Savidge, C. Robinson, P. Boyd, T. Takahashi, D. M. Karl, C. Langdon, D. Chipman, J. Marra, and L. Codispoti. 1993. Pp 248–250. Elevated consumption of carbon relative to nitrogen in the surface ocean. New York: Lamont-Doherty Earth Observatory of Columbia University. Nature (Lond). 363:6426.
- Sanger, G. A. 1972. Fisheries potentials and estimated biological productivity of the Subarctic Pacific region. In Biological Oceanography of the Northern North Pacific Ocean, A. Y. Takenouti et al. eds. Pp. 561–574. Tokyo: Idemitsu Shoten.
- Sanger, G. A. 1986. Diets and Food Web Relationships of Seabirds in the Gulf of Alaska and Adjacent Marine Regions. MMS/NOAA OCSEAP Final Rep. 45:631–771.
- Sapozhnikov, V. V., N. V. Arzhanova, and V. V. Zubarevitch. 1993. Estimation of primary production in the ecosystem of western Bering Sea. Russ. J. Aquat. Ecol. 2:23–34.
- Savikko, H., and T. Page. 1990. 1989 Preliminary Alaska Commercial Fisheries Harvests and Values. ADF&G, Regional Information Rep. No. 5T90-07.
- Sayles, M. A., K. Aagaard, and L.K. Coachman. 1979. Oceanographic Atlas of the Bering Sea Basin. Seattle: University of Washington Press.
- Scarff, J. E. 1991. Historic distribution and abundance of the right whale (*Eubalaena glacialis*) in the North Pacific, Bering Sea, Sea of Okhotsk and Sea of Japan from the Maury Whale Charts. Rep. Int. Whaling Comm. 41:467–489.
- Scheffer, V. V. 1981. Newborn body size in marine mammals. Pac. Discovery 34(3):19–26.
- Schell, D. M., and Saupe. 1989. Primary Production, Carbon Energetics, and Nutrient Cycling. In Environmental Characterization and Biological Utilization of the North Aleutian Shelf Near shore Zone. J.C. Truett ed. MMS/NOAA OCSEAP Final Rep. 60:99–140.

- Schmutz, J. A., S. E. Cantor, and M. R. Petersen. 1994. Seasonal and annual survival of Emperor Geese. *J. Wildl. Manage.*
- Scholl, D., E. Buffington, and D. Hopkins. 1966. Exposure of basement rock on the continental slope of the Bering Sea. *Science* 153:992–994.
- Scholl, D., E. Buffington, and D. Hopkins. 1968. Geologic history of the continental margin of North America in the Bering Sea. *Mar. Geol.* 6:297–330.
- Scholl, D., E. Buffington, and M. Marlow. 1975. Plate tectonics and the structural evolution of the Aleutian-Bering Sea Region. In *The Geophysics and Geology of the Bering Sea Region*. R.B. Forbes ed. Geological Society of America, Memoir 151.
- Schumacher, J. D., and R. K. Reed. 1992. Characteristics of currents over the continental slope of the eastern Bering Sea. *J. Geophys. Res.* 97:9423–9433.
- Schumacher, J. D., T. H. Kinder, D. J. Pashinski, and R. L. Charnell. 1979. A structural front over the continental shelf of the eastern Bering Sea. *J. Phys. Oceanogr.* 9:79–87.
- Schumacher, J. D., C. A. Pearson, and J. E. Overland. 1982. On exchange of water between the Gulf of Alaska and the Bering Sea through Unimak Pass. *J. Geophys. Res.* 87:5785–5795.
- Schwing, F. B. 1994. Long-term and seasonal patterns in coastal temperature and salinity along the North American west coast. Pp. 115–126 in *Proceedings of the Tenth Annual Pacific Climate (PACLIM) Workshop*, K. T. Redmond and V.L. Tharp eds. Tech. Rep. 36, California Department of Water Resources.
- Searing, G. F. 1977. Some Aspects of the Ecology of Cliff-Nesting Seabirds at Kongkok Bay, St. Lawrence Island, Alaska, during 1976. MMS/NOAA OCSEAP Final Rep. 5:263–412.
- Sease, J. L. 1992. Status review: harbor seals (*Phoca vitulina*) in Alaska. NMFS AFSC Processed Rep. 92–15. 74 pp.
- Sease, J. L., J. P. Lewis, D. C. McAllister, R.L. Merrick, and S.M. Mello. 1993. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in southeast Alaska, the Gulf of Alaska, and Aleutian Islands during June and July 1992. NOAA Tech. Memo. NMFS-AFSC-17. 57 pp.
- Sedinger, J. S., C. J. Lensink, D. H. Ward, R. M. Anthony, M. L. Wege, and G. V. Byrd. 1993. Current status and recent dynamics of the Black Brant (*Branta bernicla*) breeding population. *Wildfowl* 44: 49–59.
- Sekine, Y. 1988. Anomalous southward intrusion of the Oyashio east of Japan. I. Influence of seasonal and interannual variations in the wind stress over the North Pacific. *J. Geophys. Res.* 93:2247–2256.
- Sekine, Y. 1991. Anomalous southward intrusion of the Oyashio east of Japan. In *Long-Term Variability of Pelagic Fish Populations and Their Environment*. New York: Pergamon Press.
- Shakespeare, D. 1991. Recent US-USSR Agreements Relating to the Bering Region. *Arctic Res. U.S.* 5:37–47.
- Sharma, G. D. 1977. *The Alaskan Shelf: Hydrodynamic, Sedimentary, and Geochemical Environment*. New York: Springer-Verlag.
- Shaughnessey, P. D., and F. H. Fay. 1977. A review of the taxonomy and nomenclature of North Pacific harbor seals. *J. Zool. (Lond.)* 182:385–419.

- Sherman, K. 1991. The large marine ecosystem concept: A research and management strategy for living marine resources. *Ecol. Appl.* 349–360.
- Sherman, K. 1993. Large marine ecosystems as global units for marine resources management an ecological perspective. Pp. 3–14 in *Large Marine Ecosystems. Stress, Mitigation, and Sustainability*. K. Sherman, L. M. Alexander, and B. D. Gold eds. Washington, D.C.: AAAS Press.
- Sherman, K., and L. M. Alexander (eds). 1986. *Variability and Management of Large Marine Ecosystems*. Boulder, Colo: Westview.
- Shuert, P. G., and J. J. Walsh. 1993. A coupled physical-biological model of the Bering/Chukchi Seas. *Cont. Shelf Res.* 13(5/6).
- Shuntov, V. P. 1972. *Seabirds and Biological Structure of the World Ocean*. Vladivostok. 373 pp. [In Russian].
- Shuntov, V. P. 1986. The structure of the biological resources and catch dynamics in the far eastern economic zone of the USSR. [In Russian]. *Rybn. Khoz.* 12:14–18.
- Shuntov, V. P. 1994a. Specifics of anadromous migrations of Asian Gorbusha in 1993. *Rybn. Khoz.* 2:18–23.
- Shuntov, V. P. 1994b. Distribution of whales and dolphins in the far-eastern seas and adjacent waters of the Pacific Ocean. *Rybn. Khoz.* 1:27–32.
- Shuntov, V. P., and E. P. Dulepova. 1991. Ecosystems of the Bering and Okhotsk seas. *Rybn. Khoz.* 6:25–31. [In Russian].
- Shuntov, V. P., and V. I. Radchenko. 1994. Brief Summary of the Ecosystem Investigations TINRO in the Bering Sea. Report to the Commission.
- Shuntov, V. P., A. F. Volkov, and A. Ya. Efimkin. 1988. Composition and current status of pelagic communities of the western Bering Sea. *Biol. Morya* 2:56–65. [In Russian].
- Shuntov, V. P., L. A. Borets, and E. P. Dulepova. 1990. Some results of ecosystem research of biological resources of the Far Eastern sea. *Izvestiia TINRO* III:3–26. [In Russian].
- Simenstad, C. A., J. A. Estes, and K. W. Kenyon. 1978. Aleuts, sea otters and alternate stable state communities. *Science* 200:403–411.
- Sinclair, E. 1991. *Fur Seal Investigations*. Alaska Fisheries Science Center, 1993. NOAA technical memorandum, NMFS, AFSC, Vol., 24.
- Sinclair, E., T. Loughlin, and W. Pearcy. 1994. Prey selection by northern fur seals (*Callorhinus ursinus*) in the eastern Bering Sea. *Fish. Bull.* 92:144–156.
- Sirenko, B. I., and V. M. Koltun. 1992. Characteristics of benthic biocenoses of the Chukchi and Bering Seas. Pp. 257–258 in *Results of the Third Joint U.S.-U.S.S.R. Bering and Chukchi Sea Expedition (BERPAC)*, P.A. Nagel, ed. U.S. Fish and Wildlife Service. *Biol. Rep.*
- Skalkin, V. A. 1963. Diet of flatfishes in the southeastern Bering Sea. Pp. 235–250 in *Soviet Fisheries Investigations in the Northeast Pacific*, vol. 2, P. A. Moiseev, ed. (Israel Prog. Sci. Transl., Jerusalem, 1968).
- Skud, B. E. 1977. Drift, Migration, and Intermingling of Pacific Halibut Stocks. *International Pacific Halibut Commission Scientific Report* 63. Seattle: International Pacific Halibut Commission.

- Slizkin, A. G. 1989. Tanner-crabs (*Chionocetes opilio*, *C. bairdi*) of the Northwest Pacific: distribution, biological peculiarities, and population structure. Pp. 27–33. In Proc. Int. Symp. King and Tanner Crabs, November, Anchorage, Alaska.
- Sobolevsky, E. I., V. P. Shuntov, and A. F. Volkov. 1989. The composition and the present state of pelagic fish communities in the western Bering sea. Pp. 523–536. In: Proc. Int. Symp. Biol. Mgmt. Walleye Pollock. University of Alaska Sea Grant Rep. No. 894. Fairbanks: University of Alaska.
- Sovetsky Rybak. 1992. No. 7, p. 5. [In Russian].
- Soviet Fishery Research in the North-Eastern Pacific Ocean. 1963. Trudy VNIRO, 1, vol. 48. [In Russian].
- Sowls, A. L., S. A. Hatch, and C. J. Lensink. 1978. Catalog of Alaskan Seabird Colonies, U.S. Anchorage, Alaska: Fish and Wildlife Service.
- Spelman, M. J., and S. Manabe. 1984. Influences of oceanic heat transport upon the sensitivity of a model climate. *J. Geophys. Res.* 89:571–586.
- Springer, A. M. 1991. Seabird relationships to food webs and the environment: Examples from the North Pacific Ocean. In *Studies of High-Latitude Seabirds. I. Behavioral, Energetic, and Oceanographic Aspects of Seabird Feeding Ecology*. W. A. Montevecchi, and A. J. Gaston eds. Ottawa: Canadian Wildlife Service.
- Springer, A. M. 1992. A review: Walleye pollock in the North Pacific—how much difference do they really make? *Fish. Oceanogr.* 1:80–96.
- Springer, A. M. 1993a. Status and Conservation Concerns of Seabirds in Alaska. Working paper prepared for Greenpeace International. 97 pp.
- Springer, A. M. 1993b. Report of the Seabird Working Group. In *Is It Food?* University of Alaska Sea Grant Rep. 93–01. Fairbanks: University of Alaska.
- Springer, A. M., and C. P. McRoy. 1993. The paradox of pelagic food webs in the northern Bering Sea—III. Patterns of primary production. *Cont. Shelf Res.* 13:575–599.
- Springer, A. M., and D. G. Roseneau. 1985. Copepod-based food webs: auklets and oceanography in the Bering Sea. *Mar. Ecol. Prog. Ser.* 21:229–237.
- Springer, A. M., D. G. Roseneau, D. S. Lloyd, C. P. McRoy, and E. C. Murphy. 1986. Seabird responses to fluctuating prey abundance in the eastern Bering Sea. *Mar. Ecol. Prog. Ser.* 32:1–12.
- Springer, A. M., and C. P. McRoy. In review. The Bering Sea Greenbelt: Shelf edge processes and ecosystem production.
- Springer, A. M., C. P. McRoy, and K. R. Turco. 1989. The paradox of pelagic food webs in the northern Bering Sea—II. Zooplankton communities. *Cont. Shelf Res.* 9:359–386.
- Springer, A. M., D. G. Roseneau, E. C. Murphy, and M. I. Springer. 1984. Environmental controls of marine food webs: Food habits of seabirds in the eastern Chukchi Sea. *Can. J. Fish. Aquat. Sci.* 41:1202–1215.
- Springer, A. M., E. C. Murphy, D. G. Roseneau, C. P. McRoy, and B. A. Cooper. 1987. The paradox of pelagic food webs in the northern Bering Sea—I. Seabird food habits. *Cont. Shelf Res.* 7:895–911.
- Stabeno, P. J., and R. K. Reed. 1992. A major circulation anomaly in the western Bering Sea. *Geophys. Res. Lett.* 19:1671–1674.

- Stabeno, P. J., and R. K. Reed. 1994. A schematic of mean circulation in the Bering Sea basin observed by satellite tracked drifters, 1986–1993. *J. Phys. Oceanog.* 24(4):848–854.
- State Report On the State of Environment in the Russian Federation in 1993. Ministry of Environment and Natural Resources. 1993. *Evrasia*. 9. [In Russian].
- Steele, J. H. 1974. *The Structure of Marine Ecosystems*. Department of Agriculture and Fisheries for Scotland, Marine Lab. Cambridge: Harvard University Press. 133 pp.
- Steele, J. H. 1985. A comparison of terrestrial and marine ecological systems. *Nature* 313:355–358.
- Steele, J. H. 1991. Marine functional diversity. *BioScience* 41:470–474.
- Stehn, R. A., C. P. Dau, B. Conant, and W. I. Butler, Jr. 1993. Decline of spectacled eiders nesting in western Alaska. *Arctic* 46:264–277.
- Stepanova, V. 1937. Biological characteristics of currents in the northern part of the Bering Sea. *Issled. Morei SSSR*. 25:175–213. [In Russian].
- Stevens, B. G., R. A. MacIntosh, J. A. Haaga, and J. H. Bowerman. 1993. Report to the Industry on the 1992 Eastern Bering Sea Crab Survey. Alaska Fisheries Science Center Processed Rep. 93–14. Kodiak: Alaska Fisheries Science Center, Kodiak Facility, NMFS, NOAA, 53 pp.
- Stewart, B. S., and R. L. Delong. 1993. Seasonal dispersal and habitat use of foraging northern elephant seals. *Symp. Zool. Soc. Lond.* 66:179–194.
- Stirling, I. 1988. *Polar Bears*. Ann Arbor: University of Michigan Press.
- Stoker, S. W. 1981. Benthic invertebrate macrofauna of the eastern Bering/Chukchi continental shelf. Pp. 1069–1090 in *The Eastern Bering Sea Shelf: Oceanography and Resources*. vol. 2, D. W. Hood and J. A. Calder, eds. Seattle: University of Washington Press.
- Stoker, S. W., and I. I. Krupnik. 1993. Subsistence whaling. Pp. 579–629 in *The Bowhead Whale*. J. J. Burns, J. J. Montague, and C. J. Cowles eds. Society for Marine Mammalogy Spec. Publ. No. 2.
- Summary report on the UN Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks. 1993. *Earth Negotiations Bulletin*. Vol. 7, no. 16.
- Swartz, L. G. 1966. Sea-cliff birds. Pp. 611–678 in *Environment of the Cape Thompson region, Alaska*. N.J. Wilimovsky and J.N. Wolfe eds. Oak Ridge, Tenn: U.S. Atomic Energy Commission, Oak Ridge, Tennessee.
- Swartzman, G. L., and R. J. Hofman. 1991. Uncertainties and Research Needs Regarding the Bering Sea and Antarctic Marine Ecosystems. Washington, D.C.: U.S. Marine Mammal Commission. 110 pp.
- Swift, J. H., and K. Aagaard. 1976. Upwelling near Samalga Pass. *Limnol. Oceanogr.* 21:399–408.
- Tabata, S. 1982. The anticyclonic, baroclinic eddy of Sitka, Alaska in the Northeast Pacific Ocean, *J. Phys. Oceanogr.* 12:1260–1282.
- Tabata, S. 1991. Long-term ocean variability at Ocean Station P in the northeast Pacific Ocean—an update to 1989. In *Long-Term Variability of Pelagic Fish Populations and their Environment*. New York: Pergamon Press.

- Takenouti, A. Y., and K. Ohtani. 1974. Currents and water masses in the Bering Sea: A review of Japanese work. In *Oceanography of the Bering Sea with Emphasis on Renewable Resources*, D.W. Hood and E.J. Kelley, eds. Occasional Publ. No. 2. Institute of Marine Science, Fairbanks: University of Alaska. 623 pp.
- Taksami Ch. Ethnic Traditions of the Arctic people. 1988. Pp. 314–320. In *Arctic Research: Advances and Prospects* vol. II. Moscow: Nauka.
- Taniguchi, A. 1969. Regional variations in surface primary production in the Bering Sea in summer and the vertical stability of water affecting the production. *Bull. Fac. Fish. Hokkaido Univ.* 20:169–179.
- Tansley, A. G. 1935. The use and abuse of vegetational concepts and terms. *Ecology* 16:284–307.
- Testa, W. J., G. Oehlert, D. G. Ainley, J. L. Bengston, D. Siniff, R. M. Laws, and D. Rounsevell. 1991. Temporal variability in Antarctic marine ecosystems: Periodic fluctuations in the phocid seals. *Can. J. Fish. Aquat. Sci.* 48:631–639.
- The United Nations Conference on Environment and Development. 1992. Protection of the oceans, all kinds of seas, including enclosed and semi-enclosed seas, and coastal areas and the protection, rational use and development of their living resources, agenda 21. Chapter 17 in *Earth Summit 1992*, J. Quarrie, ed. London: The Regency Press.
- Thomas, D. J., B. Tracey, H. Marshall, and J. R. Norstrom. 1992. Arctic terrestrial ecosystem contamination. *Sci. Total Environ.* 122:135–164.
- Thompson, W. F., and N. L. Freeman. 1930. History of the Pacific Halibut Fishery. Report No. 5 of the International Fisheries Commission, Vancouver, British Columbia.
- Thomson, R. E. 1972. On the Alaskan Stream, *J. Phys. Oceanog.* 2:363–371.
- Thorsteinson, F. V., and C. J. Lensink. 1962. Biological observations of Steller sea lions taken during an experimental harvest. *J. Wildl. Manage.* 26:353–359.
- Tietenberg, T. 1992. *Environmental and Natural Resources Economics*, 3rd ed. New York: Harper Collins Publishers.
- Tikhmenev, P. 1863. *The Historical Description of the Russian-American Company and Its Activities to the Present Time*. St. Petersburg. [In Russian].
- Tovar, H., V. Guillen, and M. E. Nakama. 1987. Monthly population size of three guano birds species off Peru, 1953–1982. Pp. 208–218 in *The Peruvian Anchoveta and its Upwelling Ecosystem: Three Decades of Change*. D. Pauly and I. Tsukayama eds. Callao, Peru: Instituto del Mar del Peru.
- Traditional Beliefs and Lifestyle of Siberian People. 1987. Novosibirsk, Nauka.
- Trapp, J. L. 1975. Distribution and Abundance of Seabirds along the Aleutian Islands and Alaska Peninsula, Fall 1974. Field Rep. U.S. Fish and Wildl. Serv., Aleutian Islands National Wildlife Refuge. 39 pp.
- Trenberth, K. E. 1990. Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Am. Meteorol. Soc.* 71:988–993.
- Trenberth, K. E., and J. W. Hurrell. 1994a. Decadal atmosphere-ocean variations in the Pacific *Climate Dyn.* 9:303–319.
- Trillmich, F., and K. A. Ono. 1991. *Pinnipeds and El Nino: Responses to Environmental Stress*. Berlin: Springer-Verlag.



- 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.). *Func. Ecol.* 4:753–768.
- Trites, A. W. 1992a. Fetal growth and the condition of pregnant fur seals off western North America from 1958 to 1972. *Can. J. Zool.* 70:2125–2131.
- Trites, A. W. 1992b. Northern fur seals: Why have they declined? *Aquat. Mam.* 18:3–18.
- Trites, A. W., and M. A. Bigg. 1992. Changes in body growth of northern fur seals from 1958 to 1974: Density effects or changes in the ecosystem? *Fish. Oceanogr.* 1:127–136.
- Trites, A. W., and P. A. Larkin. 1989. The decline and fall of the Pribilof fur seal (*Callorhinus ursinus*): A simulation study. *Can. J. Fish. Aquat. Sci.* 46:1437–1445.
- Trites, A. W., and P. A. Larkin. 1992. The status of Steller sea lion populations and the development of fisheries in the Gulf of Alaska and Aleutian Islands. Vancouver: Fisheries Center, University of British Columbia.
- Trites, A. W., and A. E. York. 1993. Unexpected changes in reproductive rates and mean age at first birth during the decline of the Pribilof Northern fur seal (*Callorhinus ursinus*). *Can. J. Fish Aquat. Sci.* 50:858–864.
- Tully, J. P., and F. G. Barber. 1960. An estuarine analogy for the subarctic Pacific Ocean. *J. Fish. Res. Bd. Can.* 17:91–112.
- Turner, L. M. 1885. Notes on the birds of the Nearer Islands, Alaska. *Auk* 11:150–159.
- Tziperman, E., L. Stone, M. A. Cane, and H. Jarosh. 1994. El nino chaos: Overlapping of resonances between the seasonal cycle and Pacific ocean-atmosphere oscillator. *Science* 264:72–74.
- U.S. Military Academy. Department of Earth, Space, and Graphic Sciences. landscape Atlas of the USSR (by) Thomas Plummer, Jr. and others. New York: West Point.
- U.S.F.W.S. [U.S. Fish and Wildlife Service]. 1989. Comprehensive Management Plans for Arctic Nesting Geese in Alaska. Anchorage, Alaska: U.S. Fish and Wildlife Service. 96 pp.
- United Nations Convention on the Law of the Sea (UNCLOS). 1982. U.N. Doc. A/Conf. 62/121, 1982. In International Legal Materials. 21 pp.
- Vader, W., R. T. Barrett, K. E. Erikstad, and K. B. Strann. 1990. Differential responses of common and thick-billed murres to a crash in the capelin stock in the southern Barents Sea. *Stud. Avian Biol.* 14:175–180.
- Van Scoy, K. A., D. B. Olson, and R. A. Fine. 1991. Ventilation of North Pacific Intermediate water: The role of the Alaskan Gyre. *J. Geophys. Res.* 96:16801–16810.
- Variability of Ichthyofauna Composition, Yield Year Classes and Forecasting Techniques of Fishes in the Western Pacific. 1988. Vladivostok: TINRO. [In Russian].
- Venrick, E. L., J. A. McGowan, D. R. Cayan, and T. L. Hayward. 1987. Climate and chlorophyll a: Long-term trends in the central North Pacific Ocean. *Science* 238:70–72.
- Verkhunov, A. V., and Y. Y. Tkachenko. 1992. Recent observation of variability in the western Bering Sea current system. *J. Geophys. Res.* 97:14369–14376.
- Vidal, J., and S. L. Smith. 1986. Biomass, growth, and development of populations of herbivorous zooplankton in the southeastern Bering Sea during spring. *Deep-Sea Res.* 33:523–556.
- Vidovin, I. 1965. Essays of the History and Ethnography of the Chukchis. Moscow: Nauka.

- Vidovin, I. 1976. *Nature and Man in the Religious Perceptions of the People of Siberia and the North*. Leningrad: Nauka.
- Vinogradov, L. G. 1970. The distribution of the dependent populations of red king crab within its range. Pp. 201–205 in *Biological Principles of Ocean Production and Exploitation* (Osnovy. biol. produktiv. okeana i ee ispoliz.). Moscow: Nauka.
- Vladimirov, V. A. 1991. Present status of populations of northern fur seals in the U.S.S.R. and problems of their utilization. Pp. 130–164 in *Russian Scientific Research in the Northern Part of the North Pacific Ocean 1990–1991*.
- Volfson, A. G. 1987. Whaling and its importance in the life of aboriginal people of Chukotka. Unpublished manuscript.
- Volterra, V. 1931. In translation in R.N. Chapman *Animal Ecology*. New York: McGraw-Hill. 464 pp.
- Wabkabayashi, K., and R. G. Bakkala. 1985. Discussions and interpretations of findings. In *Results at Cooperative U.S.-Japan Groundfish Investigations in the Bering Sea during May–August, 1979*. Int. North Pacific Fish Comm. Bull. 44:223–229.
- Waldrop, M. M. 1992. *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Touchstone. 380 pp.
- Wallace, J. M., and D. S. Gutzler. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Weather Rev.* 109:784–812.
- Wallace, R. compiler. 1994. *The Marine Mammal Commission Compendium of Selected Treaties, International Agreements, and Other Relevant Documents on Marine Resources, Wildlife, and the Environment*. Washington, D.C.: Government Printing Office: 3 vols.
- Waller, T. R. 1991. Evolutionary relationships among commercial scallop (Mollusca: Bivalvia: Pectinidae). Pp. 1–73 in *Scallops: Biology, Ecology and Aquaculture*, S.E. Shumway ed. *Developments in Aquaculture and Fisheries Science*, vol. 21. New York: Elsevier.
- Walsh, J. E., and C. M. Johnson. 1979. An analysis of Arctic sea ice fluctuations, 1953–77. *J. Geophys. Res.* 84:580–591.
- Walsh, J. J. 1983. Death in the sea: Enigmatic phytoplankton losses. *Prog. Oceanogr.* 12:1–86.
- Walsh, J. J. 1988. *On the Nature of Continental Shelves*. New York: Academic Press. 520 pp.
- Walsh, J. J., and C. P. McRoy. 1986. Ecosystem analysis in the southeastern Bering Sea. *Cont. Shelf Res.* 5:259–288.
- Walsh, J. J., G. T. Rowe, R. L. Iverson, and C. P. McRoy. 1981. Biological export of shelf carbon is a sink of the global CO<sub>2</sub> cycle. *Nature* 291:196–201.
- Walters, C., and Hilborn, R. 1986. *Adaptive management of renewable resources*. New York: MacMillan.
- Ware, D. M., and R. E. Thompson. 1991. Link between long-term variability in upwelling and fish production in the northeast Pacific Ocean. *CJFAS* 48:2296–2306.
- Wespestad, V. G. 1991. Pacific herring population dynamics, early life history, and recruitment variation relative to eastern Bering Sea oceanographic factors. Ph.D. dissertation, School of Fisheries, University of Washington. 237 pp.
- Wespestad, V. G. 1993. The status of the Bering Sea pollock and the effect of the "donut hole" fishery. *Fisheries* 18(3):18–24.

- West, J., ed. 1994. International Petroleum Encyclopedia. Tulsa: PennWell Publishing Company.
- Whitledge, T. E., W. S. Reeburgh, and J. J. Walsh. 1986. Seasonal inorganic nitrogen distributions and dynamics in the southeastern Bering Sea. *Cont. Shelf Res.* 5: 109–132.
- Whittow, G. C. 1987. Thermoregulatory adaptations in marine mammals: Interacting effects of exercise and body mass. *Mar. Mammal Sci.* 3:220–241.
- Whittow, G. C., D. T. Matsuura, and Y. C. Lin. 1972. Temperature regulation in the California sea lion (*Zalophus californianus*). *Physiol. Zool.* 45:68–77.
- Wickett, W. P. 1967. Ekman transport and zooplankton concentration in the North Pacific Ocean. *J. Fish. Res. Bd. Can.* 24:581–593.
- Wilke, F. 1957. Food of sea otters and harbor seals at Amchitka Island. *J. Wildl. Management.* 21:241–242.
- Wilke, F., and K. W. Kenyon. 1952. Notes on the food of fur seal, sea-lion harbor porpoise. *J. Wildl. Management.* 16:396–397.
- Williams, J. C., and G. V. Byrd. 1992. The status of kittiwakes and murrelets at Agattu and Buldir islands 1988–91. Adak, Alaska: U.S. Fish and Wildlife Service.
- Wilson, J. G., and J. E. Overland, 1986. Meteorology. Pp. 31–54 in *The Gulf of Alaska: Physical Environment and Biological Resources*, D.W. Hood and S.T. Zimmerman, eds. U.S. Departments of Commerce and the Interior, Minerals Management Service Publ. OCS Study MMS86-0095.
- Wolfe, R. J. 1993. The subsistence harvest of harbor seal and sea lion by Alaska Natives in 1992. Tech. Paper No. 229. Juneau: Alaska Department of Fish and Game, Division of Subsistence. 94 pp.
- Wolman, A. A., and D. W. Rice. 1979. Current status of the gray whale. *Rep. Int. Whaling Comm.* 29:275–279.
- Wooster, W. S., ed. 1983. *From Year to Year; Interannual Variability of the Environment and Fisheries of the Gulf of Alaska and Eastern Bering Sea*. Washington Sea Grant Publ. WSG-WO 83-3. Seattle: University of Washington. 208 pp.
- Wooster, W. 1992. King crab dethroned. Pp. 15–30 in *Climate Variability, Climate Change, and Fisheries*, M.H. Glanz, ed. Cambridge: Cambridge University Press.
- Wooster, W. S., and D. L. Fluharty, eds. 1985. *El Nino North. Nino Effects in the Eastern Subarctic Pacific*. Seattle: Washington Sea Grant. 312 pp.
- Wooster, W. S., and A. B. Hollowed. 1994. Decadal-Scale Variations in the Eastern Subarctic Pacific: A. Winter Ocean Conditions. *Can. Spec. Publ. Fish. Aquat. Sci.*
- Wynne, K. 1990. Marine Mammal Interactions with the Salmon Drift Gillnet Fishery on the Copper River Delta, Alaska, 1988 and 1989. Sea Grant Tech. Rep. No. 90-05. Fairbanks: University of Alaska.
- Yablokov, A. V., V. K. Krasev, V. M. Rumyantsev, M. Ye. Kokeyev, M. Ye. O. I. Petrov, V. N. Lystsov, A. F. Yemelyankov, and P. M. Rubtsov. 1993. *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation*. Office of the President of the Russian Federation, Moscow. (Translated by Paul Gallager and Elena Bloomstein, Small World Publishers, Inc., Albuquerque, N. Mex.)

- Yodzis, P. 1988. The indeterminacy of ecological interactions as perceived through perturbation experiments. *Ecology* 69:508–515.
- York, A. E. 1987. Northern fur seal, (*Callorhinus ursinus*), eastern Pacific population (Pribilof Islands, Alaska, and San Miguel Island, California). Pp. 9–21 in *Status, Biology, and Ecology of Fur Seals*, J. P. Croxall and R. L. Gentry eds. NOAA Tech. Rep. NMFS 51.
- York, A. E. 1990. Trends in numbers of pups born on St. Paul and St. George Islands 1973–88. In *Fur Seal Investigations, 1987 and 1988*. NOAA Tech. Memo. NMFS F/NWC-180, U.S. Department of Commerce.
- York, A. E. 1994. The population dynamics of northern sea lions, 1975–1985. *Mar. Mammal Sci.* 10:38–51.
- York, A. E., and J. R. Hartley. 1981. Pup production following harvest of female northern fur seals. *Can. J. Fish. Aquat. Sci.* 38:84–90.
- York, A. E., R. L. Merrick, and T. R. Loughlin. In Press. An analysis of steller sea lions metapopulations in Alaska. Ch. 12. in D.R. McCulloch (ed.) *Metapopulations and wildlife populations*. Covelo, California: Island Press.
- Yoshida, K., and N. Baba. 1982. Trend analysis of fur seal pups population of Robben Island origin. Unpublished. Manuscript. Far East Fisheries Res. Lab., Shimizu-shi Shizuoka-ken, Japan. (Paper submitted to 25th N. Pac. Fur Seal Comm., Ottawa 1982.)
- Young, N. M., S. Iudicello, K. Evans, and D. Baur. 1993. The Incidental Capture of marine Mammals in U.S. Fisheries: Problems and Solutions. Washington, D.C.: Center for Marine Conservation. 415 pp.
- Young, O., and G. Osherenko, eds. 1993. *Polar Politics: Creating International Environmental Regimes*. Ithaca: Cornell University Press.
- Zeh, J. E., C. W. Clark, J. C. George, D. Withrow, G. M. Carroll, and W. R. Koski. 1993. Current population size and dynamics. Pp. 409–489 in *The Bowhead Whale*, J. J. Burns, J. J. Montague, and C. J. Cowles, eds. Soc. for Marine Mammalogy, Spec. Publ. No. 2.
- Zenkevitch, L. 1963. *Biology of the Seas of the U.S.S.R.* London: Allan and Unwin. 955 pp.
- Zilanov, V. A. 1994. Russia and world fisheries. Ways of reforms and integration. *Rybn. Khoz.* 2:10–14 [In Russian].
- Zilanov, V. A., L. I. Shepel, A. N. Vylegianin, M. A. Stepanenko, T. I. Spivakova, N. V. Yanovskaya. 1989. International problems of conservation and exploitation of Bering Sea living resources. *Mirovye Rybolovstvo* 1:1–102. [In Russian].
- Zwanenburg, K. C. T., and W. D. Bowen. 1990. Population trends of the grey seal (*Halichoerus grypus*) in eastern Canada. Population biology of sealworm (*Pseudoterranova decipiens*) in relation to its intermediate and seal hosts. *Bull. Can. J. Fish. Aquat. Sci.* 222:185–197.

## Appendix A

### Biographical Sketches of the Committee Members

**Robert C. Francis** is professor in the School of Fisheries Research, University of Washington. He has a Ph.D. in biomathematics from the University of Washington. His areas of expertise include fisheries science, fishery oceanography, applied statistics, and resource modeling.

**Lee G. Anderson** is professor of economics and marine studies at the University of Delaware. He has a Ph.D. in economics from the University of Washington. His areas of expertise include economics and management of fisheries.

**W. D. Bowen** is the section head, Marine Mammals, Marine Fish Division, Bedford Institute of Oceanography, Department of Fisheries and Oceans, Dartmouth, Nova Scotia. He has a Ph.D. in zoology from the University of British Columbia. His areas of expertise include the population dynamics, physiology, and energetics of Marine Mammals, particularly seals, and their interactions with commercial fisheries.

**Steven K. Davis** is director of the fishery management program, LGL Alaska Research Associates, Anchorage, Alaska. He has an M.S. in fisheries science from the University of Washington. His areas of expertise include fisheries management, marine policy, and the commercial fishing industry in the Bering Sea and Gulf of Alaska.

**Jacqueline M. Grebmeier** is a research assistant professor at the University of Tennessee, Knoxville, and a visiting scientist at the Oak Ridge National Laboratory. She has a Ph.D. in biological oceanography from the University of Alaska. Her areas of expertise include the biological oceanography and ecology of the Bering, Chukchi, and Beaufort seas.

**Lloyd F. Lowry** is the marine mammals coordinator, Alaska Department of Fish and Game, Fairbanks, Alaska. He has an M.S. in marine science from the University of California, Santa Cruz. His areas of expertise are the ecology and management of marine mammals in the North Pacific and Bering Sea.

**Natalia S. Mirovitskaya** is a senior researcher at the Institute of World Economy and International Relations, Department of Ocean Affairs, Russian Academy of Sciences, Moscow. She received an M.S. in economic geography and a Ph.D. in world economy from the Russian Academy of Sciences. Her areas of expertise include ocean and environmental issues, Russian national policy, international cooperation, and arctic problems, including fisheries exploitation as a threat to environmental security.

**Charles H. Peterson** is a professor of marine science at the University of North Carolina, Chapel Hill. He has a Ph.D. in biology from the University of California, Santa Barbara. His areas of expertise include population biology and community ecology, especially of marine benthic invertebrates and barrier island plants, and invertebrate fisheries biology.

**Caleb Pungowiyi** is the President of the Inuit Circumpolar Conference, and was formally the executive director of the Arctic Marine Resources Commission and Chief Commissioner of the Bering Straits Regional Commission. He graduated from Sheldon Jackson High School, Sitka, Alaska. Mr. Pungowiyi is involved in several national and international boards and commissions that address natural resource management issues, indigenous rights, and health issues in arctic Alaska.

**Thomas C. Royer** is a professor of physical oceanography at the University of Alaska. He has a Ph.D. in physical oceanography from Texas A&M. His areas of expertise include ocean circulation, especially the Alaskan Gyre; measurement of currents, waters masses and air-sea interactions; long-period ocean waves, including tsunamis and storm surges.

**Alan M. Springer** is a research assistant professor, Institute of Marine Science, University of Alaska. He has a Ph.D. in biological oceanography from the University of Alaska. His areas of expertise include the ecology of seabirds, Bering Sea and arctic marine ecosystems, and food webs in the Bering Sea.

**Warren S. Wooster** is professor emeritus, School of Marine Affairs, University of Washington. He has a Ph.D. in oceanography from the University of California, Los Angeles. His areas of expertise include fisheries, marine policy, marine ecology, and oceanography.



## Appendix B

### Organizations and Individuals that Provided Information to the Committee

#### WORKSHOP SEPTEMBER 22–24, 1994 ANCHORAGE, ALASKA

Vera Alexander, University of Alaska, Fairbanks  
Patricia Berg, ARCO, Anchorage, Alaska  
Joseph Blum, American Factory Trawler Association, Seattle, Washington  
Vladimir Burkanov, Kamchatka Institute of Ecology and Nature Management, Russia  
Michael Castellini, University of Alaska, Fairbanks  
Joseph Chythlook, Dillingham, Alaska  
Michelle Davis, Native American Fish and Wildlife Society, Anchorage, Alaska  
Charles Edwardson, Kasigluk Elders Conference, Anchorage, Alaska  
Michael Flint, Institute of Oceanology, Russia  
Moses Kritz, Togiak, Alaska  
Hideo Miyake, Research Institute of North Pacific Fisheries, Japan  
Joji Morishita, Embassy of Japan, Washington, D.C.  
Hazel Nelson, Western Alaska Fisheries Development Association, Anchorage, Alaska  
Tsuneo Nishiyama, Hokkaido Tokai University, Japan  
Robert Otto, Kodiak Laboratory, National Marine Fisheries Service, Kodiak, Alaska  
Cmdr Vince O'Shea, U.S. Coast Guard, Anchorage, Alaska  
Penny Pagel, Greenpeace, Seattle, Washington  
Clarence Pautzke, North Pacific Fishery Management Council, Anchorage  
Steven Pennoyer, Alaska Region, National Marine Fisheries Service, Anchorage  
Mark Springer, Emmonak Tribal Council, Hooper Bay, Alaska  
Arni Thompson, Alaska Crab Coalition, Anchorage  
Terrance Quinn, University of Alaska, Fairbanks at Juneau  
John Winther, Petersburg, Alaska  
David Salmon, University of Alaska, Fairbanks

### WORKSHOP DECEMBER 1–3, 1993 SEATTLE, WASHINGTON

William Aron, Alaska Fisheries Science Center, Seattle, Washington  
John Bengtson, National Marine Mammal Laboratory, Seattle, Washington  
Charles Broches, Paragon Public Affairs, Seattle, Washington  
Lowell Fritz, Alaska Fisheries Science Center, Seattle, Washington  
George Hunt, University of California, Irvine  
Patricia Livingston, Alaska Fisheries Science Center, Seattle, Washington  
Art Kendall, Alaska Fisheries Service, Seattle, Washington  
Richard Merrick, National Marine Mammal Laboratory, Seattle, Washington  
James Overland, NOAA/PMEL, Seattle, Washington  
Gordon Swartzman, University of Washington, Seattle  
Jim Schumacher, NOAA/PMEL, Seattle, Washington  
Andrew Trites, University of British Columbia, Vancouver, B.C., Canada  
Carl Walters, University of British Columbia, Vancouver, B.C., Canada

### ADDITIONAL PARTICIPANTS

E.U. Curtis Bohlen, U.S. Department of State, Washington, D.C.  
Robert Hofman, Marine Mammal Commission, Washington, D.C.  
Philip Johnson, U.S. Arctic Research Commission, Washington, D.C.  
Igor Krupnik, Smithsonian Institution, National Museum of Natural History, Washington, D.C.  
Lyle Perrigo, Arctic Research Commission, Anchorage, Alaska  
Cmdr Richard Rooth, U.S. Coast Guard, Washington, D.C.  
John VanDerwalker, U.S. Department of State, Washington, D.C.  
Cmdr Alan Walker, U.S. Coast Guard (Ret.), Washington, D.C.

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