Marine Ecosystem Studies of Physical and Biological Interactions in the Eastern Bering Sea and Western Gulf of Alaska

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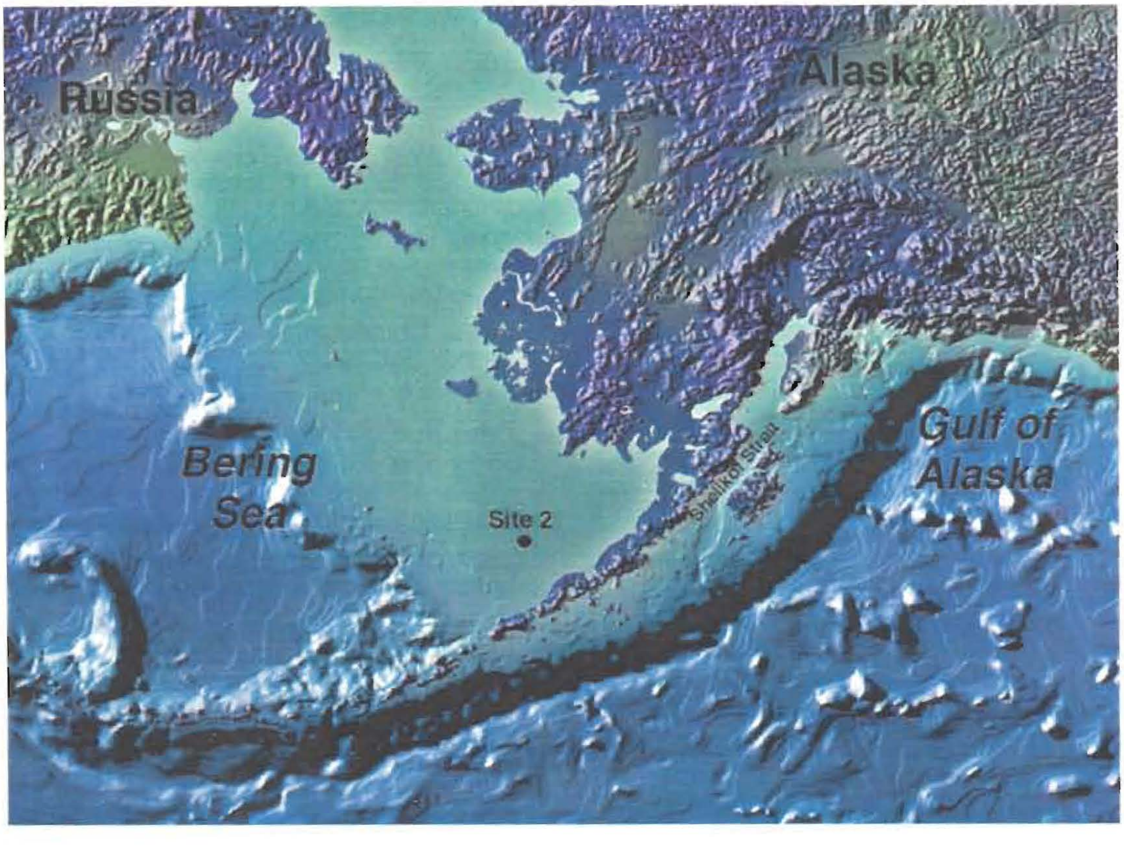
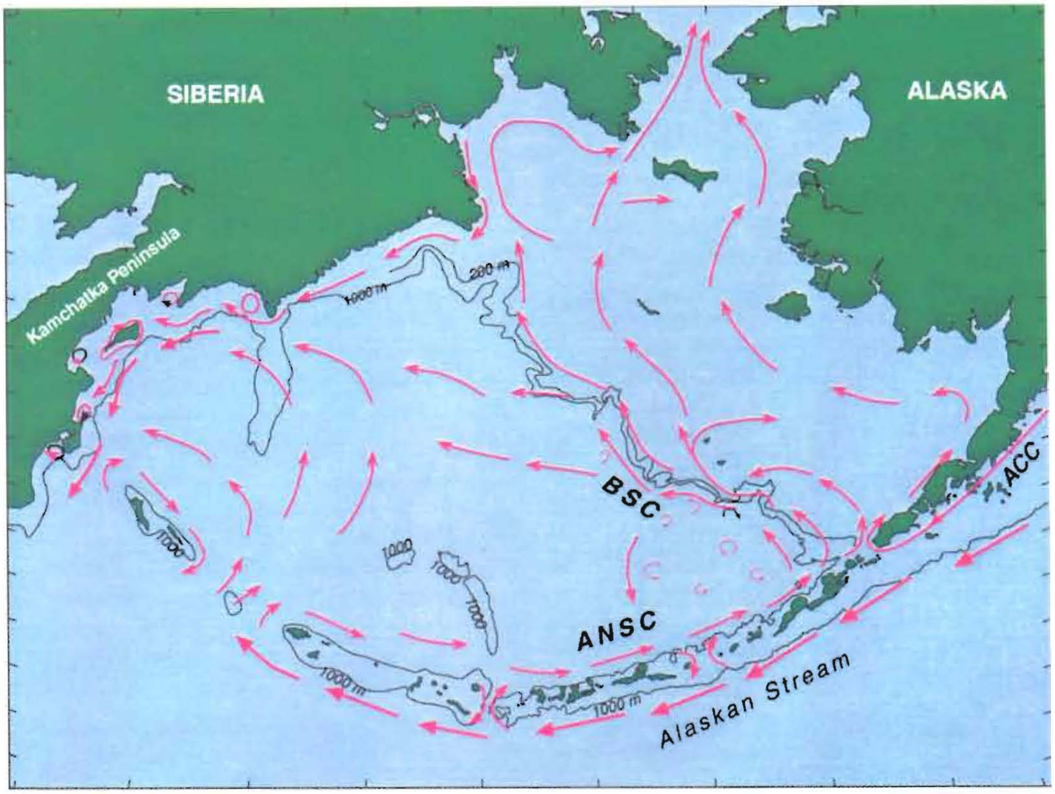
The Pacific Marine Environmental Laboratory (PMEL), part of the National Oceanic and Atmospheric Administration's Office of Oceanic and Atmospheric Research (NOAA/OAR), conducts fisheries oceanography and ecosystem studies in the Bering Sea and Gulf of Alaska. The principal research program, Fisheries-Oceanography Coordinated Investigations (FOCI), is a cooperative venture between PMEL and the National Marine Fisheries Service's Alaska Fisheries Science Center. Additional funding comes from a variety of sources, including the National Ocean Service's Coastal Ocean Program, the International Arctic Research Center, and the North Pacific Marine Research Program. This funding has enabled academic partnerships with researchers at the University of Alaska, University of Washington, and University of California. FOCI's goals are to increase understanding of the Alaskan marine ecosystem, specifically examining the role of walleye pollock as a nodal species in the ecosystem. Pollock are an important economic commodity and play a pivotal role in the bioenergetic balance, preying on zooplankton and being themselves the food for other fish, marine mammals, and seabirds. FOCI scientists research the character and dynamics of the



The southeastern Bering Sea and western Gulf of Alaska, where FOCI conducts ecosystem research. Most research is concentrated on the continental shelves north of the Aleutians and in the vicinity of Shelikof Strait. Site 2 is the location of a biophysical mooring and focus for shipboard sampling.



Principal currents contributing to circulation of the Bering Sea. (ANSC is the Aleutian North Slope Current; BSC is the Bering Slope Current.) Water flows into the Bering Sea through passes in the Aleutian Islands and out of the Bering Sea through Kamchatka Strait and, to a lesser degree, Bering Strait. Circulation is cyclonic in the basin and northwestward on the eastern shelf.

biophysical environment through field and laboratory experiments, computer simulations, and conceptual models.

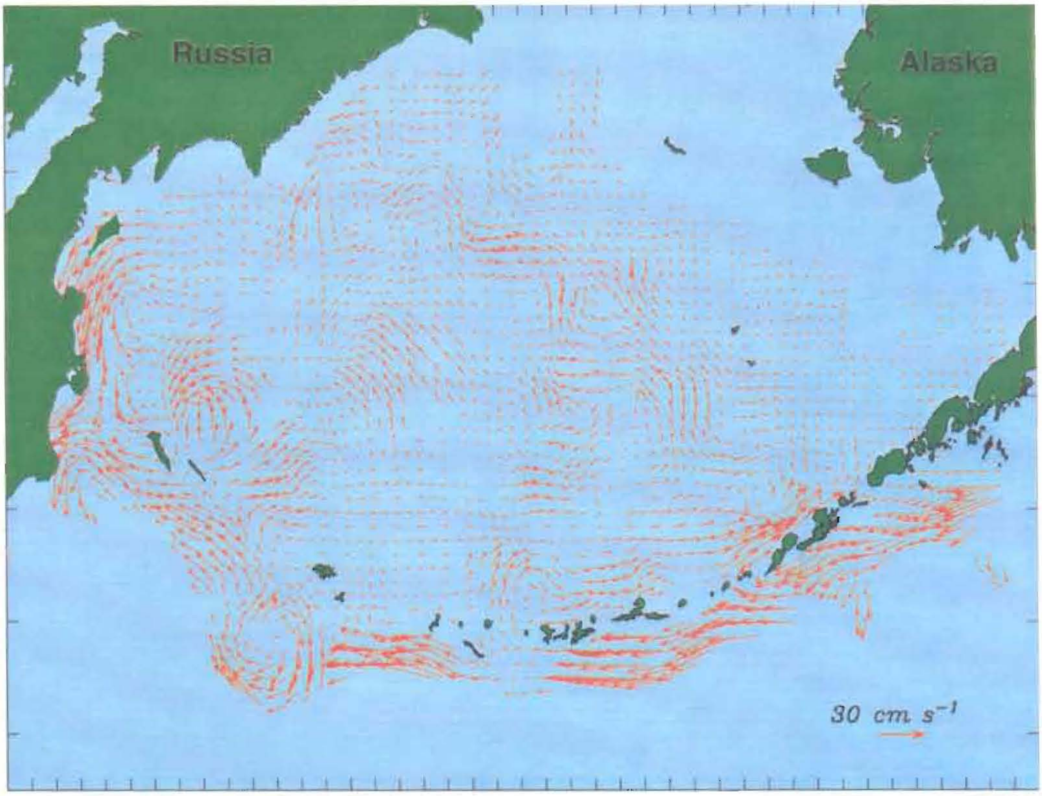
Understanding the southeastern Bering Sea is particularly important because it is the most productive marine ecosystem in the U.S. and one of the most productive in the world. In both the Bering Sea and Gulf of Alaska regions, research concentrates on long-term environmental variability and decadal shifts that influence the ecosystem, as well as physical and biological processes that support the first few months of pollock life. It is during this brief period that most mortality occurs. In the Bering Sea, pollock spawn over a vaster area and longer interval than in Shelikof Strait, where spawning is confined to a small location at the southwestern end of the Strait and a few weeks during March. Another significant difference between the Bering and Gulf systems is the presence of sea ice over the southeastern Bering Sea shelf. The extent and duration of sea ice, for example, are controlling factors in the annual spring bloom that feeds the zooplankton that are prey for pollock larvae.

Bering Sea

In the Bering Sea, FOCI has refined our understanding of Bering Sea circulation, documented the stock structure of walleye pollock, determined the biophysical processes leading to the survival of young pollock, monitored interannual ecosystem variability (including near-shelf-wide blooms of coccolithophores during the last four summers), and demonstrated that seasonal pack ice directly affects the primary productivity of the shelf. From these and other findings, FOCI is developing a predictive ability for Bering Sea pollock.

General Circulation

The general circulation over the deep basin is characterized by a cyclonic gyre. There are three well-defined, distinct currents: the Kamchatka Current along the western boundary; the Bering Slope Current (BSC) along the eastern boundary; and the Aleutian North Slope Current (ANSC) connecting inflow from the Alaskan Stream through Amukta Pass and Amchitka Pass with the BSC. Transport within the gyre can vary by more than 50%. Modeling studies have simulated such large



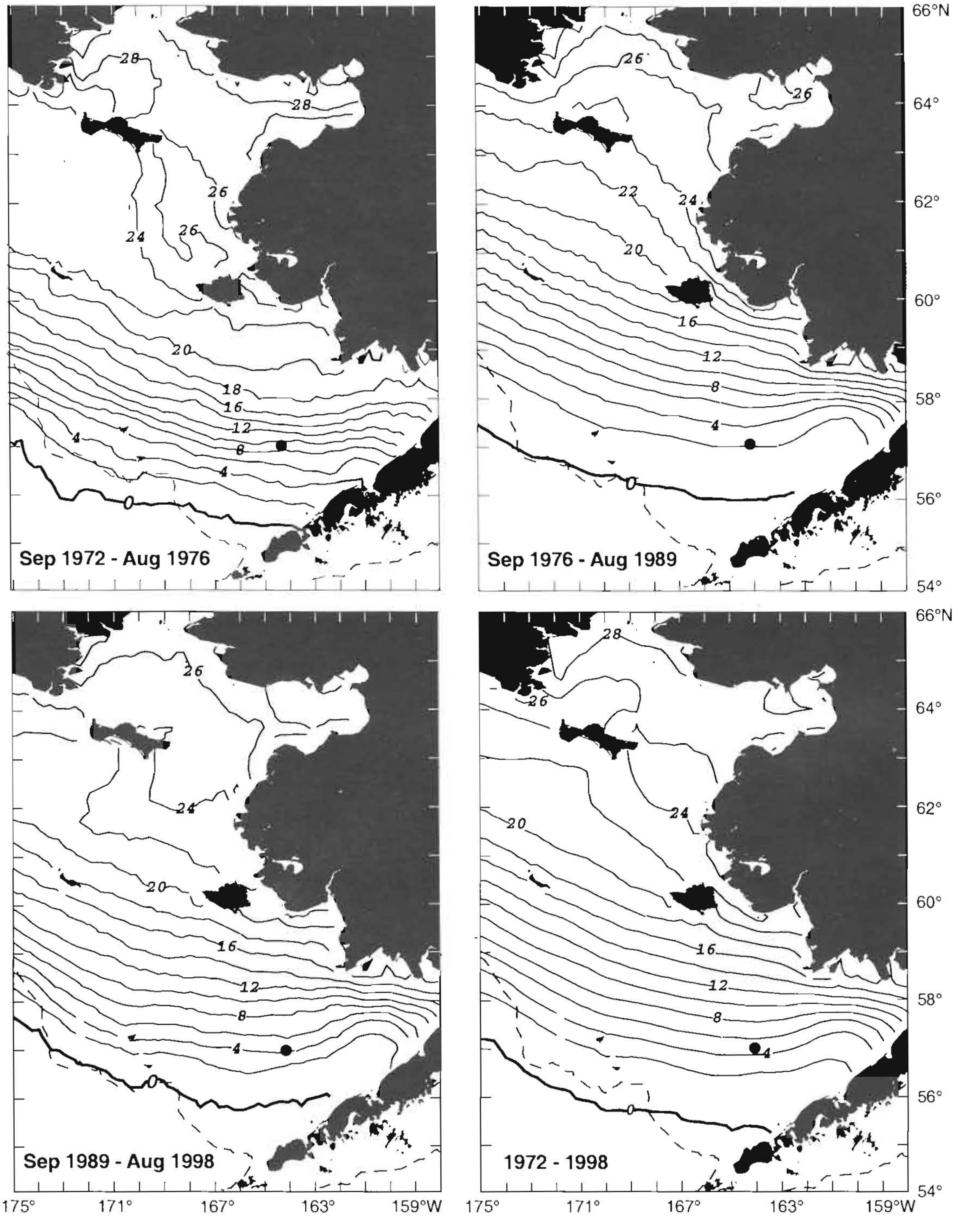
Current velocities at 40 m deep derived from satellite-tracked drifters, showing the dominant currents of the Bering Sea basin.

changes in transport and identified the causes to be fluctuations of the Alaskan Stream inflow and/or changes in the wind-driven transport within the basin. Circulation in the Bering Sea basin may be more aptly described as a continuation of the North Pacific subarctic gyre. Circulation on the eastern Bering Sea shelf is generally northwestward. The net northward transport through the Bering Strait, while important to the Arctic Ocean, has virtually no effect on the circulation in the Bering Sea basin. It does, however, play the dominant role in determining the circulation on the northern shelf. The currents of the Bering Sea have been examined principally through inferred baroclinic flow and to a lesser extent by satellite-tracked drift buoys, current meter moorings, and models. Satellite-tracked buoys led to the discovery and characterization of the ANSC by PMEL's FOCI scientists. It is best documented between 174°W and 167°W by hydrographic surveys, satellite-tracked drifting buoys, and more recently, current meter records.

The general northwestward circulation over the eastern shelf is important to the distribution of eastern Bering Sea pollock. Most spawning occurs in the southeastern sector near the continental slope and on the shelf. Larvae are slowly transported northwestward, and most juveniles are found on the northern shelf, many in Russian waters. Despite the transport of pollock to other areas of the Bering Sea, they appear to return to their birth areas to spawn. Genetic analysis of pollock has shown that the stocks on the east and west sides of the Bering Sea are discrete. Although the basin is rich in nutrients, it has relatively poor supplies of the zooplankton on which larval pollock prey, compared to the shelf. It is not likely that there is a spawning stock of pollock indigenous to the basin.

Eddies

As elsewhere in the world's oceans, eddies are ubiquitous in the Bering Sea. They occur on horizontal scales ranging from approximately 10 to 200 km. Proposed mechanisms for the creation of these eddies include instabilities, wind forcing, strong flows through the eastern passes, and topographic interactions. Every year, eddies form in the southeastern corner of the Bering Sea basin and northward along the shelf break. These eddies coincide with an area known as the Green Belt, a

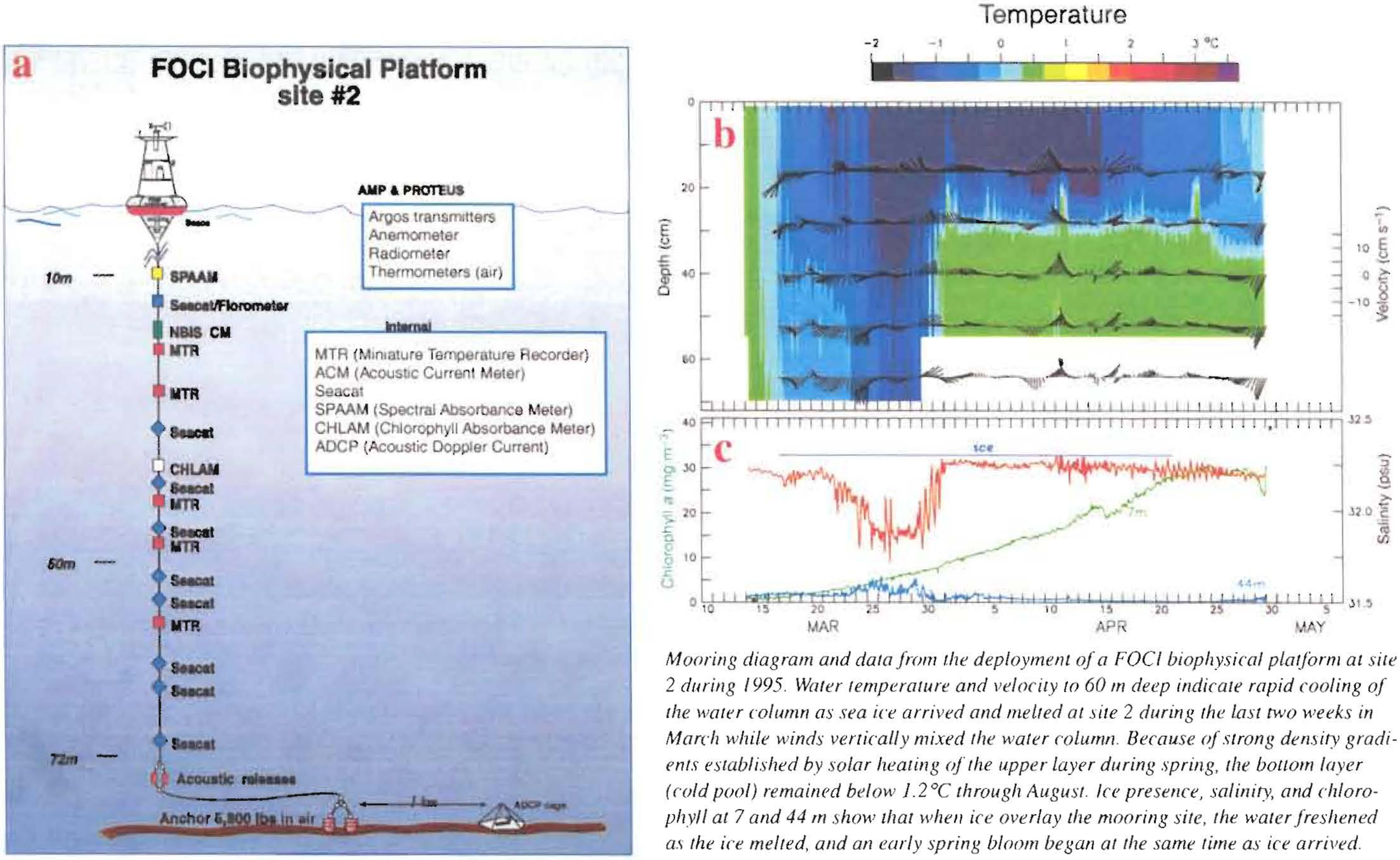


Average maximum sea ice extent and duration in weeks for cold (1972–1976), warm (1976–1989), and weaker cold (1989–1998) regimes and the entire 1972–1998 record. Site 2 is marked by a dot in each panel; the shelf break is indicated by a dashed line.

region of high productivity and biological diversity. Evidence supports the hypothesis that eddies play an important role in prolonging production, and they are important contributors to the transport of nutrient-rich basin water to the shelf. In more than one instance, eddies detected by satellite-tracked drifters have coincided with above-average abundance patches of pollock larvae.

Sea Ice

A defining characteristic of the eastern Bering Sea shelf is the annual advance and retreat of sea ice. Beginning in November, ice is formed along

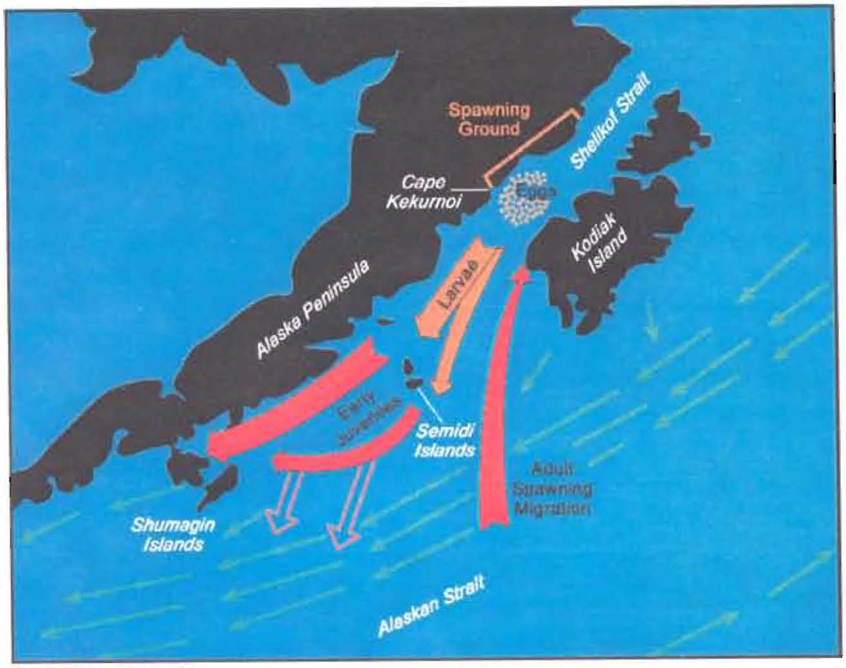


Mooring diagram and data from the deployment of a FOCI biophysical platform at site 2 during 1995. Water temperature and velocity to 60 m deep indicate rapid cooling of the water column as sea ice arrived and melted at site 2 during the last two weeks in March while winds vertically mixed the water column. Because of strong density gradients established by solar heating of the upper layer during spring, the bottom layer (cold pool) remained below 1.2°C through August. Ice presence, salinity, and chlorophyll at 7 and 44 m show that when ice overlay the mooring site, the water freshened as the ice melted, and an early spring bloom began at the same time as ice arrived.

the leeward sides of islands and coasts. It is advected southward, freshening and cooling the water column as it melts at its leading edge. The maximum ice extent typically occurs in late March, and ice can remain over areas of the southeastern shelf into June. The extent and duration of ice cover vary with climatic regime shifts such as the Pacific Decadal Oscillation. For example, the period from 1972 through 1976 was cold, and ice often covered the shelf out to and over the upper continental slope, arriving in January and retreating in May. From 1977 to 1988—a warm period—ice did not extend as far seaward, and its residence time was typically 2–4 weeks less than during the cold period. Since 1989 there has been a return to a weaker cold period, and sea ice has been more extensive than in the warm period but not as extensive as in the early 1970s.

The extent and timing of sea ice cover over the eastern Bering Sea shelf dramatically affect the time and space characteristics of primary and secondary production and thus food for larval pollock. In years when ice is not present, the spring bloom typically occurs as late as May or even June. When ice is present over the southern shelf after mid-March, it induces an early spring bloom of phytoplankton. This early bloom strips the upper layer of nutrients, precluding a later spring bloom. Because zooplankton may not be present in sufficient abundance to graze the early bloom, most of it settles to the bottom, enriching the benthic community. Such was the case in 1997. An early, ice-associated spring bloom depleted the upper-layer nutrients, and a late May storm mixed nutrients from the lower layer to the upper layer, where they were rapidly depleted. The warmed, nutrient-depleted water was not the proper environment for typical Bering Sea shelf phytoplankton. Instead, a vast coccolithophore bloom occurred that summer and has recurred each summer since. Although sediment analysis suggests that coccolithophores may have occurred sometime in the past, the present blooms are unprecedented.

The maximum annual extent of sea ice also has other biological effects. For example, it determines the size of the cold pool of bottom water on the shelf. Because Bering Sea pollock are cannibalistic, with adults preying on juveniles, their distribution and survival are partly determined by



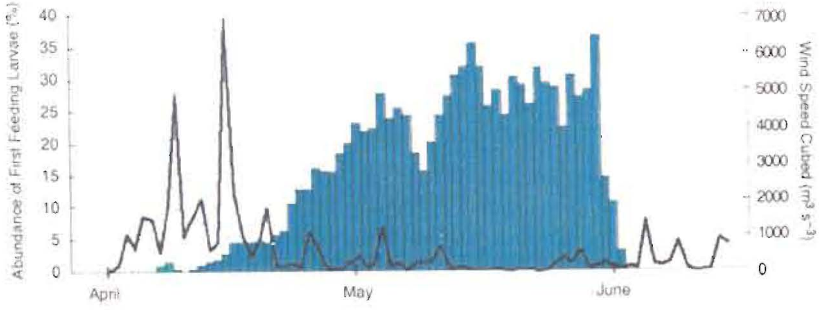
Locations where pollock spawn at the same time and place each spring in Shelikof Strait. After hatching, the larvae are advected by local currents. Some are lost to the Alaskan Stream; others remain on the continental shelf in nursery waters where they develop into juveniles.

the extent of the cold pool. When the cold pool is large, juvenile pollock are crowded to the outer portion of the shelf, where they are subject to predation by adults.

Gulf of Alaska

FOCI research in the Gulf of Alaska began in 1984 and is focused on the early life history of walleye pollock in Shelikof Strait. Adult fish return to spawn in the coastal water and Alaska Coastal Current (ACC) at the southwest end of Shelikof Strait during March and April each year, with each female producing about one-half million eggs. The dense, localized spawning pattern creates large patches of eggs that develop over about a two-week period near the bottom. Larvae hatch and rise into the mixed layer, where they drift southwestward with the ACC. Physically mediated variations in production, standing stock, and distribution of plankton have a significant impact on the growth and survival of the larvae. Some larvae are carried offshore through the Shelikof Strait sea valley, where they are swept away by the fast-moving, nutrient-poor Alaskan Stream. Others remain on the continental shelf in nursery waters that are more suited to their survival. By summer the pollock have developed into free-swimming juveniles and are no longer at the mercy of currents. After this period we know little about their life history until they enter the fishery (recruitment) and become sexually mature at age 2.

Abundance of first-feeding pollock larvae (blue bars) and wind speed (black line) in 1988. The larvae that survived to be sampled were most abundant during periods of relatively calm winds.



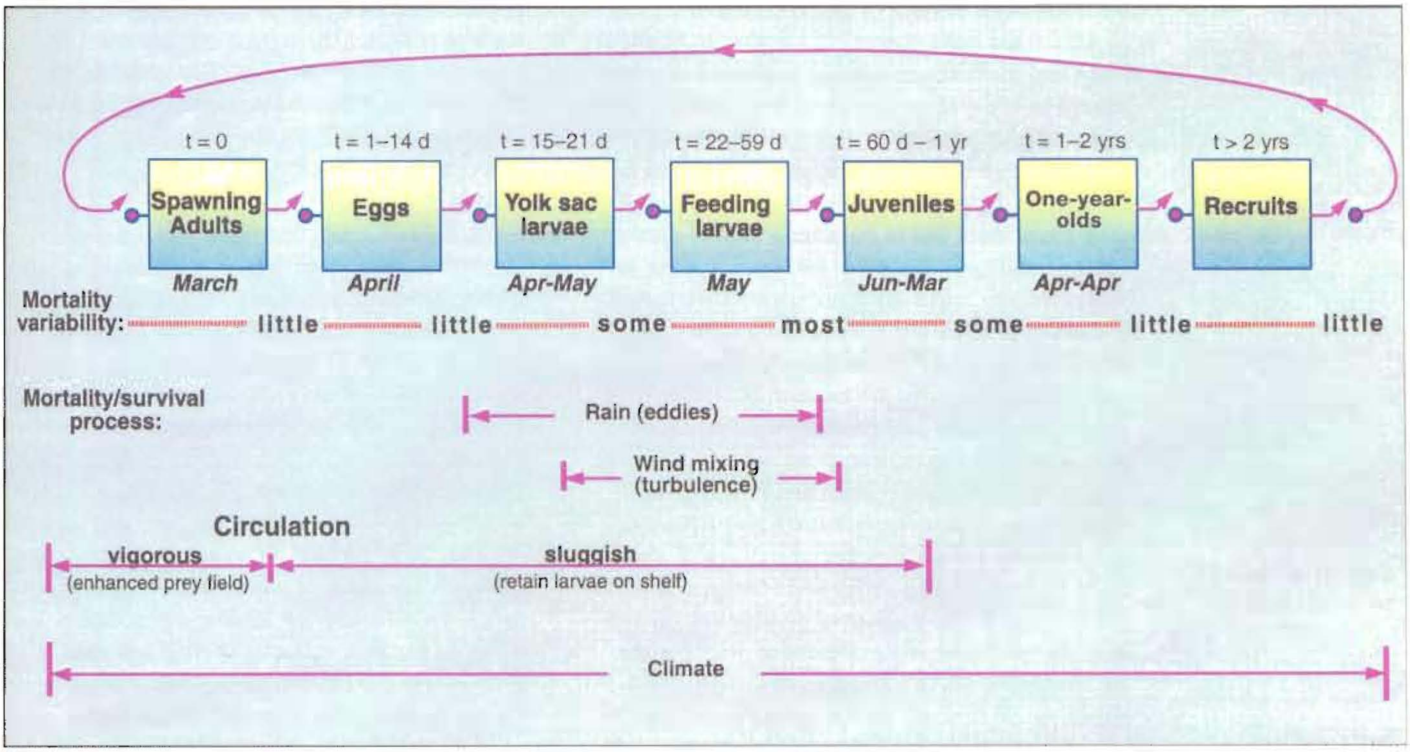
The physical environment in which pollock live varies on many scales. Decadal climate changes such as the "regime shift" that occurred in the late 1970s have profound effects on abundance. On a smaller scale, larval survival may be enhanced by incorporation into eddies with lifetimes of days to weeks. Finally, larval survival may be determined by a single storm.

FOCI forecasts Shelikof Strait pollock recruitment from relationships of fish survival to phenomena of various scales: baroclinity, transport, wind mixing, and climate forcing. In FOCI's conceptual model of recruitment, all environmental conditions must be favorable for a pollock to advance from one life stage to the next. Processes identified with pollock survival are ocean climate, circulation, wind mixing, and eddy potential. Although FOCI scientists understand conceptually how these environmental conditions affect survival, research remains to be completed to understand what mechanisms actually come into play and how they operate. Using time series associated with the processes identified in the conceptual model, FOCI has forecast recruitment of Shelikof Strait pollock since 1992.

FOCI has developed a biophysical model of the Shelikof Strait system. The model merges three components: a three-dimensional hydrodynamic model to determine ocean circulation, a spatially explicit nutrient–phytoplankton–zooplankton model to determine the prey field for pollock larvae, and a spatially explicit, individual-based model of pollock through the late larval stage of development. FOCI is generating an archive of model runs for each year back to 1976.

Future Directions

While our knowledge of the ecology of the Bering Sea and Gulf of Alaska has expanded greatly



FOCI's conceptual model of the processes that affect survival of Shelikof Strait pollock from one life stage to the next.

over the past few decades, many phenomena are not understood, primarily because observations are limited or nonexistent. Processes on a variety of scales—from climate to microstructure—must be investigated to supply answers to questions about these ecosystems. Some are more easily addressed than others, but in all cases there is the need to monitor critical ecosystem factors at appropriate periods and locations. That a vast percentage of the Bering Sea lies within the domains of two nations has not facilitated research programs that could provide the needed observations. Further, while the eastern continental shelf continues to have ongoing research programs, and interest in the role of physical processes over the western shelf is growing, the deep basin remains largely unexamined.

While it is recognized that flow through the Aleutian passes is a primary source of circulation within the basin, many questions remain regarding the current systems of the Bering Sea. Particularly needed is information on spatial and temporal variability in the Kamchatka, BSC, and ANSC. Dynamic processes within these currents provide nutrients to the euphotic zone and are responsible for the region of prolonged biological production known as the Green Belt. While the processes are unknown, the results of their interactions are evident. The continental shelf of the Bering Sea exhibits extremely high productivity, and this richness applies throughout the food chain. Not only are there vast quantities of commercially valuable species, but the eastern shelf is the summer feeding ground for numerous marine bird and marine mammal populations of the North Pacific Ocean. The eastern Bering Sea provides an ideal location to examine exchange mechanisms between slope water of an eastern boundary current and a continental shelf. Because the coast and its inherent topographic and coastal convergence processes are far removed from the slope, the processes involved in shelf/slope exchange should provide a clear signal. The continental shelf of the western Bering Sea is bounded by a typical western boundary current, so studies of contrasts of processes between the eastern and western shelves should be fruitful.

In the Gulf of Alaska, too, questions remain to be answered. Fundamentally, why is the northwestern shelf so productive? The basis for this production is enigmatic, given that downwelling winds prevail throughout most of the year and that the shelf receives a massive coastal influx of nutrient-poor fresh water. The ACC is a crucial habitat for young-of-the-year pollock and other species. Physical processes within the ACC could enhance the aggregation of zooplankton and therefore be critical to recruitment success. What are the upstream physical and biological conditions that precondition Shelikof Strait as an adequate feeding environ-

To learn more about the ecosystem and fisheries oceanography research that PMEL conducts in the Arctic, visit the following Web sites: the Fisheries-Oceanography Coordinated Investigations home page (http://www.pmel.noaa.gov/foci/) and the Southeast Bering Sea Carrying Capacity home page (http://www.pmel.noaa.gov/sebscc/).

ment for larval pollock? FOCI research in the Gulf of Alaska has been generally restricted to Shelikof Strait and its exit region to the southwest. Because advection is the most important feature of the circulation, what happens upstream is important. What are the mechanisms that cause mortality to first-feeding pollock larvae during high wind conditions? Dilution or dispersal of prey, reduction of prey production, and larval behavior (reduced feeding success, avoiding upper-layer turbulence) are factors that could be involved. Eddies seem to be conducive to enhanced larval condition and survival, but again the mechanisms are unclear. Is greater prey production, diminished predator abundance, or increased retention in near-shore waters involved?

Our knowledge of climate and how it affects marine ecosystem dynamics must also advance. In the last decade we have become aware of regime shifts that are North-Pacific-wide changes in multidecadal, quasi-stable states of climate and ecosystems. What causes these alterations and how are the changes in climate transferred through the biological environment? Future studies that focus on how the extant physical phenomena affect marine populations offer the best opportunity to enhance our understanding of ecosystem dynamics. This, in turn, could lead to management strategies aimed at sustainable production to ensure a rich ecosystem for our future generations. The observational database is not adequate in spatial and temporal coverage to answer most of the questions noted above. In addition to further observations, modeling efforts need to be improved, especially for the Bering Sea. A primitive equation basin-shelf model that couples both outflow through Bering Strait and exchange in the North Pacific Ocean is a likely starting place. Once the model provides accurate simulations of the physical features, then biophysical processes and rates can be incorporated. Some of the questions that must be addressed to understand the ecosystem are best investigated by modeling efforts.

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