
NOAA Coastal Ocean Program



Final Report of Phase I Research
August 1996 – September 1998

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(Editor)



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July 1, 1999

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Contribution S370 from Fisheries-Oceanography Coordinated Investigations

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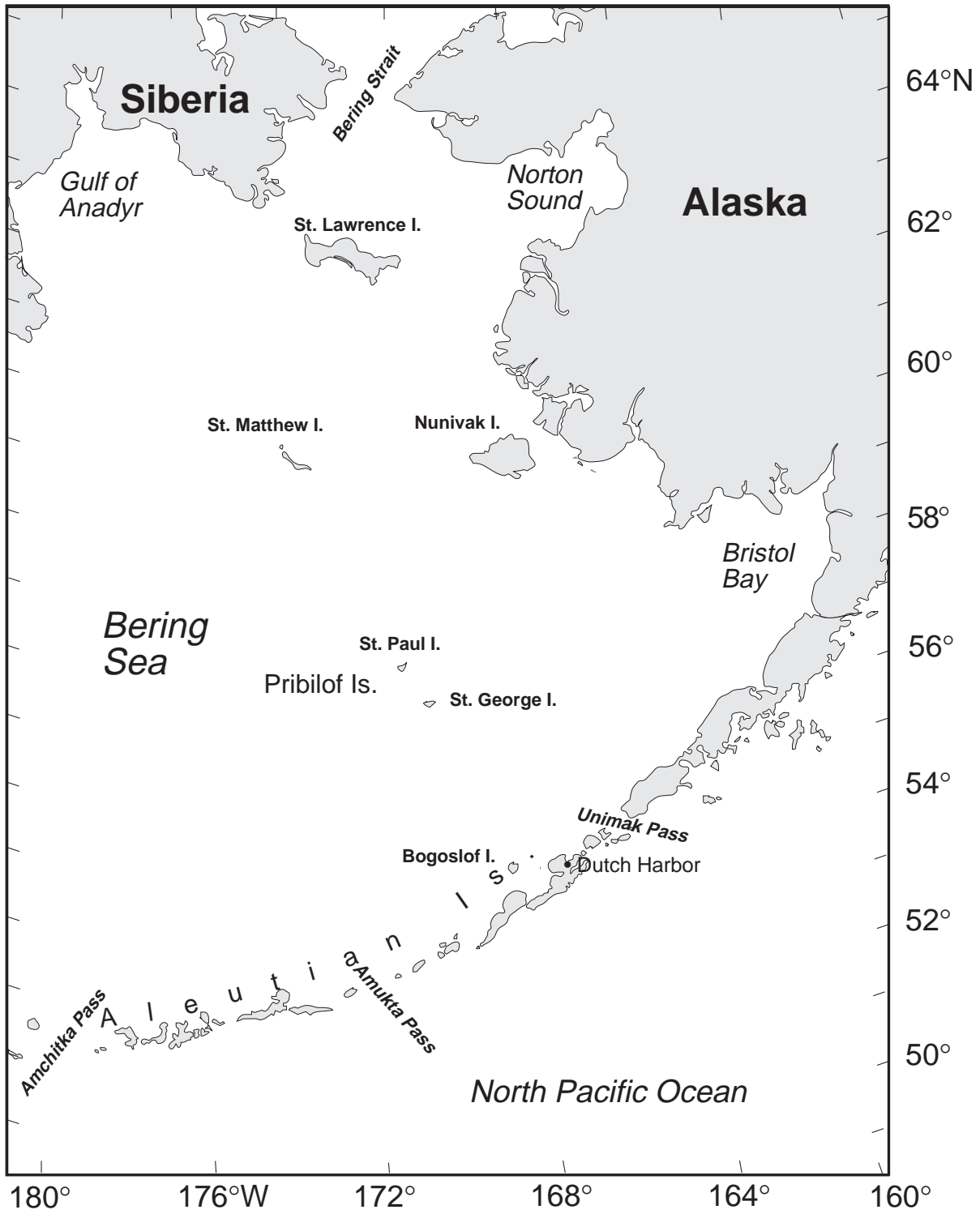


Figure 1.0.1 The eastern Bering Sea.

1.0 INTRODUCTION

Southeast Bering Sea Carrying Capacity (SEBSCC) is a regional ecosystem study funded by the Coastal Ocean Program (COP) of the National Oceanic and Atmospheric Administration (NOAA). At the time that SEBSCC came into existence, a prior COP project, Bering Sea Fisheries-Oceanography Coordinated Investigations (BS FOCI), was in its sixth year of studying stock structure and recruitment dynamics of walleye pollock in the Bering Sea. SEBSCC began operations in the final quarter of Fiscal Year (FY) 1996 with an abbreviated field season to allow continued monitoring of the southeastern Bering Sea while commencing modeling and retrospection efforts. Process-oriented studies were started in FY 1997. The first phase of research ended September 30, 1998. The second phase is now underway and will be followed in October 2000 by a final synthesis phase.

The Bering Sea (Fig. 1.0.1) is among the most productive of high-latitude seas, and as such produces a large biomass of fishes, birds and mammals. This productivity is important to the U.S. economy. Fish and shellfish constitute almost 5% of the world and 40% of the U.S. fisheries harvest. Pollock, salmon, halibut, and crab generate over 2 billion dollars each year in fisheries revenue and provide a major source of protein. At present, some Bering Sea fisheries, such as pollock, appear not to be overexploited, although there have been major changes in abundance over the last thirty years. Populations of several species, such as king crab and Greenland turbot, however, are at near historical lows. We do not fully understand the present state of the ecosystem. Pollock, however, plays a singularly important role, and its population historically has varied over a wide range.

The relative importance of natural cycles and exploitation in explaining variability in abundance is a key management issue for the Bering Sea. In addition to perturbations created by human activities, environmental factors are seldom stable and are subject to large-scale fluctuations, at times of a regular nature. It is clear that production of new organic matter, which provides the basis for exploitable fish populations and all other higher trophic level animals, is greatly affected by environmental factors. Questions remain, however, concerning the ecosystem dynamics of the vast Bering Sea shelf that supports this high productivity.

In the early 1980s, Processes and Resources of the Bering Sea Shelf (PROBES) defined specific hydrographic regimes for southeastern Bering Sea (Fig.1.0.2): the coastal or inner shelf domain, the middle shelf domain, the outer shelf domain, the continental slope, and the transitional areas (fronts) between them. Each of these domains is also a different marine habitat. SEBSCC research is focused on the middle shelf, outer shelf, and slope domains. By cooperating with other agencies, groups, and investigators with broad ecological interest in the southeastern Bering Sea, SEBSCC shares knowledge pertaining to the areas of the shelf that it studies and obtains information relating to other areas. In particular, the National Science Foundation project "Prolonged Production and Trophic Transfer to Predators: Processes at the Inner Front of the Southeastern Bering Sea" (Inner Front Project) complements SEBSCC research by examining the inner shelf domain and the front separating it from the middle shelf domain.

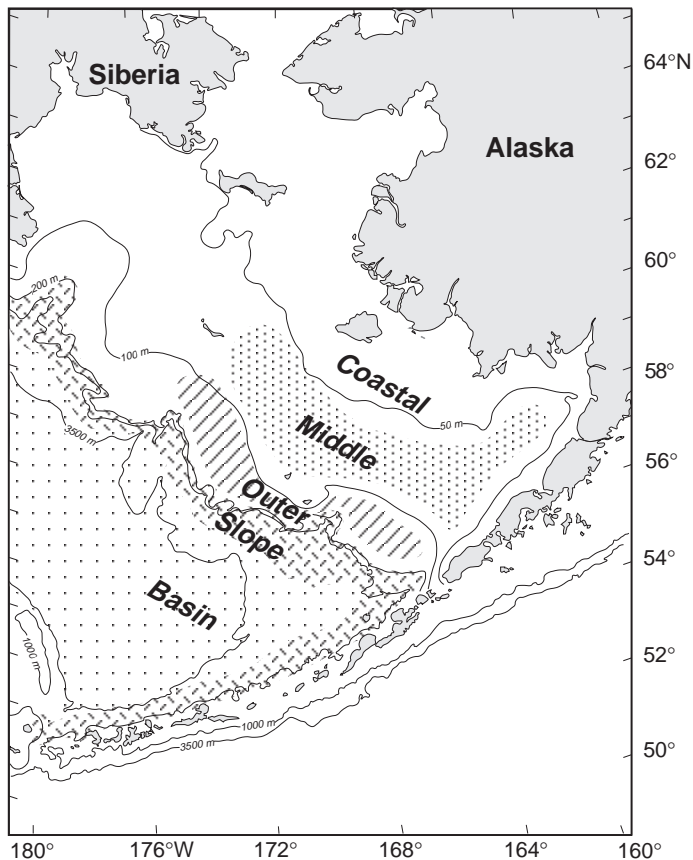


Figure 1.0.2 The eastern Bering Sea is divided into unique hydrographic and habitat domains with transition areas (fronts) between them. Depths are shown in meters.

SEBSCC is divided into monitoring, process, modeling, and retrospective and synthesis components focused on four central scientific issues:

1. How does climate variability influence the Bering Sea ecosystem? Is there historical evidence for a biophysical regime shift on the Bering Sea shelf? How is this reflected in ecological relationships and species mix? Are there "top-down" ecosystem effects associated with climate variations as well as "bottom-up" effects?
2. What limits population growth on the Bering Sea shelf? Is there evidence of a single species carrying capacity, e.g., for pollock, or a more complex structure? How are pollock, forage fish, and apex species linked through energetics and life history? How important is cannibalism in the dynamics of pollock?
3. How do oceanographic conditions on the shelf influence biological distributions? How do the separate hydrographic domains, sea ice, and the cold pool influence the overlap or separation between predators and prey?
4. What influences primary and secondary production regimes? What are the sources of nutrients to the southeastern Bering Sea shelf, and what processes affect their availability? Is the variability in sea ice extent and timing the primary factor influencing productivity? What determines the relative allocation of organic carbon going to the benthos versus that remaining in the pelagic system? What are the lower trophic level structure and energetics on the shelf in summer and winter, especially regarding euphausiids? What is the role of gelatinous organisms?

These broad issues support SEBSCC's narrower goal of understanding the ecosystem in terms of pollock and provide a basis for selection of proposed research. Funded research also needs to provide information that supports industry and management of the region. For example, results from SEBSCC research related to short-term forecast of pollock recruitment will improve stock assessments used to recommend "allowable biological catch" estimates to the North Pacific Fishery Management Council. Research results pertaining to the availability of juvenile pollock to apex predators will assist Council decisions regarding restriction of fishing around marine mammal rookery areas. The project's focus on ecosystem response to changes in environmental conditions provides a context for resource management in a changing environment.

SEBSCC proposes that juvenile pollock are a nodal species in the ecosystem in utilizing the high primary and secondary productivity and providing food for the pelagic upper trophic level species, including adult pollock. By nodal, we imply that a large fraction of the system energy flow passes through this species population. SEBSCC focuses on pollock in terms of their linkages to other species in order to understand 1) interspecific overlaps in feeding habits through various stages of life history, including energy flow into the pollock population and outward flow via predation by other species; 2) synchronized increases or decreases in biomass at different trophic levels that may indicate the co-influence of factors; 3) changes in distribution and intensity of secondary productivity as one of the bases for change in year-class strength; and 4) pollock as a key to the large scale changes in productivity of the Bering Sea over the last three decades. As an abundant resource, pollock provides an important measure of the health of the ecosystem.

The next sections of this report discuss SEBSCC's goal, objectives, management, funding, field operations, and research results. Following these sections are individual principal investigator reports on research funded during phase I. The reports are arranged by scientific approach: modeling, monitoring, lower- and upper-trophic-level processes, and retrospective analysis.

1.1 Goal

The goal of SEBSCC is to better understand the southeastern Bering Sea ecosystem and the role of juvenile pollock in it, including the factors that affect their survival. From this study the project is developing and testing annual indices of pre-recruit (age-1) abundance.

1.2 Objectives

We planned an inclusive approach to implement SEBSCC that engaged agencies, groups, and investigators with broad ecological interest in the southeast Bering Sea. The World Wide Web facilitates exchange of project information, preliminary results and data. With the advice and experience of the Technical Advisory Committee, the Project Management Team assembled a core research team from proposals solicited from the University of Alaska, other universities and agencies, the Alaska Fisheries Science Center, and the Pacific Marine Environmental Laboratory.

1. Conduct a first-quality scientific project that supports a specific goal to provide critical knowledge needed for formulating policy and management of resources of the southeast Bering Sea ecosystem.
2. Build partnerships and encourage multidisciplinary cooperative efforts among research scientists within the academic community, NOAA, and other agencies interested in the SE Bering Sea.
3. Provide an open process in establishing research objectives and proposal selection to ensure quality and diversity.
4. Scientific pursuits use four approaches, retrospective analysis, observational analysis, process-oriented studies, and numerical modeling, to examine biophysical domains, juvenile pollock productivity, and relationships between them and the ecosystem of the southeastern Bering Sea.

1.3 Management

As described in the SEBSCC Home Page (<http://www.pmel.noaa.gov/sebscc/>), the project is managed by a partnership between NOAA and the University of Alaska Fairbanks, with an advisory panel of technical experts from science and industry offering programmatic guidance. Personnel are identified in Tables 1.3.1 and 1.3.2, respectively.

Table 1.3.1 Managers, coordinator, and Coastal Ocean Program representative

<p>Dr. Vera Alexander Dean, School of Fisheries and Ocean Sciences University of Alaska Fairbanks Fairbanks, AK 99775-7220 907-474-6824 907-474-7386 fax vera@ims.alaska.edu</p>	<p>Dr. Anne Hollowed NOAA/NMFS Alaska Fisheries Sci. Ctr. 7600 Sand Point Way NE Seattle, WA 98115-0070 206-526-4223 206-526-6723 hollowed@afsc.noaa.gov</p>	<p>Dr. James Overland NOAA/ERL Pacific Marine Env. Lab. 7600 Sand Point Way NE Seattle, WA 98115-0070 206-526-6795 206-526-6485 fax overland@pmel.noaa.gov</p>
<p><i>Coordinator</i> Mr. Allen Macklin NOAA/ERL Pacific Marine Env. Lab. 7600 Sand Point Way NE Seattle, WA 98115-0070 206-526-6798 206-526-6485 fax macklin@pmel.noaa.gov</p>	<p><i>COP Representative</i> Dr. Elizabeth Turner NOAA/NOS Coastal Ocean Program 1315 East-West Highway Silver Spring, MD 20910-3282 301-713-3338 301-713-4044 fax elizabeth.turner@noaa.gov</p>	

Table 1.3.2 Technical Advisory Committee

<p>Dr. Michael Dagg LUMCON 8124 Highway 56 Chauvin, LA 70344 504-851-2800 504-851-2874 fax mdagg@smtpgw.lumcon.edu</p>	<p>Dr. Eileen Hofmann Dept. of Oceanography Old Dominion University Norfolk, VA 23505 757-683-5334 757-683-5550 fax hofmann@ccpo.odu.edu</p>	<p>Dr. Al Tyler Institute of Marine Science University of Alaska - Fairbanks Fairbanks, AK 99775-7220 907-474-6732 907-474-7204 fax ffavt@aurora.alaska.edu</p>
<p>Mr. Bart Eaton Trident Seafoods Corporation 5303 Shilshole N.W. Seattle, WA 98107 206-783-3818 206-781-7883 fax cassieowens@tridentseafoods.com</p>	<p>Dr. Thomas Royer Dept. of Oceanography Old Dominion University Norfolk, VA 23505 757-683-5547 757-683-5550 fax royer@ccpo.odu.edu</p>	<p>Dr. Warren Wooster School of Marine Affairs Box 355685 University of Washington Seattle, WA 98195-5685 206-685-2497 206-543-1417 fax wooster@u.washington.edu</p>

SEBSCC holds annual meetings for managers, technical advisors, and researchers. These meetings have occurred in Nanaimo, British Columbia, Canada (1996), Seattle, Washington (1997), and Fairbanks, Alaska (1998). A planning workshop was held in Seattle in November 1995. At the workshop, invited Bering Sea experts provided a scientific overview of the status of the Bering Sea. Using this overview and information from the Concept Paper for SEBSCC (<http://www.pmel.noaa.gov/sebscc/concept/>, July 1995), project managers prepared the initial announcement of opportunity for research that was released in February 1996.

Research for SEBSCC is determined through an open, competitive process. The project's first research cycle was from August 1996 through September 1998, and included scientists from two NOAA laboratories and five universities. Funded research for the first research cycle is identified in Tables 1.3.3a-e. A Senior Investigators Council (SINCO, Table 1.3.4) was formed in May 1997 to provide scientific leadership, integration, and communication among principal investigators. SINCO has six members - one for each scientific approach and one member-at-large. SINCO meetings are held about every half year or as called by the SINCO chairperson.

Communication between project personnel occurs informally by telephone, e-mail, and face-to-face conversation, and formally through monthly meetings of FOCI principal investigators and annual SEBSCC meetings. The SEBSCC web site contains complete information for the project, including annual reports, cruise schedules, personnel lists, meeting announcements, and links to ancillary information pertaining to the Bering Sea. SEBSCC research recently was highlighted at the seventh annual meeting of the North Pacific Marine Science Organization (PICES) and at the FOCI International Workshop on Recent Conditions in the Bering Sea (http://www.pmel.noaa.gov/foci/bs_98workshop/).

Table 1.3.3a Funded modeling studies

• Individual-based modeling of walleye pollock in the Southeast Bering Sea

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Hermann, Al
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• A spatial model of upper-trophic level interactions in the eastern Bering Sea

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• Circulation modeling for the S.E. Bering Sea

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Table 1.3.3b Funded monitoring studies

- Monitoring and development of biophysical indices of the southeastern Bering Sea

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Napp, Jeff
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- An altimetric census of mesoscale eddy-like features in the Bering Sea

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Table 1.3.3c Funded research on lower-trophic-level processes

- Investigation of the origin and dynamics of nutrients on the southeast Bering Sea shelf in relation to dominant physical and biological processes

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- Isotopic and biomarker composition of sinking organic matter in the southeast Bering Sea: indicators of food web structure

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- Using optical measurements to explore the influence of mesoscale eddies on the interaction of lower and higher trophic levels in the southeast Bering Sea

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Table 1.3.3d Funded research on upper-trophic-level processes

• High-resolution acoustic and juvenile pollock retrospective data analysis

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• Habitat differences in frontal regions around the Pribilof Islands and their importance to juvenile pollock growth and survival in the Bering Sea

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Doyle, Miriam
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• Low-temperature incubation of walleye pollock eggs (*Theragra chalcogramma*) from the southeast Bering Sea region

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Table 1.3.3e Funded retrospective studies

- Natural scales of variability in coastal marine ecosystems of the eastern Bering Sea

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- Historical trends in the number of foraging trips made by lactating northern fur seals

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- The role of atmospheric forcing on the cold pool and ecosystem dynamics of the Bering Sea shelf: A retrospective study

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- A retrospective investigation into relationships between southeast Bering Sea pollock recruitment and biophysical correlates

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Table 1.3.4 Senior Investigators Council

Monitoring, Chairman	Jim Schumacher
Modeling	Al Hermann
Lower-Trophic-Level Processes	Susan Henrichs
Upper-Trophic-Level Processes.....	Ric Brodeur
At Large: Upper-Trophic-Level Processes, Retrospective Studies	George Hunt
Retrospective Studies	Bern Megrey

1.4 Funding

SEBSCC received \$2.5123M in funding from the Coastal Ocean Program for Phase I research. SEBSCC started with \$500K in the last quarter of FY 1996 to begin monitoring, modeling, and retrospective studies. For FY 1997, Coastal Ocean Program provided \$1,070.5M, and for FY 1998, \$941.8K. These funding levels do not include the cost of ship time for field studies. The distribution of funds for the scientific approaches that SEBSCC used during Phase I is shown in Figure 1.4.1. Administrative funds were used to host a workshop on the Bering Sea, convene two meetings of SEBSCC principal investigators, for project coordination and to establish and maintain presence on the worldwide web.

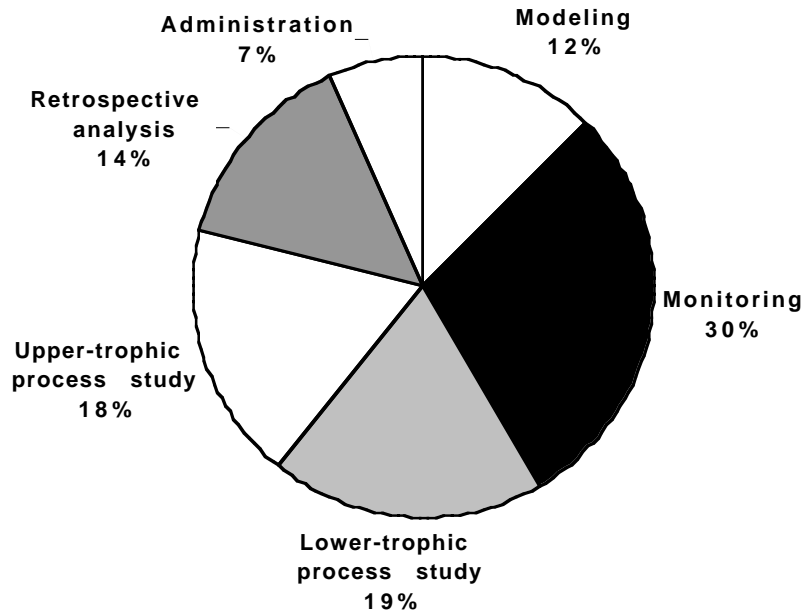


Figure 1.4.1 Distribution of SEBSCC Phase I funds by scientific approach and administrative activity.

1.5 Field operations

SEBSCC's field operations consist of broad-scale field surveys over the SE Bering Sea using ships, multi-disciplinary moorings, and drifting buoys. Cruises are conducted from late winter through fall using principally the NOAA Ship *Miller Freeman* and the University-National Oceanographic Laboratory System (UNOLS) Research Vessel *Wecoma*. Generally, cruises occur during February to deploy moorings and measure late winter conditions; April, to monitor the progress of the spring bloom; June, to measure post-bloom conditions; and September, to survey habitats of pollock near the Pribilof Islands and to recover moorings. SEBSCC has been fortunate to cooperate on July cruises to the southeastern Bering Sea shelf aboard the Japanese Fisheries Research and Training Vessel *Oshoru Maru*. An areal survey of the southeastern Bering Sea shelf for age-0 pollock is conducted during this cruise. In all, SEBSCC logged 262 sea days aboard 5 vessels during Phase I research. Figure 1.5.1 locates study areas, mooring sites and the cruise track for hydrographic, nutrient, phytoplankton, and zooplankton collections that are performed three or four times during the field year. Observations from mooring site 2 form the longest historical oceanographic time series in the southeastern Bering Sea, as the site has been occupied nearly continuously since it was first occupied in 1995 for BS FOCI.

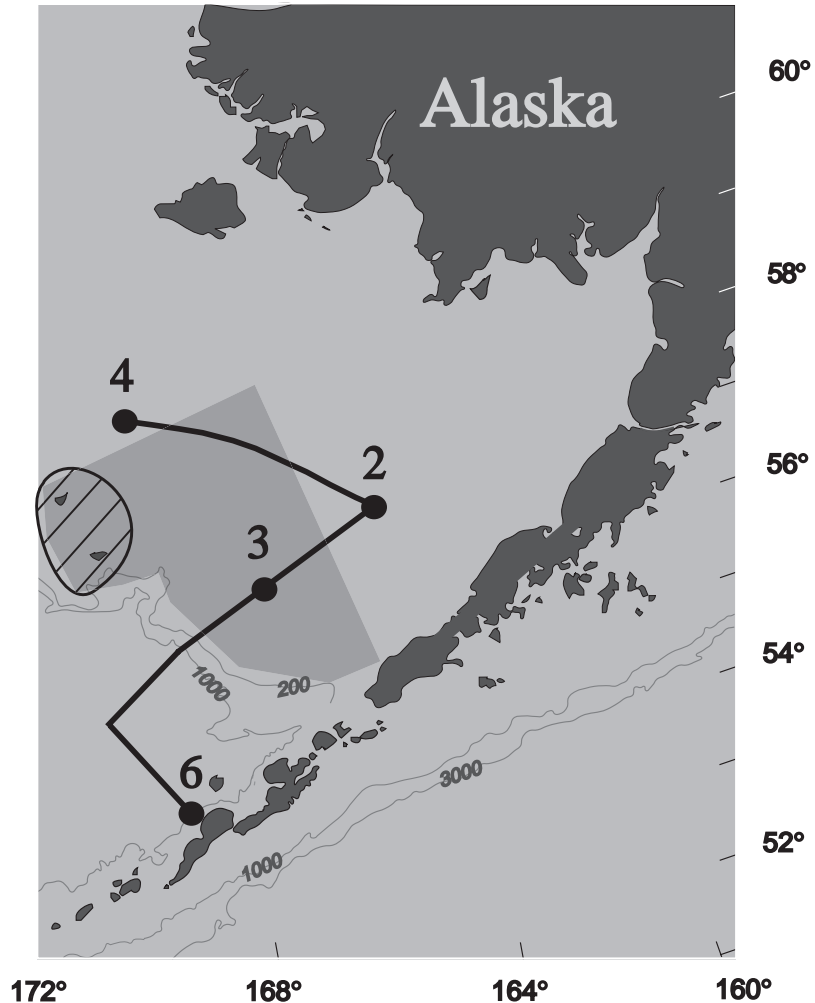


Figure 1.5.1 The SEBSCC study area includes mooring sites 2, 3, 4, and 6; hydrographic, chemical, and biological sampling transects between moorings; a juvenile pollock habitat (hatched area) around the Pribilof Islands; and a juvenile pollock survey area (shaded). Depths shown are in meters.

Observations from mooring site 2 form the longest historical oceanographic time series in the southeastern Bering Sea, as the site has been occupied nearly continuously since it was first occupied in 1995 for BS FOCI.

Measurements from the mooring include water temperature, salinity, chlorophyll absorbance and fluorescence, current speed and direction, and, during the ice-free part of the season, surface

atmospheric variables. Sedimenting particles have also been collected using traps moored near mooring 2. The Pribilof survey, also started by BS FOCI in 1994, occurs in the fall. The Pribilof region is a very informative site as all three shelf domains, with their respective stratification regimes, occur there. The hypothesis of this study is that unique physical and biological conditions associated with the frontal region between the coastal and middle shelf domains around the Pribilof Islands provide an exceptionally good nursery habitat for juvenile (age-0) pollock. In particular, occupation of Transect A, a survey line (Fig. 5.1.1) extending about 45 km north-northeastward from St. Paul Island, the northernmost of the Pribilofs, has been repeated annually since 1994. Hydrographic, chemical, and biological (juvenile pollock, their predators and prey) observations and samples are collected there.

1.6 Summary of research results

SEBSCC Phase I research has contributed to our understanding of the Bering Sea ecosystem. Details of this research are presented in sections 2 through 6 of this report. The following paragraphs provide an overview of how our knowledge has advanced.

The monitoring components have documented important changes in the southeastern Bering Sea ecosystem from 1996 through 1998. SEBSCC's results and results from the Inner Front Project permit interpretation of conditions over the slope and shelf. Extreme variability was observed in the climatology, physical oceanography and biology of the region. Particularly noteworthy were the ranges of ice extent; storminess; insolation; sea surface temperature; thermal stratification; timing of the spring bloom; changes in phytoplankton community; blooms of the coccolithophore *Emiliana huxleyi*; abundance of euphausiids; timing of euphausiid mating on the inner shelf; and distribution, mortality, and shifts in reproductive success of seabirds. Conditions experienced during 1997 and 1998 are indicative of the range affecting the southeastern Bering Sea.

In 1997, atmospheric conditions over the eastern Bering Sea were characterized by light winds, warm temperatures and clear skies during spring and summer. The atmosphere forced an oceanic response that, in turn, cascaded through the ecosystem, although the exact mechanisms are not well understood. An early spring diatom bloom was associated with sea ice. By the end of April 1997, chlorophyll concentrations had decreased to pre-bloom values, and nutrients were depleted in the upper layer. Winds generally were weak except during one strong storm in mid-May. The impact of this storm was to mix the upper 45-50 m, thereby making nutrients from the lower layer available in the upper water column. This redistribution of nutrients, accompanied by net phytoplankton production below the shallow mixed layer, reduced the reservoir of nutrients often found throughout the summer in the lower layer. These processes altered primary production from the normal bloom of diatoms to one of coccolithophores. The coccolithophore bloom dominated productivity, and a shortage of adult euphausiids at the inner front, compared to other years, is indicated in the mass mortality of seabirds during the summer of 1997.

By contrast, 1998 was very different in forcing, yet produced a similar coccolithophore bloom. As determined by field measurements during February 1998, the water over the shelf failed to mix to the bottom when sea ice was present. Incomplete mixing allowed retention of

some of the heat accumulated in the bottom layer during 1997. This and a stronger than average atmospheric heat flux in late winter and early spring contributed to the warming of the shelf in 1998. The seasonal ice pack arrived and retreated early, and spring temperatures in the southeastern Bering Sea were warmer than 1997. Also, there was much more storm activity than the previous year. The storms that followed retreat of the sea ice mixed stored heat from the bottom layer to the surface. Although high nitrate uptake was observed near the surface, wind mixing was so strong that it prevented a recognizable spring phytoplankton bloom. Anomalous conditions prevailed again during summer 1998 with a second year's coccolithophore bloom over the shelf from Bering Strait to the Pribilof Islands. Abnormal circulation was indicated by sampling of oceanic copepods, normally native to slope and outer shelf waters, in the coastal domain. During mid-August, shelf water was still warm, but by early September, storm winds had deepened the mixed layer, and the surface water was colder than at the same time during 1997. Seabird abundance was low; those sampled were under weight, and there were signs of reproductive failure in Pribilof Island colonies. Shelf waters were rich in nutrients, and zooplankton was in greater abundance, as opposed to 1997 when coccolithophores dominated. During mid-September the coccolithophore bloom was still prevalent.

Although these unusual conditions did not seem to have an immediate effect on the groundfish of the area, they may impact future abundance. NOAA fishery surveys in 1997 and 1998 located fewer young-of-the-year pollock than in previous years. Participants on the July 1998 *Oshoro Maru* cruise reported that the abundance of age-0 pollock seemed low relative to the previous four years. However, observations from the Inner Front Project during August 1998 suggest that young pollock, in fact, were quite abundant but located further onto the shelf than usual. This displacement could derive from wind-driven transport of pollock larvae northeastward from their spawning area during the stormy spring. Ramifications of these recent changes won't be known for several years until the young pollock mature into adult fish and are harvested.

SEBSCC's process studies have shed light on conditions leading to pollock hatching and the sequential blooms of phytoplankton and zooplankton that form the basis for the food web. Pollock egg development studies showed that Bering Sea eggs develop faster at low water temperatures than do Gulf of Alaska eggs, but Bering Sea eggs are found higher in the water column. Thus Bering Sea pollock eggs are more vulnerable to wind-driven advection but, because of their shorter development time, are less prone to predation. Sediment trap samples provided a history of lower-trophic conditions for pollock from April 1997 through February 1998. Spring samples were abundant in diatoms. By early summer, sediments were primarily from zooplankton. There was a secondary diatom bloom in mid to late summer that was recorded by the traps. However, coccolithophores did not appear in samples until late September. Then, the large numbers of coccoliths sampled by the traps suggests that there was little grazing of the vast coccolithophore summer bloom. By winter, the traps were collecting resuspended sediments from storm mixing or nothing at all. It is interesting that during the fall, sediment traps collected a quantity of organic matter that was comparable in magnitude to that collected during spring. Because only 1997 data are available, it is not clear whether the fall maximum was linked to the unusual coccolithophorid bloom, or whether fall conditions result in substantial sinking particulate material in more normal years as well.

At higher trophic levels, researchers developed and evaluated a method for distinguishing fish from plankton using multi-frequency acoustic data (38, 120 and 200 kHz). This has never been done before in a rigorous, quantitative fashion. Three years of Bering Sea survey data sets including acoustic, CTD (temperature-depth profiles), bird observations, surface temperature, salinity and fluorescence from the Pribilof Islands, when processed and combined, enabled analysis of spatial relationships between elements of the food web. For example, only at lower plankton densities is it necessary for fish to remain close to their prey while the two are separated in depth due to diel migration by plankton. When densities of plankton are high enough there is no advantage to maintain proximity because densities of plankton are probably sufficient throughout the region for fish feeding. Another SEBSCC component explored the hypothesis that the unique physical and biological conditions associated with the structural fronts around the Pribilof Islands provide an exceptionally good nursery habitat for age-0 pollock in the Bering Sea. Comparisons were made of the abundance, size composition, growth, and condition of juvenile pollock at these fronts, on either side of the front, and at a control station near the Middle Shelf Front on the Bering Sea shelf away from the islands. Year of spawning was not found to be an important factor in determining condition although the location with respect to the front was.

Retrospective studies determined that interannual variations in the wintertime atmospheric forcing are considerable. These variations are well correlated with the duration of sea ice, and in particular, the southernmost extent of sea ice. Interannual variations in the latter have correlation coefficients of 0.64 and 0.72 with the winter-average net surface heat fluxes and meridional wind stresses, respectively. Striking interannual variations have also been documented in the atmospheric forcing during the spring and summer. Interannual variations in sea surface temperature tendency during May through July are correlated about equally with the net surface heat fluxes (largely due to variations in low cloud cover) and a combination of wind mixing and Ekman pumping. The latter are important because of their impacts on the depth of the mixed layer. Based on the net heat fluxes at the surface, and the fraction of these fluxes that go towards heating the mixed layer, estimates have been made in the rate of heating below the pycnocline. The years with a persistent cold pool (e.g., the early 1970s, 1995) typically had about 30 W m⁻² less heating below the mixed layer than those without a cold pool. This result indicates the importance of dynamics of the mixed layer and pycnocline for establishing the stratification that can insulate the cold pool from summer heating.

A seasonal sea ice index begun for BS FOCI was updated through 1997 and 1998. Sea ice extended across the shelf beyond 57°30'N. The unusual occurrence of a coccolithophore bloom during 1997 led to further analysis of sea ice characteristics that may help us understand the physical conditions that exist during, and preceding, such an unusual bloom. We found that in spring, sea ice retreated 2.5 degrees of latitude within one week. Sea ice retreat of at least 2.5 degrees in one week has occurred 10 times in the previous 26 years, but never before coupled with the late timing of May 22. In 1998 we again observed a large coccolithophore bloom on the shelf, and again this spring we witnessed a rapid retreat of ice of 3 degrees latitude. However, the timing was earlier, falling within the average time of mid-April. Perhaps the previous year's bloom influenced the dominance of coccolithophores on the shelf.

SEBSCC Phase I developed three models. One is an eddy-resolving circulation model of the southeastern Bering Sea. This model is intended for use as input to a suite of biological models focusing on walleye pollock and higher trophic levels. It is implemented as a free-surface, primitive equation, eddy-resolving model at 4-kilometer resolution with both tidal and subtidal forcing. Presently, the model reproduces the observed tidal residual circulation around the Pribilof Islands, while replicating the Aleutian North Slope Current, the Bering Slope Current, and the shallow inflow through Unimak Pass. SEBSCC's spatial model of upper-trophic level interactions has completely parameterized a multispecies virtual population analysis (MSVPA) model. It characterizes the predation interactions between major groundfish populations and one marine mammal predator, northern fur seal, in the eastern Bering Sea for the time period 1979-1995. This model will provide starting values of juvenile walleye pollock abundance and estimates of prey suitability for the full spatial model. An individual-based model of the early life stages of walleye pollock, originally developed for the western Gulf of Alaska pollock stock, has been reconfigured and expanded to describe processes affecting young Southeast Bering Sea pollock. The model describes processes affecting each life stage (egg, yolk-sac larval, feeding larval and age-0 juvenile) such as development, feeding, bioenergetics and growth. Many attributes of individuals are tracked, such as age, size, weight and location. When they are known, the mechanisms of physical forcing, e.g., temperature or salinity, of biological processes are included.

The project has begun to synthesize information. One hypothesis thus far reasonably well supported is that oceanographic conditions are controlled by climate/weather fluctuations. During winters with a strong and eastward displaced Aleutian low (most often accompanying an El Niño), the Bering Sea shelf is warm and the cold pool is small. During winters with a weak and westward-displaced Aleutian low (most often accompanying La Niña), the Bering Sea shelf is cool and the cold pool is large. However, a climate-driven physical regime shift occurred on the Bering Sea shelf in the mid to late 1970s. Since the regime shift, El Niño-driven Aleutian lows have moved so far to the east that winds actually come off Alaska and cause the Bering Sea ice to advance as in 1998. The regime shift in the physical environment was largely responsible for the changes in fish populations on the Bering Sea shelf that occurred in the mid-late 1970s. The physical conditions occurring after the regime shift have persisted to some extent, but the biological response was short lived. Only one pollock year class was strongly affected, but that year class supported the pollock fishery for years.

A second, but less tested, hypothesis is that oceanographic conditions, particularly temperatures, limit the growth of some populations. In cold years with an extensive cold pool, pollock are forced off the shelf on to the outer shelf. Pollock recruitment is reduced because of lower egg hatch, and concentration of adult pollock result in increased cannibalism. In warm years with a small cold pool, pollock recruitment is enhanced because of higher egg hatch, and the dispersal of pollock results in decreased cannibalism. Within a year or so, the population catches up so that cannibalism balances egg hatch. This may have been the mechanism that caused the pollock fluctuations over the regime shift.

One hypothesis has been refuted. Because lactating northern fur seals prey primarily on pollock, it was thought that an indication of foraging success as determined from fur seal teeth

would correlate with observed pollock abundance. SEBSCC research does not show a strong, direct link.

SEBSCC researchers have identified several more features of the ecosystem that are candidate indices of status of the Bering Sea (see also section 3.1). Among these are:

1. extent of ice and its influence on the timing of the phytoplankton bloom and hence the succession of bottom-up mechanisms that must match in time and space the needs of first feeding pollock larvae,
2. wind which influences the ecosystem through mixing (mixed layer depth was markedly shallow in summer 1997) and by advection as direct wind-driven flow. The latter may increase the separation between early life history stages and their cannibalistic parents, since recent evidence suggests that many larvae over the shelf may be in water depths less than 10 m. The timing of storms also play a role in the intensity of stratification over the middle shelf and the depletion of nutrients in the cold pool.
3. concentration of nutrients retained in the bottom layer of the middle shelf (essential for prolonged production at the inner front),
4. species composition of phytoplankton (e.g., rare coccolithophorid blooms),
5. location, strength and stability (eddies) of the Aleutian North Slope Current and Bering Slope Current system that affects advection of nutrients and pollock larvae onto the shelf, and
6. increased presence of previously low abundance biota (e.g., jellyfish and coccolithophores).

SEBSCC has extended the knowledge base of the southeastern Bering Sea at a critical moment. More and more attention is focused on the Bering Sea. Just a few years ago, as other fisheries of the United States were suffering serious declines, the eastern Bering Sea fishery was considered stable. In the past two years there have been indications that this may not be the case. Commercial salmon failures, curtailment of fishing areas and times because of declining marine mammal populations, massive deaths of seabirds, and indications that a major shift in Bering Sea climate may be occurring, all suggest that the Bering Sea ecosystem is changing in a significant way. It is clear that we must understand this change in order to manage responsibly the bountiful resources that this region provides. SEBSCC contributes measurements and results that are vital to a more complete understanding of the Bering Sea ecosystem.

1.7 SEBSCC Publication List

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2.0 MODELING

2.1 Individual-based modeling of walleye pollock in the Southeast Bering Sea

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Period of Research: August 1996 - September 1998

Goal and Objectives

The goal of this study has been to configure an individual-based model (IBM) of walleye pollock (*Theragra chalcogramma*) early life stages, developed for the Gulf of Alaska (Hinckley et al. 1999), to the southeastern Bering Sea. This model will be used, along with a 3-dimensional hydrodynamic model and an upper trophic level model, to examine questions and hypotheses related to walleye pollock population dynamics, stock mixing, larval and juvenile transport and ecology, and the role of pollock in the ecosystem. The model synthesizes information on young walleye pollock from the literature, from the Gulf of Alaska FOCI project, from the Bering Sea FOCI project and from other studies in SEBSCC.

Project Description

Modeling is an integral part of ecosystems studies. Complex systems such as the Southeast Bering Sea ecosystem are not generally amenable to experimentation. Numerical biophysical simulation models allow us to integrate our knowledge of a system, and to examine our hypotheses about its structure and functioning. Ecologists have increasingly used models that deal specifically with individuals to examine hypotheses. This is particularly appropriate when processes of interest occur to individuals locally due to incomplete population mixing, as is true of young pollock in the Bering Sea. Therefore, the inclusion of spatial factors also can be critical in these studies. Individual-based models, coupled with three-dimensional circulation models, have the capability of examining processes affecting individuals over time and space.

This modeling effort, in conjunction with the physical modeling of Hermann et al. (Section 2.3 of this report), focuses on the growth and transport processes affecting young pollock during their first year, with the goal of gaining insight into mechanisms leading to variability in year-class strength. The biological part of this work uses a probabilistic and mechanistic individual-based model, developed for pollock, that tracks fish separately through space and time.

Results

An individual-based model of the early life stages of walleye pollock, originally developed for the western Gulf of Alaska pollock stock, has been reconfigured and expanded to describe processes affecting young Southeast Bering Sea pollock. This model follows individual fish from spawning until the fall of their age-0 year. The basic structure of the model has been

described in Hinckley et al. (1996) and Hinckley (1999). The model describes processes affecting each life stage (egg, yolk-sac larval, feeding larval and age-0 juvenile) such as development, feeding, bioenergetics and growth. Many attributes of individuals are tracked, such as age, size, weight and location. When they are known, the mechanisms of physical forcing, e.g., temperature or salinity, of biological processes are included.

Initially in the model, individual eggs are released having characteristics of spawning time and location and egg size. The probability of mortality on any day is a random variable based on a constant daily rate. Development is a function of age and temperature (derived from the physical model). Yolk-sac larval daily mortality is also stochastic, based on a constant daily rate, and development is related to degree days. For feeding larvae, mortality is a stochastic function of size. Consumption is a function of prey density, larval size and turbulence, as described by MacKenzie et al. (1994). Consumption is transformed to daily growth through bioenergetics equations. Larvae can die of starvation if they drop below a critical condition factor. Feeding larvae metamorphose into juveniles at 25 mm SL. Mortality of juveniles is again a random variable based on a constant daily rate, with the additional possibility of starvation due to a drop below a critical condition factor, as for feeding larvae. Consumption is a function of prey density, and bioenergetics equations transform consumption into growth.

Elements of the IBM as configured specifically for the Southeast Bering Sea consist mainly of new methods of calculating the depth of individuals by life stage, expansion of the juvenile stage section (especially with respect to prey encounter and the feeding process, and bioenergetics), and estimation of parameters specific to Southeast Bering Sea pollock, where possible.

The specification of depth, as it changes with development or life stage, is critical to modeling correctly the horizontal trajectory of individuals (Hinckley 1996). Eggs of Bering Sea pollock over the southeast slope and shelf appear to be much shallower than in the Shelikof Strait region or the Aleutian Basin. Egg depth in the IBM, therefore, is based on location. Over the shelf and slope regions of the Southeast Bering Sea, eggs are constrained in the model to remain in the upper 20 m of the water column. The depth of eggs in the Aleutian Basin is modeled as in Hinckley (1996), with initial depth equal to the depth of spawning. Thereafter, changes in depth with development result from changes in egg density. The depths of the yolk-sac and feeding larval stages are modeled as described in Hinckley et al. (1996) for all areas. Yolk-sac larvae move from the depth of hatching to the upper water column. Feeding larvae develop a diel migration cycle, driven by light levels, after they reach 6 mm SL. The depth of juveniles is modeled as follows. If a thermocline is present, small juveniles stay above it day and night, while larger juveniles migrate vertically through it, staying deeper during the day and rising to nearer the surface at night. If no thermocline is present, both large and small juveniles migrate vertically. The depth of the thermocline is derived from the hydrodynamic model. This is based on the work of Bailey (1989), Brodeur and Wilson (1996) and Brodeur (1998).

A major development in the juvenile life stage section has been the development of a stochastic, volume-searched feeding model. Average prey densities by hydrographic region of *Pseudocalanus*, spp., *Neocalanus*, spp. and euphausiids were used. These values were obtained by a review of the literature. Ideally, data from recent field studies and perhaps a nutrient-

phytoplankton- zooplankton model would be used to provide a spatially and temporally varying prey source, as the growth of young pollock in the model is very sensitive to these values. The volume searched by an individual juvenile on any day is based on its length (and therefore swimming speed). The number of prey items consumed per day has been calculated using a random deviate from a negative binomial distribution with two parameters, 1) the mean number of prey items encountered, and 2) a parameter describing the patchiness of prey.

Low-temperature metabolic rate parameters of Porter (1999) were used to parameterize the energetics of the feeding larval stage. Bioenergetics equations and parameters for the juvenile stage have been based on the work of Cianelli et al. (1998).

Also added to the individual-based model is an algorithm for determining sunset and sunrise times based on location. These are needed for feeding and depth calculations. Another addition is a method of determining in which of 10 hydrographic regions an individual is located at any time. These regions include the southeast and northwest inner, middle or outer shelf or slope, the oceanic region and the region around the Pribilof Islands. Determination of the region an individual is in is used to set the spawning depth and date, and to set average food densities. The area around the Pribilof Islands has been designated as a separate region. More detail may be added to this area later if desired, as it is thought to be an important juvenile nursery area. The Pribilof region has been the focus of much of the field research on juvenile pollock.

Growth rates of larvae correspond well to those reported by Yoklavich and Bailey (1990). Growth of juveniles at prey densities reported in the literature is somewhat greater than rates reported by Doyle (National Marine Fisheries Service, Seattle, WA, pers. comm.). However, it is thought that net sampling of zooplankton may significantly overestimate the prey density actually available to juveniles (Cianelli, National Marine Fisheries Service, pers. comm.). We therefore have tuned the model by reducing prey densities until average growth rates correlate with those reported by Doyle (Fig. 2.1.1). Research is needed on how actual prey density available to juveniles relates to net-sample-derived estimates of prey biomass. Growth of juveniles in the model appears to slow at the age of about 125-150 days. It is not certain why this occurs, but a slowing of growth in the fall, as the summer feeding season ends, is likely.

Three-dimensional simulations of the model, using flow, temperature, salinity, mixed layer and thermocline depths from the physical model, have not yet been performed, as the physical model results are not yet complete. Hermann et al. (Section 2.3 of this report) describe the present status of the physical model, which includes forcing by 12-hourly winds, surface heat flux and five tidal components, but no explicit ice dynamics. Details of the physical model are available at <http://pmel.noaa.gov/~hermann/sebscc.html>. Runs have been carried out for the first half of 1995 and 1997 using this intermediate version of the model, and initial float-tracking experiments were performed with the output (these results are also posted at the web site). For the 1995 and 1997 model years, floats were released in four regions (southeast middle and outer shelf and slope, and basin) with spawning dates and depths appropriate for each area. Floats were tracked until DOY 135. Floats released in the basin (Fig. 2.1.2, top left) generally remained in the basin, travelling to the northwest after initial entrainment in an eddy. Floats released at the 200-m depth contour on the slope (Fig. 2.1.2, top right), mostly traveled to the northwest along

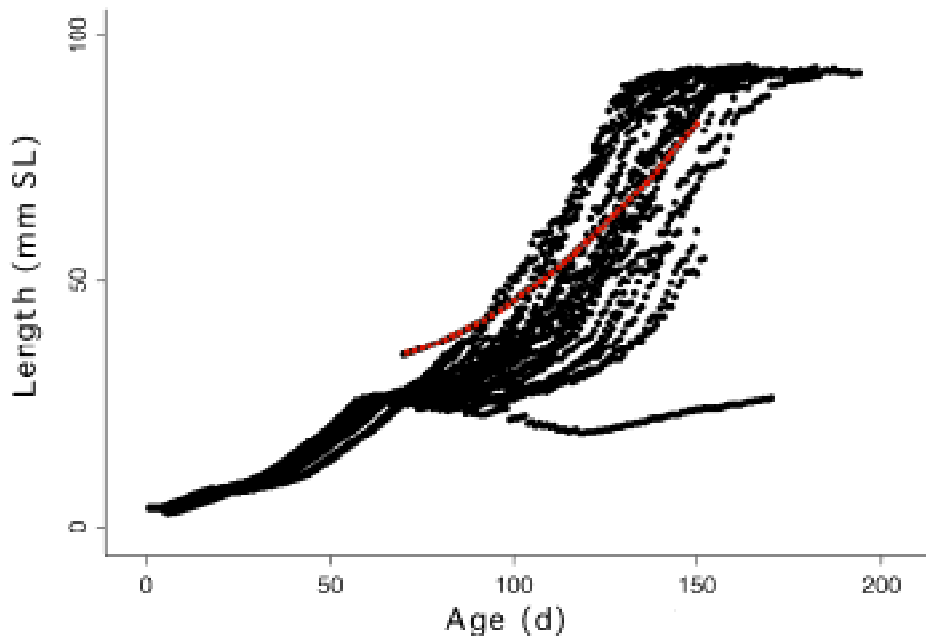


Figure 2.1.1 Modeled age-length curve for 25 individuals from the Bering Sea pollock IBM. The red line shows the actual age-length curve from 1994 samples.

that depth contour during both years, whereas those released over deeper water on the slope moved into the basin. Floats released between the 100- and the 200-m depth contours (Fig. 2.1.2, bottom left) moved towards and past the Pribilof Islands. Those released at depths less than 100 m (Fig. 2.1.2, bottom right) did not move as far as those released in other areas. One float from this group ended up near the Pribilofs.

Later simulations using the final flow fields and the complete individual-based model will track floats for longer periods, and allow us to examine characteristics of individuals for the simulation period. Simulations will be designed to allow examination of specific questions, such as the relationship between spawning in different regions and the final location of juveniles, stock mixing, and the importance of the Pribilof region as a juvenile nursery area depending on spawning location.

Products

The one-dimensional IBM is complete, as described above, and ready to be used in conjunction with the three-dimensional hydrodynamic model and the upper trophic level model (Livingston et al., Section 2.2 of this report) when these are sufficiently well calibrated.

Outlook

Work on this project is ongoing (without additional SEBSCC funding). The one-dimensional model has been completed. However, it has not yet been possible to complete the three-dimensional simulations, as these depend on the availability of calibrated physical model runs.

As soon as calibrated flow fields from that model are ready, simulations using the coupled hydrodynamic model and IBM will be implemented. Coupling with the upper trophic level model (Livingston et al, Section 2.2 of this report) must also wait until that model is completed.

An important further extension of this work would be the coupling of a 3-D model of the prey fields, perhaps derived from a nutrient-phytoplankton-zooplankton model, with the IBM and the physical model. The growth and survival of individuals in the IBM is very sensitive to food availability (Hinckley 1999), and adequate temporal and spatial data coverage for the prey resources of young pollock is not available.

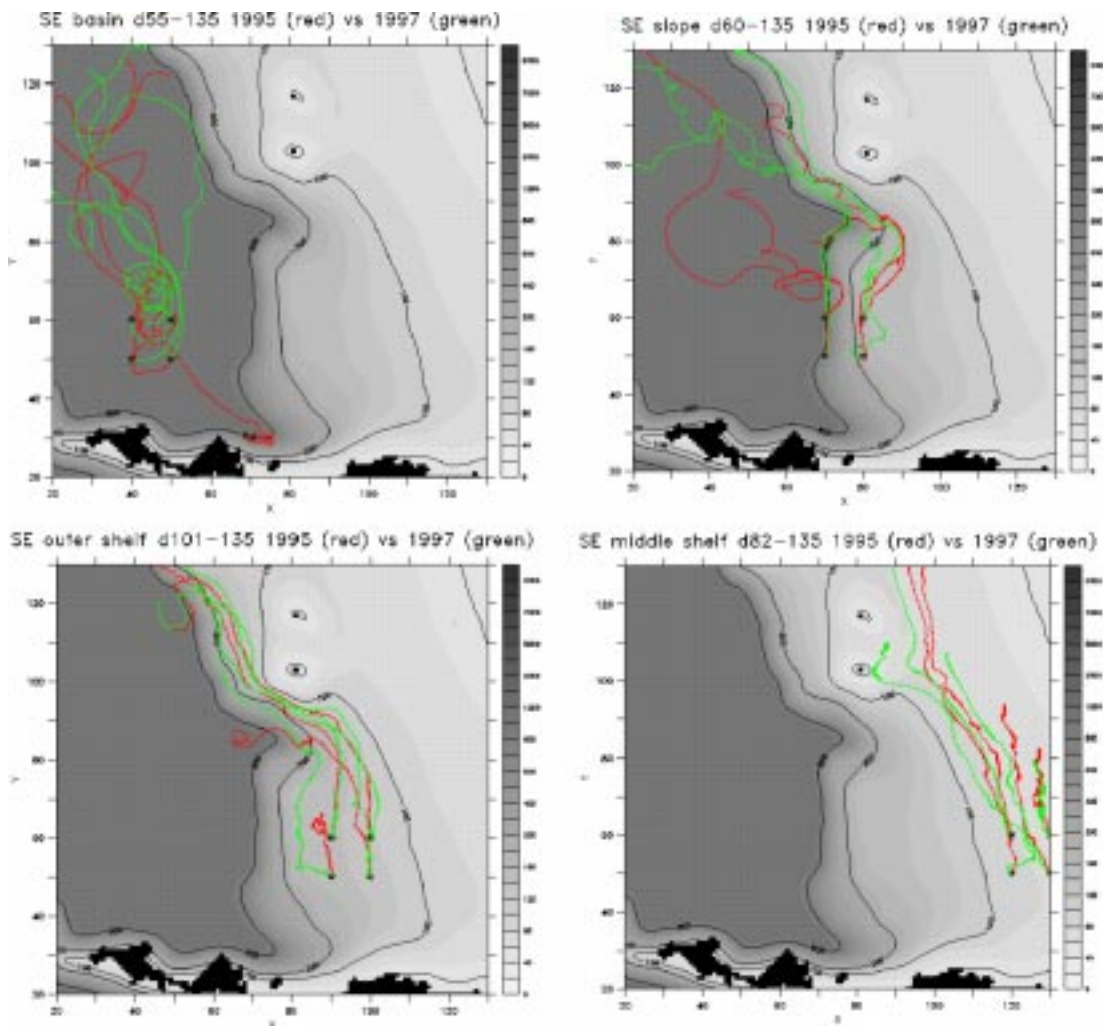


Figure 2.1.2 Trajectories of floats released in the Aleutian basin (top left), slope region (top right), outer shelf region (bottom left) and middle shelf (bottom right). Floats were released in each area at the time when pollock spawning occurs in that area (see note above each map for float tracking dates). Float trajectories for 1995 are shown in red, and trajectories for 1997 are shown in green.

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2.2. A spatial model of upper-trophic level interactions in the eastern Bering Sea

Principal Investigator: Pat Livingston, Alaska Fisheries Science Center

Period of Research: August 1996 - September 1998

Goal and Objectives

This project proposed to investigate the hypothesis that spatial processes that affect the overlap and availability of juvenile pollock to predators, particularly adult pollock, are important determinants of juvenile pollock survival rates. In order to investigate this hypothesis, we first developed a non-spatial model of predation interactions and are developing a spatially resolved model of upper trophic level predators on juvenile walleye pollock, with particular emphasis on cannibalism. The models will serve as a focus for synthesizing information on juvenile and adult pollock and other upper trophic level predators on juvenile pollock.

Project Description

Adult walleye pollock have been the dominant component of the pelagic fish consumer guild in the eastern Bering Sea over the last 15 years. The primary fish prey of this guild is juvenile walleye pollock and cannibalism appears to be the main source of predation mortality on juvenile walleye pollock, at least during the 1980's. Cannibalism occurs primarily on age-0 and age-1 walleye pollock and some year classes appear to suffer higher mortality rates due to cannibalism than others.

It has been hypothesized that predator switching to more abundant year classes may be one mechanism explaining the higher mortality rates of certain year classes of walleye pollock, such as the 1985 year class. However, there is also evidence that spatial separation of juveniles from adults in some years could be important in reducing cannibalism rates. For example, the above-average 1982 year class of pollock was quite abundant as 1-year olds in the middle shelf habitat while 1-year olds of the below-average 1987 year class were found mainly in the outer shelf area where most adult pollock reside. These two year classes were spawned from adult populations of similar size. However, a surface current model suggests that onshelf and northward transport was stronger in 1982 than in 1987 and may have transported larvae to areas of low adult abundance. Other factors, such as the extent of the cold pool of bottom water in the middle shelf and degree of vertical stratification, also have the potential to change the spatial overlap and vulnerability of juvenile pollock to cannibalistic adults.

A series of models to address these questions are being developed. First, a multispecies virtual population analysis model of the predation interactions in the eastern Bering Sea was developed to examine hypotheses about predation interactions and multispecies effects of fishing in a non-spatial context. This model will also be used to assess the multispecies implications of fishing by forecasting the population changes that might occur under different hypothetical fishing scenarios. Finally, a spatial model of upper trophic level predators on juvenile walleye

pollock is being constructed that will be initialized with the juvenile pollock abundance estimates from MSVPA. Predators of pollock will be allocated to different geographic regions corresponding to the seven biophysical domains outlined in the SEBSCC concept paper and seasonal movements will be simulated based on available data. Other processes relating to upper trophic level predators that affect their population abundance and predation rates on juvenile pollock include: food consumption, prey selection, growth, natural mortality, and fishing removals. Some of these processes, such as food consumption and growth rates are temperature dependent. As physical circulation models, nutrient-phytoplankton-zooplankton (NPZ) models, and individual- based models of pollock larval transport and survival are developed and validated, their outputs can be linked to the spatial predation model.

Results

We have completely parameterized a multispecies virtual population analysis (MSVPA) model which characterizes the predation interactions between major groundfish populations and one marine mammal predator, northern fur seal, in the eastern Bering Sea for the time period 1979-1995. Multispecies virtual population analysis (MSVPA) is a retrospective method of analyzing catch-at-age data in conjunction with information on diet linkages between species to obtain more realistic estimates of numbers-at-age and natural mortality for juvenile fish, particularly walleye pollock.. Juvenile pollock abundance in the spatial model will be derived from MSVPA outputs. We have completed parameterization of the MSVPA for the eastern Bering Sea and are now conducting a sensitivity analysis of the model.

The MSVPA model, as currently parameterized for the eastern Bering Sea, includes the following species as predators: walleye pollock, Pacific cod, Greenland turbot, yellowfin sole, arrowtooth flounder, and northern fur seal. Arrowtooth flounder and northern fur seals are entered as "other predators", which means that VPAs are not performed for these species. Instead, inputs on their consumption rates, diet, and population abundance are input so that their predation on VPA prey species in the model can be calculated. Prey species are walleye pollock, Pacific cod, Greenland turbot, yellowfin sole, rock sole, and Pacific herring (Table 2.2.1). The modeled time period is 1979 to 1995 and we have included an extensive amount of diet data from 70 predator/year/quarter combinations derived from close to 40,000 stomach samples collected during that time period. We added arrowtooth flounder and northern fur seals to the model, added substantial amounts of diet data, and updated and re-tuned the VPA inputs to reflect the 1995 stock assessment data. The single-species VPAs have been tuned to fit the outputs of the more complex stock assessment models that are presently being used for most groundfish species in the eastern Bering Sea.

Sensitivity analysis of the Bering Sea MSVPA revealed which input parameters were most important in determining the values of selected key output variables. For example, model input perturbations of ration and parameters determining population size of arrowtooth flounder, walleye pollock and Pacific cod were the most significant variables explaining changes in model estimates of age-1 walleye pollock population size. Perturbations in input parameters for predators such as Greenland turbot, northern fur seal, and yellowfin sole were not important in explaining changes in age-1 walleye pollock population size. These analyses give us information as to which predators contribute most to the predation mortality of a particular groundfish

species. This will help guide future modeling and field sampling plans on these species interactions.

Table 2.2.1. Species included in the eastern Bering Sea multispecies virtual population analysis model (MSVPA).

Common name	Scientific name	MSVPA or Other Predator	Prey
Walleye pollock	<i>Theragra chalcogramma</i>	MSVPA predator	Yes
Pacific cod	<i>Gadus macrocephalus</i>	MSVPA predator	Yes
Greenland turbot	<i>Reinhardtius hippoglossoides</i>	MSVPA predator	Yes
Yellowfin sole	<i>Pleuronectes asper</i>	MSVPA predator	Yes
Arrowtooth flounder	<i>Atheresthes stomias</i>	Other predator	No
Northern fur seal	<i>Callorhinus ursinus</i>	Other predator	No
Rock sole	<i>Lepidopsetta bilineatus</i>	No	Yes
Pacific herring	<i>Clupea pallasii</i>	No	Yes

Model results show that most predation mortality for the prey species in the model (walleye pollock, Pacific cod, Greenland turbot, yellowfin sole, rock sole, and Pacific herring) occurs on juveniles that have not yet recruited to the fishery. Model estimates of population abundance for exploited ages of each prey species are similar to those provided by single species models. However, abundance estimates of juveniles, particularly walleye pollock, are substantially larger than estimates from single-species model (Fig. 2.2.1). Walleye pollock was the main prey species consumed by MSVPA predators, and cannibalism constituted the majority of the predation mortality of age-0 fish. The dominant predators on age-1 pollock included adult pollock, Pacific cod, arrowtooth flounder, and northern fur seals. In some years, Pacific cod consumed the largest biomass of walleye pollock prey relative to other predators (Fig. 2.2.2). However, most of the biomass of pollock consumed by cod tended to be from older pollock.

Ricker stock recruitment curves were fitted to estimates of walleye pollock spawning stock biomass and age-0 and age-1 recruit numbers from MSVPA and single-species virtual population analysis (SSVPA) (Fig. 2.2.3). The SSVPA recruitment curves exhibit more of a downward bend at the right hand side of the fitted curves. The coefficients of determination (R^2) from all the model fits were low, ranging from 0.06 to 0.22. The highest R^2 of 0.22 was from the fit of age-0 recruits to spawning biomass estimates from MSVPA.

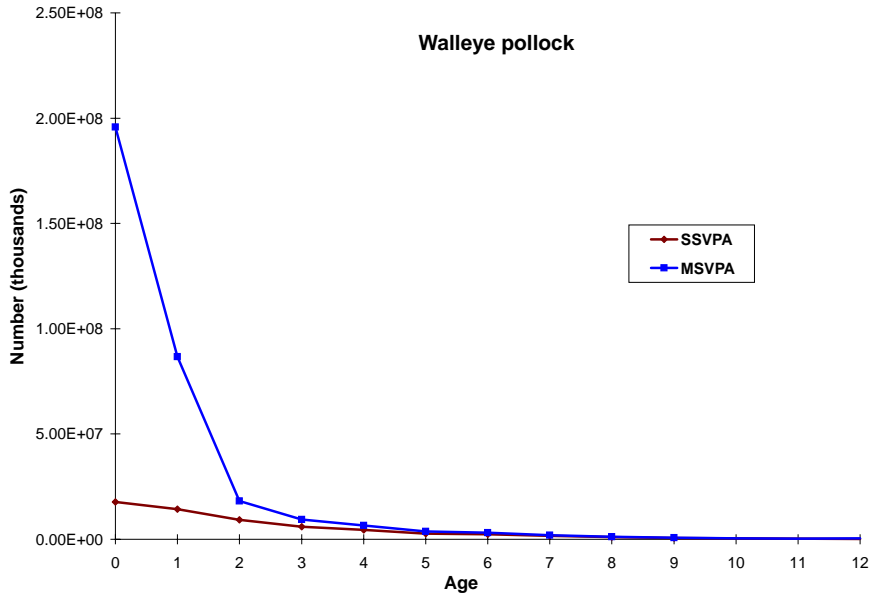


Figure 2.2.1 MSVPA and SSVPA estimates of walleye pollock number at age, averaged over the time period of 1984 to 1993 in the eastern Bering Sea. (Age-0 mortality rate from MSVPA and SSVPA is a half-year rate.)

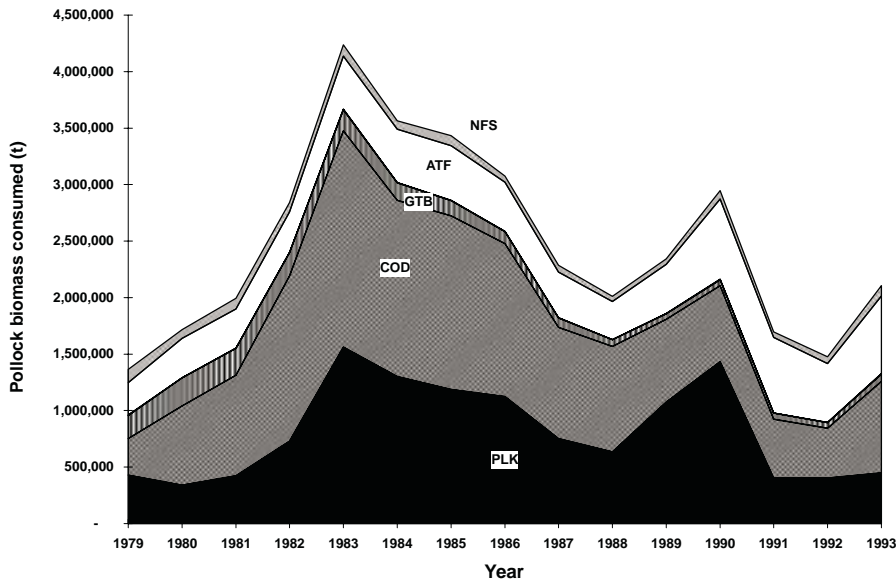


Figure 2.2.2 MSVPA estimates of biomass of walleye pollock consumed by northern fur seals (NFS), arrowtooth flounder (ATF), yellowfin sole (YFS), Greenland turbot (GTB), Pacific cod (COD), and walleye pollock (PLK) from 1979 to 1993 in the eastern Bering Sea.

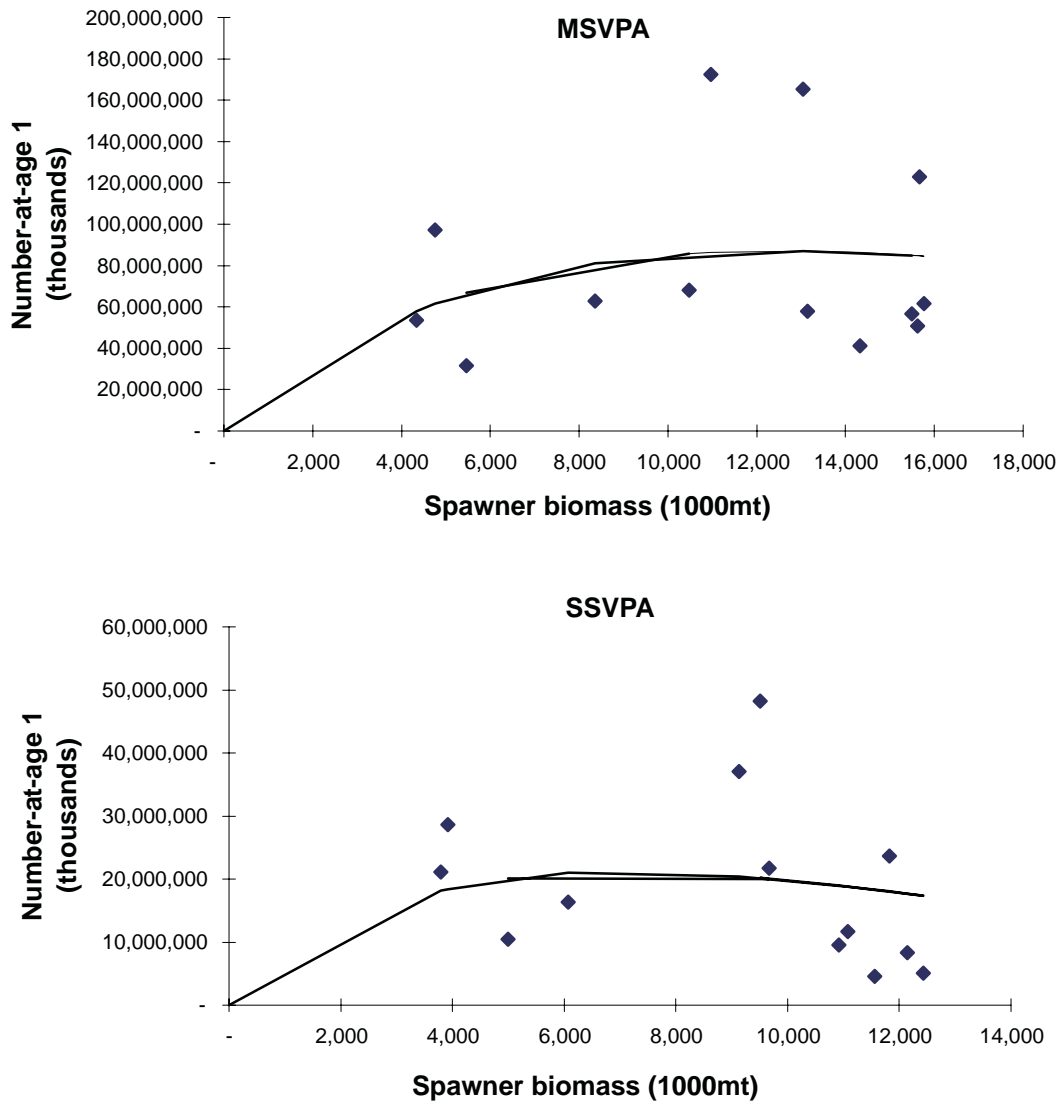


Figure 2.2.3 Spawning stock biomass and age-1 number-at-age relationships for walleye pollock estimated from MSVPA (upper panel) and SSVPA (lower panel).

The MSVPA model estimated rates of total natural mortality for juvenile walleye pollock in the eastern Bering Sea are comparable to rates estimated by other models and methods (Table 2.2.2). Livingston (1993) calculated age 0-1 predation mortality for 1985-87 using diet, ration, and groundfish and marine mammal predator population estimates and obtained annual instantaneous rates that were higher than MSVPA estimates for age-0 but very similar to MSVPA model estimates for age-1 pollock mortality. Age-2 predation mortality estimated in that paper is low compared to the other sources because it did not include the residual natural mortality rate of 0.3 used in MSVPA and Livingston and Methot (1996). Total natural mortality rates estimated from an integrated catch-at-age model of walleye pollock with predators produced estimates of age-1 M . These estimates were comparable to MSVPA estimates for the

recent modeled time period, but were lower for the 1963 to 1980 period not included in the MSVPA model of the eastern Bering Sea. Estimates of age-2 mortality from MSVPA seem high relative to other estimates and suggest the possibility that residual natural mortality rate (M1) for age-2 pollock used in the MSVPA model should be lowered.

Table 2.2.2. Comparison of instantaneous natural mortality rates at age for juvenile pollock in the eastern Bering Sea derived from several different methods. (Mortality rates of age-0 pollock apply to the second half of the year only.)

Source	Time Period	Age-0	Age-1	Age-2
MSVPA model	1984-1993	1.05	1.55	0.77
Livingston (1993)	1985-1987	2.84	1.90	0.31
Livingston and Methot (1996)	1984-1992	-	1.50	0.35
Livingston and Methot (1996)	1963-1980	-	0.59	0.35
Wespestad and Terry (1984)	1963-1980	-	0.85	0.45

The initial increase and then decline in total biomass consumed of walleye pollock during the 1982 to 1987 period generally reflects the trends in population biomass of two dominant pollock predators: adult pollock and Pacific cod. Estimated total biomass of pollock consumed by predators was higher than fishery removals of pollock during the time period, which ranged from 859,000 t to 1,455,000 t. Given the strength of the predation on pollock by adult pollock and cod, it will be important to investigate how changes in fishing intensity of these two species could affect pollock recruitment. When sensitivity analyses are completed on MSVPA, we will begin forecasting the effects of different fishing strategies using the estimated suitabilities from the model.

Although predation on age-0 pollock was dominated by cannibalism, there were several important predators on age-1 pollock including cod (an exploited species) and arrowtooth flounder and northern fur seal (two non-exploited species). About half the estimated number of age-1 pollock consumed were eaten by these non-exploited species and suggests the possibility that there may be limited ability to influence recruitment of pollock into a fishery using various fishing strategies. An integrated catch at age model of pollock that included pollock, cod, and northern fur seals as predators, using the same basic food habits data sources for this MSVPA model, estimated much lower predation mortality rates on age-1 pollock from these predators. That model had difficulty fitting model parameters relating to cod and fur seals, given the other sources of data and suggests the need to examine more closely the inputs relating to these predators. The importance of arrowtooth flounder as a predator on age-1 pollock is highlighted by the results of this MSVPA. Other models of predation on pollock in the eastern Bering Sea should probably include this important predator, particularly since its biomass has been steadily increasing on the eastern Bering Sea shelf from under 100,000 t in 1982 to over 500,000 t in 1996.

The relationship between spawning stock and recruitment of pollock is different depending on whether estimates from single species virtual population analysis (SSVPA) or MSVPA are

used. Although the total amount of variability explained by the MSVPA recruitment curve, particularly for age-0 recruits, is somewhat higher than the amount explained by the SSVPA curve, there is still a great deal of variability around the respective curves. The time series of recruitment used here contains only 13 points and the estimated recruitment curves would probably be improved with a longer time series of data. An important contrast will be to compare recruitment variability estimated from this non-spatial model and the spatially explicit model to see if we are able to explain more of the recruitment variability in pollock by considering spatial variability in predation.

Products

Models

A multispecies virtual population analysis model of groundfish in the eastern Bering Sea.

Publications

Jurado-Molina, J., and P.A. Livingston, in preparation: A description and analysis of the eastern Bering Sea multispecies virtual population analysis model. NOAA/NMFS Processed Report.
Livingston, P.A., and J. Jurado-Molina, submitted: A multispecies virtual population analysis model of the eastern Bering Sea. *ICES Mar. Sci. Symp. Series*.

Presentations

Jurado-Molina, J., 1997: A multispecies approach to stock assessment in the Bering Sea. Presented Nov. 1997 as a Quantitative Seminar of the School of Fisheries, University of Washington, Seattle, WA.
Jurado-Molina, J., 1998: A multispecies approach to stock assessment in the Bering Sea. Presented April, 1998 at the Graduate Symposium in Fish Populations and Management, School of Fisheries, University of Washington, Seattle, WA.

Posters

Livingston, P.A., and J. Jurado-Molina, 1997: A multispecies virtual population analysis model of the eastern Bering Sea. Poster presented at: 1997 ICES Recruitment Symposium, Baltimore, MD.

Outlook

We have spent the majority of research effort for this project on validating and documenting the MSVPA model, a crucial step that was not included in our original proposal. Validation of the model included a sensitivity analysis of the model to perturbation of key input parameters, analysis of the varying assumptions that can be made about the values of other food available to predators, and statistical analysis of the variability in estimates of prey suitability. The results from these analyses are now being documented in a draft report of the eastern Bering Sea MSVPA model and its results. This report will be sent out for review upon completion and published as a NMFS processed report and later as chapters in a doctoral dissertation, and as peer-reviewed publications. Since September 1998, we have updated the model to reflect the 1998 stock assessment information and we have developed a forecasting model as a companion

model to the MSVPA that will be able to consider the possible multispecies implications of fishing. This will be used in 1999 to provide advice to the North Pacific Fishery Management Council groundfish plan teams, who have expressed concern about the ecosystem implications of unbalanced exploitation rates. The MSVPA will continue to be used and updated to incorporate new food habits and stock assessment information. A prototype version is also being developed that will explicitly consider uncertainty in the inputs.

We are presently parameterizing the spatial model of upper trophic level predation in the eastern Bering Sea. We have obtained area specific data for bottom temperature, pollock catch, survey, and other biological information such as growth. We are also compiling information on pollock spatial abundance patterns by size. This information will be used to do a retrospective analysis of walleye pollock distribution by season in the eastern Bering Sea in cold, warm, and average years. The analysis will determine how differently pollock distribute themselves across the Bering Sea shelf by age and season, and how physical factors may influence these distributions. This will be important information needed to refine the spatial model's definition of pollock movement. We hope to have a parameterized spatial model and begun some initial validation work by the end of 1999.

Our initial proposal was to link this spatial model to lower trophic level models. These models are not yet ready for linking but we intend to do the linking when the models are completed and validated. It is evident from this modeling exercise that we lack knowledge of zooplankton abundance and distribution (a necessary input to a spatially explicit model of pollock feeding) and that we have a lot of retrospective analysis to do to refine our characterization of pollock movement patterns and mechanisms influencing movement. We lack seasonal understanding of pollock distribution since independent surveys are typically conducted only during summer. Further research could include: N-P-Z model development, quantitative zooplankton sampling, seasonal survey of pollock distribution and feeding habits, expanded area of summer surveys to determine age-0 and age-1 pollock distribution in that season, and a tagging program to better understand pollock movement patterns from the juvenile to adult stage.

2.3 Circulation modeling for the S.E. Bering Sea

Principal Investigators: A. Hermann, P. Stabeno, D. Haidvogel, D. Musgrave

Period of Research: 6/1/96-10/1/98

Goal and Objectives

The overall goal of this project is the implementation of an eddy-resolving circulation model of the southeastern Bering Sea that includes tides and tidal mixing. This circulation model is used for investigations of the interannual variability of circulation in the region, and as input to a suite of biological models focusing on walleye pollock and higher trophic levels.

Project Description

In the first year of this project a rigid-lid, primitive equation model with 20-kilometer resolution and no tidal dynamics was expanded to include seasonal variability. Much of the research of the second year focused on the implementation of a free-surface, primitive equation, eddy-resolving regional Bering Sea model at 4-kilometer resolution with both tidal and subtidal forcing. The development of a suitable open boundary condition for the regional model was a major part of this effort.

Concurrently with the regional model development, a global spectral element ocean model (SEOM, developed at Rutgers University) was used to generate tides for use by the free-surface regional model. A tidal run with the five major tidal components of the Bering Sea (M2, S2, N2, K1 and O1), on a grid with finest resolution in the Bering Sea has been converted to equivalent amplitudes and phases, for use in boundary conditions on the regional model.

Results of the new global and regional simulations have been very encouraging. In particular we have reproduced the observed tidal residual circulation around the Pribilof Islands, while replicating the Aleutian North Slope Flow, the Bering Slope Current, and the shallow inflow through Unimak Pass. The regional model has been driven with realistic winds (from ECMWF) and climatological heat flux (from Oberhuber's analysis of COADS data), as well as tidal forcing from a global model. Having performed well in barotropic (tidal) simulations, SEOM is now being implemented as a multi-layer (and ultimately continuously stratified) primitive equation model of the world ocean. A new global grid has been developed with greater emphasis on the full equatorial and coastal waveguides. This grid should help capture more of the interannual variability of the North Pacific (including the Alaskan Stream and Alaska Coastal Current, which influence the Bering Sea) due to El Niño dynamics.

Results

The rigid-lid model

The coarse vertical and horizontal resolution of the preliminary rigid-lid model precluded many important physical processes known to occur in the region (in particular, all tidal

dynamics). However, we were still able to replicate several of the first order features of the area. These included:

1. a strong current along the northern boundary of the Aleutians (the Aleutian North Slope Flow);
2. a weaker current along the shelf break (the Bering Slope Current), which broadens and peels away from the slope as it heads northwestward;
3. weak flows on the middle shelf;
4. a moderate northwestward flow along the Alaska coastline;
5. vigorous flows along the Siberian coastline (e.g. the Anadyr Current); vigorous flows upstream of the Bering Strait;
6. flows both into and out of Amukta Pass;
7. meanders and eddies of ~100-km scale (Fig. 2.3.1).

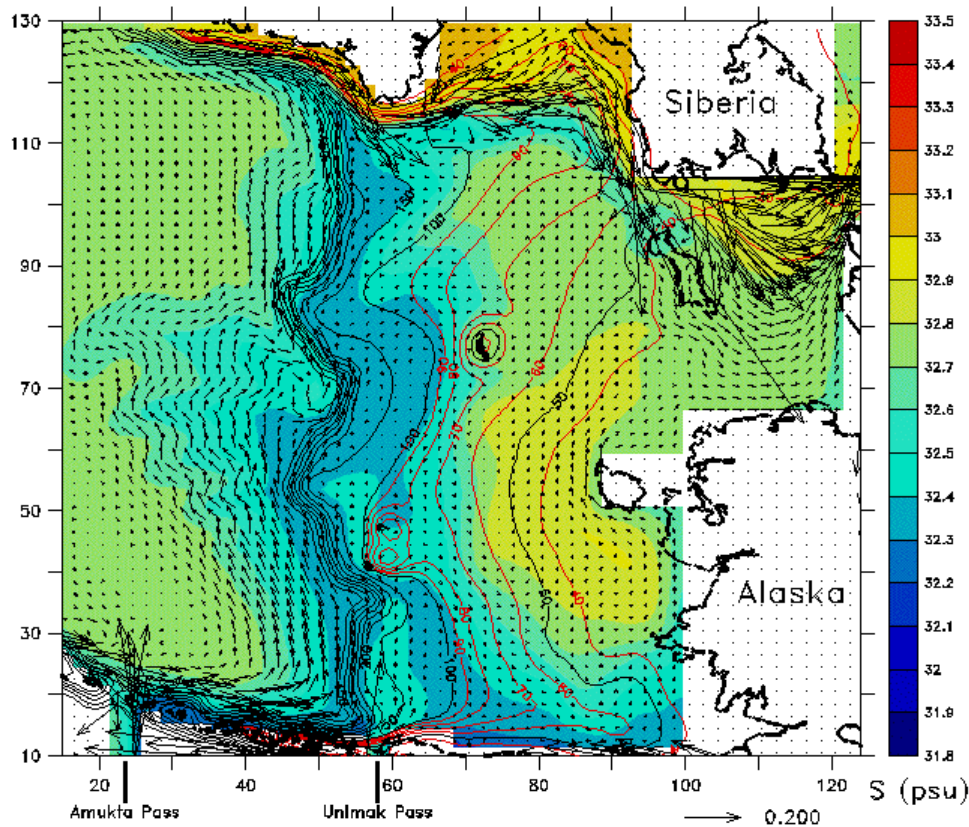


Figure 2.3.1a Snapshot of regional model output at 20 meters depth in July after 540 days of spin up with climatological winds and specified inflows and outflows through passes. True coastlines are shown with thick black lines, and location of Unimak and Amukta passes are marked. Note that the model domain is rotated 45 degrees with respect to North. The x- and y-axes indicate the native coordinate system of the model, with 130 grid points in each direction. Salinity is shaded, with velocity vectors (m/s) and bathymetry contours (m) superimposed. Contour levels for bathymetry are every 10 m for 30-100 m, and every 50 m for 100-500 m.

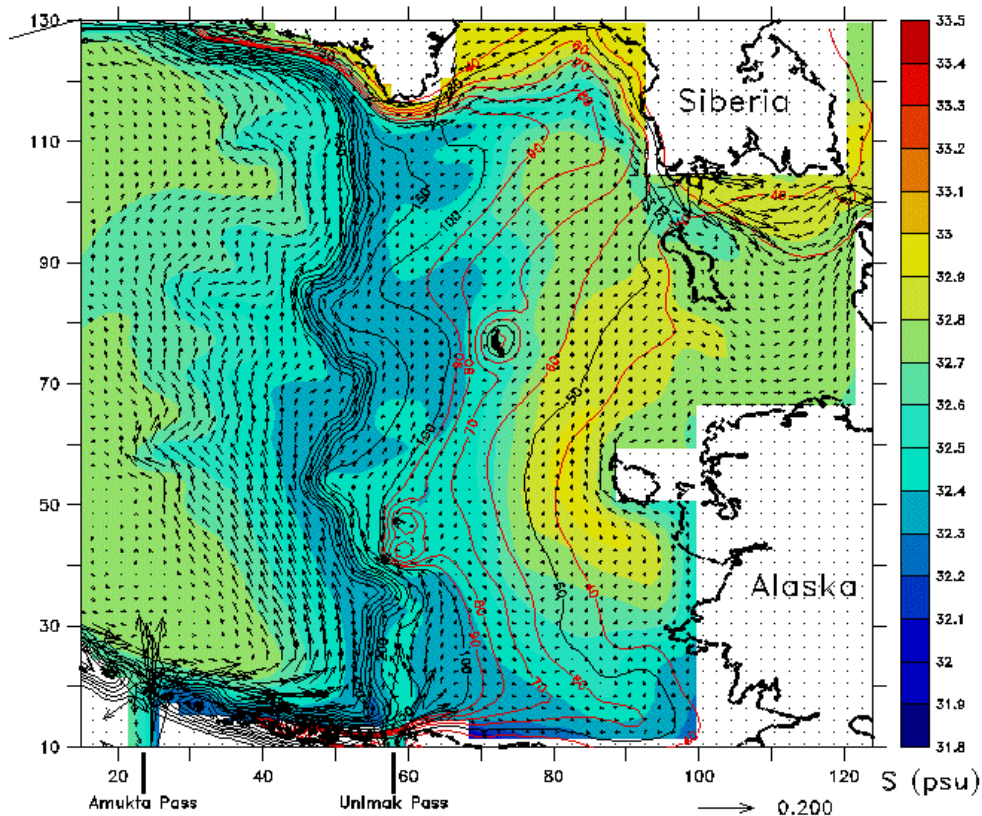


Figure 2.3.1b Snapshot of regional model output at 20 meters depth in December after 730 days of spin up.

The influence of shallow bathymetry near unresolved islands is apparent in the velocity field. Note that the following features are inadequately resolved: the shelf flow is too weak, cross-shelf flow is weak, flows are probably excessive at the northern boundary, and frontal structures dependent on tidal mixing are absent.

We compared output for the summer and winter periods (Figs. 2.3.1a and b). In the summer, we have successfully reproduced flows through both Anadyr and Spahnburg Passes, to the north and south of St. Lawrence Island, respectively, as is observed. The weaker wintertime flux through Bering Strait (prescribed here as a boundary condition) produces weaker upstream flows along the Siberian coastline in that season.

The rigid-lid model was used to explore the impact of seasonally varying inflows through the passes as it affects the interior flows generally, and basin/shelf exchange in particular. A simple way to examine cross-shelf flux is through mapping the barotropic streamfunction for winter and summer periods. In the summer, when Bering Strait outflow is maximal and Unimak Pass inflow is minimal, barotropic streamlines join Amukta Pass with Bering Strait (Fig. 2.3.2a). The streamlines follow the bathymetric contours of the shelf break, crossing over into shallow waters only after encountering the northern boundary with Siberia.

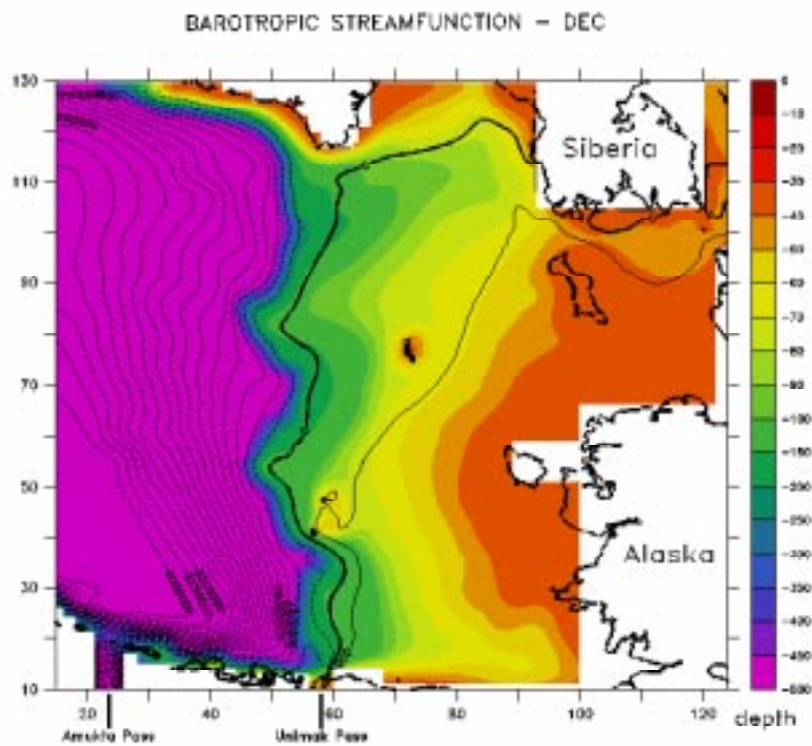
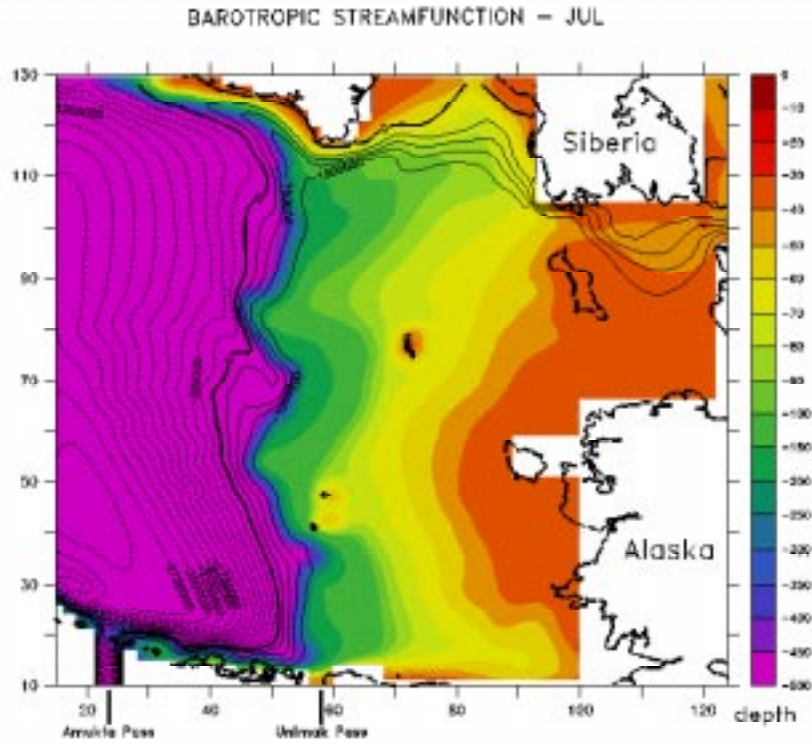


Figure 2.3.2 (a) Barotropic streamfunction values for July, superimposed on bathymetry (shaded). Contour levels for streamfunctions are $0.25 \times 10^6 \text{ m}^2/\text{s}$. (b) Barotropic streamfunction values for December.

Apparently the tendency to follow geostrophic (constant f/h) contours is very strong in this model; greater vertical and horizontal resolution (especially of cross-shelf canyons) can change this result. In the winter, when Bering Strait outflow is minimal and Unimak Pass inflow is maximal, streamlines join Unimak Pass with Bering Strait, crossing the shelf in a gradual northeastward direction (Fig. 2.3.2b). The greater tendency for these streamlines to cross isobaths is likely due to their origin in Unimak Pass, which is shoreward of the major shelf break. However, the true paths of water parcels should be considerably more complex, as the transit time from southwest to northeast should be slower than these seasonal changes over much of the shelf.

The free-surface model

A suitable boundary condition technique was developed for the regional model, which involves a nudging technique combined with a telescoped horizontal grid (Fig. 2.3.3). The global spectral element ocean model (SEOM) was used to generate tides for use by the free-surface regional model (Fig. 2.3.4). A tidal run with the five major tidal components of the Bering Sea (M2, S2, N2, K1 and O1), on a grid with finest resolution in the Bering Sea was converted to equivalent amplitudes and phases, for use in boundary conditions on the regional model (Fig. 2.3.5).

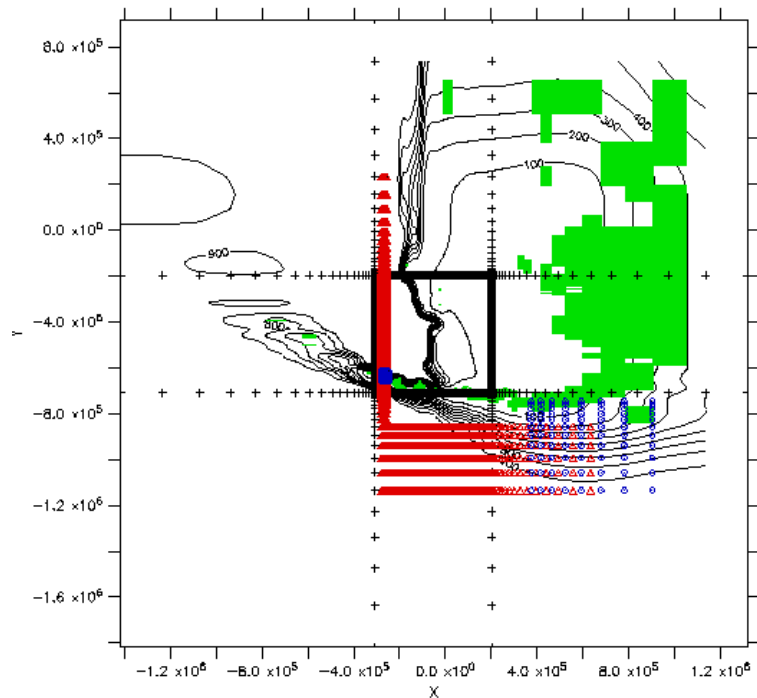


Figure 2.3.3 General layout, grid and boundary technique for the regional model of the southeastern Bering Sea. Model bathymetry is contoured, and land (Alaska) is colored green. Units on the axes are in meters. The interior box is resolved with ~ 4 km spacing. Representative grid point locations (shown as crosses) illustrate telescoping of the grid beyond this interior box. Closed walls surround the full domain. At red grid points we nudge the free surface height towards its proper tidal value, obtained from the global model (SEOM). At blue grid points we nudge the depth-integrated velocity towards values appropriate to the Aleutian North Slope Current and the Alaskan Stream/Alaska Coastal Current.

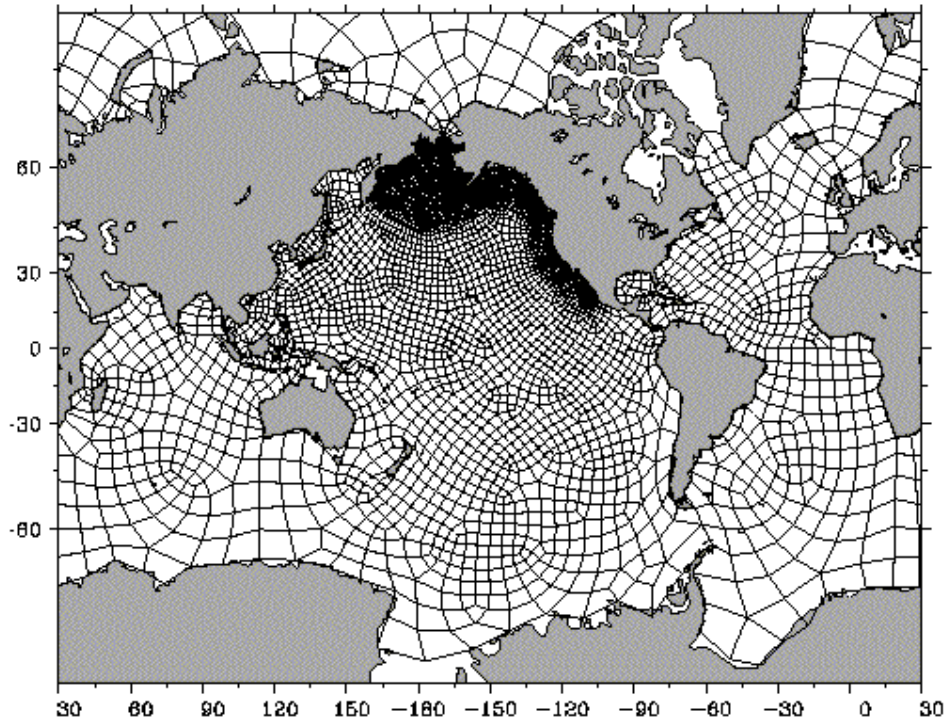


Figure 2.3.4 The grid of the Spectral Element Ocean Model (SEOM) used to generate tidal information for the regional model. Structure internal to each quadrilateral element is represented by a polynomial basis set. Minimum grid spacing is approximately 20 km.

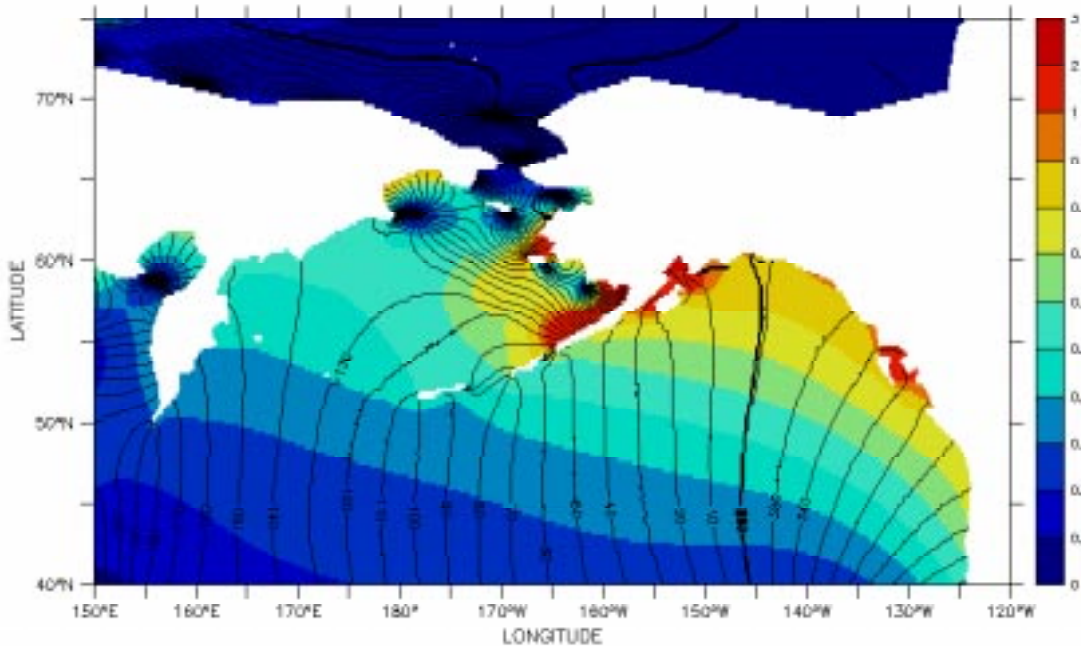


Figure 2.3.5 Amplitudes (shaded; in m) and relative phase (contoured; in degrees) of the M2 tidal component derived from the global simulation.

Using the free-surface model with tides, we have reproduced several major observed circulation features in the southeastern Bering Sea, and model runs for 1995 and 1997 have illustrated interannual differences. Hydrographic and current meter measurements (many of these funded by SEBSCC) are available for each of these years, and they were remarkably different in character. In particular, 1997 was much warmer, and produced a coccolithophore bloom over broad areas of the shelf. Details of our findings are as follows.

1. Regional circulation – The Aleutian North Slope Flow, the Bering Slope current and a shallow inflow through Unimak Pass all emerge from the simulations for years 1995 and 1997 (Fig. 2.3.6). Much of the flow through Unimak Pass follows the 80-120-meter isobaths to the Pribilof Islands, where it bifurcates into a western and eastern branch. The Bering Slope current appears especially strong along the 160-meter isobath. West of the Pribilofs, the two currents (Bering Slope Current and the western bifurcation of the mid-shelf flow) appear to merge into a single, strong slope current.

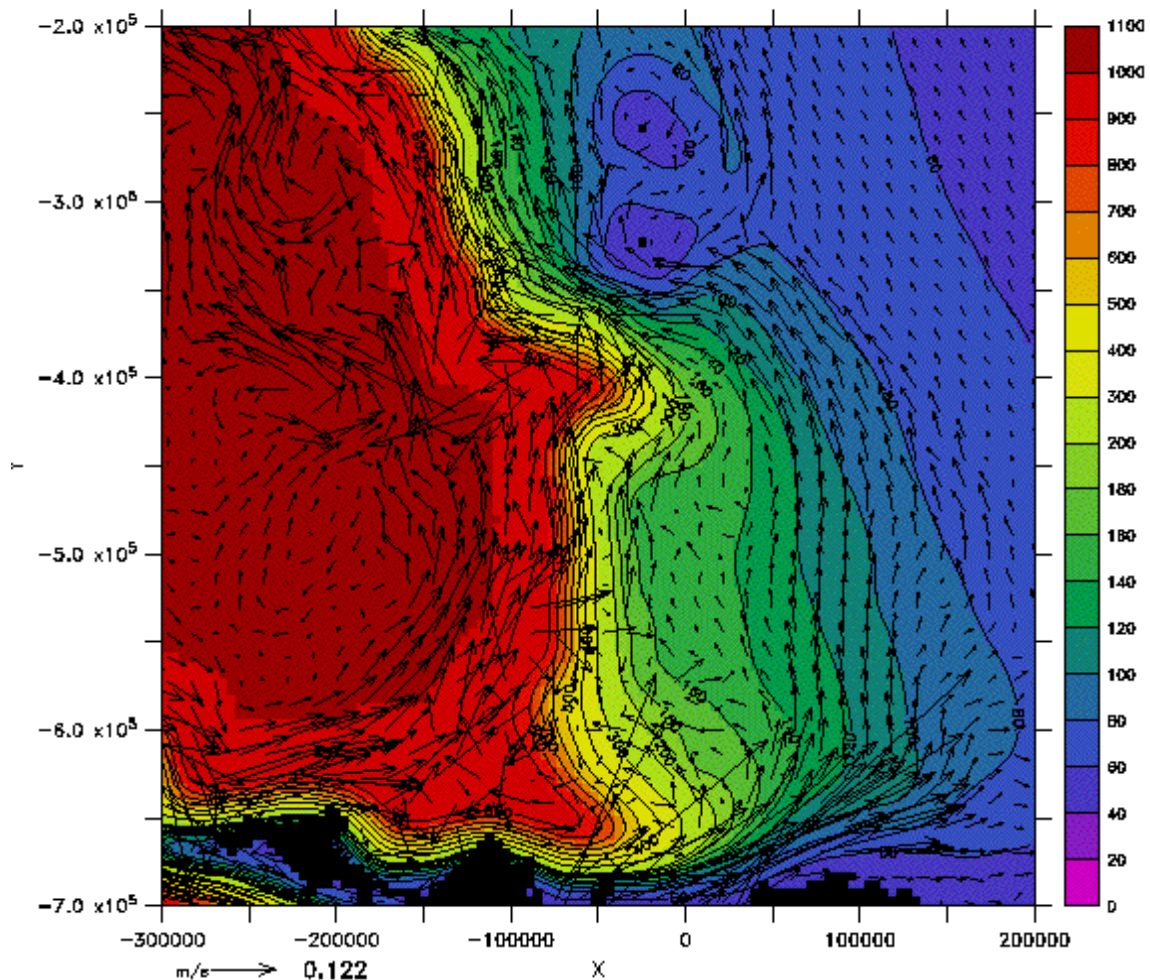


Figure 2.3.6 Results from the regional model for early April 8, 1997. Velocity vectors (in m s^{-1}) are shown superimposed on bathymetry (m). Every other grid point is shown. The Pribilof Islands are shown as black squares near the top of the figure; x and y-axis units are in meters. Note that the model grid is rotated with respect to true north, such that the positive y-direction is approximately northward.

2. Tides and tidal residuals – A significant tidal residual signal has been observed in current meter records from mornings near the Pribilof Islands. The residual signal is manifest as a clockwise circulation around each of the Pribilof Islands. Our regional model replicates this signal when forced with either the M2 tides alone or a mixture of five tidal components (Fig. 2.3.7). It is likely this residual circulation, in conjunction with subtidal currents, plays an important role in advecting young pollock in the vicinity of the Pribilof Islands.

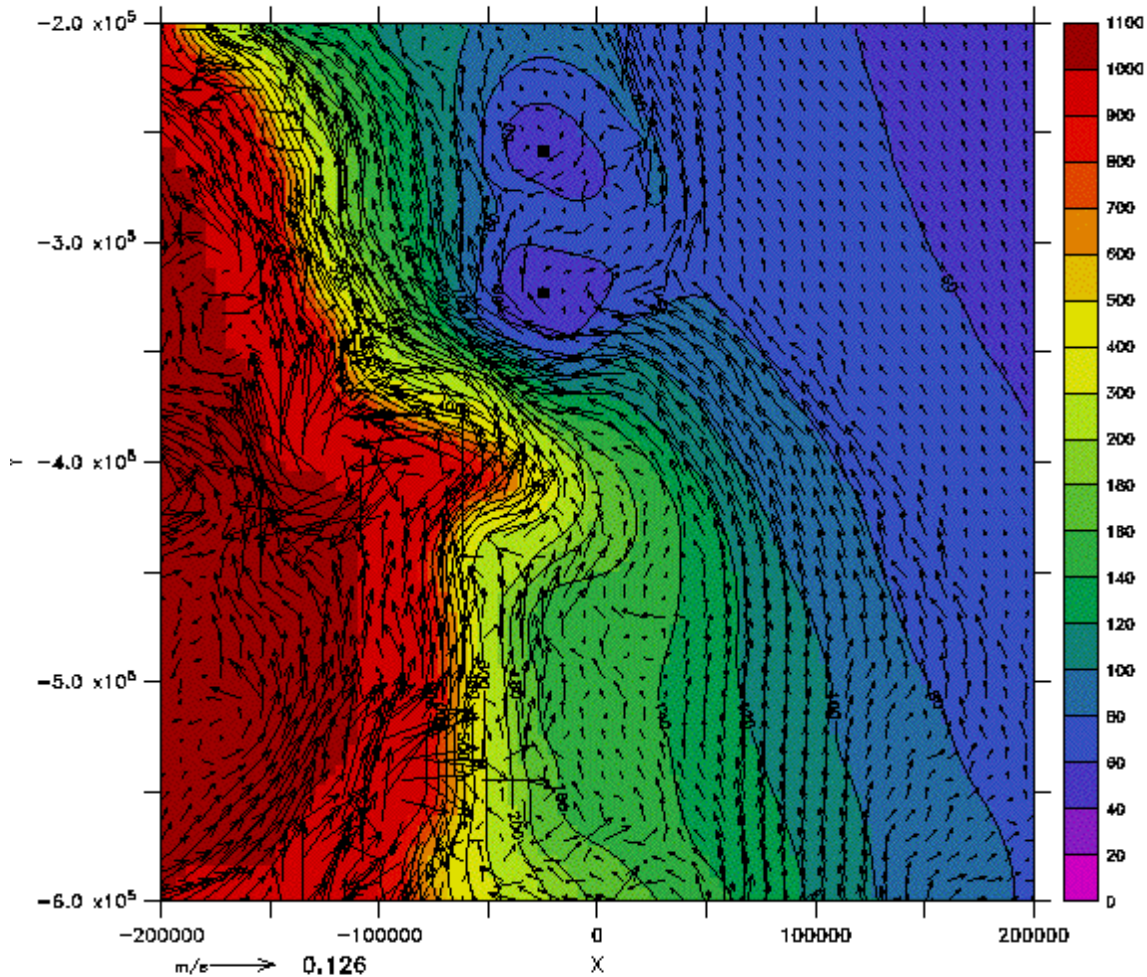


Figure 2.3.7 Close up of Fig. 2.3.6 showing model results in the vicinity of the Pribilof Islands. Every grid point is shown.

3. Eddies – There is considerable eddy activity in the basin, which the sea surface height (shaded, in m) of mid-May 1997 exemplifies (Fig. 2.3.8). The magnitude of this signal is comparable to that revealed by satellite altimetry. A larger amount of mesoscale eddy activity was observed in the basin during the 1995 simulation than during the 1997 simulation. Energetic small-scale eddies abound near the shelf break and along the 100-meter isobath (see Fig. 2.3.7), and probably play an important role in cross-shelf exchange.
4. Vertical mixing – A related issue to horizontal transport of nutrients is their vertical transport. We presently use Mellor-Yamada level 2.0 mixing dynamics to calculate

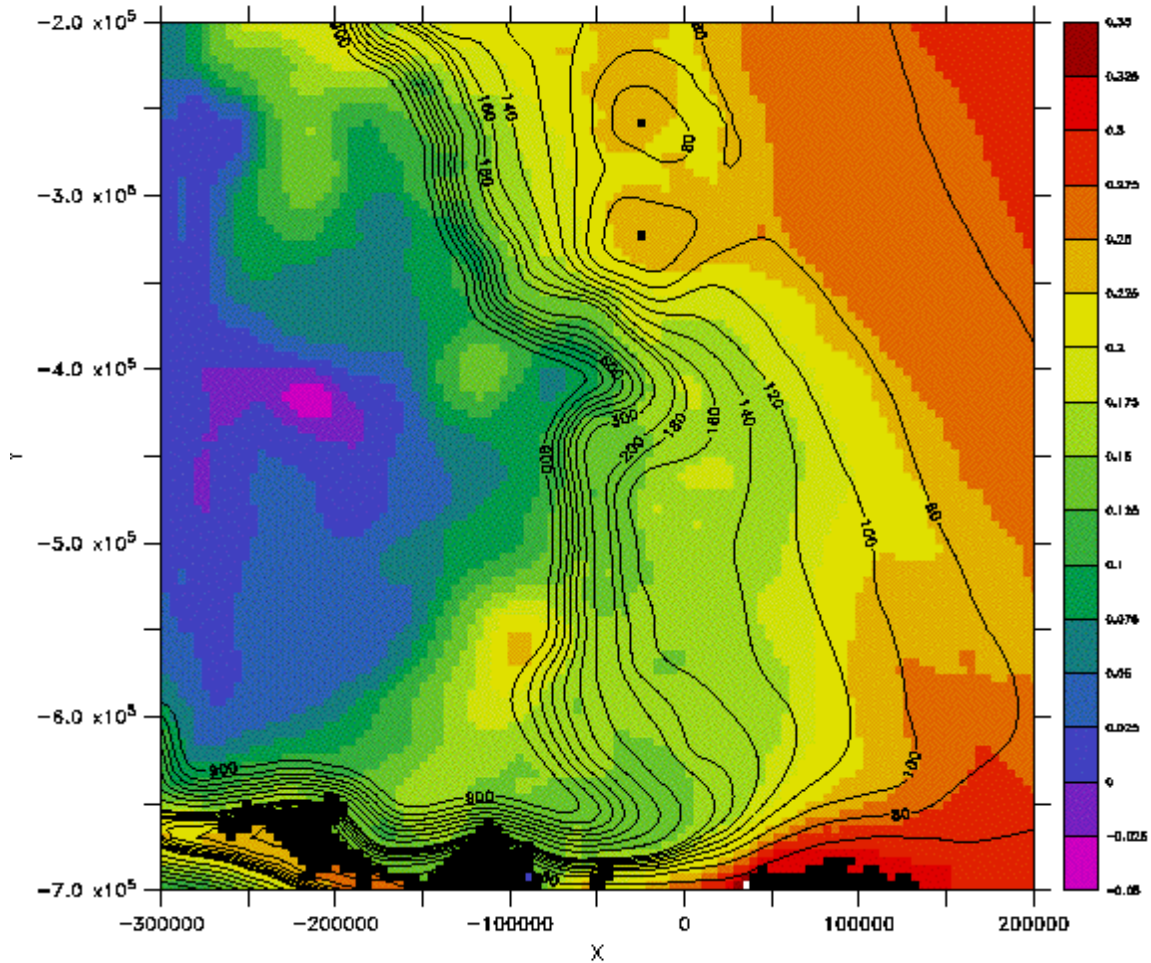


Figure 2.3.8 Free surface heights (m) from the regional model for April 8, 1997, superimposed on bathymetry (contoured, in m).

effective vertical diffusivity in the model. The simulations for 1995 and 1997 suggest that the most intense vertical mixing occurs not in the shallow region of Bristol Bay, but rather at the shelf break, and along the 100-meter isobath (Fig. 2.3.9). This issue needs to be addressed with more realistic bathymetry, however; the present implementation of the model limits model bathymetry to the greater than 50 meters throughout the domain.

5. The cold pool – A cold pool was observed at the end of the simulation for both 1995 and 1997. No explicit ice dynamics were included in these simulations; instead we assumed zero surface heat flux for typically ice covered areas in each month. The appearance of a cold pool in each of the simulated years does suggest that tidal mixing is a major element of the cold pool dynamics.
6. Nutrient mixing across isobaths – One of the core issues of the SEBSCC program is how nutrients are supplied to the shelf area to feed the annual production there. As an investigation of cross-shelf nutrient flux, we initialized a three-dimensional scalar field with the value of the local bathymetric depth, i.e., $g(x,y,z,0) = h(x,y)$, where g is the tracer and h is the model bathymetry. We then tracked the evolution of this tracer field over a 60-day run of the model with M2 tidal forcing and subtidal inflows corresponding to the

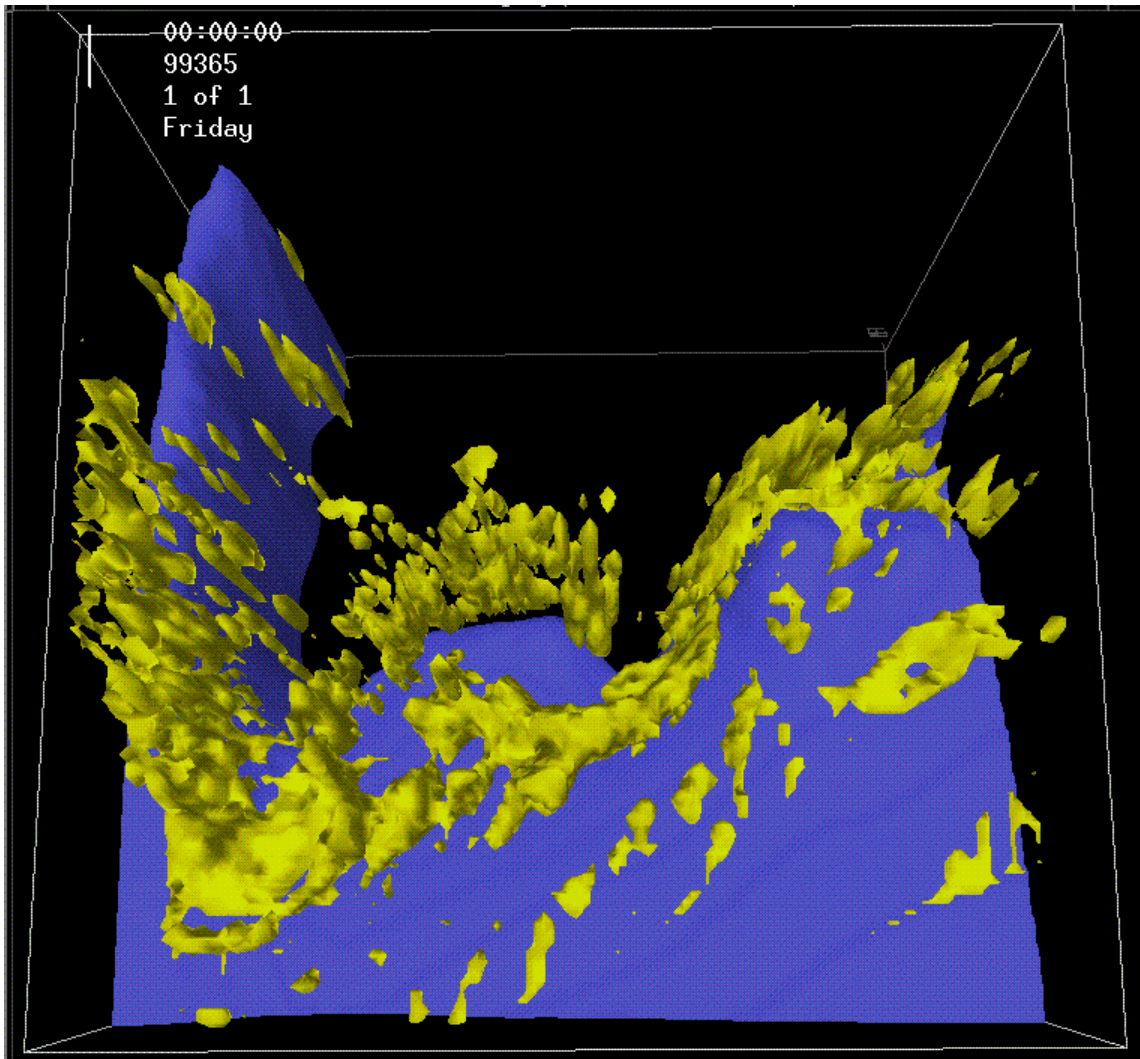


Figure 2.3.9 A 3-D view of the Bering Sea shelf, looking over the edge of the shelf break into the basin. Regions of high viscosity (and diffusivity) are colored yellow. Strongest mixing occurs at the shelf break and along the 100-meter isobath.

Aleutian North Slope Current and the Alaskan Stream/Alaska Coastal Current. As the simulation proceeds, cross-isobath mixing and advection are indicated by the difference between the value of the tracer $g(x,y,z,t)$ and the value of the local bathymetry. A positive difference syndicates either flow of initially deeper (and typically more nutrient-laden) water parcels into shoal areas, or sub-grid-scale mixing across isobaths. Results at day 60 are shown in Figure 2.3.10. Mixing and/or advection of deeper water across the shelf break is clearly implied, and a large tongue of deeper waters flows into the Southeast Bering Sea through Unimak Pass. A tongue of initially deep water penetrates up Pribilof Canyon, though its surface signal is far weaker than the Unimak tongue. An intriguing aspect of the surface pattern is its strong resemblance to the spatial pattern of primary production suggested by Springer et al. (Fish. Oceanogr., 1986).

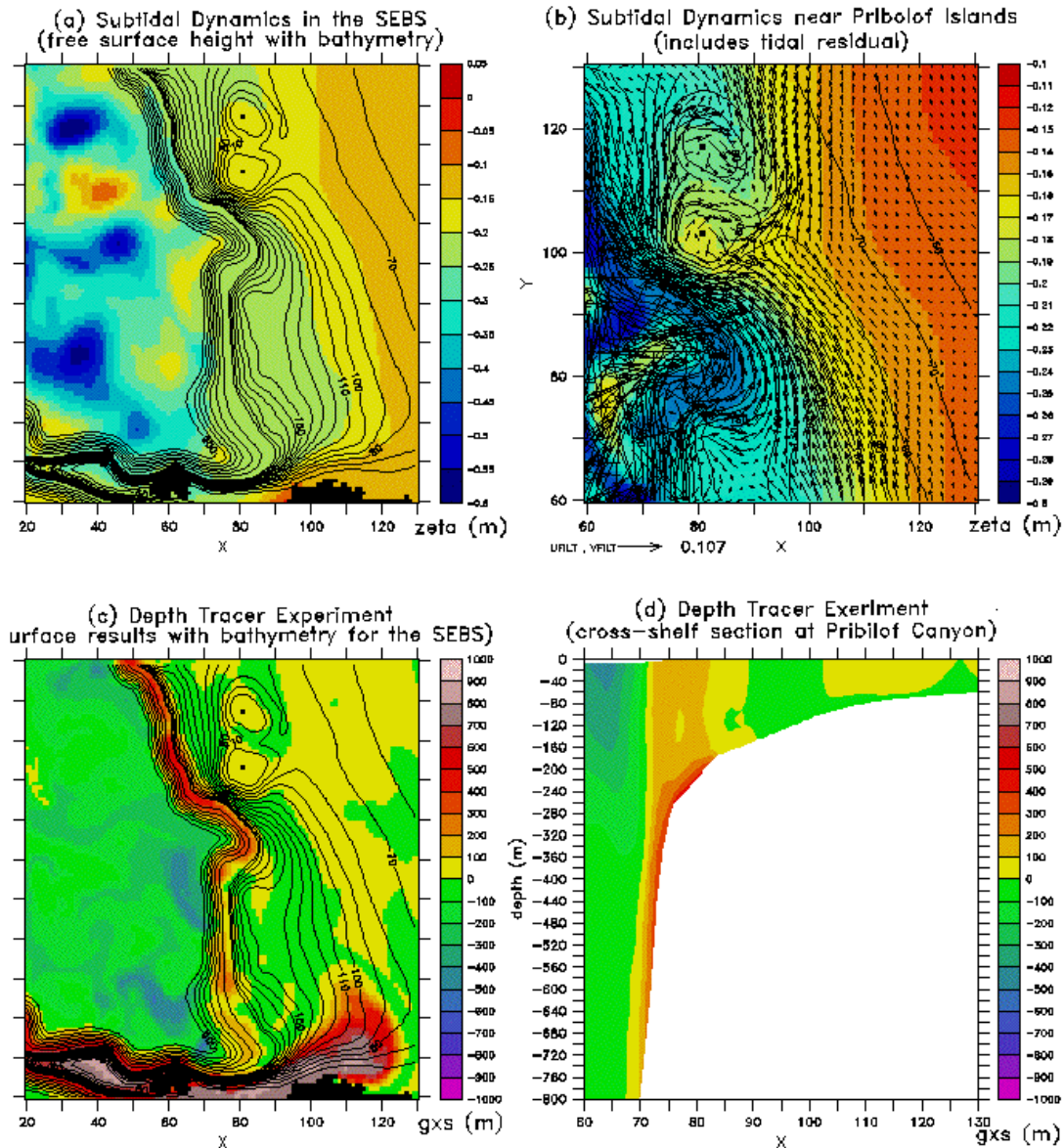


Figure 2.3.10 (a) De-tided sea surface height (m, shaded) with bathymetry, after 60 days spin up. The x and y axes are labeled by indices of the model grid. (b) Close up of de-tided sea surface height and circulation ($m\ s^{-1}$) in the vicinity of the Pribilof Islands (with St. Paul Island and St. George Island indicated by the small black squares). (c) Surface values of a "depth tracer variable" (gxs) from a passive tracer experiment, exhibiting cross-isobath mixing and advection. A positive value of gxs indicates either flow of initially deeper (and typically more nutrient-laden) water parcels into shoal areas, or sub-grid-scale mixing across isobaths. (d) Cross-shelf profile of the depth tracer variable at Pribilof canyon, exhibiting on-shelf penetration of waters from deeper areas.

7. Float tracking – Lagrangian float tracking of representative “fish” has been achieved using depth-averaged velocities for 1995 and 1997. These velocities include both tidal and subtidal components. Hinckley et al. describe this work in their final report to Phase I of SEBSCC.

Products

Presentations

Hermann, A.J., and P.J. Stabeno, 1996: A preliminary regional circulation model of the eastern Bering Sea. Theme session on "Exchanges of water, organisms and sediment between continental shelf waters and the nearby ocean", 5th Annual Meeting of the North Pacific Marine Science Organization (PICES), Nanaimo, B.C., 11-20 October 1996.

Hermann, Albert J., 1998: An open boundary technique for the simultaneous modeling of tidal and subtidal dynamics in the coastal gulf of Alaska and the Bering Sea. International conference on coastal ocean and semi-enclosed seas: circulation and ecology modeling and monitoring. Moscow, Russia, 8-12 September 1998.

Hermann, A.J., 1998: Regional modeling of the Bering Sea and CGOA. SPEM/SCRUM/ROMS/SEOM/SEAM Users Meeting, University of California - Davis, 28-31 October 1998.

Worldwide web

A Bering Sea model results home page (<http://www.pmel.noaa.gov/~hermann/sebscc.html>) has been set up with sample output (including animations and virtual worlds) from model runs.

Outlook

Interannual comparisons of circulation fields driven by tides, winds and buoyancy (including ice) must be delivered to fulfill the initial contract to Phase I of SEBSCC. Results need to be made available to other researchers through the World Wide Web. We have developed a web page with our results thus far and will continue to update it as new runs become available. Since computer and human resources are limited, we will continue to focus on the years 1995 and 1997 as an interannual comparison; once these are established we will expand to a larger range of years.

Thus far we have forced the regional model with model-generated tides, observed subtidal flows at lateral boundaries, twice-daily ECMWF winds and monthly climatological buoyancy fluxes at the surface. We are now ready to set tidal phases to correspond specifically to 1995 and 1997, and to use satellite-derived ice coverage to generate proper heat and freshwater fluxes due to ice in those years.

Results of the physical model have been coupled to a rudimentary fish model (passive float tracking with depth-integrated velocities) but must be coupled to a more elaborate pollock Individual Based Model, and upper trophic level models. We have applied for additional funds from other programs, to speed development of a lower trophic level (NPZ) model for the southeastern Bering Sea.

Results from a layered version of SEOM will be used as a boundary condition on the regional model; this will be replaced by continuously stratified results as they become available.

The funding to complete this work is from Phase II of SEBSCC.

Time line for completion

- 08/99: Interannual runs of regional model available (tides from SEOM, phased for specific years; subtidal information from SEOM, winds and buoyancy fluxes from NCEP, new ice algorithm).
- 12/99: Coupling of physical model results with more elaborate biological models
- 01/00: Three-dimensional coupling of global and regional physical models

Projected publication

Hermann, A.J., D. Haidvogel, D. Musgrave, and P. Stabeno, in preparation: An interannual comparison of circulation in the southeastern Bering Sea. *J. Phys. Oceanogr.*.

3.0 MONITORING

3.1 Monitoring and development of biophysical indices of the southeastern Bering Sea

Principal Investigators:

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R. D. Brodeur and J. M. Napp (Alaska Fisheries Science Center)
G. L. Hunt, (University of California, Irvine)

Collaborators: J. J. Cullen and R. F. Davis (Dalhousie University)

Period of Research: August 1996 through September 1998.

Goal and Objectives

The objectives of our proposed project were to:

- monitor biophysical features of the ecosystem,
- develop indices that relate to survival potential of young pollock.

Project Description

We hypothesized that biophysical indices exist that reflect the status and vitality of the southeastern Bering Sea ecosystem. To test this, we monitored critical aspects of the ecosystem from the distinct habitats extant in the southeastern Bering Sea and from these observations developed indices. In addition to providing a measure of the survival-potential of larval pollock and of the abundance of juveniles, these indices can be applied to other components of the ecosystem.

To develop indices, we took observations from moored biophysical platforms and discrete stations. We made hydrographic measurements at stations in the vicinity of Unimak Pass and at stations spanning the Aleutian North Slope and Bering Slope Current. We measured hydrography across the shelf and along the 70-m isobath, and sampled nutrient chemistry and plankton biomass at clusters of stations along those transects. We measured hydrography, nutrients and plankton biomass on four transects radiating from the Pribilof Islands. By interpreting these observations we developed indices (Table 3.1.1) that have increased our knowledge of the ecosystem, its variations from year-to-year, and differences among its habitats.

In developing the indices, our thinking benefited from a description of potential pathways through which changes in climate influence the biological environment (Francis et al., 1998). We added ice (Fig. 3.1.1) because it is a dominant feature linked to climate variability (Niebauer, 1998). Its influence is through ocean mechanisms affecting biota in a bottom-up mode, and it directly influences distributions of marine mammals and fishes thereby exerting top-down control. While not explicit in our schematic, coccolithophorid blooms also have direct influence on light penetration (primary production) and success of visual feeders.

Table 3.1.1 Indices for the southeastern Bering Sea ecosystem

Feature of the Environment	Impact on the Ecosystem	Index
1. Volume transport & water properties in the ANSC & BSC	Shelf/slope exchange (T,S, plankton & nutrients) and mesoscale variability of the slope environment	Volume transport from CTD data and characteristics of the Eulerian flow moored current observations
2. Number of eddies & their size	Same as above	#, size and energy from Eulerian and satellite sea surface height anomalies
3. Timing & strength of storms	Pelagic/benthic food web coupling and determinant of both nutrient reservoir size and stratification.	[Wind Speed] ³ modified by water column structure from platform observations
4. Extent & timing of sea ice	Initiates bloom, stratification and characteristics of cold pool.	Extent of sea ice along selected longitudes using existing NOAA-Navy ice information
5. Concentration of nutrients	Nutrient reservoir and related primary production and species composition	[N] and [Si] from discrete sampling monitoring lines, and moorings
6. Shelf/slope exchange, flux of nutrients onto shelf	Same as above	Bottom currents, temperature & salinity #3, [N], [Si] time series
7. Over wintering zooplankton population	Produces food for first feeding larvae and age-1 juveniles	Mesozooplankton & micronekton discrete samples from monitoring transects
8. Summer production based on regenerated nutrients	Determines prey production for late larvae and juvenile pollock	Standing stock of prey as measured on transects and monitoring stations. Number of phytoplankton pulses
9. Abundance, distribution and size of juvenile pollock during summer / fall	Early indication of year-class strength	Abundance from NMFS annual trawl surveys from acoustic & trawl data on Pribilof transects.
10. Jellyfish abundance	Relationship to juveniles, indicator of ecosystem change	Abundance from NMFS annual trawl surveys
11. Abundance and distribution of seabirds	Integrator of ecosystem health and change	Bird counts on Pribilof transects.

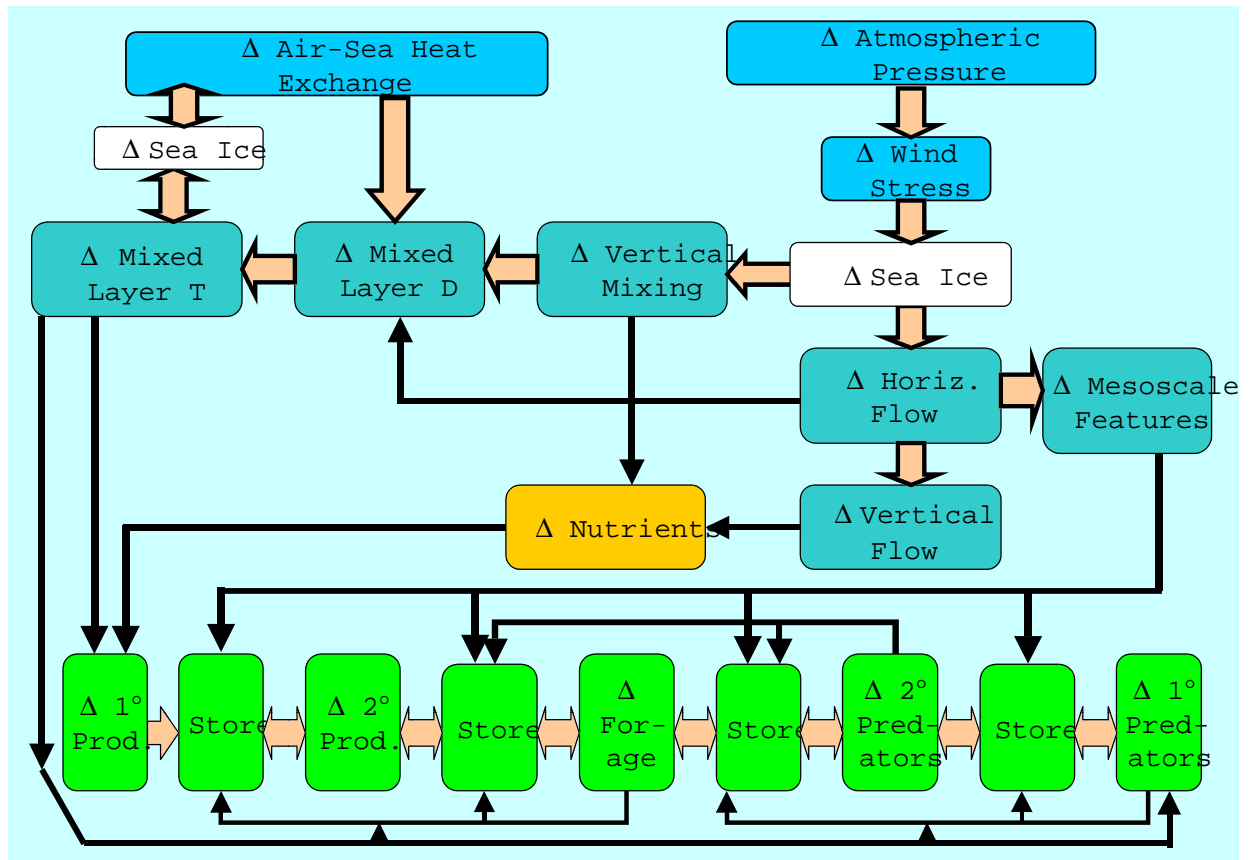


Figure 3.1.1 Mechanistic pathways through which changes in climate influence biology (after Francis et al., 1998). We added ice, which can act through both bottom-up and top-down modes.

Results

Changes in the physical environment

Because there is a relative wealth of environmental observations at Site 2 (Stabeno et al., 1997 and submitted; Fig. 3.1.2), we use observations of sea ice at this location to create an index for the southeastern middle shelf. The observations (Fig. 3.1.3) indicate ice arrived as early as January and remained as late as mid May. Between 1979-1981, ice was largely absent from the middle shelf near Site 2. This was the period of intensive study of the southeastern shelf by PROBES (Processes and Resources of the Bering Sea Shelf; Walsh and McRoy, 1986). Beginning in the early 1990's, ice once again became more common in this region, although not to the extent that was observed in the early 1970s. The manifestation of El Niño as indexed by ice is not consistent. During two of the five El Niño events since 1972, there was no ice at Site 2.

We divided ice observations into three subsets according to generally agreed upon regime shifts and/or interdecadal variations (Fig. 3.1.4): 1972-1976 (cold period), 1977-1988 (warm period), and 1989-1998 (weaker cold period) to characterize the temporal variability in the spatial pattern of sea ice. During the first period, ice covered the shelf out to and over the slope

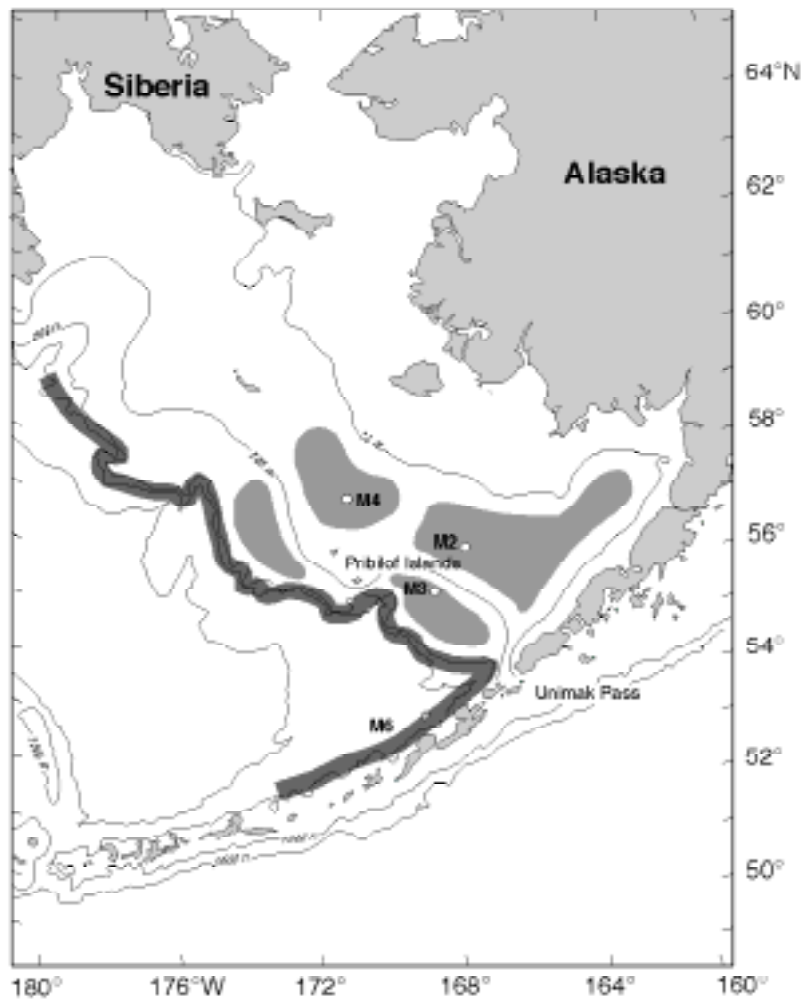


Figure 3.1.2 The eastern Bering Sea showing the location of the moored observation sites, M2, M3, M4, and M6. Shaded regions are unique habitats.

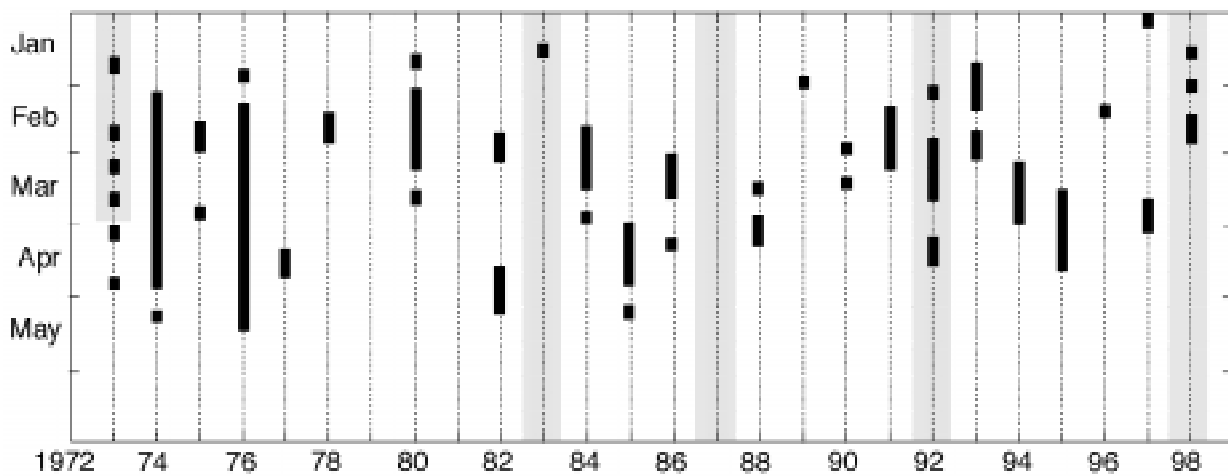


Figure 3.1.3 Persistence of ice cover at the position of Site #2 is indicated by the dark bars. The shaded areas indicate periods when an El Niño was occurring on the equator (from Stabeno et al., submitted).

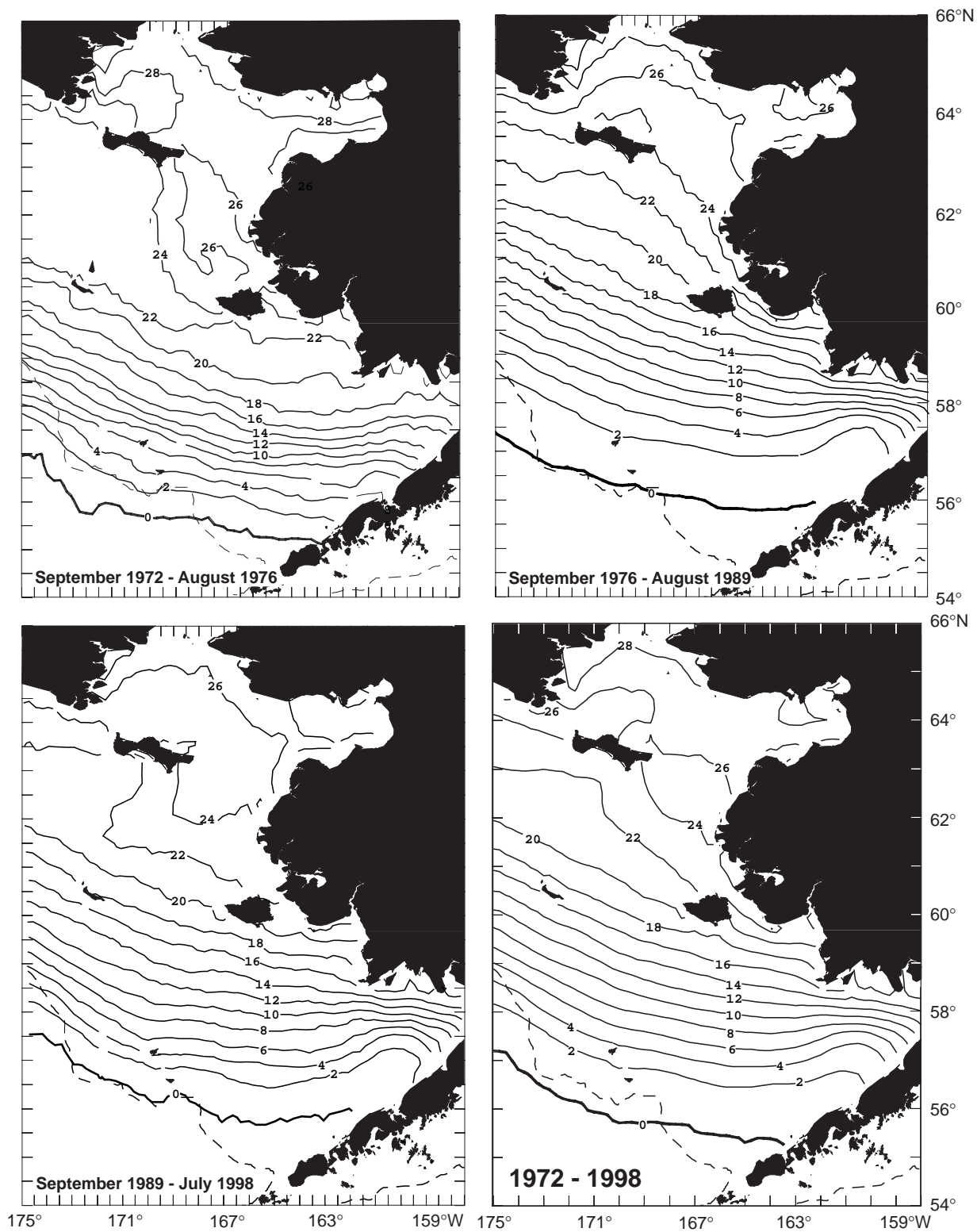


Figure 3.1.4 Contours of the number of weeks that sea ice was present over the Bering Sea shelf, shown as the average ice coverage during: a) 1972 – 1976, b) 1977 – 1988, c) 1989 - 1998 and d) 1972- 1998 (from Stabeno et al., submitted).

and remained around St. Paul Island for more than a month. During the later years, ice did not extend as far seaward and its residence time was typically 2 to 4 weeks less than during the cold period. The differences between the two latter regimes is more subtle, but still evident. Along 59°N, there were 2-4 weeks more ice during 1989-98, than during 1977-1988. Marked differences also exist in the ice distribution and extent along the Alaskan peninsula. During the cold period, ice concentration extended seaward nearly to Unimak pass, whereas in the other two periods contours of ice persistence were curved land ward into inner Bristol Bay. This pattern is likely related to variations of inflow and/or temperature of the Gulf of Alaska shelf water that flows through Unimak pass onto the Bering Sea shelf. Either condition would move the thermodynamic limit of ice further into Bristol Bay.

Temperature records (Fig. 3.1.5) reveal a large seasonal cycle that is typical for the southeastern middle shelf. In January, the water column is well mixed. This condition persists

until buoyancy is introduced to the water column either through ice melt or solar heating. The very cold temperatures that occurred in 1995, 1997 and 1998 resulted from the arrival and melting of ice. During 1996, ice was present for only a short time during February when no mooring was in place. Generally, stratification develops during April. The water column exhibits a well-defined, two-layer structure throughout the summer consisting of a 15-25 m wind mixed layer and a 35-40 m tidally mixed bottom layer. Deepening of the mixed layer by strong winds and heat loss begins as early as mid August, and by early November the water column is again well mixed.

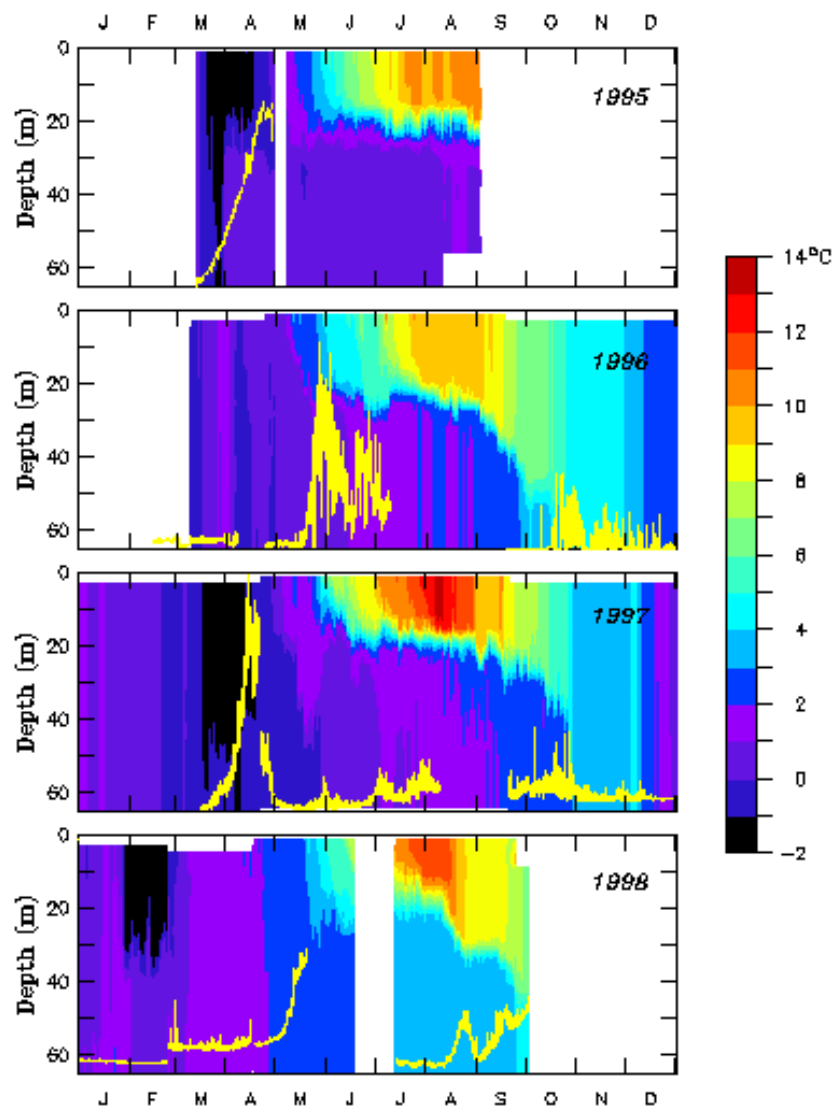


Figure 3.1.5 Time-series of water temperature and chlorophyll/fluorescence collected at Site #2. The coldest temperatures (black) indicate the presence of ice (from Stabeno et al., submitted).

During a given year, marked variations are superimposed on the mean warming trend. During 1995, ice persisted for more than a month. However, the water column was mixed to the bottom only for a short period in March because advection of warmer, more saline water in the lower layer (from the continental slope) created a strong density gradient between the upper and lower layers. This effectively insulated the lower layer, limiting warming of the cold pool to less than 0.3°C/month. The mixed layer was shallow (<20m), because of the weak winds that persisted in June and July. During 1996, sea ice arrived early in February and remained for only a short time. Since there was little buoyancy contribution from ice melt, the density gradient was weak, and above-average wind mixing resulted in a deeper surface layer than in 1995. Between April and August, the bottom temperature warmed by ~1°C/month. During 1997, ice was less persistent than in 1995, and weak winds and strong heating resulted in a shallow warm mixed layer. A storm during late May mixed the water column to 50 m, reducing the density gradient between the upper and lower layer. As in 1996, there was substantial warming (~1° C/month) of the cold pool. In contrast to 1995 and 1997, ice arrived early in February 1998, during a period of weak winds. Thus, while the ice quickly cooled the upper layer, it did not affect temperatures of the bottom layer. Only after the retreat of the ice in late February did wind energy become sufficient to mix the water column to the bottom. The combination of the warm bottom water with the cold surface water, produced above average water column temperatures. The water column then remained well mixed in 1998 until late May. The weak of stratification permitted a steady warming of the bottom layer by ~0.8°C/month from June through August.

In addition to temperature and salinity, fluorescence and chlorophyll have been measured at the FOCI biophysical platforms. A phytoplankton bloom occurred in March/April during 1995 and 1997, associated with the arrival and melting of sea ice. The bloom began even though the water column was not stratified. In 1996 and 1998, when ice was present early in the year (February) the earliest bloom occurred during may. It is likely that during 1996 and 1998, the ice was present too early in the year (insufficient sunlight) to initiate an ice associated bloom.

The data collected at Site 2 have provided insight into dynamics over the southeast Bering Sea middle shelf and characterized the extremes of 1997 and 1998. The major findings from data collected at this site include:

1. Melting ice did not result in a stratified water column that persisted through the summer. Strong mixing typically occurs during the presence of ice.
2. The presence of ice after mid-March (when there is adequate light) results in an early phytoplankton bloom in March/April that depletes nutrient from the upper layer (photic zone). This bloom can occur without water column stratification. If ice is not present after mid-March, the bloom does not occur until May/June.
3. The spring phytoplankton boom can begin before stratification of the water column.
4. The strong summer thermocline breaks down in November, and accompanying this is a fall bloom marked by an increase in fluorescence.
5. Monthly mean currents are strongest during the winter months when the frontal systems over the shelf are weak or nonexistent.

Moorings at Site 3 were maintained for about 6 months each year centered on the summer. The lack of winter data clearly limits the understanding of cross shelf flow and the replenishment of nutrients. Despite the lack of data, there are however, clear results from this data set.

1. Salinity is higher at Site 3 than at Site 2. There is a positive trend of increasing salinity from March until September, especially below the mixed layer. Since higher salinity over this shelf is often associated with slope water (generally higher nutrients), there may be a replenishment of nutrients over the outer shelf during the summer.
2. Although in recent years ice has been uncommon to the site, when ice is present after mid-March, a bloom is associated with it just as over the middle shelf domain.
3. During the years without an ice associated early bloom, the spring phytoplankton bloom occurred at either the same time or later than at site 2. This is different from what was observed during PROBES where the spring phytoplankton bloom began first over the Outer Shelf and then later over the Middle Shelf.
4. Maximum SST is less at Site 3 than at Site 2 and occurs about a week later.

A subsurface mooring was deployed at Site 4 for 18 months. Although Site 4 is at the same water depth as site 2 (72m), there is a marked difference in the dominant mechanisms. Ice persists longer (on average ~6 weeks) here than at Site 2 (on average 2 weeks). Although this site was only occupied for 18 months, several observations resulted.

1. Three phytoplankton blooms were evident during September 1996-May 1997. One in October, second in late March and the third in early May.
2. The two-layer structure appears weaker at Site 4 than that observed at site 2. It is also not as well mixed during the winter. This is likely due to the cross shelf advection that occurs in this region (Reed and Stabeno, 1996).
3. Pulses of horizontal advection are evident during the winter and spring.

Subsurface moorings have been placed at Site 6 since April 1995. Strongest currents are at the surface and can exceed 100 cm/s. During 1997 and 1998, transport in the ANSC has been above normal and inflow through Amukta Pass is evident in the time series of temperature at this site. The effect of higher transport in the ANSC/BSC system on shelf slope exchange will be explored during the next year, but initial results indicate that when the slope currents are particularly large, on shelf transport is reduced.

Biotic responses

Mechanisms, many of which are neither known nor understood, transfer climate changes to biota (Fig. 3.1.1). Identifying and understanding how these mechanisms function is central toward comprehension of ecosystem dynamics (Francis et al., 1998). Physical phenomenon impact biota through changes in the nutrient-phytoplankton-zooplankton sequence (i.e., bottom-up control) and/or by altering habitat resulting in changes in abundance and/or composition of higher trophic level animals (i.e., top-down control). For the eastern Bering Sea, top-down control may be responsible for year-to-year fluctuation of zoo-and phytoplankton biomass, while bottom-up control has been suggested as the mechanism for longer period (decadal) variations (Sugimoto and Tadokoro, 1997). A feature not present in more temperate ecosystems, sea ice and its interannual variation, has a marked impact on the ecosystem (Schumacher and Alexander, in press). Distributions of marine mammals (Tynan and DeMaster, 1997) and fish (Wyllie-Echeverria and Wooster, 1998), as well as survival of age-1 pollock (Ohtani and Azumaya, 1995), respond to the extent of sea ice itself and to that of the cold pool of bottom water which is directly related to ice cover (Schumacher and Stabeno, 1998). The substantial increase in

jellyfish biomass observed over the eastern shelf of the Bering Sea may be linked to climate change through ice cover (Brodeur et al., submitted). The extent, timing and persistence of ice cover dramatically alters time/space characteristics of primary production (Niebauer et al., 1995; Stabeno et al., 1998), secondary production and hence food for larval fishes (Napp et al., submitted). Knowledge of mechanisms that link the intimately coupled atmospheric-ice-oceanic system to biota is crucial toward understanding the ecosystem of the Bering Sea.

It is clear that climatic factors have a profound impact on populations of marine biota in the Bering Sea (e.g., Napp and Hunt, submitted). Although the details of how this occurs typically are obscure, temperature, turbulence and transport are primary candidates for operative mechanisms. Recent results support the belief that interannual and decadal changes in the environment (using ocean temperature as an index or measure of the changing state of the physical environment) play a significant role in salmon production in Alaskan waters (Downton and Miller, 1998; Kruse, 1998; Welch et al., 1998). Another study suggests the importance of turbulent mixing processes in the North Pacific Ocean to salmon production (Gargett, 1997). In the southeastern Bering Sea, the mechanism of advection of the planktonic stages of pollock (Wespestad et al., in press) and Tanner crabs (Rosenkranz et al., 1998) accounts for some of the observed fluctuations in year-class strength. In these studies the mechanism which links advection to year class strength is predation. The advection models use wind-drift of the planktonic stages either to or away from regions where strong predation pressure exists. Such examples of research show that we are making progress towards linking climate changes and biological processes to form a more realistic and complete understanding of the ecosystem.

The coccolithophorid blooms in 1997 to present occurred under different environmental conditions (Hunt et al., submitted). Why did this happen and what are the implications for the occurrence of blooms in the future? What are the implications of coccolithophores replacing the small flagellates that normally dominate in summer? It is likely that favoring another trophic level between primary producer and consumer (i.e., microzooplankton; Nejstgaard et al., 1997) will affect ecosystem dynamics (Napp and Hunt, submitted). Attenuation and scattering of light by whole cells and detached liths alters submarine light fields (Voss et al., 1998), influencing competition among phytoplankton species and affecting the quality and quantity of light for subsurface visual predators (e.g., diving seabirds). Dense concentrations of coccolithophores also alter regional biogeochemical cycles making large positive contributions to calcite and dimethylsulfide production (e.g., Matrai and Keller, 1993; Brown and Podesta, 1997).

Other dramatic changes in the ecosystem have occurred which emphasize the importance of biological interactions. During the regime shift of the mid-1970s, the physical system of the Bering Sea experienced significant change. Atmospheric conditions which had favored strong winds from the north, extreme ice cover and an extensive cold pool became those which generated minimal ice cover and magnitude/extent of the cold pool. In addition, surface wind-drift (transport of planktonic material) also changed markedly (Wespestad et al., in press). The environmental conditions in winter and spring of 1977/78 established a set of crucial biophysical features that promoted the development of the extremely large 1978 year class of pollock. While the exact nature of this increase is unknown, the role of cannibalism resulting from the strong year class is being elucidated (Livingston and Methot, 1998). The abundance of a cannibalistic population began to increase sharply around 1983, when individual pollock in the 1978 year

class became large enough to start eating juvenile pollock to a large extent and caused age-1 predation mortality to increase sharply (Fig. 3.1.6). Livingston and Methot (1998) used a predation model to examine estimates of the absolute abundance of pollock year classes at the beginning of age-1 (i.e., the number that existed before cannibals ate them; Fig. 3.1.6), and showed that there were several good year classes after 1978. These started out at age-1 in greater abundance than the 1978 year class, but, due to cannibalism, a lower year class abundance when seen as age-3 recruits into the fishery. Model results indicated the possibility of two different spawner-recruit relationships, one for average to cold years and one for warmer years. This result would not have stood out as clearly if predation mortality was not understood and taken into account. Further, the results highlight the importance of studying the biotic interactions in order to pinpoint which life history stage of a given population is most influence by abiotic factors. Although there have been above-average year classes since 1978, none have appeared quite so large when they recruit to the fishery because of this increase in predation mortality. We likely won't see a year class as large as the 1978 year class again until we get a combination of a relatively low adult population and winter/spring conditions favoring larval survival.

Smaller than average adult salmon (Kruse, 1998), and decreases in the numbers of seabirds breeding on the Pribilof Islands since the mid 1970s point to a recent change in the carrying capacity of the middle shelf region (Hunt and Byrd, in press). Food may be becoming a limiting resource for populations such as walleye pollock due to the increased abundance of some planktivorous marine mammals that are rebounding from decades of whaling (Merrick, 1995; Tynan, 1998). Further pressure on food resources results from the marked increase in biomass of jellyfish in the 1990s that may be related to climate changes this decade (Brodeur *et al.*, submitted). It was found by direct examination of stomach contents and use of stable isotopes that these large medusae occupy a similar trophic level as adult pollock and may in fact be consuming late larval and early juvenile pollock (Sugisaki and Brodeur in prep.). As noted by Napp and Hunt (submitted), if food becomes limiting, then climate induced perturbations that affect production and availability of zooplankton may have an even greater effect on the structure of trophic webs than was observed in 1997.

Products

Manuscripts submitted

- Brodeur, R. D., C. E. Mills, J. E. Overland, G.E. Walters, and J. D. Schumacher, submitted: Evidence for a substantial increase in jellyfish biomass in the Bering Sea, with possible links to climate change. *Fish. Oceanogr.*
- Hunt, Jr., G.L., C.L. Baduini, R.D. Brodeur, K.O. Coyle, N.B. Kachel, J.M. Napp, S.A. Salo, J.D. Schumacher, P.J. Stabeno, D.A. Stockwell, T.E. Whitledge, and S.I. Zeeman, submitted: The Bering Sea in 1998: A second consecutive year of extreme weather-forced anomalies. *EOS Trans. Amer. Geophys. Union.*
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- Napp, J.M., A.W. Kendall, Jr., and J.D. Schumacher, submitted: Biophysical processes relevant to recruitment dynamics of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea. *Fish. Oceanogr.*

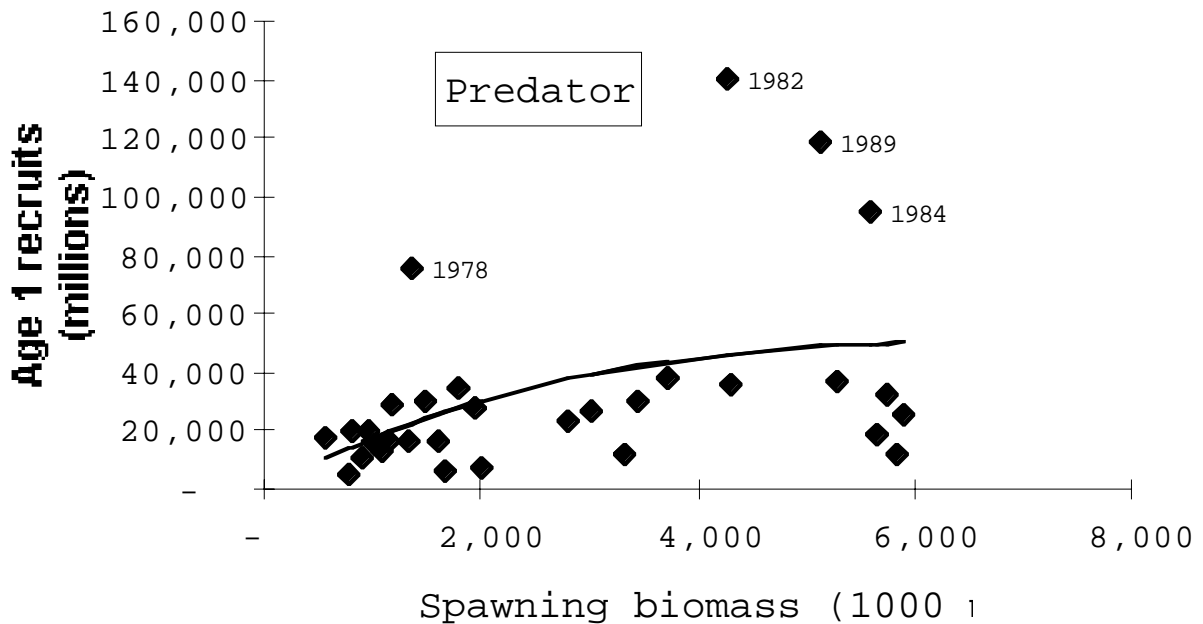


Figure 3.1.6 (top panel) Predation mortality of age-1 walleye pollock from 1963 to 1995 estimated by the eastern Bering Sea pollock population model with predation by adult pollock, Pacific cod and northern fur seals. (bottom panel) Estimates of age-1 recruitment of pollock recruits versus pollock spawning biomass from the pollock population model with predators and the fitted Ricker stock recruitment curves. (from Livingston and Methot, 1998).

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Outlook

While we made outstanding progress, our objectives could not be met to the extent we wanted. This was due to several factors as we noted in the First Annual Report:

1. The program needs to replace lost equipment if monitoring at the present level is to be maintained.
2. The capability to monitor dissolved nitrate and nitrite concentrations from the moorings is necessary to examine biophysical coupling of nutrient dynamics.
3. The importance of the ANSC/BSC to the supply of nutrients on the outer shelf requires more extensive monitoring. (We recommend deployment of satellite-tracked buoys near mooring sites 6 and 4.)

We lack complete annual coverage of shipboard collections during critical times in the production cycle (November and June/July). Lack of equipment resulted in limited data acquisition at Sites 3 and 4. We are now seeking funds from the North Pacific Research Initiative to address this unfortunate situation. SEBSCC has now funded nitrate meters, addressing the second recommendation. An active satellite tracked buoy program is still missing. Funds were requested from SEBSCC, Phase II for funding fall and summer cruises, but there was not enough money to cover salaries for the cruises. Therefore this is still an unfunded, critical need. In Results, we provided many examples of changes in ecosystem dynamics of the southeastern Bering Sea. To further our understanding of how this ecosystem functions requires a greater monitoring effort of both physical and biological parameters. This will allow identification of the important fluctuations and elucidation of the mechanisms by which changes in physical phenomenon are transferred to biota. In addition, this would permit the development of more complete knowledge of the life histories of the central species in ecosystem and elucidate biological mechanisms such as predation.

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3.2 An altimetric census of mesoscale eddy-like features in the Bering Sea

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Period of Research: August 1996-September 1997

Goal and Objectives

The goal of this research was to compile a census of eddy-like mesoscale features in the deep Bering Sea from measurements of sea surface height (SSH) anomalies acquired by GEOSAT and TOPEX satellite altimeters. Our objective was to employ spectral and least squares methods to analyze satellite altimetry in the Bering Sea to describe the distribution and variability of mesoscale eddy-like features in the space-time domain.

Project Description

Model results and isolated observations of individual eddies indicate the presence of eddies in this region. However, a comprehensive description of the mesoscale eddy field in the Bering Sea has not yet been developed. Combined observations from satellite altimeters provide nearly 5 years of SSH measurements for the Bering Sea. The region of principal interest and effort for the present study is the shelf break region in the central Bering Sea, a region of high primary productivity and along which flows the Bering Slope Current (Fig. 3.2.1). Isolated eddies as well as groups of eddies are identified in individual along-satellite-track profiles of SSH anomalies. Altimetry data was subjected to spectral and empirical orthogonal function analyses to relate mesoscale variability to gyre-scale variability.

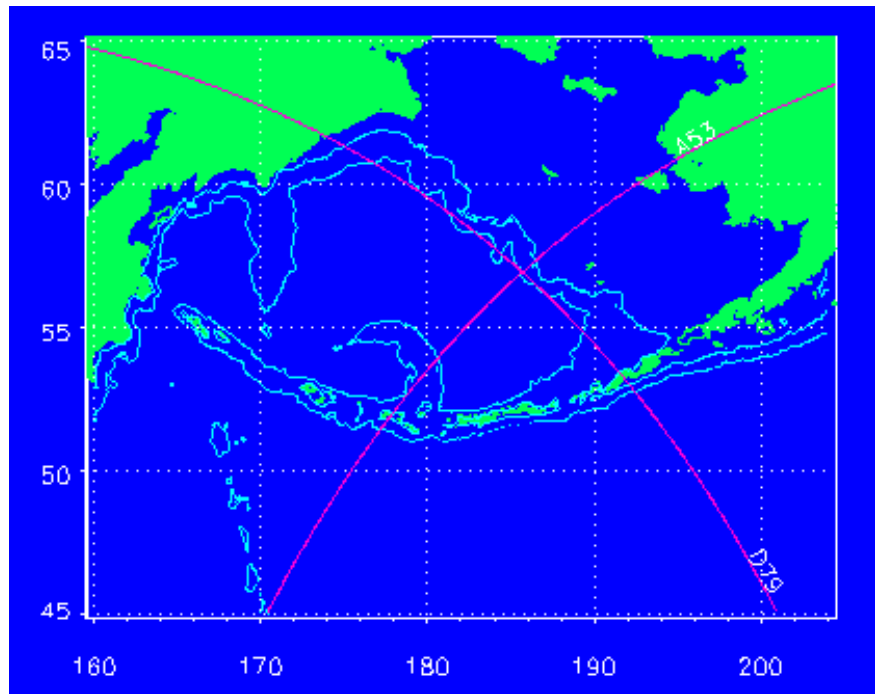


Figure 3.2.1 The Bering Sea region. TOPEX altimeter orbital ground tracks A53 and D79 are labeled. The 200-m and 3000-m isobaths are also shown.

Results

Maps of SSH variability in the Bering Sea constructed for the periods of GEOSAT and TOPEX missions indicate that eddy-like activity along the shelf break region of the basin is greater than that which occurs in the central basin. The altimeter data reveal mesoscale activity occurring near the shelf break region during the entirety of the data record (Fig. 3.2.2). The observed mesoscale features exhibit a component of propagation along the shelf break. Other analyses of the data reveal both on-shelf and off-shelf components of propagation. Those features exhibiting an on-shelf component of propagation are interpreted to be topographic planetary waves, whereas, the mesoscale features which are observed to propagate into the central Aleutian Basin are interpreted to be baroclinic planetary waves. The topographic planetary waves have a representative

wavelength and period of

about 100 km and 2-3 months, respectively. The baroclinic planetary waves are characterized by wavelengths of hundreds of kilometers and periods of hundreds of days. Shorter period activity typically occurs nearer the shelf break than longer period activity (Fig. 3.2.3), and this may be

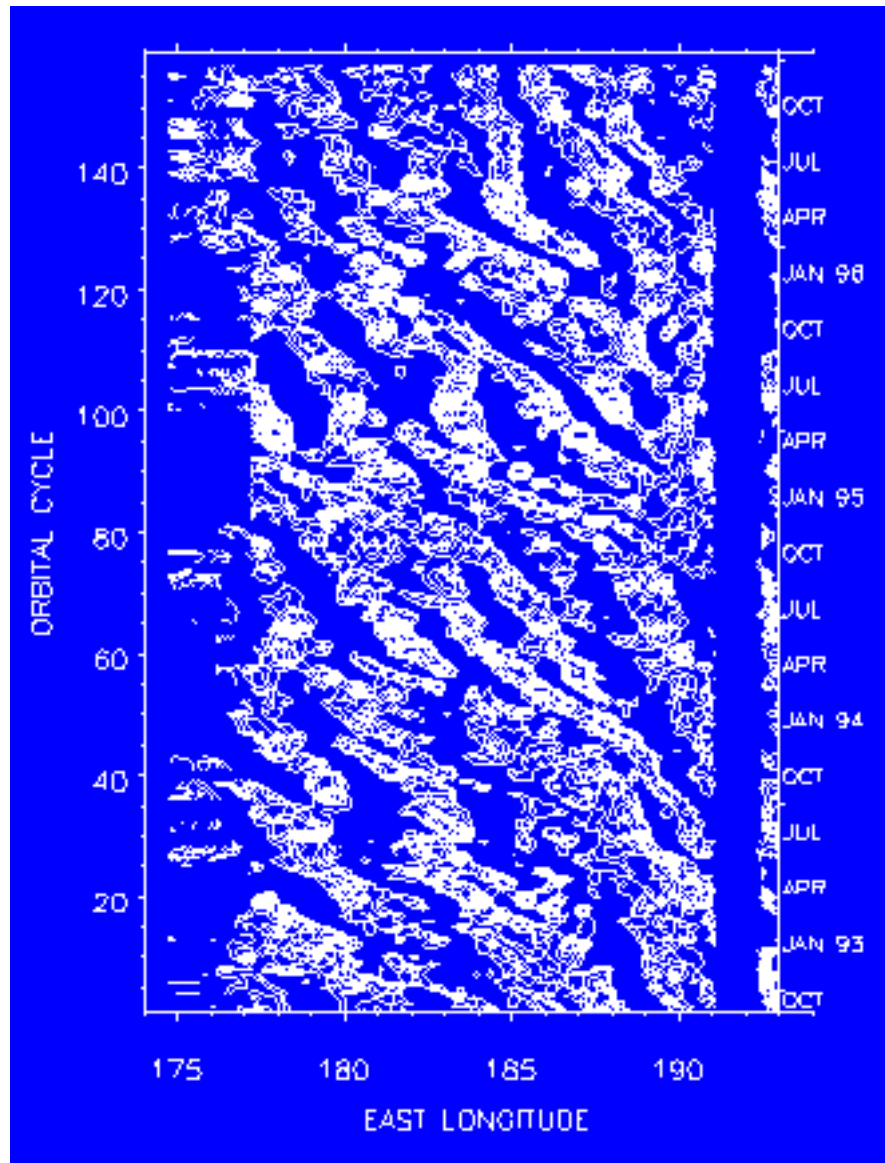


Figure 3.2.2 A time-longitude distribution of anomalous sea surface slope along TOPEX orbital ground track D79. This ground track passes from northwest to southeast just seaward of the shelf break in the central Bering Sea. Only positive slopes are shown for clarity. The contour interval is 0.5 microradian. Long-lived mesoscale SSH anomalies, exhibiting a northwestward component of propagation, are readily apparent.

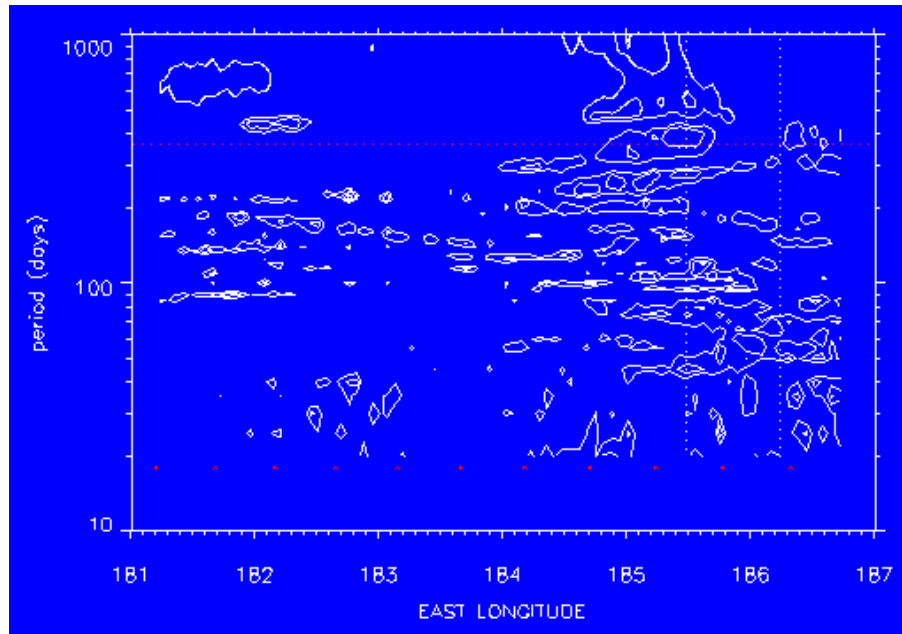


Figure 3.2.3 The distribution of relative eddy energy along orbital ground track A53 for the range of eddy periods 20 days to 1000 days (in 5-day increments). The contour interval is standard deviations in excess of the mean eddy energy at each incremental period. The horizontal dotted line indicates the annual period. Vertical dotted lines indicate the locations of the 3000-m and 200-m isobaths (i.e. the nominal extent of the continental slope).

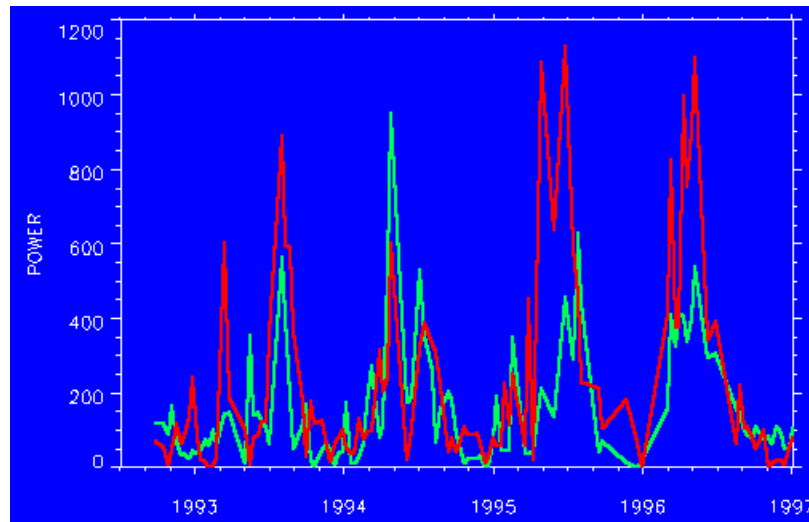


Figure 3.2.4 Time series of autospectral power for eddy activity at wavelengths of 197 km (green) and 262 km (red) along orbital ground track D79.

evidence of wave dispersion as waves propagate away from the shelf break. The eddy field undergoes a seasonal modulation such that greatest amplitudes typically occur in the spring and summer months (Fig. 3.2.4). Very little eddy activity, coherent with that occurring seaward of the shelf break, is observed on the continental shelf.

Products

Publications

A manuscript summarizing this research is currently being prepared.

Presentations

Okkonen, S.R., 1997: Altimetric census of mesoscale eddy-like features in the Bering Sea. SEBSCC PI Workshop, 15 -16 December 1997, Battelle Seattle Conference Center, Seattle Washington.

Okkonen, S.R., 1998: Altimeter observations of the mesoscale eddy field along the shelf break in the central Bering Sea. North Pacific Marine Science Organization (PICES) Seventh Annual Meeting, Fairbanks, Alaska, October 14-25, 1998.

Outlook

Present efforts are directed at investigating (1) what relationship may exist between wind forcing and the nature of the mesoscale response and (2) cross-shelf influence of the shelf break planetary wave field.

4.0 LOWER-TROPHIC-LEVEL PROCESSES

4.1 Investigation of the origin and dynamics of nutrients on the Southeast Bering Sea shelf in relation to dominant physical and biological processes

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Goal and Objectives

The goal of this research was to determine the nutrient dynamics of the southeastern Bering Sea shelf in collaboration with physical and biological components to obtain quantitative estimates of

1. onshore fluxes of nutrients from the open ocean;
2. vertical nutrient fluxes resulting from wind mixing events;
3. nutrient utilization by the dominant phytoplankton species; and
4. nutrient remineralization by biota in the upper and lower water columns.

Overall, the objectives tested the following hypotheses with respect to the nutrient investigations proposed herein:

1. nutrient enrichment of the shelf occurs as the result of advection of new water into the Bering Sea through Aleutian passes, shoreward propagation of eddies that dissipate their energy at the shelf break, or eddy diffusion from deep source waters.
2. vertical mixing from wind events significantly enriches the nutrient concentrations of surface waters of the shelf ecosystem to help sustain summer rates of primary production and interannual variations of vertical mixing help drive changes in primary production.
3. storage of nutrients in the bottom layer on the shelf occurs as a result of sinking and remineralization processes and provides significant nutrient carryover from one year to the next.
4. primary production consumes all available inorganic nitrogen nutrients in the euphotic zone on the shelf hence physical processes primarily control total annual amounts of primary production.
5. concentrations of dissolved organic nitrogen in shelf waters vary significantly during spring, summer and fall seasons and spatially over 10s of km.
6. variable ratios of N:Si:P in the euphotic zone influence the dominant types of phytoplankton that occur on the shelf.

Project Description

The productivity of the southeastern Bering Sea shelf is strongly related to the quantity of nutrients required for primary production processes. This research investigated the nutrient dynamics of the study region in collaboration with physical and biological components to obtain quantitative estimates of 1) onshore fluxes of nutrients from open ocean sources, 2) vertical nutrient fluxes resulting from wind mixing events, 3) nutrient utilization by the dominant phytoplankton species, and 4) nutrient remineralization by biota in the upper and lower water columns. In addition, a description of ambient nutrient availability provided a general context of the nutrient environment of the study area. The more detailed understanding of the nutrient dynamics in the ecosystem provided a better link among physical processes, nutrient enrichment, primary production and the food environment for higher trophic levels. The results of the research were attained from a highly integrated, multidisciplinary approach that built on substantial results of prior research.

Results

The shipboard nutrient analyses for nitrate, nitrite, ammonium, phosphate and silicate was carried out using a segmented flow automated chemical analyzer using standard techniques (Whitledge et al, 1981). The basic analytical methods were described by Armstrong et al (1967) but modified for small sample volumes and maximum precision. Ammonium was measured by the phenolhypochlorite method of Koroleff (1970) as adapted to automated analysis by Slawyk and MacIsaac (1972) and modified by Patton and Crouch (1977). Urea analyses using the automated thiosemicarbazide method (Rahmatullah and Boyd, 1980) was performed on water samples for primary productivity measurements. DON frozen samples were analyzed with an automated, high-intensity UV irradiation method that utilized hydrogen peroxide and pH manipulation to achieve >95% oxidation.

Measurements

Water samples were collected on several cruises listed below for:

1. Nitrate plus nitrite	all fresh and frozen samples
2. Nitrite	all fresh and frozen samples
3. Ammonium	all fresh and frozen samples
4. Phosphate	all fresh and frozen samples
5. Silicate	all fresh and frozen samples
6. Urea	productivity frozen samples
7. Dissolved organic N	selected hydro and productivity frozen samples
8. Chl/HPLC pigments	selected depths on hydro and prod samples

SEBSCC Cruises:

MF 97-01	Feb 97	Miller Freeman	frozen hydrography
MF 97-05B	May 97	Miller Freeman	fresh hydro and productivity
WE 97-06B	June 97	Wecoma	fresh hydro and productivity

MF 97-09	Sept 97	Miller Freeman	fresh hydro and productivity
MF 98-01	Feb 98	Miller Freeman	frozen hydrography
MF 98-05A	May 98	Miller Freeman	fresh hydro and productivity
WE 98-04D	May 98	Wecoma	fresh hydro and productivity
WE 98-05A	May 98	Wecoma	fresh hydro and productivity

Other Cooperative Program Cruises (Bering Sea Inner Front Studies):

AH 97-196	June 97	Alpha Helix	fresh hydro and productivity
AH 97-200	Aug-Sept 97	Alpha Helix	fresh hydro and productivity
AH 98-209	June 98	Alpha Helix	fresh hydro and productivity
AH 98-213	Aug-Sept 98	Alpha Helix	fresh hydro and productivity

1997 and 1998 nutrient regimes on the SE Bering Sea shelf

The April-May period of 1997 exhibited an unusual lack of wind mixing events over the Bering shelf. This resulted in an unusual early April bloom that peaked before our cruise arrival in early May. The 1997 bloom occurred several weeks earlier than was observed during the late 70s and early 80s (i.e. mid-May). This may have had a profound effect on the food web of migratory animals dependent on spring bloom production. A major proportion of the bloom phytoplankton during the 1997 spring bloom settled out of the euphotic zone and thus effectively nourished deep water and benthic food webs. A strong stratification of the shelf water column was observed during the 5-7 May SEBSCC cruise. Water column phytoplankton biomass (as measured by chlorophyll) indicated that peak bloom conditions were already occurring over the outer shelf domain while post-bloom conditions prevailed in the middle shelf domain with most of the chlorophyll having already settled to depths below the euphotic zone (Fig. 4.1.1). Ice melting apparently provided the physical mechanism for bloom initiation by causing density-driven intense stratification. This stratification along with a much below 1997 wind stress over the shelf allowed the early spring bloom to quickly exhaust all euphotic zone nutrients in the middle shelf domain by 5-7 May.

We started the 1998 cruises earlier in the year to make sure that we observed the spring bloom because it was missed during the 1997 cruises. In 1998 another unusual bloom sequence was observed. During the 1998 cruises (April and May), stratification, an essential factor for bloom development, did not develop due to strong wind mixing over the Bering Sea shelf. The typical spring bloom could thus not develop because of the extensive water column mixing and poor light conditions (Fig. 4.1.1). The extensive mixing continued through the spring and early summer producing conditions that allowed only slow growth of phytoplankton. As the phytoplankton grew slowly, they depleted the nutrients of the water column at slower rates than those previously observed. We can speculate that under these conditions, greater proportions of primary production were transferred to pelagic food webs than to benthic food webs.

Deep nitrate uptake

Vertical profiles of nutrients in 1997 over the Bering shelf showed a normal progression from high winter surface values to low values after the peak of the spring bloom. However, nutrients

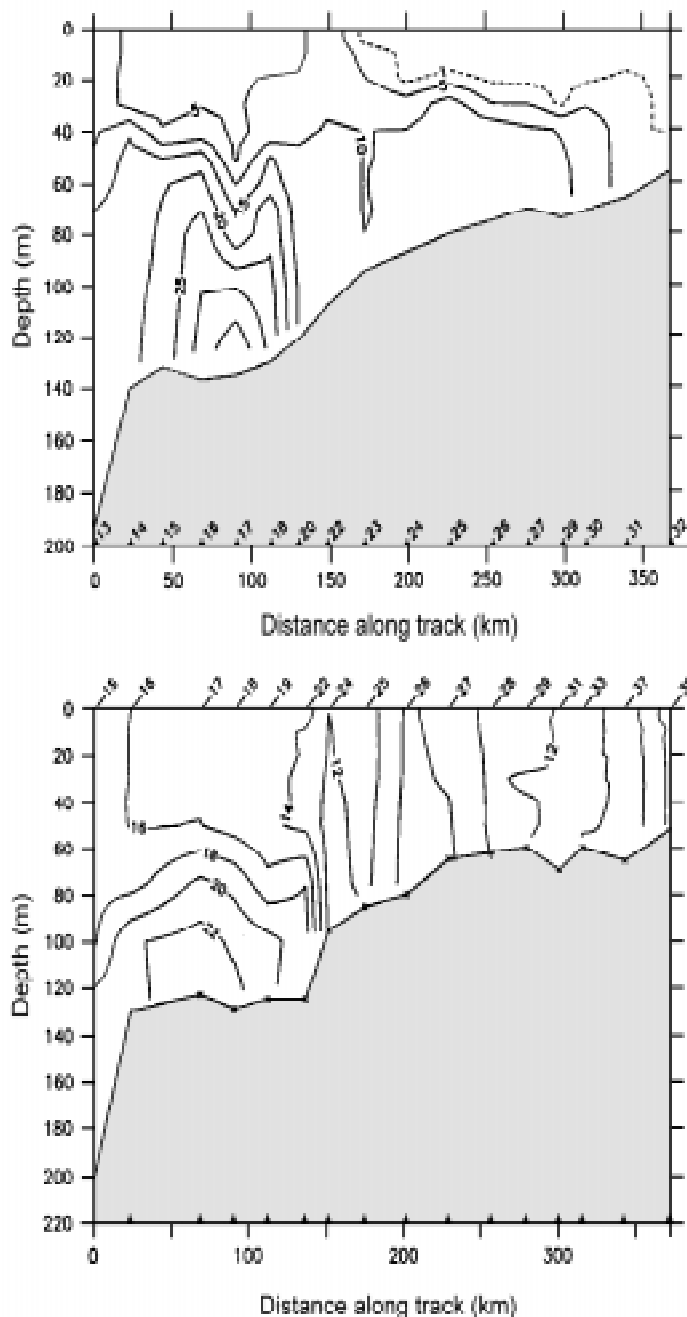


Figure 4.1.1 Cross sections of nitrate ($\mu\text{M l}^{-1}$) on the southeastern Bering Sea shelf near 56.3°N 165.6°W sampled May 5-7, 1997 (top) and May 9-12, 1998 (bottom).

Ammonium concentration was especially high along the 60 - 80m isobath. High nutrient concentrations remained over the whole southeastern Bering Shelf area throughout May. Because of frequent storm activity, suitable conditions for phytoplankton blooms did not develop

during 1997 were also depleted below the pycnocline (Fig. 4.1.2). Normally a much larger nutrient pool ($8\text{-}10 \mu\text{M NO}_3$ and $20\text{-}30 \mu\text{M}$ silicate) remains under the pycnocline for the duration of the summer. The bottom nutrient pool was depleted in June 1997 by “new” production (nitrate consumption) occurring in the pycnocline. Wind mixing over the eastern Bering Sea shelf during the 1997 summer was low compared to most years. Calm conditions result in shallow upper wind-mixed layers. The shallow, upper mixed layer during the 1997 summer allowed the euphotic zone to extend below the pycnocline. Phytoplankton thus had access to deep-water nitrate and other nutrients. This led to deep nitrate uptakes for most of the early summer and an unusual depletion of nutrients below the pycnocline to the shelf seabed (Fig. 4.1.2). During the PROBES studies, such calm mixing conditions were never observed and a significant summer depletion of nutrients below the shelf pycnocline did not occur.

Vertical profiles of nutrients during 1998 did not show similar low values below the pycnocline as were observed in 1997 (Fig. 4.1.1). During the May WE9805A cruise, we observed homogeneous nutrient concentrations throughout the 80-m water column from February through June (Fig. 4.1.2). We also observed unusually high levels of ammonium ($4\text{-}20 \mu\text{M}$) over the whole shelf area.

during 1998. These storms also transported high-nutrient deep water to the shelf region continuously. The concentration of nutrients across the shelf decreased toward shore, which implies that significant amounts of nutrients were transported from deep water. Nitrate uptake rates were high at the surface and decreased with depth due to light limitation.

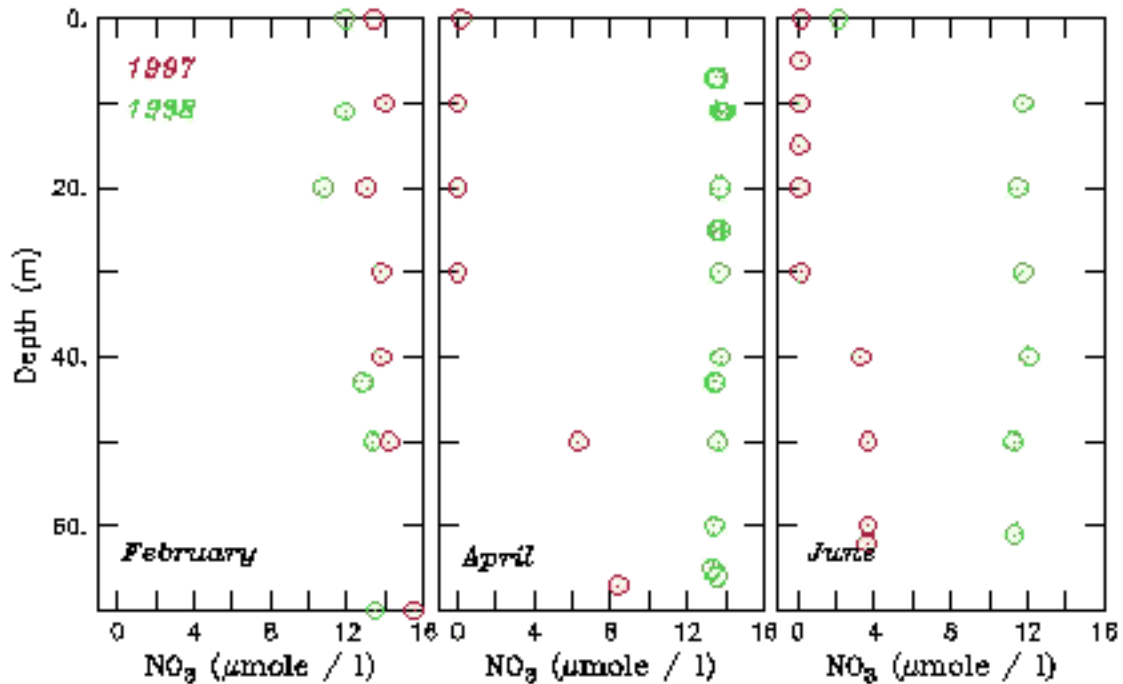


Figure 4.1.2 Profiles of nitrate show the depletion of nutrients in 1997 as opposed to 1998.

Coccolithophorid bloom

Sometime between the spring 1997 diatom bloom (late April) and the onset of fall storms (September), an environmental “switch” or series of switches were set that favored the outbreak of a coccolithophorid phytoplankton population. The bloom was first observed by water color in early July 1997. In September the aerial extent was documented with the first available SeaWiFS ocean color satellite images. During late September the bloom was ca. 700 km, and extended from the Alaska Peninsula north to Nunivak Island, and from Bristol Bay to just west of the Pribilof Islands. The vertical extent of opaque coccolithophorid water was 10-50m with secchi depths as low as 2m. This appears to be the largest coccolithophorid bloom reported for the Bering Sea. The bloom organism, *Emiliania huxleyi*, is small (approximately 6- μm diameter) and covers itself with calcium carbonate plates or coccoliths. Each cell contains about 10pg organic carbon.

During 1998 we also observed a coccolithophorid bloom around Nunivak Island. Although the first clear SeaWiFS image was obtained in mid-July 1998, there is some isotopic evidence that the bloom started in early spring. During the MF9804 cruise, we occupied several stations between the Pribilof Islands and Nunivak Island.

Products

Publications

- Stockwell, D.A., T.E. Whitledge, S.I. Zeeman, K.O. Coyle, J.M. Napp, R.D. Brodeur, and A.I. Pinchuk, submitted: Anomalous conditions in the southeastern Bering Sea, 1997: Nutrients, phytoplankton, and zooplankton. *Fish. Oceanogr.*
- Vance, T.C., J.D. Schumacher, P.J. Stabeno, C.T. Baier, T. Wyllie-Echeverria, C.T. Tynan, R.D. Brodeur, J.M. Napp, K.O. Coyle, M.B. Decker, G.L. Hunt, D.A. Stockwell, T.E. Whitledge, M. Jump, and S.I. Zeeman, 1998: Aquamarine waters recorded for first time in eastern Bering Sea. *Eos, Trans. Amer. Geophys. Union* 79: 121-126.

Meeting abstracts and presentations

- Hunt, G.L., C.L. Baduini, R.D. Brodeur, K.O. Coyle, J.M. Napp, J.D. Schumacher, P.J. Stabeno, D.A. Stockwell, T.E. Whitledge, and S.I. Zeeman, 1999: Ecosystem responses of the southeastern Bering Sea to abnormal weather patterns in 1997 and 1998. The Oceanographic Society Meeting, March.
- Hunt, G.L., J.D. Schumacher, P.J. Stabeno, D.A. Stockwell, T.E. Whitledge, and S.I. Zeeman, 1998: Ecosystem anomalies in the eastern Bering Sea: Seabird dieoff and coccolithophorid bloom follow calm spring and strong stratification. AGU/ASLO Ocean Sciences Meeting, San Diego.
- Napp, J.M., R.D. Brodeur, J.J. Cullen, R.F. Davis, M.B. Decker, J.J. Goering, C.E. Mills, J.D. Schumacher, S. Smith, P.J. Stabeno, T.C. Vance, and T.E. Whitledge, 1998: The 1997 eastern Bering Sea shelf-wide coccolithophorid bloom: Ecosystem observations and hypotheses. AGU/ASLO Ocean Science Meeting, San Diego.
- Stockwell, D.A., and T.E. Whitledge, 1999: Apparent nutrient/phytoplankton responses to unusual physical conditions in the southeast Bering Sea during 1997-1998. ASLO Santa Fe, February.
- Stockwell, D.A., T.E. Whitledge, S.I. Zeeman, K.O. Coyle, and A.I. Pinchuk, 1998: Processes at the inner front of the southeastern Bering Sea: 1997- the year of anomalies. AGU/ASLO Ocean Sciences Meeting, San Diego.
- Whitledge, T.E., 1999: Recent productivity changes in the Bering Sea and implications for the Arctic Ocean during climate change. Presentation at Biogeochemical Processes in the Arctic Ocean Workshop, International Arctic Research Center, March.
- Whitledge, T.E., and J.J. Goering, 1998: Bering Sea nutrient dynamics: Then and now. Presentation at FOCI International Workshop on Recent Conditions in the Bering Sea, Seattle, November.

Outlook

The goals and objectives of the research project have been obtained according to the original timeline of milestones. The research has continued with continued efforts in SEBSCC Phase II to obtain additional nutrient data for collaborative analysis with investigators in physical and biological processes.

In addition, a new related project was funded in SEBSCC Phase II entitled “In situ monitoring of nitrate concentrations on the southeastern Bering Sea shelf” in collaboration with Dr. P. J. Stabeno. The continued shipboard analysis of nutrients combined with the in situ time series of nitrate concentrations will contribute greatly to the goal of understanding the processes enriching the nutrient environment of the southeastern Bering Sea shelf.

4.2 Isotopic and biomarker composition of sinking organic matter in the Southeast Bering Sea: indicators of food web structure

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Period of Research: August 1996-September 1998

Project Goal

The project goal was to test the hypothesis that the temporal variation of the quantity and composition of sinking particles depends on interactions among weather, climate, and geographic location over the Southeast Bering Sea shelf. Since the composition of the sinking organic matter collected by sediment traps reflects the pelagic food web, the research aimed to improve understanding of primary production and of the transfer of water column production to the benthos.

Project Description

Moored sediment traps were used to examine temporal variability, on time scales of weeks to years, in the source and quantity of sinking particles over the southeastern Bering Sea shelf. Traps were deployed at Site 2 (56°53' N, 164°02' W) in the middle shelf domain from late April 1997 through September 1998, and at Site 3 (56°04' N, 166°20' W) in the outer shelf domain from late February through mid September 1998. Also, phytoplankton, zooplankton, and bottom sediment samples were collected near Sites 2, 3, and 4 (57°52' N, 169°12'W), in the middle shelf domain). Single zooplankton species were sorted from the samples for isotopic analysis. The sediment trap samples were examined microscopically and analyzed to determine carbon and nitrogen stable isotope composition. Diatom and organic matter collection by the Site 2 sediment trap peaked in spring 1997, as expected, but also was high in July and late September-early October. These patterns in diatom numbers and organic matter were reflected in the temporal variations of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of trap samples, which appear to be related to variations in primary productivity and the extent of nutrient depletion. The sediment trap at Site 2 did not collect substantial numbers of coccoliths until late September 1997, after the stratification of the water column weakened. Zooplankton had lighter $\delta^{15}\text{N}$ at Site 3 than at Sites 2 and 4 at all sampling times, consistent with expected cross shelf patterns in the extent of nitrogenous nutrient depletion by primary production (Schell et al., 1998). During spring 1998 (the only time data are

available for comparison), the $\delta^{15}\text{N}$ of organic matter collected by the Site 3 sediment trap was similarly lighter than that of material collected by the Site 2 trap. The $\delta^{15}\text{N}$ of Site 2 sediment trap material was heavy in 1997, presumably due to the strong stratification and consequent nutrient depletion of surface layers. The $\delta^{15}\text{N}$ of sediment trap material was lighter during the late spring and summer of 1998 than for the same period in 1997, probably reflecting a lesser extent of nutrient depletion of surface waters during 1998 due to weaker stratification and stormy weather. The $\delta^{15}\text{N}$ of zooplankton was lighter in April and May of 1998 than 1997, probably also reflecting the differences in stratification and nutrient depletion. Overall, the particulate material collected by the sediment traps reflected temporal and geographic differences in phytoplankton production, nutrient utilization, and zooplankton grazing.

Results

The southeastern Bering Sea shelf has been divided into three distinct domains characterized by differences in water column structure (Coachman 1986). The coastal domain is that region shallower than 50 m. It is characterized by weakly stratified or well-mixed water. The middle shelf includes depths between 50 and 100 m and has a strongly stratified 2-layer structure. The outer shelf domain, between depths from 100 to 180 m, has mixed upper and lower layers separated by a zone of gradually increasing density. The three domains also differ in amount and duration of sea ice cover, zooplankton communities (Cooney and Coyle, 1982) and nutrient distributions (Whitledge et al. 1986). Because cross-shelf transport from the nutrient-rich continental slope waters is the source of new nutrients to the shelf, there is an onshore decrease in concentrations at all depths, except when surface waters are depleted by primary production (Whitledge et al. 1986). Grazing of open-water blooms by crustaceans is typically less intense over the middle shelf than over the outer shelf (Vidal and Smith, 1986; Cooney and Coyle, 1982). This is because the outer shelf waters harbor large, overwintering species of oceanic copepods, *Neocalanus* spp., while a smaller species that reaches maturity after the bloom has passed, *Calanus marshallae*, predominates over the middle shelf. Over the middle shelf, more grazing was observed in late May-June than was found at the ice edge in late April-early May (Coyle and Cooney, 1988).

Moored, time-series sediment traps were used to examine temporal and geographic variability in the source and quantity of sinking particles. Traps have been deployed continuously since late April 1997 at Site 2 (35-m depth) within the middle shelf domain. A trap was successfully deployed at Site 3 (40-m depth) within the outer shelf domain during spring and summer 1998. Mercuric chloride was added to the trap sample cups to prevent microbial decomposition during the long deployment (Wakeham et al., 1993). We used swimmer-excluding traps of a design that minimizes trapping efficiency artifacts (Gardner, 1980; Butman et al., 1986; Peterson et al., 1993). We have seen very few intact zooplankton, or even zooplankton fragments, in any of the SEBSCC trap samples, indicating that the swimmer-exclusion mechanism of the traps has been effective. Resuspended sediment is likely to be collected by traps within about 50 m of the bottom (e.g., Gardner et al., 1983), and extreme storm events in winter resulted in collection of some resuspended bottom sediment at Site 2. After trap recovery, one split of the trap samples was preserved in formalin for later microscopic examination. The remainder was stored frozen until analysis. Samples were analyzed for total

organic carbon (TOC), total nitrogen (TN), the difference between the ratio of $^{13}\text{C}/^{12}\text{C}$ in the sample and that in a standard reference material ($\delta^{13}\text{C}$), and the difference between the ratio of $^{15}\text{N}/^{14}\text{N}$ in the sample and that in a standard reference material ($\delta^{15}\text{N}$). Analyses were conducted using the Europa mass spectrometer facility (with Roboprep) located at UAF.

Phytoplankton and zooplankton samples were collected using 150 and 333 μm mesh bongo nets at the five "X" stations centered on Sites 2, 3, and 4 during June 1997 and May 1998. Single zooplankton species were sorted from these samples. Zooplankton samples were also collected near Sites 2 and 3 during February 1997 and 1998, and April 1997 and 1998. Bottom sediment samples were collected using a Soutar-type box corer near the mooring sites during June, 1998. All of these samples were analyzed for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ using the Europa mass spectrometer.

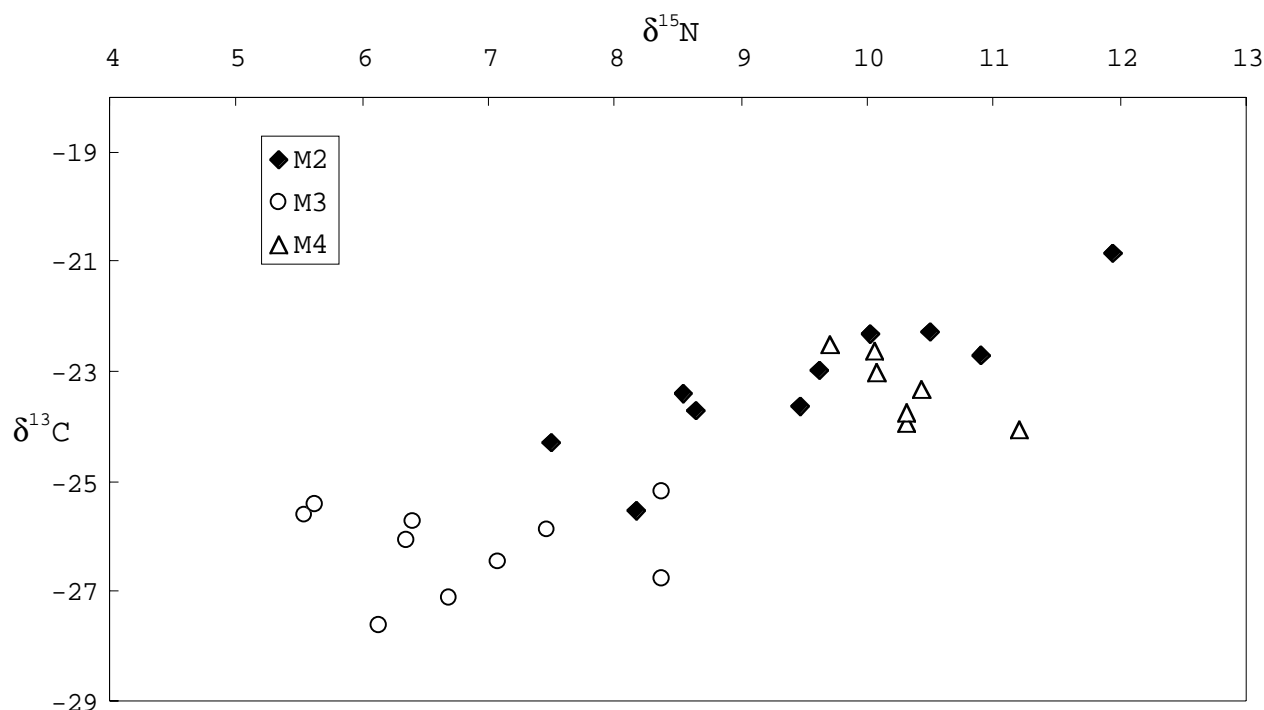


Figure 4.2.1 Variation in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of copepods among Sites 2, 3, and 4. Sites 2 and 4 are located in the middle shelf domain, while Site 3 is in the outer shelf domain. The samples were collected during April and May 1998.

At all sampling times, the copepods and other zooplankton near Site 3 were significantly ($P < 0.05$) lighter in $\delta^{15}\text{N}$, by an average of 2 to 4‰, than near Sites 2 and 4 (Fig. 4.2.1, Table 4.2.1). This comparison must be made within a single trophic level (see below) but is observed for carnivores as well as herbivores. We also observed a significant ($P < 0.05$) $\delta^{13}\text{C}$ difference for copepods, with Site 3 $\delta^{13}\text{C}$ averaging 2.8‰ lighter than that at Site 2 (Table 4.2.2). Because lipids are depleted in ^{13}C , differing lipid content of *Neocalanus* spp. and *Calanus marshallae* could contribute to this. Ideally, the comparison would be made for a single species, but this is not feasible because of the cross-shelf changes in zooplankton community composition. Schell et al. (1998) also found that carbon and nitrogen isotope composition of copepods showed a geo-

Table 4.2.1 Comparison of the $\delta^{15}\text{N}$ of zooplankton at Sites 2 and 4 with that at Site 3. The means differ significantly ($P<0.05$) for all organism groups and sampling dates. Also, the mean $\delta^{15}\text{N}$ of copepods and euphausiids differs significantly among all sampling dates except the pair marked with *.

Organism, Date	Sites 2 and 4, $\delta^{15}\text{N}$ (‰) mean \pm 1 s.d.	Site 3, $\delta^{15}\text{N}$ (‰) mean \pm 1 s.d.
Copepods and Euphausiids, Feb.-Apr., 1997	13.74 \pm 1.57 n=10	9.65 \pm 1.56* n=7
Copepods and Euphausiids, June, 1997-Feb. 1998	11.77 \pm 0.85 n=11	9.42 \pm 0.93* n=7
Copepods and Euphausiids, Apr., 1998-May, 1998	9.71 \pm 1.03 n=32	7.29 \pm 1.19 n=18
Jellyfish, Apr., 1998-May, 1998	12.54 \pm 1.09 n=7	10.56 \pm 1.21 n=4
Chaetognaths, Apr., 1998-May, 1998	14.81 \pm 1.13 n=13	11.36 \pm 0.46 n=4

Table 4.2.2 Comparison of $\delta^{13}\text{C}$ of zooplankton at Sites 2 and 4 with that at Site 3. The means differ significantly ($P<0.05$) only for the pair marked with #.

Organism, Date	Sites 2 and 4, $\delta^{13}\text{C}$ (‰) mean \pm 1 s.d.	Site 3, $\delta^{13}\text{C}$ (‰) mean \pm 1 s.d.
Copepods, Feb., 1997-Feb., 1998	-22.63 \pm 1.62 n=9	Insufficient data
Euphausiids, Feb., 1997-Feb., 1998	-20.35 \pm 1.56 n=12	Insufficient data
Copepods, Apr. 1998-May, 1998	-23.41 \pm 0.87# n=15	-26.17 \pm 0.79# n=10
Euphausiids, Apr. 1998-May, 1998	-21.12 \pm 1.46 n=17	-22.04 \pm 1.12 n=8

graphic pattern over the southeastern Bering Sea. They found a decrease of 1-2‰ in $\delta^{13}\text{C}$ and an increase of 3-4‰ in $\delta^{15}\text{N}$ from the 200-m isobath to the boundary of the inner domain. Their result is very similar to ours for $\delta^{15}\text{N}$ but opposite for $\delta^{13}\text{C}$. They attributed the pattern in $\delta^{13}\text{C}$ to increasing isotopic fractionation by primary producers as the productivity decreases in response to greater nutrient limitation over the middle shelf. They interpreted the $\delta^{15}\text{N}$ pattern as arising from ^{15}N enrichment of the residual dissolved inorganic nitrogen as nitrogen becomes depleted (e.g., Altabet and Francois, 1994). The $\delta^{15}\text{N}$ can show a related seasonal pattern, as has been

observed in organisms from a variety of locations, including Auke Bay, Alaska (Goering et al., 1990). However, we did not observe any clear seasonal differences between February (winter) and April-June (spring) zooplankton. Rather, there was a significant ($P < 0.05$) decrease in both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ over our 1.5-year sampling period, but the isotopic composition was the same within the February and April 1997, the February and June 1998, and the April and May 1998 pairs of sampling dates.

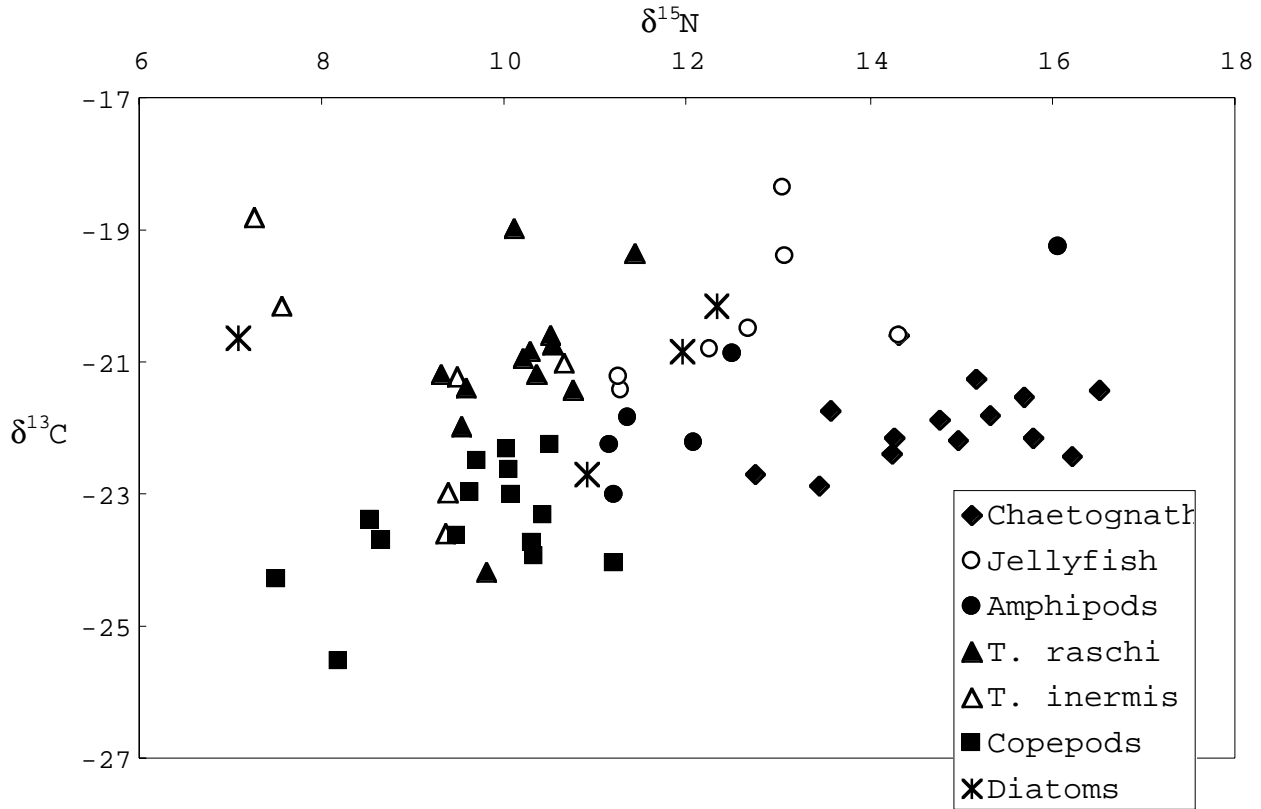


Figure 4.2.2 Variation in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ among plankton groups at Site 2. The plankton were collected during April and May 1998.

There is usually a substantial enrichment in ^{15}N with trophic level, about 3-4‰ in other studies (e.g., Fry, 1988; Altabet and Small, 1990). For the southeastern Bering Sea zooplankton samples we have collected, this pattern was seen at all sites and times; data from Sites 2 and 4, April and May 1998, are presented as an example (Fig. 4.2.2, Table 4.2.2). The copepods (mainly *Calanus marshallae* at Sites 2 and 4) and euphausiids (mainly *Thysanoessa raschi* at Sites 2 and 4, but *Thysanoessa inermis* was found at Sites 2 and 4 in May 1998) have similar ranges of $\delta^{15}\text{N}$, and both are likely herbivorous. The mean jellyfish enrichment relative to the copepods and euphausiids is about 3‰, indicating that they are primary carnivores. The chaetognaths (*Sagitta* spp.) average 4 to 5‰ heavier than the copepods and euphausiids, suggesting that some of their prey is at a higher trophic level (e.g., amphipods) or that their trophic fractionation is greater than the typical one. An odd finding is that diatoms sampled at the same time and location as the zooplankton are substantially heavier than expected based on the isotopic composition of the herbivores. There are several potential explanations, including that the net phytoplankton (mainly large aggregates and chains) are not consumed by the

zooplankton and are enriched in ^{15}N compared with those that are eaten. Another is that the heavy diatom $\delta^{15}\text{N}$ reflects nutrient limitation at the time of sampling, while the zooplankton composition integrates the $\delta^{15}\text{N}$ of their food over a longer period, including times when nitrogenous nutrients were not depleted.

Temperature, nutrient, and chlorophyll results mentioned in the following discussion of the sediment trap data are from two other SEBSCC components. They are “Monitoring and development of biophysical indices of the southeastern Bering Sea,” section 3.1 of this report; and “Investigation of the origin and dynamics of nutrients on the Southeast Bering Sea shelf in relation to dominant physical and biological processes,” section 4.1 of this report. Temperature and chlorophyll fluorescence data were collected using moored instruments located at Sites 2 and 3, while nutrient measurements were conducted on discrete samples collected near the mooring sites. Some of the results from these other projects are summarized in Stabeno et al. (submitted), Goering et al. (1998), and Napp et al. (1999). Also, funding for the sediment trap deployed at Site 2 during the winter was provided through the Arctic Research Initiative (ARI) of the Cooperative Institute for Arctic Research (CIFAR).

In 1997, sea ice was more persistent over the Southeast Bering Sea shelf than in either 1996 or 1998. There was apparently no ice-edge bloom in 1996 or 1998, but one did occur in March/April 1997 in conjunction with the melting of the sea ice. Sediment traps were first deployed in late April 1997, about the time that water column thermal stratification began. However, in late May there was a severe storm that mixed the water column to 50 m. After this, weak winds and strong heating led to a shallow, very warm mixed layer, extending to about 20-m depth for most of June through August. From April 22 to May 6, 1997, the identifiable constituents of the sediment trap samples included diatoms, such as *Chaetoceros* spp., *Thalassiosira* spp., *Odontella aurita*, *Fragilariopsis oceanica*, and *Navicula* spp. along with small flagellates. From May 6 to 20, there were fewer diatoms relative to flagellates, with the diatoms including *Odontella aurita*, *Pleurosigma* spp., *Thalassionema* spp., and *Thalassiosira* spp. These may have represented remnants of the ice-edge bloom, plus primary production associated with thermal stratification of the water column at about this time. From May 20 to July 17, the sample contained few intact diatoms and more amorphous material and flagellates, and the quantity of material collected was much less. The $\delta^{15}\text{N}$ of the trapped material was relatively low from April 22 to May 6, 12.2‰, maximized at 15.6‰ from May 20 to 27, then declined to about 13.5‰ from June 17 to July 17 (Fig. 4.2.3). Overall, these patterns indicate that the trap collected substantial intact phytoplankton in late April and early May, following the spring bloom. Late May through early July material probably contains more zooplankton-derived organic matter. In addition to trophic level effects on $\delta^{15}\text{N}$ of sediment trap material and nutrient depletion of surface waters associated with the strong stratification could have contributed to high $\delta^{15}\text{N}$ from late May through August.

The July 17 to 29 and July 29 to August 12 samples contained larger numbers of intact diatoms, mainly *Detonula* spp., and *Odontella aurita* in early August. Small flagellates were also abundant in both samples, especially July 17 to 29. Both samples also contained dinoflagellates and the July 29 to August 12 sample included a relatively large number of fecal pellets. July 17 to 29 was associated with a peak in the amount of organic matter collected by

the traps, comparable to that in late April-early May. However, the spring sample may have missed some sinking organic matter from earlier spring productivity. The $\delta^{15}\text{N}$ increased slightly, to 14.2‰, in the early August sample (Fig. 4.2.3). The August 12 to September 2 sample had similar isotopic composition, but fewer diatoms, numerous flagellates, and fecal pellets. The water column remained strongly stratified at this time; however, after about August 10, the mooring temperature data indicate more mixing near the thermocline. We cannot identify any mixing events that might have precipitated increased productivity in July (e.g., Sambrotto et al., 1988). Since in 1997 the strong stratification and surface water nutrient depletion resulted in nitrate uptake being maximal below the pycnocline (Napp et al., 1999), the apparently high July productivity could have resulted from this sub-pycnocline algal growth.

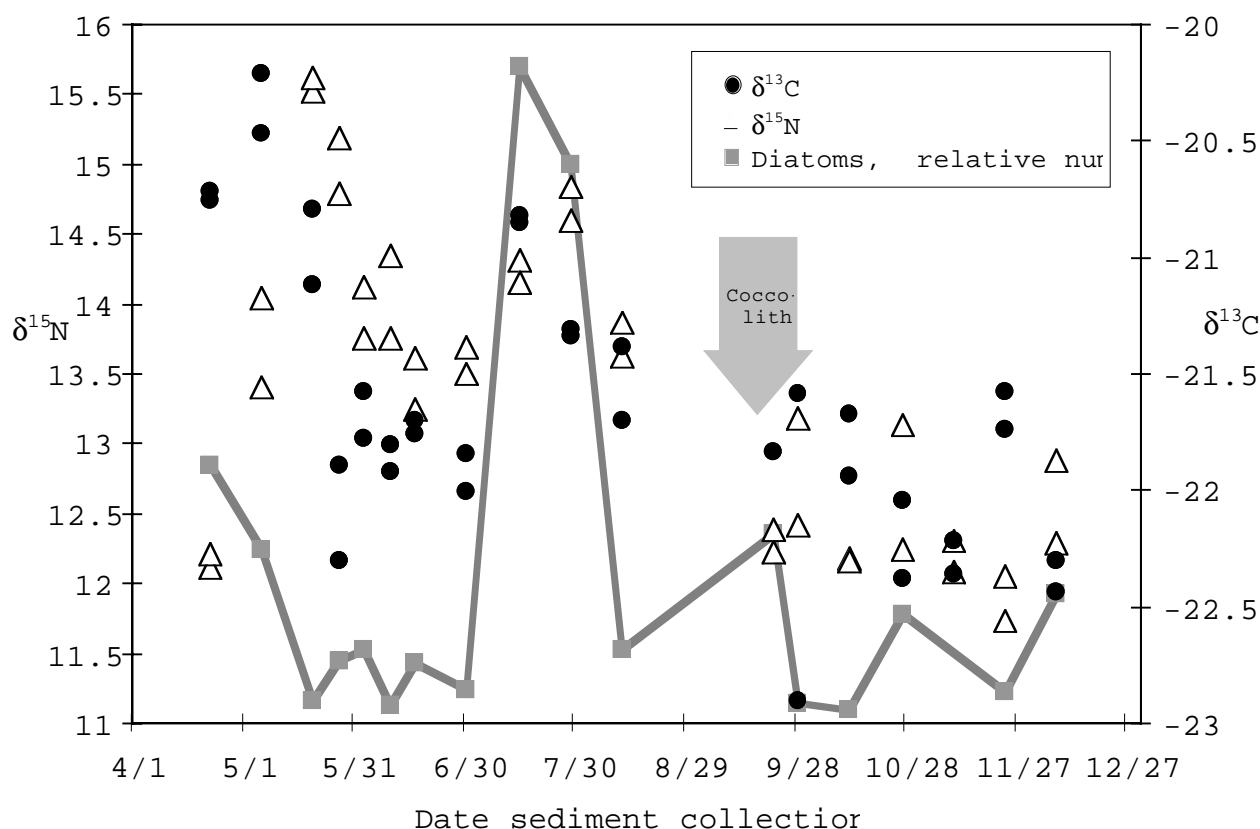


Figure 4.2.3 Composition of particulate material collected by a sediment trap deployed at 35-m depth over the southeastern Bering Sea shelf during 1997. The relative number of diatoms is plotted from 0 to 100% of maximum abundance, where full scale = 100%. The numerous diatoms in late July-August were mostly much smaller species than those present in spring.

Through September 2, very few coccoliths were observed in the Site 2 sediment trap. However, coccoliths were found in sediment trap samples representing September 22 to 29 and September 29 to October 13. Coccoliths of *Emiliania huxleyi* were especially abundant from September 29 to October 13, giving the sample a “milky” appearance distinct from the brownish coloration of other trap samples; this sample also contained numerous flagellates. The late September to mid October samples also corresponded to another maximum in organic matter collected by the traps. The September 22 to 29 sample had some pennate diatoms and fecal

pellets, as well. The September occurrence of the coccoliths in trap samples, rather than earlier, suggests that there was little grazing of the summer bloom. An abrupt cooling of surface waters and deepening of the thermocline occurred in early September. Surface waters cooled from about 8° to 6° C during late September to mid October, while the coccoliths were being collected by the trap. Coincident with this, the thermocline deepened to about 30 m. The October 13 to 27 sample did not contain obvious coccoliths when examined by scanning electron microscope, but this sample contained a lot of reddish-brown, amorphous material which might have obscured the coccoliths if they were not very numerous. This sample did contain numerous flagellates. The $\delta^{15}\text{N}$ values of sediment trap samples collected after September 22 were lighter than those collected earlier in the summer (Fig. 4.2.3). This may represent an influx of relatively light, “new” nutrients to the phytoplankton due to greater fall mixing, as well as the sinking of phytoplankton (coccolithophorids and pennate diatoms) observed in the traps.

The October 27 to November 10 sample contained mostly flagellates, pennate diatoms, fecal pellets, and amorphous particles. The water column became isothermal about November 1. The November 10 to 24 sample contained a large amount of resuspended bottom sediment, due to a very severe storm that occurred during that period, and fecal pellets. Subsequent samples through December 22 contained broken diatom tests, which probably also were resuspended from the sediment. Samples collected from December 22 to February 16 contained almost nothing.

The Site 2 sediment trap samples from spring and summer 1998 contained more organic material than the samples collected at the same times during 1997. Also, there was much less temporal variation in the amount of organic matter collected over the April-September interval. Especially for the spring samples, when there were many storms, the material collected may include some resuspended sediment. However, the microscopic examination and stable isotopic composition do not strongly indicate resuspended sediment as a major component. Bottom sediments collected near Site 2 had a mean $\delta^{15}\text{N}$ of $7.5\text{‰} \pm 0.8$, and a mean $\delta^{13}\text{C}$ of $-21.8\text{‰} \pm 0.3$. The $\delta^{13}\text{C}$ of the sediment was similar to the mean of sediment trap samples, but the sediment $\delta^{15}\text{N}$ was markedly lighter. The trap samples containing resuspended sediment collected during November 1997 had a $\delta^{15}\text{N}$ of about 12‰, lighter than either the preceding fall or spring 1998. Also, diatom fragments were prominent in the 1997 samples with resuspended sediment but not in the 1998 samples after April 16.

In 1998 sea ice was present at Site 2 only briefly, in February. Although the entire water column warmed slightly beginning in late April, there was no apparent thermal stratification of the water column until late May. From February 26 to March 19, the samples contained mostly flagellates, some pennates and a few *Coscinodiscus* spp. fragments. From March 19 to April 16 the samples consisted mainly of flagellates, amorphous material, and a few diatoms such as *Navicula* spp., *Fragalariopsis* spp., and *Coscinodiscus* spp., with the diatoms being more abundant during the last half of this period. This increased abundance of diatoms in April suggests that there was net primary productivity, despite the lack of water column stratification. From April 16 to April 30, there were fewer flagellates than in the previous samples. The diatoms were still mostly *Coscinodiscus* spp., *Fragalariopsis* spp. and *Navicula* spp. There were

also many small pennates, as well as marine snow. The April 30 to May 21 sample was similar to that from early April, except it contained more flagellates.

In addition to the diatoms that had been present earlier, *Thalassionema* spp., *Pleurosigma* spp., *Thalassiosira* spp. and *Coscinodiscus* spp. were found from May 21 to July 2. Also, flagellates were less numerous. The July 2 to 23 sample contained more fecal pellets, many centric diatoms, and fewer flagellates. July 23 to September 23 had increased flagellates, especially for the last six weeks of this period. Unfortunately, temperature data are lacking for mid June to mid July. However, the available data show that the water column was stratified throughout this period, albeit more weakly than in 1997. The depth of the pycnocline was about 25 m from late May through mid August, then increased to 30 m until late September when mixing extended throughout the water column.

None of the samples contained the numerous coccoliths found in fall 1997, but the time period corresponding to the 1997 coccolith maximum was not included in this sediment trap series. Overall, the material collected during summer and fall 1998 had fewer intact diatoms and more amorphous material and fecal pellets than in 1997. Both euphausiid and copepod pellets were present, but copepod pellets predominated.

The temporal pattern in carbon and nitrogen isotopic composition during 1997 was similar to the temporal variations in the number of diatoms collected by the trap, with maxima of $\delta^{13}\text{C}$ coinciding with the diatom peaks, and $\delta^{15}\text{N}$ maxima lagging them slightly (Fig. 4.2.3). These patterns, as those found by Schell et al. (1998) in isotopic composition of zooplankton across the shelf, could be related to the extent of nutrient depletion (heavier $\delta^{15}\text{N}$ as nitrate is depleted) and primary productivity (heavier $\delta^{13}\text{C}$ for higher primary productivity). During late spring and summer 1998, the $\delta^{15}\text{N}$ of the sediment trap samples is distinctly lighter than in 1997, probably reflecting the more intense storm mixing and less extreme nutrient depletion of surface waters in 1998 (Fig. 4.2.4). Compared to late spring and summer 1997 there is relatively little variation in $\delta^{15}\text{N}$ or in the number of diatoms collected by the traps (Fig. 4.2.4).

The sediment trap $\delta^{15}\text{N}$ ranges from about 12 to 16‰ at Site 2. The lower part of this range is consistent with an origin in a combination of sinking diatom aggregates and crustacean fecal material (Fig. 4.2.1). At sites in the Sargasso Sea, NE Pacific, and Santa Monica Basin, the $\delta^{15}\text{N}$ of copepod fecal pellets was consistently about 2.2‰ greater than their food, and 1.3‰ less than their bodies, for a variety of sampling locations and seasons (Altabet and Small, 1990). Hence, we would expect an average of about 9‰ for copepod feces at Site 2. The diatoms probably sink under nutrient-depleted conditions so that the higher observed values, around 12‰, may represent what reaches the traps. The sediment trap $\delta^{15}\text{N}$ values from 13 to 16‰ are harder to explain. Generally, zooplankton fecal material should be isotopically heavier than the ingested food, because solubilization and absorption will favor the lighter isotope. However, the extent of enrichment will vary with the type of zooplankton (or nekton), and the type of food and feces can be heavier than the organism itself under some circumstances (Checkley and Entzeroth, 1985; Altabet and Small, 1990). The heavy $\delta^{15}\text{N}$ values may also reflect microbial decomposition of the particles before they entered the traps, or origins from higher trophic level organisms.

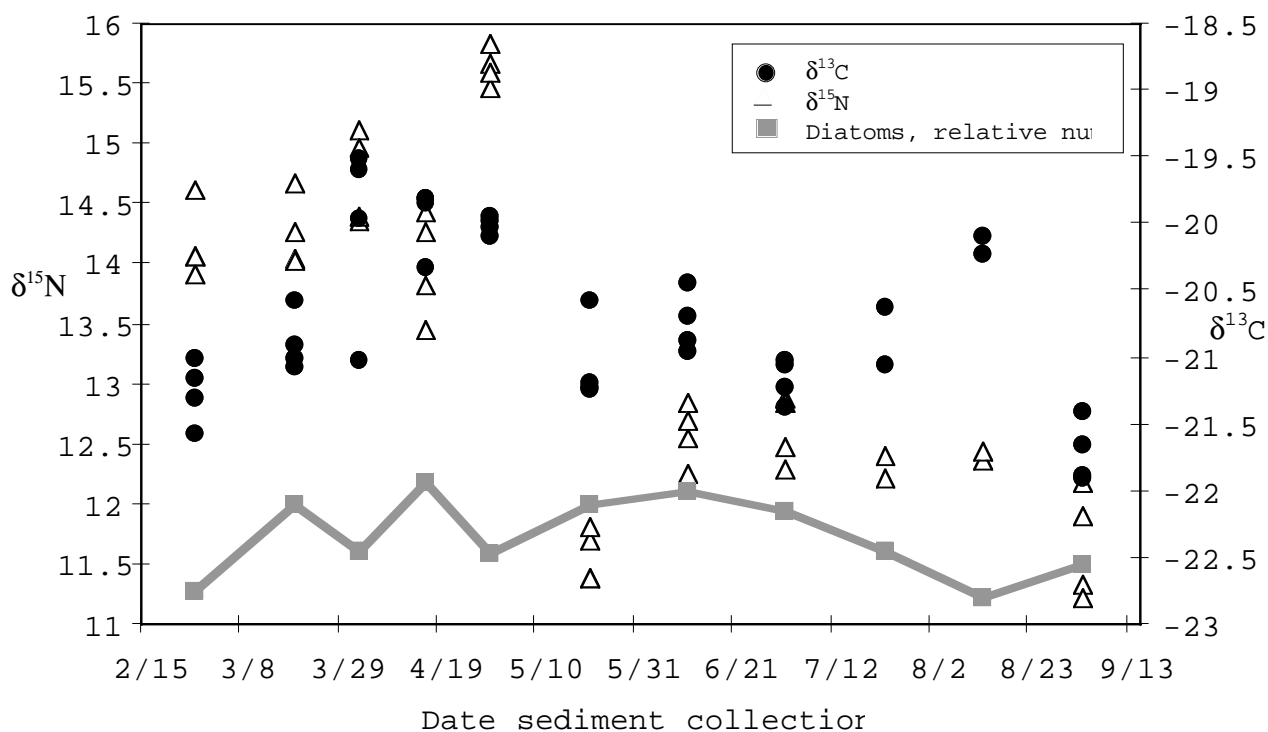


Figure 4.2.4 Composition of particulate material collected by a sediment trap deployed at 35-m depth over the southeastern Bering Sea shelf during 1998. The relative number of diatoms is plotted from 0 to 100% of the maximum value in 1997. Note the sharp drop in $\delta^{15}\text{N}$ between the 4/30 and 5/21 samples, and that late spring-summer $\delta^{15}\text{N}$ values were substantially less than in 1997.

The sediment trap samples from mooring Site 3, collected during spring and summer 1998 contained much less material than those from Site 2. The main type of diatom was *Chaetoceros* spp. Some samples, particularly from April 16 to 30, contained fecal pellets filled with either *Thalassiosira* spp., flagellates, or other fecal pellets. In contrast to the Site 2 trap, most sinking organic matter was collected in spring at Site 3. The amount of organic matter collected by the trap was relatively high during the four 3-week sampling intervals from March 19 to May 21, then declined sharply and was very low until the last, September 3 to 24, sample. There was no sign of a short, intense spring bloom. The September sample also contained fecal pellets, although these differed in size and shape from those collected earlier. Only samples collected during spring contained enough organic material for stable isotopic analysis in our initial attempt. Consistent with the zooplankton data, the $\delta^{15}\text{N}$ of these samples averaged 3‰ lighter, and $\delta^{13}\text{C}$ averaged 2.5‰ lighter, than for the sediment trap material collected during this time period at Site 2.

During both 1997 and 1998, the rate of organic matter accumulation by the Site 2 traps showed substantial maxima, comparable to those in spring, during summer and fall. Because only the 1997 and 1998 data are available, it is not clear whether this linked to the unusual coccolithophorid bloom or other unusual conditions during those years. However, the data so far indicate that the spring bloom may not be the predominant source of organic matter to the benthos of the middle shelf.

We have achieved all or a substantial part of each of the milestones listed in the original proposal. This includes all sediment trap deployments and recoveries proposed, plus an additional winter deployment enabled by CIFAR/ARI funding. Smith collected plankton samples, deployed sediment traps, or collected sediment samples aboard a total of 8 Phase I cruises, double the number originally proposed: MF97-01, MF97-05A, W97-06B, MF97-09B, MF98-01, MF98-05B, W98-05A, and LA98-02. Henrichs also participated in two of these, W97-06B and W98-05A. Over 300 stable isotopic analyses of zooplankton, sediment trap samples, and sediments have been completed. The project goal was to test the hypothesis that the temporal variation of the quantity and composition of sinking particles depends on interactions among weather, climate, and geographic location over the Southeast Bering Sea shelf. The results summarized above demonstrate effects of weather and geographic location on the composition of sinking particles. The data suggest that climatic effects are present as well, but a longer time series is needed to address this. Sediment trap deployments and zooplankton sampling are continuing during SEBSCC Phase II.

Conclusions

1. Zooplankton had lighter $\delta^{15}\text{N}$ at Site 3 than at Sites 2 and 4 at all sampling times, consistent with expected cross shelf patterns in the degree of nitrogenous nutrient depletion by primary production. During spring 1998 (the only time data are available for comparison), the $\delta^{15}\text{N}$ of organic matter collected by the Site 3 sediment trap was lighter than that of material collected by the Site 2 trap.
2. Diatom collection by the Site 2 sediment trap peaked in spring 1997, as expected, but also was high in July and September, corresponding to highs in the amount of organic matter collected by the sediment traps.
3. The sediment trap at Site 2 did not collect substantial numbers of coccoliths until late September 1997 after the stratification of the water column weakened. This suggests that these relatively small particles did not sink rapidly, nor were coccolithophorids heavily grazed.
4. The $\delta^{15}\text{N}$ of Site 2 sediment trap material was heavy in 1997, presumably due to the strong stratification and consequent nutrient depletion of surface layers. The isotopic composition of sediment trap samples show variations that are linked to productivity events, but also support the interpretation that the nutrient depleted conditions persisted from May through August.
5. The $\delta^{15}\text{N}$ of sediment trap material was lighter during the late spring and summer of 1998 than for the same period in 1997, probably reflecting a lesser extent of nutrient depletion of surface waters during 1998.
6. The $\delta^{15}\text{N}$ of zooplankton was lighter in 1998 than 1997, probably also reflecting the persistent strong stratification and nutrient depletion of 1997.

Products

Our findings have been presented at several regional and national meetings, and were summarized in the following published abstracts.

- Goering, J.J., S.M. Henrichs, T. Rho, S. Smith, T.E. Whitledge, C.T. Baier, R.D. Brodeur, D.M. Blood, J.M. Napp, J.J. Cullen, R.F. Davis, J.D. Schumacher, P.J. Stabeno, G.L. Hunt, Jr., and G.L. Swartzman, 1998: Southeast Bering Sea Carrying Capacity (SEBSCC): Ecosystem dynamics research in a marginal sea. 7th PICES Meeting, Fairbanks, AK, October, (Abstract).
- Napp, J.M., C.T. Baier, R.D. Brodeur, J.J. Cullen, R.F. Davis, M.B. Decker, J.J. Goering, C.E. Mills, J.D. Schumacher, S. Smith, P.J. Stabeno, T.C. Vance, and T.E. Whitledge, 1998: The 1997 eastern Bering Sea shelf-wide coccolithophorid bloom: Ecosystem observations and hypotheses. AGU/ASLO Ocean Sciences meeting, January, (Abstract).
- Smith, S., and S.M. Henrichs, 1998: Isotopic and microscopic analysis of sinking particulate matter on the Bering Sea middle shelf. 49th AAAS Arctic Science Conference, (Abstract).
- Smith, S., and S.M. Henrichs, 1998: Plankton collected by a time-series sediment trap deployed in the Southeast Bering Sea during 1997. 7th PICES Meeting, Fairbanks, AK, October, (Abstract).

Outlook

The one aspect of the proposed research that has not been completed is the lipid analyses of the sediment trap samples and zooplankton. Certain biomarkers specific for phytoplankton and zooplankton (wax esters, sterols) will be measured to further assess the relative extent of grazing of the phytoplankton and the sources of organic matter collected by the sediment traps (e.g., Wakeham, 1982; Prahl et al., 1985; Wakeham and Canuel, 1986; Neal et al., 1986). We intend to complete these analyses by December 1999.

One question not fully addressed by Phase I is the effects of climate on the composition of sinking particles, which should reflect effects on the pelagic food web. SEBSCC Phase II will extend the time series to three years. We are also seeking funding to continue for another two years under the North Pacific Marine Research Initiative. If funded, this work would include deployment of a sediment trap at Site 4, as well as a winter trap at Site 3. The Site 4 deployment would address north-south geographic effects due to differences in the number of storms, persistence of ice, tidal mixing, and the role of currents in transporting nutrients across the shelf.

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- Stabeno, P.J., N.A. Bond, N.B. Kachel, S.A. Salo, and J.D. Schumacher, submitted: On the temporal variability of the physical environment over the southeastern Bering Sea. *Fish. Oceanogr.*
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4.3 Using optical measurements to explore the influence of mesoscale eddies on the interaction of lower and higher trophic levels in the southeast Bering Sea

Principal Investigator: P. J. Stabeno (Pacific Marine Environmental Laboratory)

Collaborators: J. J. Cullen and R. F. Davis (Dalhousie University)

Period of Research: August 1996 through September 1998

Goal and Objectives

The objectives of our proposed project were to:

1. use measurements of near-surface optical properties to determine and compare the mean concentrations and temporal variability of surface chlorophyll within and outside at least one mesoscale eddy; and
2. relate variability of chlorophyll to relevant physics; specifically relate the vertical distributions of chlorophyll to the interaction of wind mixing and pycnocline depth as determined by the eddy structure.

Project Description

We hypothesized that eddies influence the distributions and abundance of primary producers in a manner that would enhance productivity of higher trophic levels, particularly larval pollock. We used *in situ* optical measurements (ocean color monitoring drifters, along with vertical profiles of physical and optical properties) to characterize the degree of coupling between physical forcing and biological response in the southeastern Bering Sea, focusing on the influence of mesoscale eddies on the pigment field. The ocean color monitoring (OCM) drifters were deployed and the vertical profiles of physical and optical properties were made on a research cruise to the southeastern Bering Sea in June 1997. Terry Whitley's group provided nutrient measurements in the eddy. This was an extremely valuable contribution to this study.

We first located an eddy using altimeter data. To permit us to track the eddy, personnel on the *Miller Freeman* deployed a satellite-tracked drifter in May. On June 10 we arrived at the eddy and conducted a careful survey, measuring salinity, temperature, fluorescence, nutrients and optical properties. On June 15 the ship left the eddy and conducted other research. We returned to the eddy on June 23 and made further measurements until June 27. During the two periods at the eddy, we deployed four satellite-tracked drifters (two within the eddy, one at the edge and one outside the eddy). Other drifters were deployed over the southeastern slope to examine other mesoscale features that had been identified via the altimeter data. The drifters deployed as part of this experiment together with other drifters deployed by FOCI provided information on transport and flow patterns during 1997.

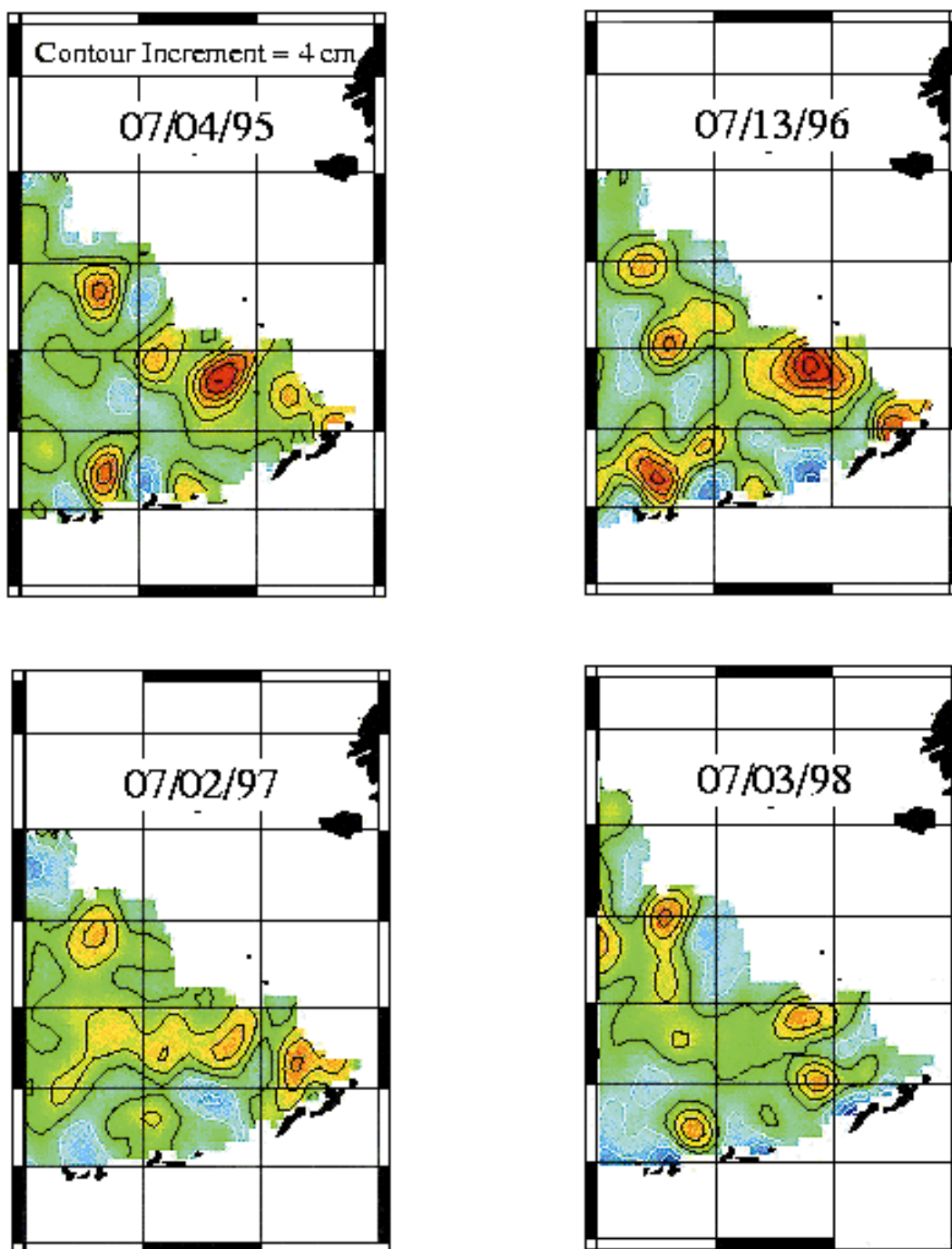


Figure 4.3.1 Maps of sea surface height anomaly in the Bering Sea are produced from altimeter data provided by TOPEX and ERS-2 satellites and is used for monitoring mesoscale variability in the Bering Sea. Dr. R. Leben at the Colorado Center for Astrodynamic Research (CCAR) provided the data. Eddies are common in the southeastern corner of the Bering Sea basin.

Patterns in pigments, vertical mixing and light penetration can be related to larval survival. Schumacher and Stabeno (1994) showed a relationship between eddies and high concentrations of pollock larvae. Also, larvae sampled from patches of larvae that were associated with eddies in the Gulf of Alaska (Bograd et al., 1994; Canino et al., 1991) tended to be healthier than their cohorts outside the patch. Finally, mortality rates were considerably lower for the fish in patches (Schumacher and Kendall 1995). At least two mechanisms could be responsible for increased larval survival inside mesoscale eddies: 1) decreased turbulence from wind mixing due to increased stability of the water column, and 2) an increase in prey items available for the larvae. Our measurements provide necessary data to researcher examining these mechanisms.

Results

Physical characteristics of the eddy

Eddies are common features over the slope and basin of the southeastern Bering Sea. In particular, eddies are often observed south of the Pribilof Islands. An examination of altimeter data since 1993 shows that eddies are typically formed in April or May, apparently from instabilities in the Bering Slope Current. During each of the last four years (Fig. 4.3.1), an eddy was evident southwest of the Pribilof Islands as a positive sea surface height anomaly. The diameter of eddies are about 100 km. The eddy that was examined in 1997 appears typical of these eddies in location and timing (May 2 or 3) of formation, and size.

Several hydrographic sections were done across the eddy, two of which are shown in Figure 4.3.2. The baroclinic structure extended to below 1500 m on June 11-12. About two weeks later, the signature of the eddy was shallower, likely as a result of the eddy interacting with the slope. Salinity plays a greater role than temperature in determining the density structure. Transport within the eddy was $\sim 6 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, approximately the same transport that was observed in the Bering Slope Current during spring 1997. The eddy was asymmetric with the highest speeds observed near the shelf break. Maximum rotational velocities within the eddy exceeded 40 cm s^{-1} .

The translation of the eddy can be inferred from the trajectory of the drifters that were deployed within the eddy (Fig. 4.3.3). The eddy moved slowly to the northwest until June 15 when it turned and moved toward the southwest. The southwestward trajectory is similar to other eddies generated in this region. We tracked the eddy this way until December when the drifters stopped transmitting.

Biotic responses

We measured solar radiation almost continuously in seven wavebands between 411 and 700 nm, including the wavebands corresponding to the SeaWiFS sensor. Data have been converted to records of photosynthetically available radiation, useful for biological models. Information on changes in spectral composition of solar irradiance with time of day and cloud cover will be very useful for interpreting data from the drifters: ocean color measurements can then be corrected for changes in the spectrum of sunlight.

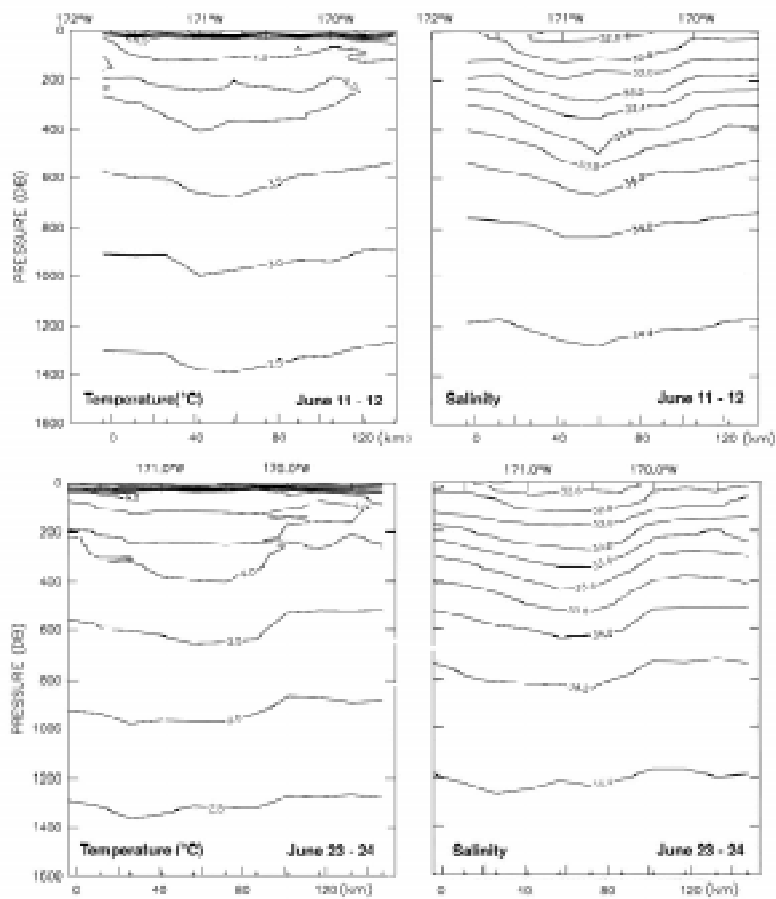


Figure 4.3.2 Temperature and salinity from a hydrographic survey across the eddy on June 11-12 (top) and June 23-24 (bottom). Data from June 11-12 were collected at 55°30'N and those on June 23-24 along 55°21'N. Arrows at the bottom of each panel indicate station locations.

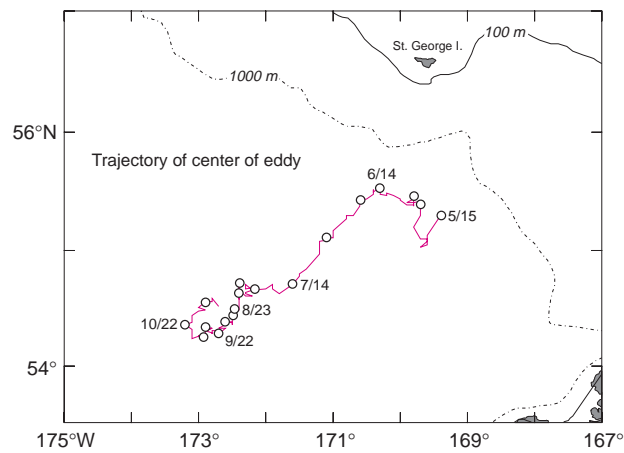


Figure 4.3.3 The eddy was tracked until December. The trajectory of the center of eddy is shown as it traveled slowly toward the southwest.

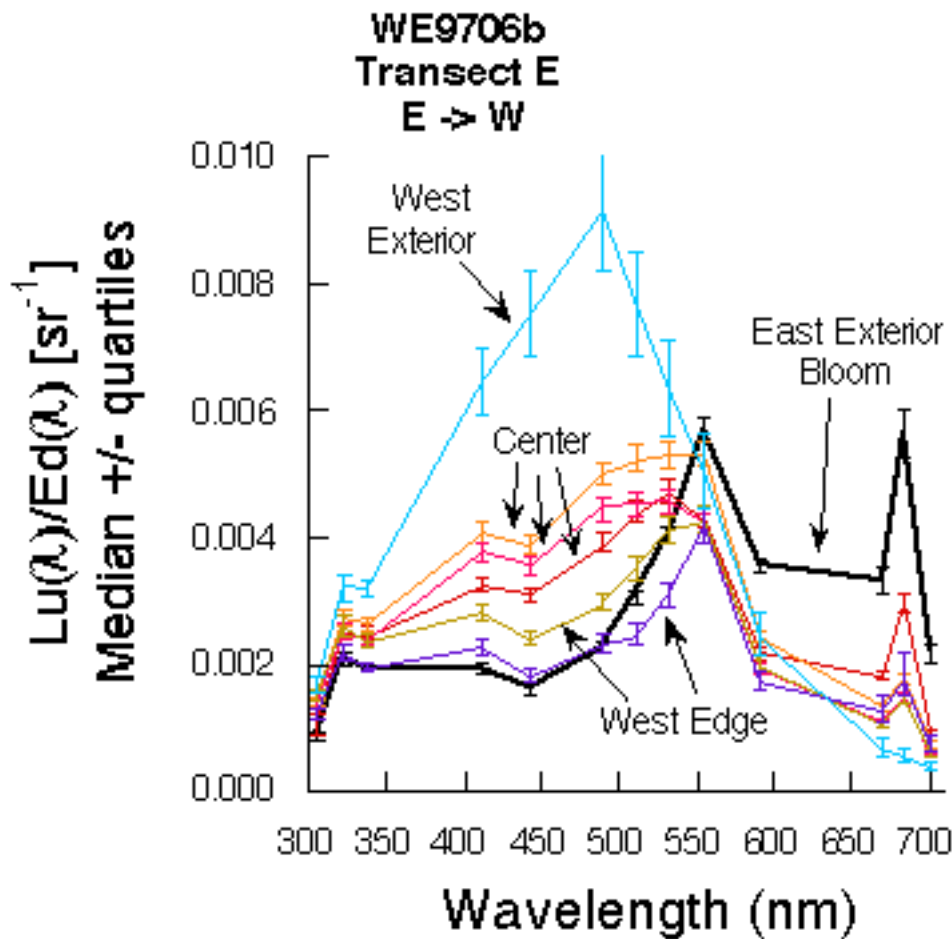


Figure 4.3.4 Data from entire deployments of the radiometer buoy are described with medians and quartiles.

A tethered radiometer buoy was used to measure upwelling radiance ($Lu(\lambda)$, $W m^{-2} nm^{-1} sr^{-1}$) and downwelling solar irradiance ($Ed(\lambda)$, $W m^{-2} nm^{-1}$) in 13 wavebands between 323 and 700 nm. We have results for eighty 5-min intervals during which surface chlorophyll was measured and samples were taken for measurement of spectral absorption by particulates and dissolved organic matter (DOM). The data are appropriate for developing algorithms for estimating chlorophyll and DOM from ocean color as measured by the drifters, moorings, aircraft, or (if the sky is ever clear) satellites. Solar-stimulated chlorophyll fluorescence (signal at 683 nm) was measured by the radiometer, and algorithms will be developed. Measurements in UV wavelengths will be useful for future projects.

Reflectance spectra ($Lu(\lambda)/Ed(\lambda)$) from the cruise show clearly the biologically determined optical variability associated with the eddy. Data are from entire deployments of the radiometer buoy (Fig. 4.3.4). Absorption by phytoplankton (strong between ca. 400 – 500 nm) reduces reflectance in the blue. Decreases in blue reflectance indicate increases in chlorophyll concentration, as do increases in the fluorescence signal at 683 nm. We see blue water to the west of the eddy, high-chlorophyll waters near the edges, and lower-chlorophyll water near the

middle. Fluorescence was measured on each CTD cast. The highest fluorescence was measured during the first day or two at the eddy. Typically the higher values of fluorescence extended to 28 m, although the mixed layer was much shallower (~12 m; Fig. 4.3.5). When we returned to the eddy on June 23, there was no evidence of the bloom that had been observed earlier. Examination of data from the OCM drifters indicates that the bloom ended a day or two before our return to the eddy. Within the eddy, there was no evidence of a bloom until September, when fall winds likely introduced nutrients into the photic zone. The nutrient data support these results. Nutrients were already drawn down (nitrate values of 0-3 $\mu\text{mole/l}$) within the eddy during our first visit to the eddy; nitrate was further drawn down by our second visit.

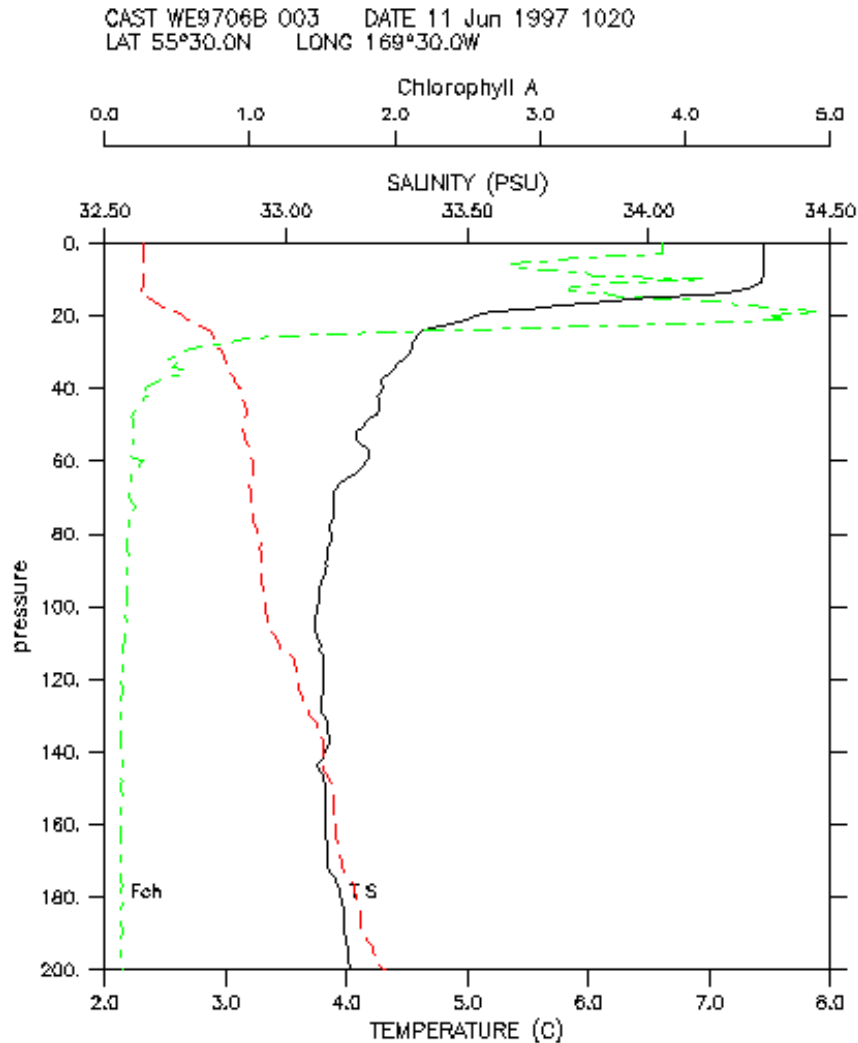


Figure 4.3.5 Temperature, salinity and chlorophyll (fluorescence) in the eddy during June 11, 1997.

We measured the concentration of chlorophyll a fluorometrically in triplicate for more than 275 samples, and the data are available for distribution. Some samples were also frozen for parallel determination in the lab using fluorometric methods and HPLC. Generally, we sampled with a bucket during radiometer deployments (depth 0 m) and also from four depths sampled

with the corresponding CTD. We sampled oligotrophic and mesotrophic waters with good coverage, and also some bloom waters.

During most deployments of the tethered radiometer, we used a free-falling, multichannel, profiling radiometer to measure downwelling irradiance in 12 wavebands, including those of the SeaWiFS sensors. High-quality data were obtained that will allow us to calculate diffuse attenuation coefficients for each waveband as functions of depth for each profile. We will report diffuse attenuation coefficients at 490 nm and relate these coefficients quantitatively to upwelling radiance ratios.

Products

Manuscripts submitted and in preparation

- Stabeno, P.J., N.A. Bond, N.B. Kachel, S.A. Salo, and J.D. Schumacher, submitted: Temporal variability in the physical environment of the southeastern Bering Sea. *Fish. Oceanogr.*
- Stabeno, P.J., J.J. Cullen, R. Davis, R. Leben, and T.E. Whitledge, in preparation: The biophysical evolution of an eddy in the southeast Bering Sea. *J. Geophys. Res.*
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Outlook

While we made improved our understanding of the biophysical interaction within an eddy, important questions remain.

1. Was the productivity observed when we first visited the eddy associated with formation of eddy and the entrainment of some shelf waters into the eddy, or was the timing of the bloom related to water column structure?
2. This eddy likely was formed from instability in the Bering Slope Current. The green belt along the shelf break, coincides with the locations of these eddies during their early stages. If the eddy we studied was typical, then much of the productivity observed in the green belt may be related to the occurrence of the eddies. Changes in the strength and stability of BSC then could influence the productivity along the eastern shelf slope.
3. Questions also arise on the importance of these instability in supplying nutrient rich waters onto the shelf. Fortunately, funding for satellite-traced drifters was obtained for 1999 and 2000, to provided critical information on flow trajectories.

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5.0 UPPER-TROPHIC-LEVEL PROCESSES

5.1 High-resolution acoustic and juvenile pollock retrospective data analysis

Principal Investigators: Gordon Swartzman, Richard Brodeur, Jeffrey Napp, George Hunt

Collaborators: Roger Hewitt, David Demer, Elizabeth Logerwell, Mary Beth Decker, and Daniel Walsh

Period of Research: August 1996 through September 1998

Goal and Objectives

1. Develop and evaluate a method for distinguishing fish from plankton using multi-frequency acoustic data (38, 120 and 200 kHz). This has never been done before in a rigorous, quantitative fashion. Compare continuous acoustic data with discrete plankton and trawl data for ground-truthing and method evaluation.
2. Process and combine three years of Bering Sea survey data sets including acoustic, CTD (temperature-depth profiles), bird observations, surface temperature, salinity and fluorescence data.
3. Examine and test for relationships between survey variables using non-parametric regression and other spatial statistical methods.
4. Suggest testable hypotheses for process-oriented studies resulting from this project.

Project Description

To address these research objectives we conducted the following research activities:

We processed acoustic data collected by the Alaska Fisheries Science Center in September 1994-1997 in the neighborhood of the Pribilof Islands, Alaska. These data were collected by the National Marine Fisheries Service as part of FOCI (Fisheries-Oceanography Coordinated Investigations). The data were collected using a SIMRAD EK-500 echosounder system at multiple frequencies (38, 120 and 200 kHz in 1994 and 1995; 38 and 120 kHz in 1996 and 1997). Processing includes bottom and bubble removal and identification of fish schools and plankton patches in the acoustic backscatter images). Fish schools were identified using a morphological image-processing algorithm based on the 38-kHz data (Swartzman et al., 1994).

We developed and tested an algorithm for identifying plankton patches from acoustic backscatter images (Swartzman et al., 1999a). This algorithm was based on morphological image processing of the difference between backscatter at two frequencies (200 and 120 kHz for 1994 and 1995; 120 and 38 kHz for 1996 and 1997). It uses theory based on geometrical backscatter models from zooplankton sized and shaped objects, which demonstrate that backscatter at the higher frequency should be higher than that at the lower frequency, while backscatter for fish should not be.

We processed environmental data collected along with the acoustic data for the four study years and fused these data with the acoustic data. Also, we combined the acoustic data with bird

sightings along the transects. To this end we developed an acoustic data viewer and data fuser called FishViewer (Swartzman et al., 1999a). We also used a connected component algorithm on the processed acoustic data to create tables of fish schools and plankton patches. We could then graph the locations of the fish schools along each transect with environmental (e.g., thermocline, isotherms, bottom, front locations) and other biotic information overlaid (e.g. bird locations at the surface).

We examined spatial proximity and overlap between fish school and plankton patches for 1994 and 1995 surveys using generalized additive models and a modification of the distance-based Ripley's K from spatial statistics (Swartzman et al., 1999a,b). To this end we separated transects into regions based on the degree of thermal stratification in the water column.

We compared the algorithm used to identify plankton patches, which we developed, to plankton data collected during the surveys using a MOCNESS (Multiple Opening Closing Net Sampling System) and found the depth distribution of both to be similar for each of the stratification regions (Swartzman et al., 1999b).

We examined the relationship between piscivorous bird spatial distributions (murre and puffins) and pollock abundance using nonparametric regression and spatial statistical methods. We defined bird clusters as groups of birds within a threshold distance of next neighbors and modeled the fish biomass as a function of size of the cluster (number of birds per cluster) (Swartzman and Hunt, submitted).

We worked with collaborators from the SEBSCC component Habitat Differences in Frontal Regions around the Pribilof Islands and Their Importance to Juvenile Pollock Growth and Survival in the Bering Sea (Section 5.2). The collaborative work included:

- Processing acoustic data to provide information about plankton abundance along the transects to be used in an energetics model by Lorenzo Ciannelli and Richard Brodeur of pollock growth, which was based on the spatial overlap of pollock schools and plankton patches as well as the spatial distribution of temperature.
- Examining the distribution of acoustically determined plankton patches and fish schools during a diel study in 1996 to compare with various net samples taken during this study at a single location over the data (Schabetsberger et al., in preparation).

Results

Methods dissemination

We developed web pages describing applications of two of the methods commonly used in this project – Generalized Additive Models and Cluster Analysis. These web pages have proven useful in providing guidance to other researchers interested in these methods but not familiar with them or the applications. The web site consists of heuristic descriptions, more detailed application and methods papers, and links to and descriptions of available software. These web pages may be accessed at <http://www.cqs.washington.edu/~gordie/cluster.html> and <http://www.cqs.washington.edu/~gordie/gampaper.html>.

Methods development – plankton patch identification; fish-plankton proximity

The basis for the plankton identification algorithm is illustrated in Figures 5.1.2-5.1.5. These show sections of acoustic transect A, north of St. Paul Island (Fig. 5.1.1) for daytime (Figs. 5.1.2 and 5.1.3) and nighttime (Figs. 5.1.4 and 5.1.5) for 120 kHz (Figs. 5.1.2 and 5.1.4) and 38 kHz (Figs. 5.1.3 and 5.1.5). The three panels in each figure are for 1995, 1996 and 1997 (top to bottom panels). The panels illustrate several phenomena. During the daytime in all three years shown (we also have results for 1994 which are not shown; they are most similar to results for 1995) the plankton patches were near the bottom. They are clearly more easily seen in the 120 kHz images than the 38 kHz images (i.e., they have higher backscatter at 120 than at 38 kHz). During the nighttime the plankton patches, where visible are higher in the water column. In 1996, the pervasive distribution of fish in the water column both during the night and day and the clearly elevated fish abundance compared with the other years, makes it difficult to observed plankton in the nighttime images because any plankton are probably overshadowed by fish backscatter. However, for 1995 and 1997, the nighttime plankton patches are clearly visible as higher backscatter regions in the 120 kHz images. Because the morphological algorithm used to identify patches is applied only to pixels having higher backscatter at the higher frequency, it will not allow randomly oriented pixels to be identified as plankton, only contiguous patches of such pixels.

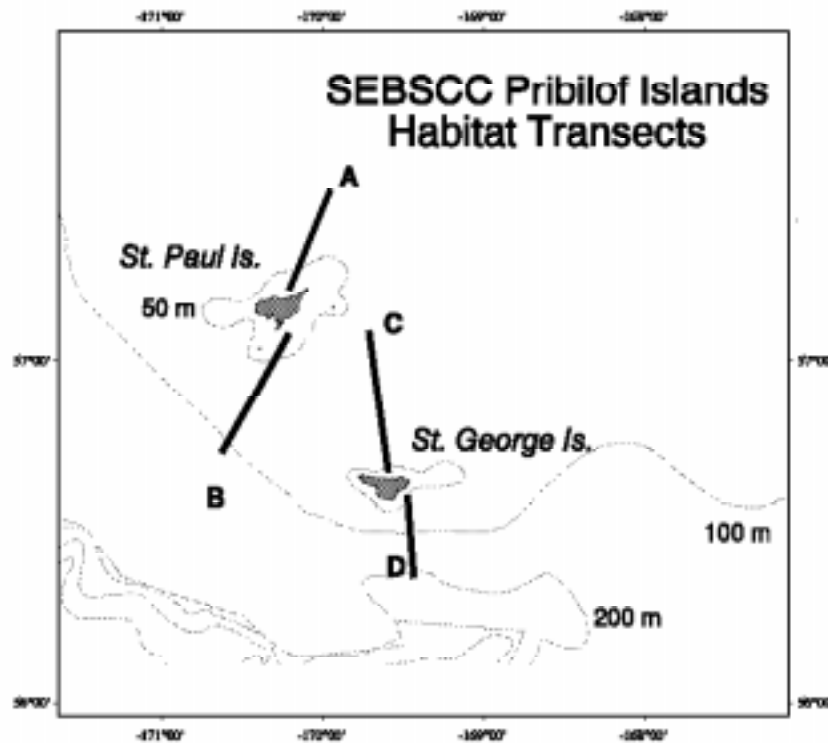


Figure 5.1.1 Acoustic survey transects near the Pribilof Islands. The transects cover several front regions around the islands. Focus of comparative studies has been on transects A and D.

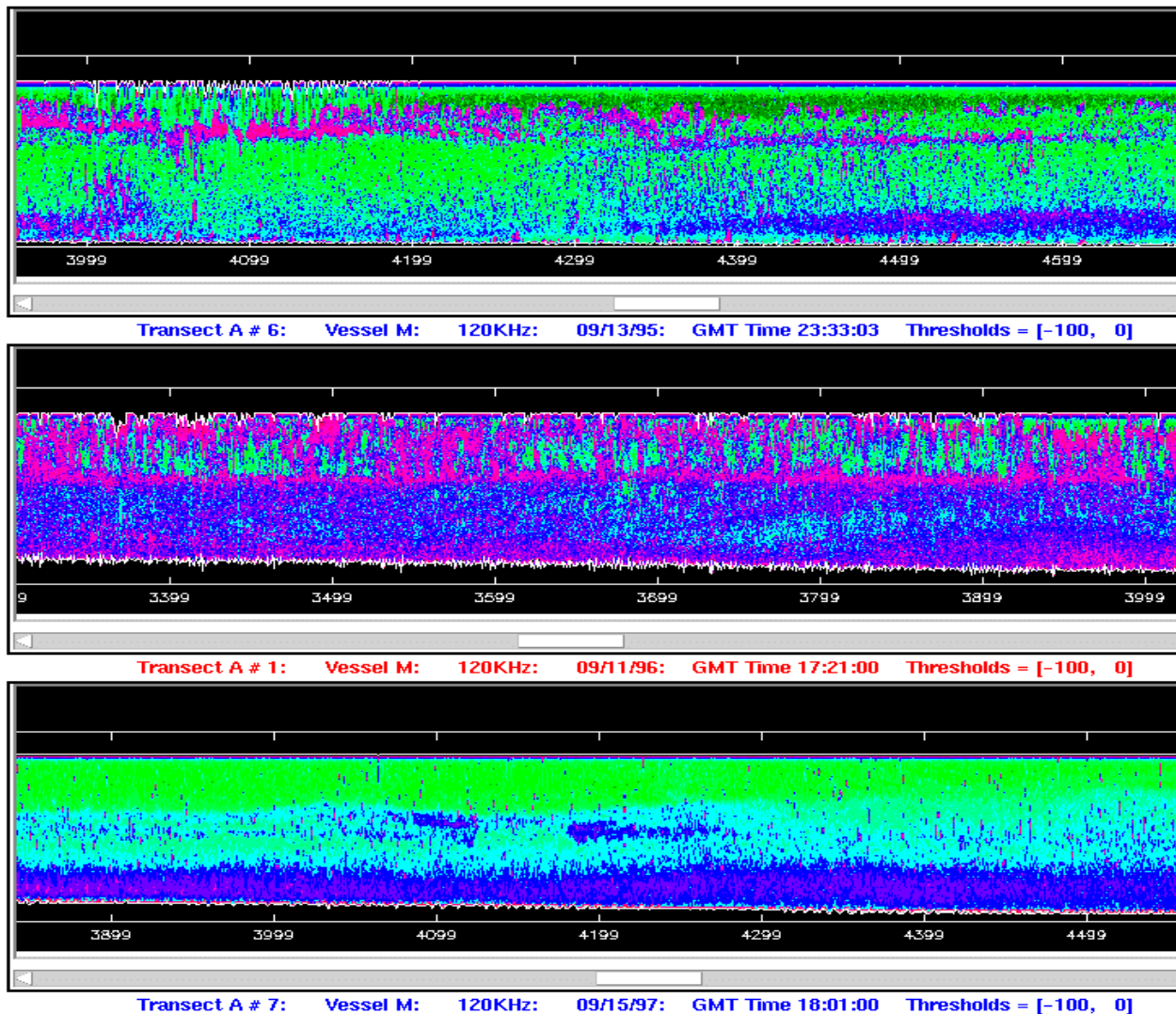


Figure 5.1.2 Sections of acoustic transect A during the daytime for 1995, 1996 and 1997, showing backscatter images at 120 kHz. At this frequency plankton patches are clearly visible near the bottom, especially for 1995 and 1997. The backscatter color range for plankton is in the light blue to dark blue and purple color range (-70 to -54 dB). The x-axis is distance in pixels from the start of the transect. Each pixel is 9 m horizontal by .5 m vertical resolution. Water depth is about 60 m in all images.

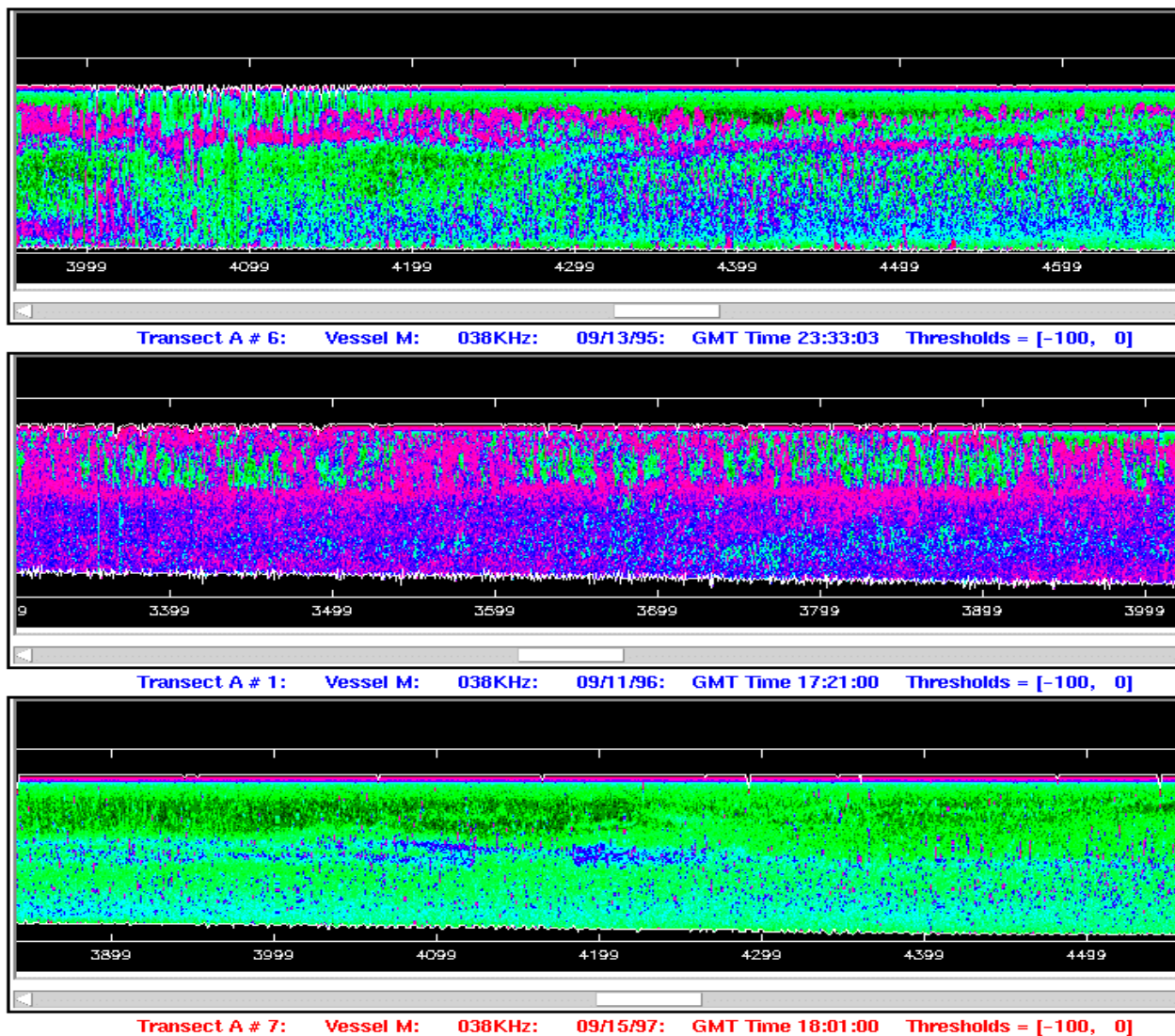


Figure 5.1.3 Sections of acoustic transect A during the daytime for 1995, 1996 and 1997, showing backscatter images at 38 kHz. At this frequency plankton patches are either not visible or barely visible near the bottom. The backscatter color range for plankton is in the light blue to dark blue and purple color range (-70 to -54 dB). The x-axis is distance in pixels from the start of the transect. Each pixel is 9 m horizontal by .5 m vertical resolution. Water depth is about 60 m in all images. Fish generally show higher backscatter than the plankton backscatter range (i.e., red color range in the images).

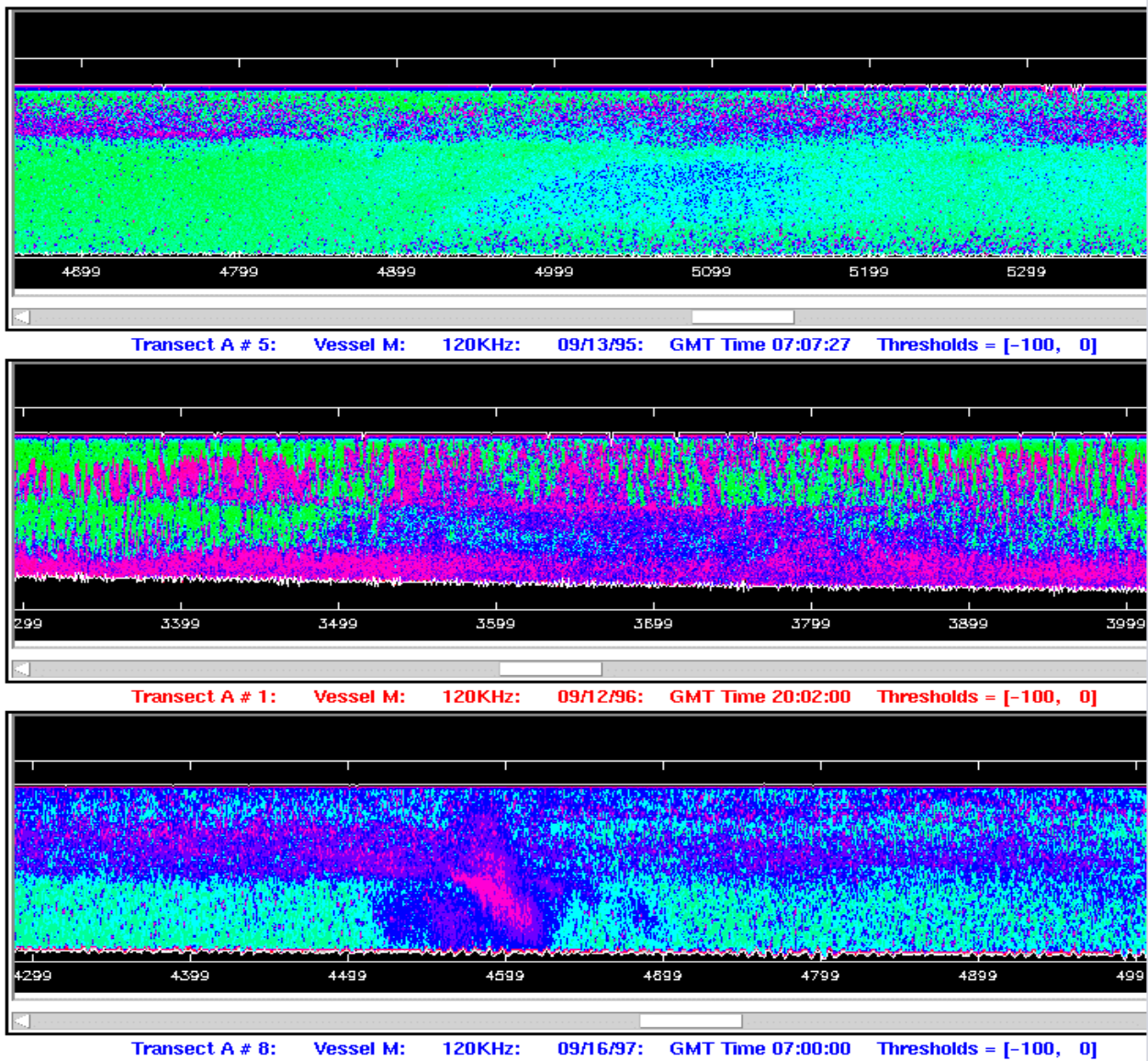


Figure 5.1.4 Sections of acoustic transect A during the nighttime for 1995, 1996 and 1997, showing backscatter images at 120 kHz. At this frequency plankton patches are clearly visible in the water column, especially for 1995 and 1997. The backscatter color range for plankton is in the light blue to dark blue and purple color range (-70 to -54 dB). The x-axis is distance in pixels from the start of the transect. Each pixel is 9 m horizontal by .5 m vertical resolution. Water depth is about 60 m in all images.

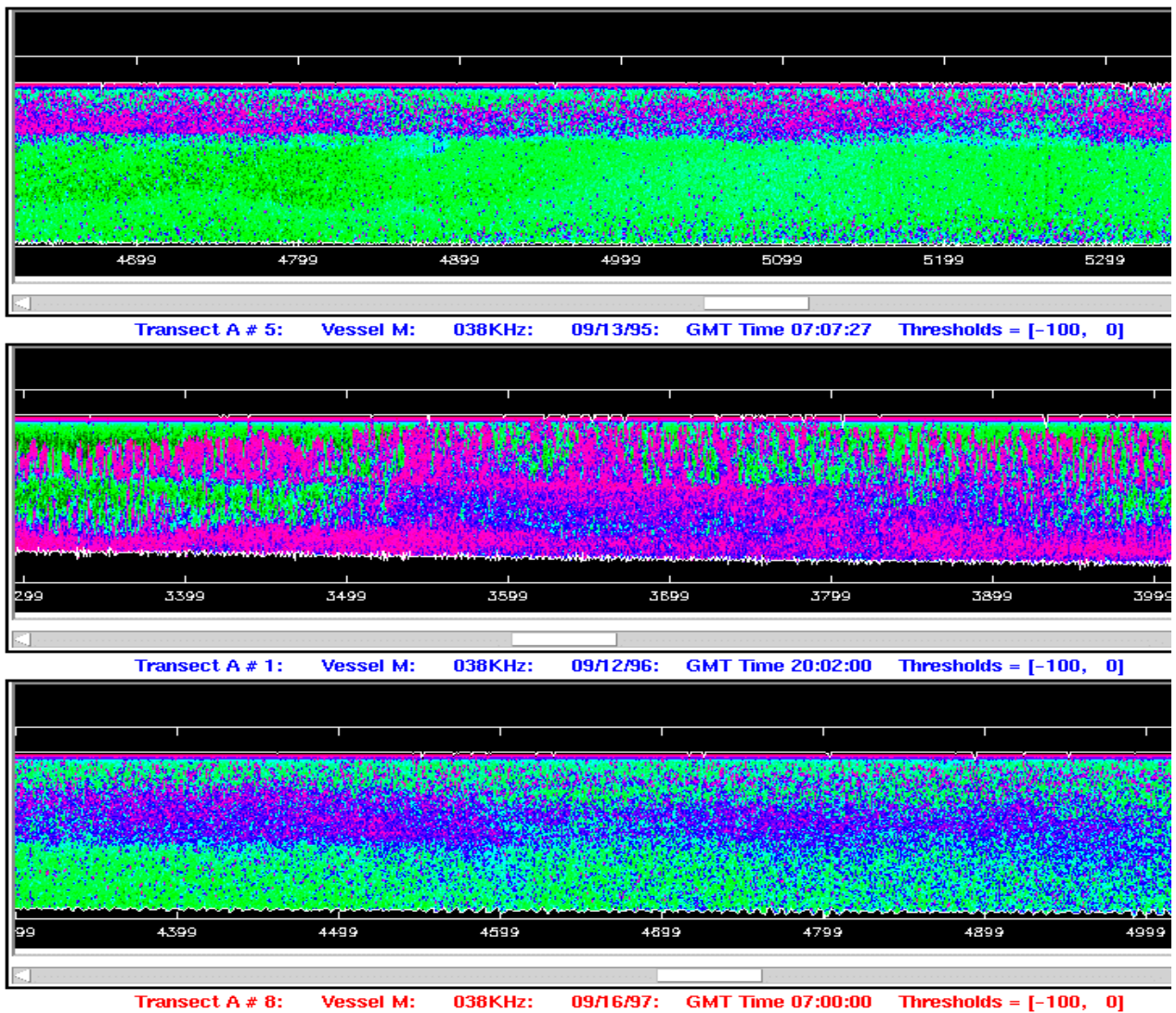


Figure 5.1.5 Sections of acoustic transect A during the nighttime for 1995, 1996 and 1997, showing backscatter images at 38 kHz. At this frequency plankton patches are not visible in the water column. The backscatter color range for plankton is in the light blue to dark blue and purple color range (-70 to -54 dB). The x-axis is distance in pixels from the start of the transect. Each pixel is 9 m horizontal by .5 m vertical resolution. Water depth is about 60 m in all images.

Fish-plankton proximity 1994-1995

Extensive analysis of multiple day and night passes of acoustic transects near the Pribilof Islands suggested that the plankton patches are statistically significantly clustered around the fish schools when the density of plankton is low (Fig. 5.1.6). At high plankton densities there is no particular spatial relationship between fish and plankton. At intermediate plankton densities there appears to be an association between the density of fish schools and plankton patches. Over an intermediate density range higher density fish schools are more likely to be associated with higher density plankton patches. These results can be interpreted from a feeding perspective to suggest that only at lower plankton densities is it necessary for fish to remain close to their prey while the two are separated in depth due to diel migration by plankton. When densities of plankton are high enough there is no advantage to maintain proximity because densities of plankton are probably sufficient throughout the region for fish feeding (Swartzman et al., 1999b).

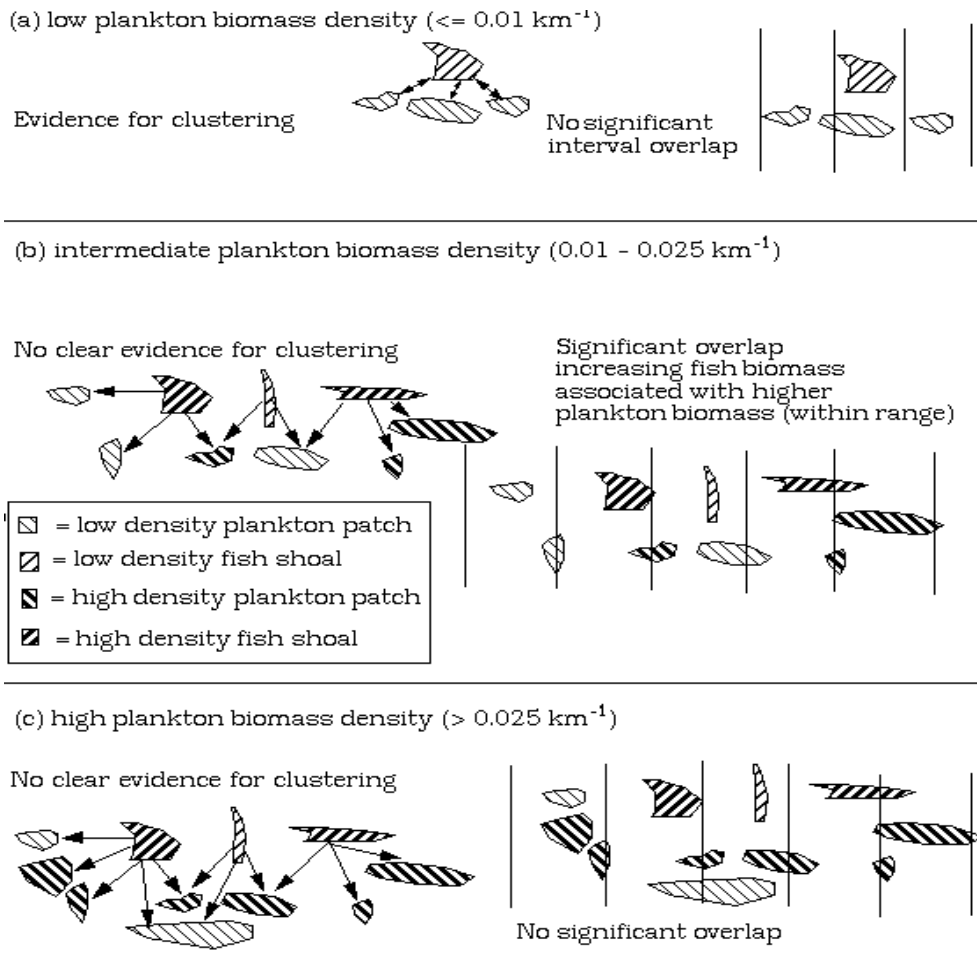


Figure 5.1.6 Graphical representation of the observed proximity relationship between fish schools and plankton patches in September 1994 and 1995 along acoustic transects near the Pribilof Islands, AK (Swartzman et al., 1999b). Plankton density is a relative index, not an actual biomass.

Interannual changes in fish and plankton distribution 1994-1997

One of the major benefits of having a multi-year time series is the possibility of examining the relationship between pollock and plankton abundance and distribution and year class strength in pollock. The four study years (1994-1997) were quite different. 1994 and 1995 featured strong thermoclines in the stratified region, with accompanying restriction of the pollock juveniles to above the thermocline. In 1996 pollock were much higher in abundance, plankton abundance was low and the pollock were found throughout the water column, even in the stratified region, both day and night (Fig. 5.1.7). In 1997 (Fig. 5.1.8), fish biomass was quite low, and plankton biomass appeared to be high, which was substantiated by the MOCNESS net samples.

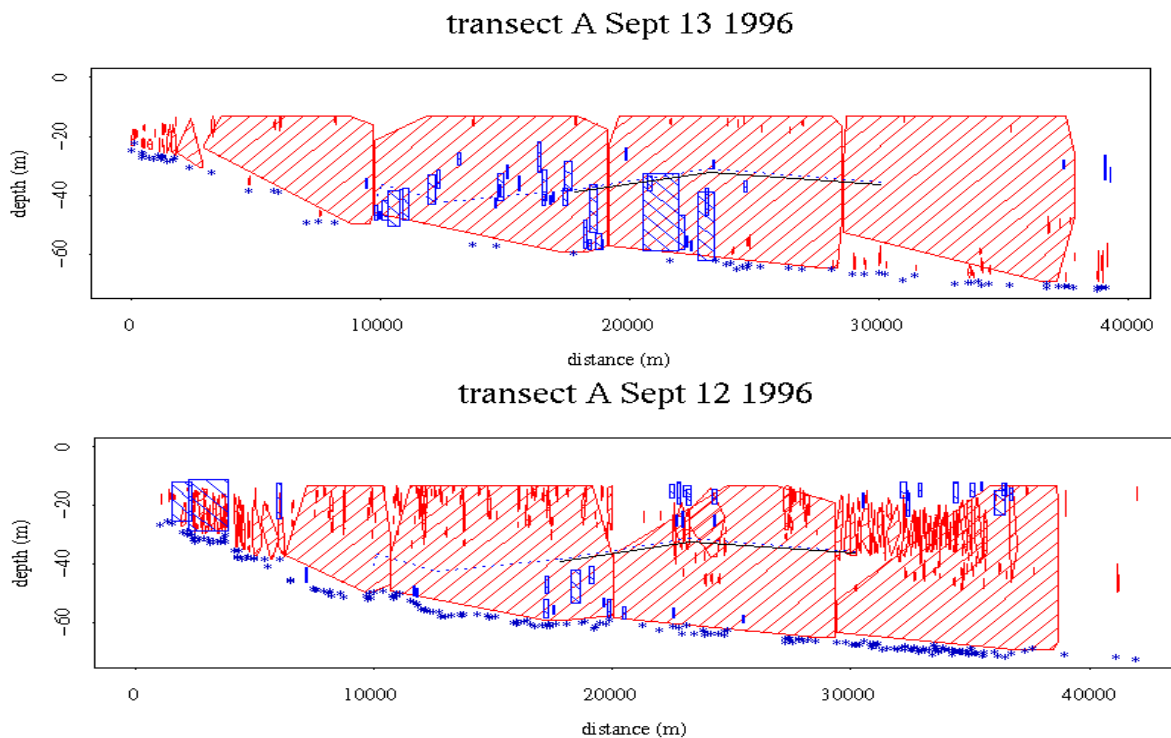


Figure 5.1.7 Distribution of fish schools (red polygons) and plankton patches (blue polygons) along transect A in September 1996 during the day (top panel) and night (bottom panel). The bottom is indicated by blue points. The thermocline is shown in the figures as a black line near 30-m depth. These figures show the pervasive nature of fish throughout the water column and the low plankton abundance, except in the nearshore, tidally mixed, region.

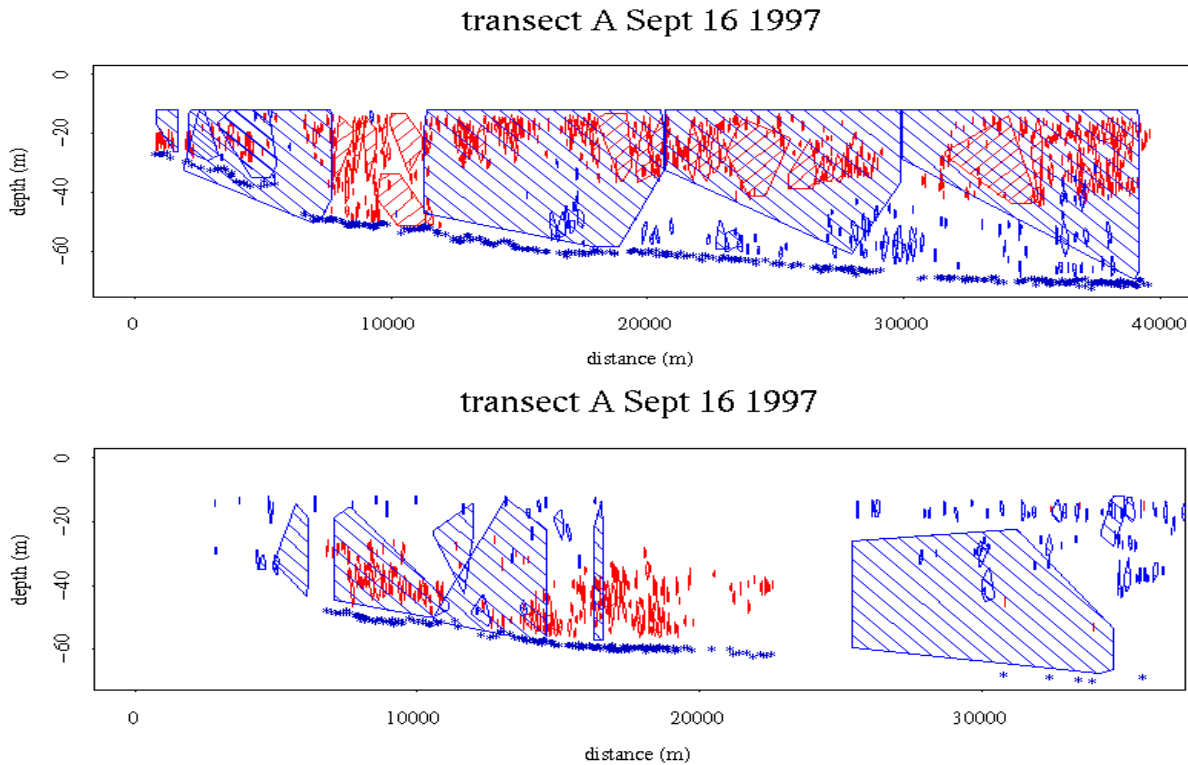


Figure 5.1.8 Distribution of fish schools (red polygons) and plankton patches (blue polygons) along transect A in September 1997 during the day (top panel) and night (bottom panel). The bottom is indicated by blue points. These figures show the low abundance of fish throughout the water column and the high plankton abundance.

Bird-fish spatial relationship 1994-1997

Comparing the distribution of cluster size (numbers of birds) of murres and puffins, to the biomass of fish under the clusters (Fig. 5.1.9, we found that above some threshold cluster size (10 birds for 1994-1996 and 50 birds for 1997) there was always abundant fish. However, for smaller clusters the fish abundance was not predictably high. These findings were supported by the use of nonparametric regressions of bird cluster size as a function of fish biomass and distance from the rookery (which was not significant in most cases). Results of this analysis have been submitted for publication (Swartzman and Hunt 1999).

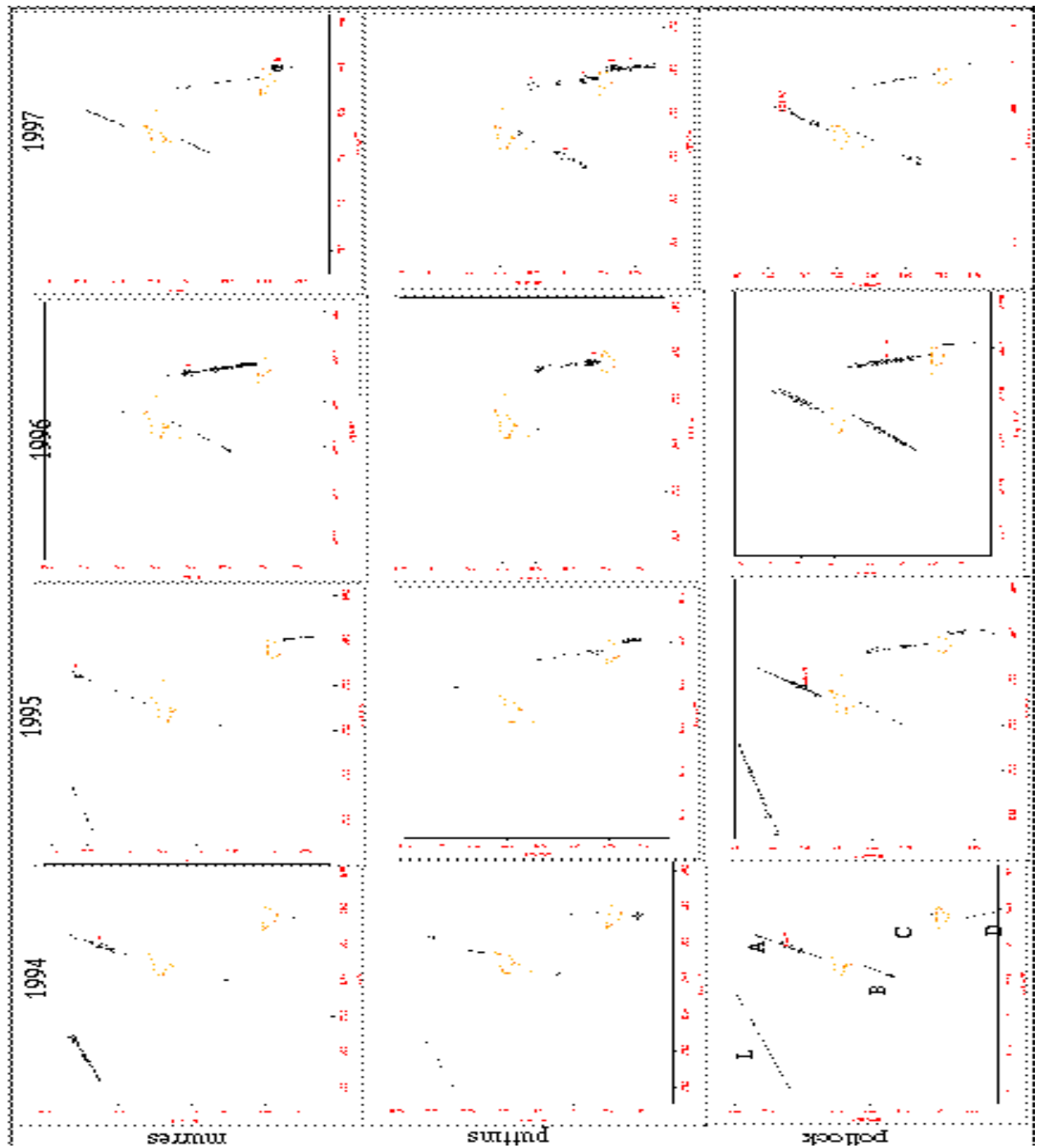


Figure 5.1.9 Spatial distribution of murre, puffin and pollock for surveys in September 1994-1997 near the Pribilof Islands, AK. Circles are proportional to abundance, scaled to the maximum for each variable in that year. Both bird and fish abundance distribution is highly variable from year to year. Overlap between bird and fish biomass distribution is not apparent.

Products

Publications in peer-reviewed literature

- Brodeur, R.D., M. Doyle, J.M. Napp, P.J. Stabeno, J.D. Schumacher, and M.T. Wilson, 1998: Fronts and fish: Interannual and regional differences in frontal structure and effects on pollock and their prey. *Oceanogr. 11(2)*: 64.
- Brodeur, R.D., and M.T. Wilson, 1999: Pre-recruit walleye pollock in the eastern Bering Sea and Gulf of Alaska ecosystems. Proceedings of GLOBEC International Marine Science Symposium on Ecosystem Dynamics, pp 238-251.
- Brodeur, R.D., M.T. Wilson, and L. Ciannelli, in press: Spatial and temporal variability in feeding and condition of age-0 walleye pollock in frontal regions of the Bering Sea. *ICES J. Mar. Sci.*
- Brodeur, R.D., M.T. Wilson, J.M. Napp, P.J. Stabeno, and S. Salo, 1997: Distribution of juvenile pollock relative to frontal structure near the Pribilof Islands, Bering Sea. Proc. Int. Symp. on the Role of Forage Fishes in Marine Ecosystems, Alaska Sea Grant AK-97-01, pp. 573-589.
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- Swartzman, G.L., and G. Hunt, submitted: Spatial association between murre (Uria spp), puffins (Fraterecula spp) and fish shoals near the Pribilof Islands, Alaska. *Marine Ecology Progress Series.*

Presentations by principal investigators

- FOCI presentation - October 1997, AFSC, Seattle WA - NMFS and University of Washington personnel in attendance
- SEBSCC Annual PI meeting - December 1997, Seattle WA - Principal Investigators on SEBSCC projects in attendance
- PICES meeting - October 1998, Anchorage, AK- (submitted abstract) Spatial proximity of age-0 walleye pollock (*Theragra chalcogramma*) to zooplankton near the Pribilof Islands

University of Washington School of Fisheries Quantitative Seminars - October 1997 and February 1998. – Plankton-fish spatial proximity. Students and faculty from UW in attendance

Resource Modeling Association National meeting Seattle, WA. June 1997;

Resource Modeling Association international symposium Hobart, Tasmania, Australia. December 1997

Resource Modeling Association National meeting Ensenada, B.C. Mexico. July 1998

Resource Modeling Association international meeting Halifax, Nova Scotia, Canada, June 1999

American Fisheries Society Meeting, Monterey, CA, August 1997 - special session on spatial data and modeling in fisheries

Fisheries Acoustics Science and Technology meeting. April 1999. St. John's Newfoundland, Canada

International Council for the Exploration of the Sea CLUSTER meeting October 1998. Heraklion, Crete (G. Swartzman. invited participant and presenter)

Informal Graduate student seminar: Gordon Swartzman, Suzann Speckman, Lorenzo Ciannelli, Robert Schabetsberger, Ric Brodeur, Daniel Schindler, Donald Gunderson, Mark Tetric, John Piatt, Tim Hammond.

Outlook

Plans for SEBSCC Phase II in 1999 through 2001 will extend and strengthen the results obtained in Phase I. These feature the following:

1. Use of a four frequency (43, 120, 200 and 420 kHz) HTI towed acoustic system on the 1999 September cruise to allow us to distinguish size classes of plankton and to better test, through direct comparison with net samples, our algorithms for distinguishing fish shoals from plankton patches.
2. Workshops, in collaboration with Dr. Van Holliday, a world-renowned expert on multifrequency acoustic data analysis, to maximize our ability to extract information from the multi-frequency echosounder systems.
3. Analysis and comparison with previous years of acoustic data collected in years 1997 and 1998.
4. Further testing of hypotheses concerning the proximity of fish shoals and plankton patches and its dependence on the density of plankton (Swartzman et al., 1998b).
5. An attempt to distinguish jellyfish aggregations from fish shoals and plankton patches. This will involve extensive review of papers on jellyfish backscatter and the development of an algorithm for acoustic location of jellyfish.
6. Comparison of the distribution and abundance of juvenile pollock and their prey with year class strength of pollock. We will look for patterns that might help distinguish a strong year class from ocean conditions and fish and plankton distribution during the September surveys.
7. Analysis of the 1997 El Niño year data and analysis of the effect of the extensive coccolithophore bloom observed during 1997 and 1998 and seabird feeding activity and distribution.

5.2 Habitat differences in frontal regions around the Pribilof Islands and their importance to juvenile pollock growth and survival in the Bering Sea

Principal Investigators: Richard D. Brodeur, Jeffrey M. Napp, and Miriam J. Doyle

Collaborators: Matthew T. Wilson, Lorenzo Ciannelli, and Robert C. Francis

Period of Research: August 1996 through September 1998

Goal and Objectives

Our fundamental hypothesis was that the unique physical and biological conditions associated with the structural fronts around the Pribilof Islands provide an exceptionally good nursery habitat for age-0 pollock in the Bering Sea. To test this, we compared the abundance, size composition, growth, and condition of juvenile pollock at these fronts, on either side of the front, and at a control station near the Middle Shelf Front on the Bering Sea shelf away from the islands. The following key questions address aspects of this hypothesis:

1. Was the availability of food resources for juvenile pollock higher in these frontal regions relative to other habitats?
2. How were the small-scale (10-100 m) distributions of pollock and their prey related?
3. Were pollock selectively feeding upon any particular prey type or size or were they randomly feeding on whatever prey were available?
4. Were the growth rates, growth potential, and condition of juvenile pollock better in the fronts than outside of them?

Project Description

To address these research questions, we conducted the following research activities:

1. Examined stomach contents of juveniles from contrasting habitats to determine amount and kinds of food eaten by these fish and compared these to available prey abundance to determine selectivity.
2. Examined hatchdate distribution, size at age, recent growth patterns of juveniles using otolith increment microstructure in different habitats.
3. Determined where elevated food (pollock prey) concentrations occur in the Pribilof Island region.
4. Used bioenergetic models to determine food consumption necessary to provide the observed growth rates of pollock for each frontal region during 1994 through 1996. Food consumption was then compared to estimates to zooplankton standing stock and production to examine whether food resources were sufficient for survival or if depletion of local prey resources occurred due to high predation rates of juvenile pollock and other fishes.
5. Developed and used a spatially explicit bioenergetics model to investigate the relationship between food resources, predators and juvenile pollock distribution.

To accomplish these goals, we have conducted sampling of juvenile pollock and their associated prey and environment during the fall of 1996 and summer and fall of 1997 and 1998. Also covered under Phase I was further analysis of data collected in the fall of 1994 and 1995.

Results

In the fall of 1997, we conducted a successful cruise aboard the R/V *Miller Freeman* sampling around the Pribilof Islands for 10 days. In addition to our normal sampling, we used a Remotely Operated Vehicle to examine in situ the distribution and habitat dependencies of juvenile pollock, their predators, and prey. We also sampled the southeastern Outer and Middle Shelf Domains, including the Pribilof Islands during a summer research cruise aboard the Hokkaido University research vessel *Oshoro Maru*. In September of 1998, we conducted a 12-day cruise in aboard the chartered Russian research vessel *Professor Kaganovsky*. We were again able to successfully complete all our sampling although we were not able to accomplish as much as we normally do on the *Miller Freeman* due to technical difficulties.

A poster on the results of our research was presented at the Oceanography Society meeting in Paris in June 1998 and at the PICES annual meeting in Fairbanks in October 1998. The poster outlines the progress made in several of our studies relating frontal structure to juvenile distribution, growth and ecology. This poster can be viewed at the following URL: <http://www.pmel.noaa.gov/programs/review98/fronts.jpg>.

The following are some results of analyses by the major topic areas of our research in 1997 and 1998.

Physical oceanography

Temperature profiles along Transect A show the inner shelf was well mixed with the water column nearly isothermal. The offshore parts of the transects clearly show the stratified 2-layer system characteristic of the Middle Shelf Domain (MSD). The upper mixed layer was much shallower in 1995 than in 1994 and 1996 and the density differences between the layers were stronger. The interannual differences may be due, in part, to the sustained presence of sea ice over the southeastern shelf during spring 1995. *In situ* melting of the ice enhanced the normal seasonal stratification of the water column resulting in a shallow mixed layer. In addition, an absence of significant wind mixing is necessary to maintain that stratification.

Nutrients and chlorophyll

Nitrogenous nutrients (nitrate plus nitrite) were $>1 \mu\text{M}$ below the thermocline (in the stratified waters) and throughout the water column in the transition and inner front area in all years. Maximum chlorophyll-a concentrations ($> 4 \text{ mg l}^{-1}$) were found in surface waters just offshore of the structural front.

Age-0 pollock density and size distribution

During mid-September of 1994 through 1996, sampling was conducted on Transect A in the vicinity of St. Paul. Our intent was to compare and contrast three habitats: at the front, inshore,

and offshore of the front. Larger age-0 pollock and other nekton were collected using a 100-m² anchovy trawl containing 3-mm mesh in the codend. The overall catch composition of the anchovy trawl was numerically dominated (> 95% of total fish catch) by age-0 pollock in all three habitats. Age-0 pollock densities in the anchovy trawl were higher at the front in 1994 and 1996 than in 1995, but showed slightly higher densities inshore of the front in 1995 (Fig. 5.2.1), although the differences were not significant. The lowest densities were found offshore of the front, especially in 1994. In 1994, age-0 pollock were significantly larger in the offshore habitat than in the inshore and front habitats ($P = 0.023$ and $P = 0.009$), but no differences were found between the latter two habitats ($P = 1.00$). In contrast, there were no significant size differences among the habitats in 1995 and 1996.

Juvenile pollock feeding and condition in relation to fronts

Dietary composition, feeding intensity, and condition index of age-0 walleye pollock *Theragra chalcogramma*, were examined for variations related to time of day, habitat, size of predator, and year. Age-0 pollock condition factor (Fulton's K) varied from 0.45 to 1.20 (mean = 0.767 \pm 0.09 (SD)) overall. Year was not found to be an important factor in determining condition although the location with respect to the front was important (Fig. 5.2.2). Stomach contents of pollock collected at a hydrographic front near the Pribilof Islands during September 1994 through 1996 were compared with those from pollock collected on either side of the front. Diets were dominated in all habitats by small zooplankton, mainly copepods, pteropods, euphausiids, and chaetognaths, but fish and some epibenthic crustaceans were also consumed. Copepods and pteropods dominated the diet in all years and areas by number, but the diet was more mixed by weight with chaetognaths, euphausiids, and fish (smaller pollock) also being important (Fig. 5.2.3). Copepods were more abundant in the diet during the day. No significant day/night differences in weight composition were noted. Stomach fullness was highly variable by year and habitat and no significant differences were observed. Stomach

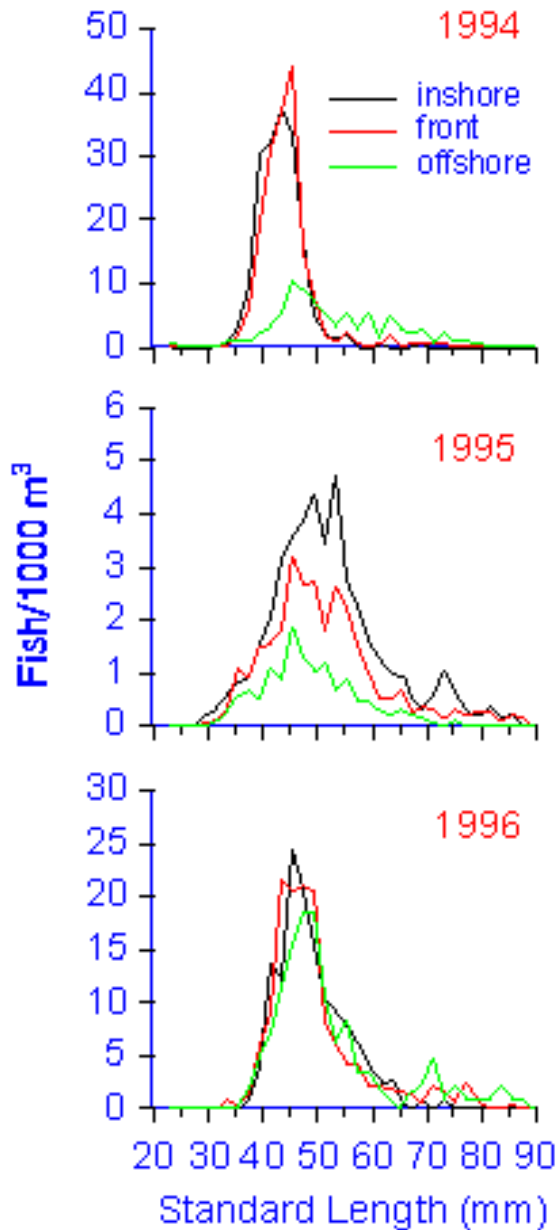


Figure 5.2.1 Density and size distribution of age-0 pollock by year and habitat. In 1994, pollock were significantly larger in the offshore habitat than in the inshore and front habitats. There were no significant size differences among the habitats in 1995 and 1996.

fullness peaked at around sunset for fish <50 mm and at night for the larger fish, implying that feeding chronology changed with ontogeny.

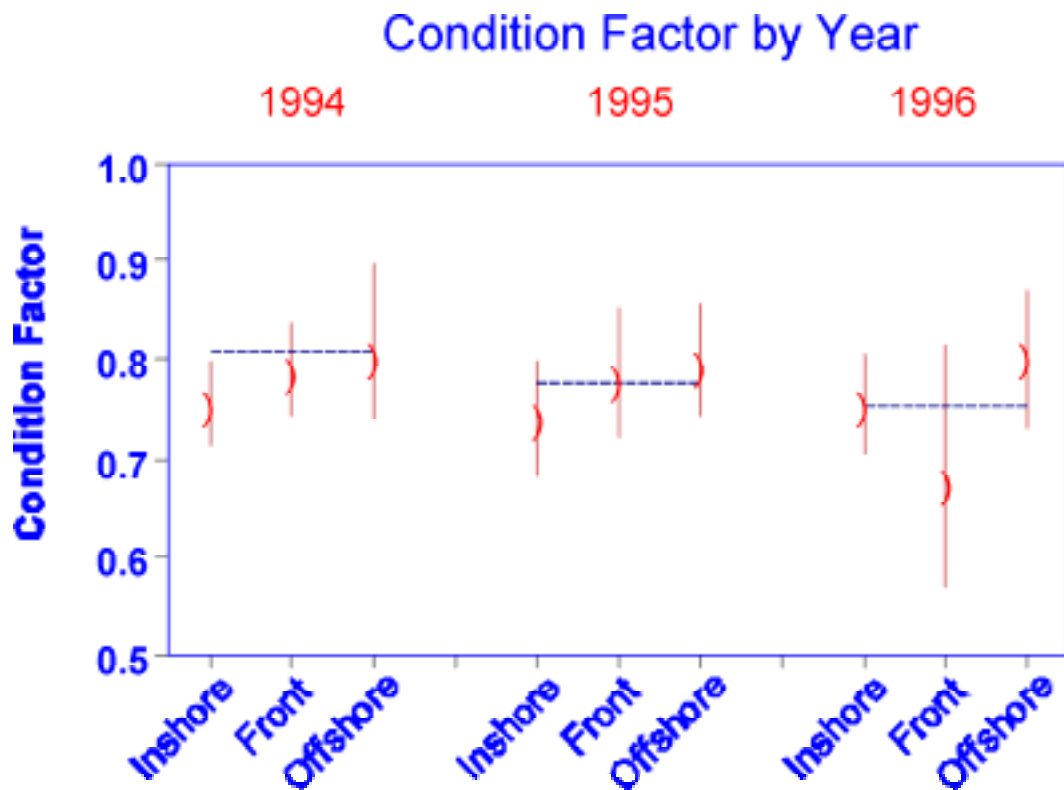


Figure 5.2.2 Comparison of the mean (± 1 standard deviation) condition factor (W/L^3) for each year and habitat and the overall means for each year (dashed lines).

Age and growth of juvenile pollock in relation to fronts

Analysis of otoliths for hatch-date distribution and daily increment structure has been carried out on age-0 pollock sampled during the fall of 1994 and 1995. The 1994 data indicate that hatching occurred from mid-April through early July with a peak occurring in early to mid June. A similar range of hatch dates was calculated for 1995 but the peak in hatching appeared slightly earlier, from the end of May through early June. Growth rates among the sampled populations have been estimated for 1994 and 1995 using regression analysis of age-length data. Some geographical distinction is noticeable in the age-length relationship, particularly during 1995 when a slight increase in size at age was apparent for fish sampled offshore relative to those at and inshore of the front (Fig. 5.2.4). The overall growth rate seems slightly higher in 1995 than in 1994. The possibility of variability in growth rates was investigated further by back-calculating growth among individual fish using otolith micro-increment measurements and an otolith length/fish length relationship.

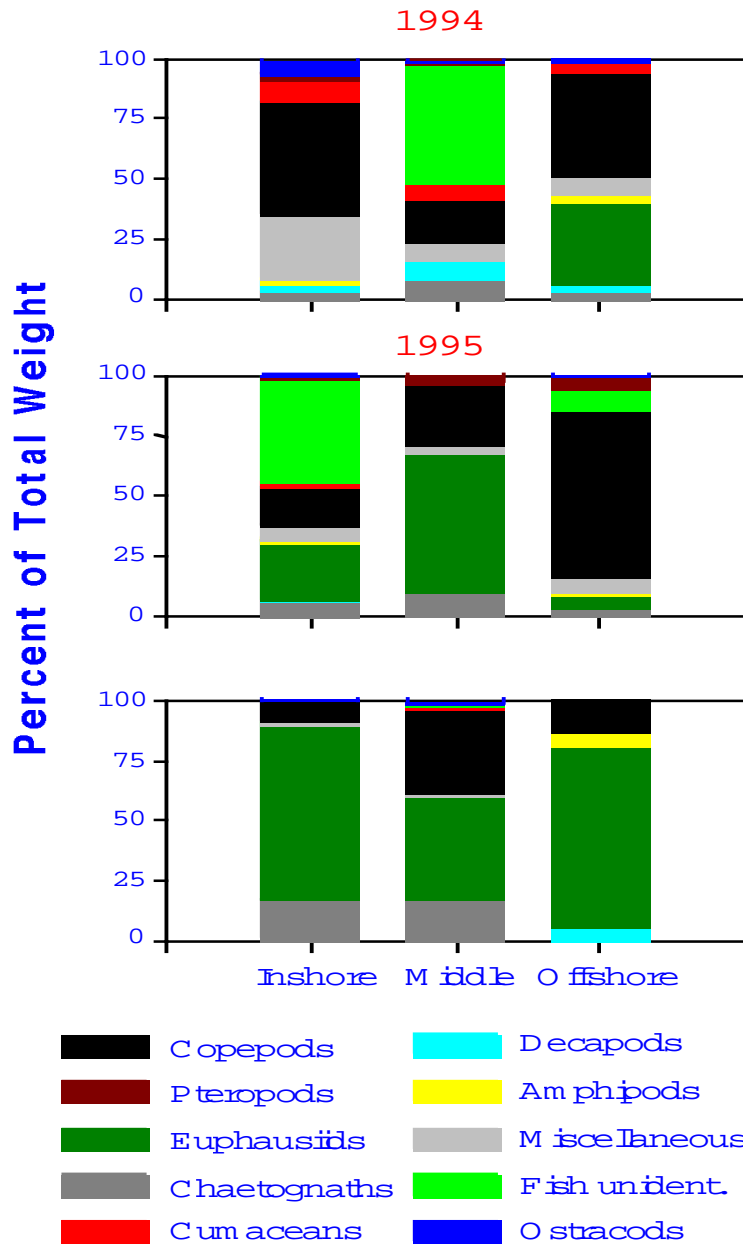


Figure 5.2.3 Stomach contents of age-0 pollock by year and location with respect to the frontal region. Diet composition was variable among years and areas but copepods, euphausiids, fish (smaller age-0 pollock), and chaetognaths were major prey.

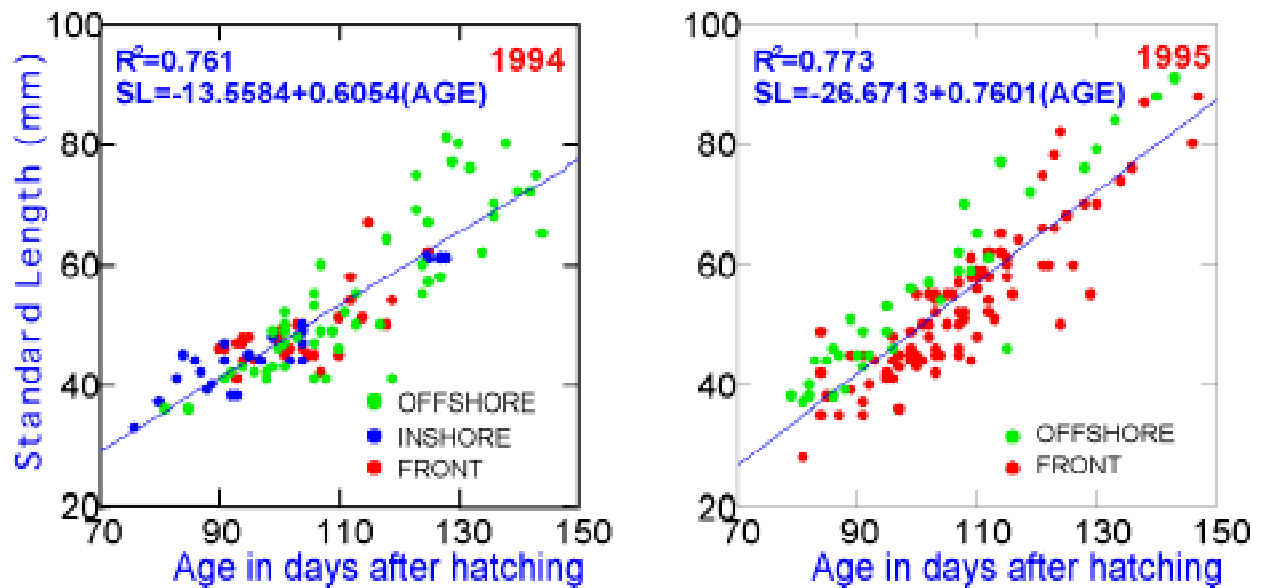


Figure 5.2.4 Growth curves for age-0 pollock showing size at age for collections from different positions relative to the front. Length at age was slightly higher overall in 1995 than in 1994 for fish over 100 days old, suggesting a higher growth rate.

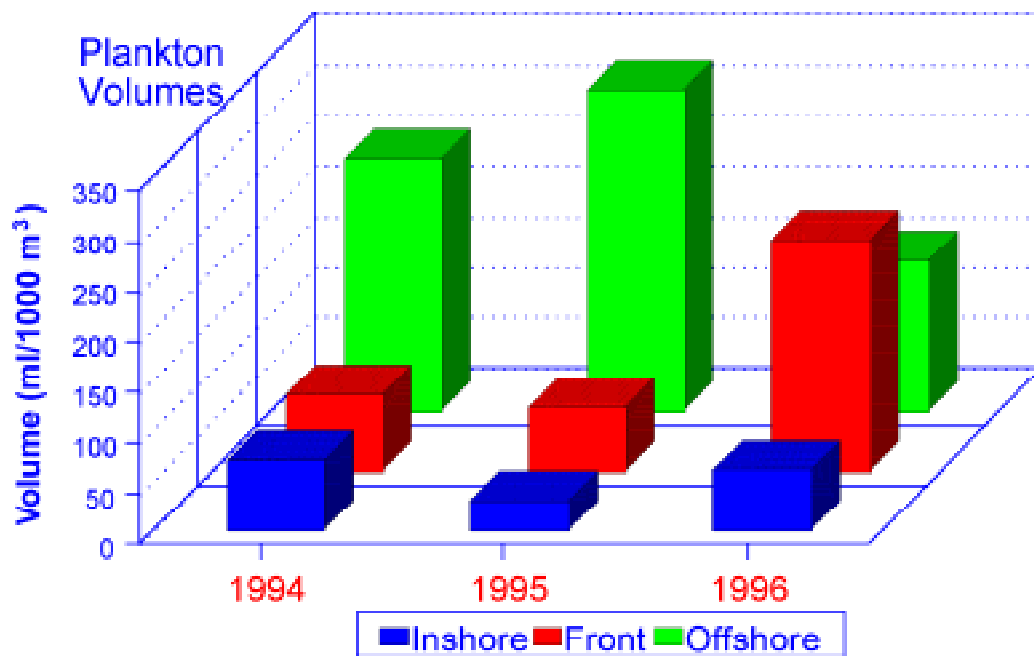


Figure 5.2.5 Displacement volumes by habitat and year for zooplankton collected in MOCNESS tows integrated over the water column. Mesh size is 505 μm in 1994 and 1995 and 333 μm in 1996.

Spatial variability in prey concentration and composition

Zooplankton displacement volumes for Transect A from the MOCNESS sampling were integrated throughout the water column and summarized each year for the three habitats. The patterns were consistent in 1994 and 1995 with the highest volumes found offshore and volumes at the front and inshore were much lower (Fig. 5.2.5). The high volume in offshore samples was due mainly to high abundances of copepods. The front had the highest volumes in 1996, but some of this difference may be due to using a smaller mesh size that year. This last year, we continued our collections of mesozooplankton in and around the Pribilof Island structural fronts in support of other projects in this study and in support of other SEBSCC studies. We have received the fall 1997 zooplankton data and added them to our relational database. The zooplankton data are an integral part of many of the recent SEBSCC manuscripts regarding the Pribilof Island structural fronts (Brodeur *et al.*, 1997, Lang *et al.*, in press, Napp *et al.*, submitted, Swartzman *et al.*, in press, Schabetsberger *et al.*, in prep).

Spatial variability in nutritional quality of prey

During fall 1997 we began a pilot program to determine if there were differences among regions in the nutritional quality of a common prey item used by age-0 pollock, C5 copepodites of *Calanus marshallae*. The purpose of the project is to determine whether or not prey concentration is the only relevant variable for spatially explicit bioenergetic models of age-0 pollock or alternatively if regional differences in prey nutritional quality must be considered in addition to differences in prey density. Our first set of samples was collected around the Pribilof Islands on Transects A, B, and C. Copepodites of *C. marshallae* were significantly lighter (lower dry weights) on the shelf edge transect, Line B, than on Lines A and C. Concurrent samples for CHN and lipid analysis were also taken. The samples for CHN were analyzed and the data await statistical analysis; the lipid samples have yet to be analyzed. Collections of samples for dry weight and CHN content were repeated in the summer of 1998 across a much broader region of the shelf and will be analyzed this fall.

Bioenergetics modeling

A bioenergetics model was developed for age-0 juvenile walleye pollock. The bioenergetics model includes physiological parameters of juvenile pollock as well as environmental features of the study area. Some physiological parameters of juvenile pollock were estimated from laboratory measurements during the summer 1997, in Seward, Alaska, in experiments carried out in cooperation with Dr. A.J. Paul from the University of Alaska. Size and temperature dependencies of growth, consumption, egestion and excretion were determined for juvenile walleye pollock. Physiological parameters not measured, but used in the model, were derived from a synthesis of literature data. Model parameter estimates were examined by doing a sensitivity analysis. Environmental characteristics of the study area include temperature profiles and zooplankton distribution and density. Temperature profiles were measured using CTD casts. Zooplankton distribution and density have been derived from the acoustic surveys in collaboration with Dr. Gordon Swartzman, and from net sampling.

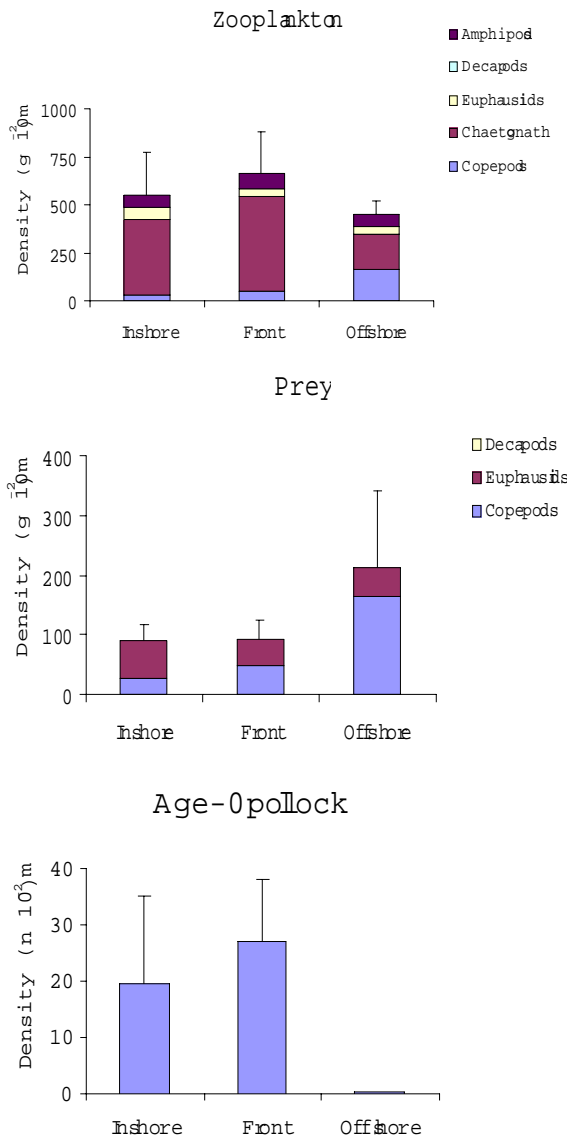


Figure 5.2.6 Distribution relative to habitat of total zooplankton biomass, prey biomass, and density of age-0 pollock on Line A in September 1995.

and 1995. Growth potential results showed that on Line A in 1994, there was a higher potential for growth than in 1995, due mainly to a higher zooplankton biomass and a deeper thermocline in 1994 than in 1995. Geographical differences also appear along the transect line, with the inshore region showing the lowest growth potential.

To investigate the effect of both food and predation on the distribution and dynamics of juvenile pollock, a spatially and temporally explicit model is being prepared in collaboration with Dr. Peter Rand. Besides food and temperature, the model includes predation fields, which

The bioenergetics model is used for two purposes. The first is to determine age-0 pollock food consumption given their growth and the environment in which they live. Age-0 pollock food consumption is then compared with food availability from net sampling, to examine the possibility of food limitation. Second, the bioenergetics model is used to estimate areas of growth potential for age-0 pollock given the environmental features and the zooplankton biomass determined from hydroacoustic data. Growth potential areas are then compared with acoustically determined density and distribution of juvenile pollock to study correlations between growth potential and fish distribution.

Results from the food consumption analysis were obtained for Line A during 1995. The analysis shows that age-0 pollock were experiencing some degree of food limitation in the areas in which their density was highest (Fig. 5.2.6) at the inshore and front regions (Fig. 5.2.7). Age-0 pollock caught in these areas also showed the lowest feeding condition index, confirming that both fish consumption and growth had been affected by the low density of food available. The offshore region was the one with lowest density of juvenile pollock, highest feeding condition index and highest density of food (Fig. 5.2.6). It is possible that age-0 pollock in this area were experiencing high predation, due to the high densities of both groundfish and seabirds that were found there (Fig. 5.2.8).

Results from the hydroacoustics zooplankton analysis have been included in the bioenergetics model to produce a growth potential map for juvenile pollock along Line A for the years 1994

in turn are derived from bottom trawl collections and fish stomach contents, seabird distribution and diet information, and marine mammal distribution and predatory behavior.

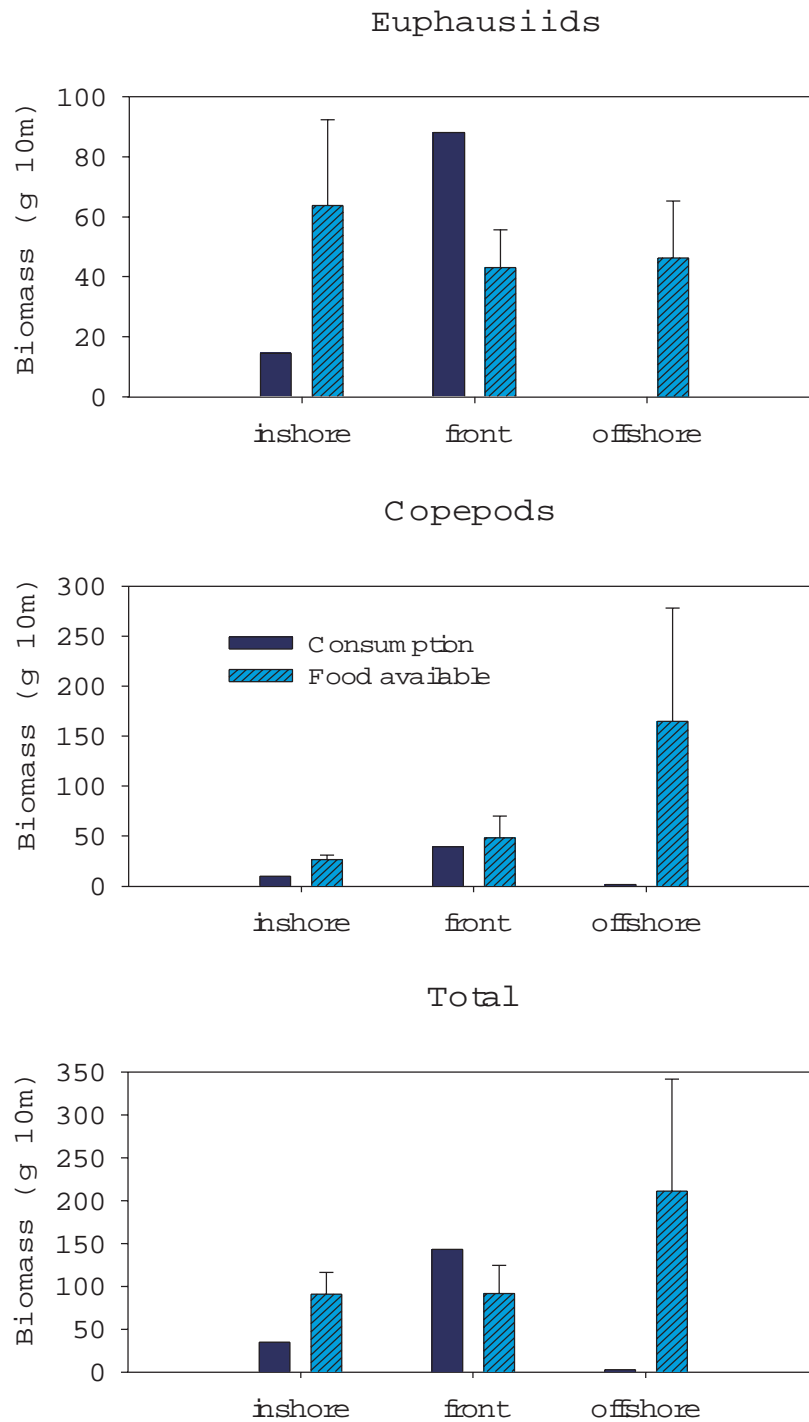


Figure 5.2.7 Comparison of euphausiids, copepods and total zooplankton available and that consumed by pollock relative to habitat on Line A in September 1995.

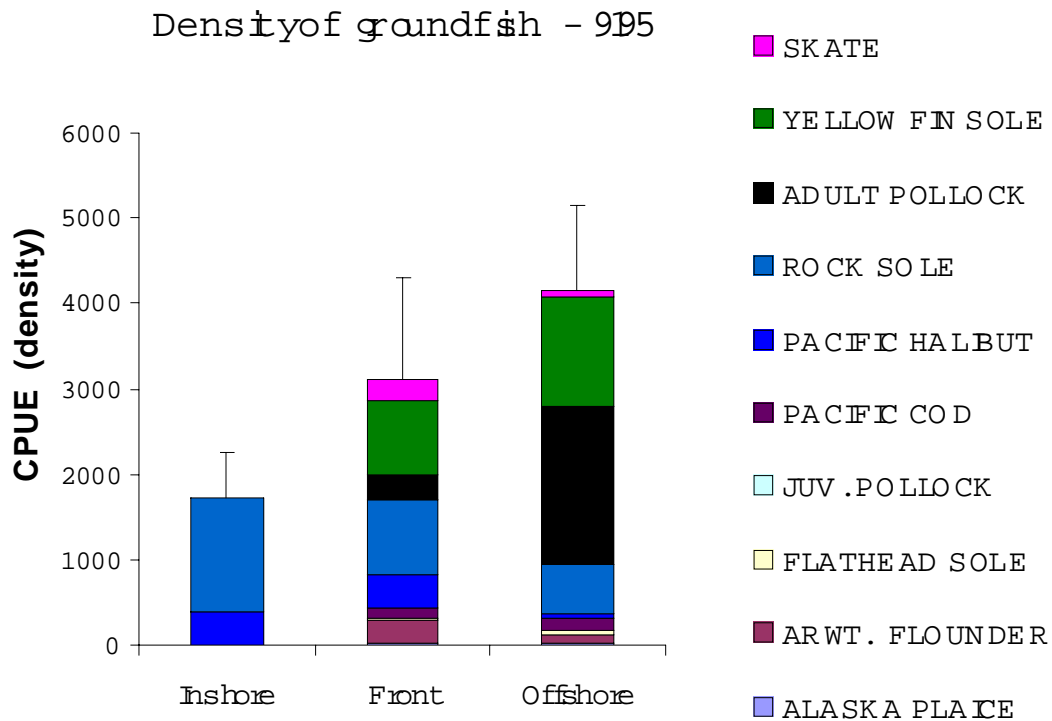


Figure 5.2.8 Density of groundfish collected in bottom trawls along Line A in September 1995.

Recent anomalies in the Bering Sea ecosystem

The Bering Sea Ecosystem appears to be undergoing major changes in key environmental factors (e.g. summer wind mixing, irradiance, spring storms). Concomitant with these changes have been major failures of the Bristol Bay sockeye salmon fishery, consecutive large-scale summer blooms of coccolithophores, new reports of whales feeding on the middle shelf domain, and high mortalities of some planktivorous seabirds (Short-tailed shearwaters). Our Habitat project allowed us to collect observations that will help determine the cause and effect of these large-scale ecosystem perturbations. Of paramount importance to SEBSCC is the effect these anomalies will have on the future recruitment of pollock to the fishery. Phyllis Stabeno, Jeff Napp and Ric Brodeur contributed to papers that describe changes in the physics, nutrients, chlorophyll and zooplankton around the Pribilof Islands in 1997 relative to previous years.

Products

In addition to the following publications and presentations, we initiated useful collaborations with several other SEBSCC studies including the Monitoring (Schumacher et al.), Modeling (Hermann et al.) and Acoustic (Swartzman et al.) projects. We also had close ties to the NSF-funded Inner Shelf Study and with Japanese researchers at Hokkaido University and Tohoku Fisheries Research Laboratory. We also received outside funding from NOAA's National Undersea Research Program to have a Remotely Operated Vehicle during our field work.

Publications

- Brodeur, R.D., 1998: Prey selection by age-0 walleye pollock, *Theragra chalcogramma*, in nearshore waters of the Gulf of Alaska. *Env. Biol. Fishes* 51: 175-186.
- Brodeur, R.D., 1998: *In situ* observations of the association between juvenile fishes and scyphomedusae in the Bering Sea. *Mar. Ecol. Prog. Ser.* 163: 11-20.
- Brodeur, R.D., M. Doyle, J.M. Napp, P.J. Stabeno, J.D. Schumacher, and M.T. Wilson, 1998: Fronts and fish: Interannual and regional differences in frontal structure and effects on pollock and their prey. *Oceanogr.* 11(2): 64.
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- Schabetsberger, R., R.D. Brodeur, L. Ciannelli, J.M. Napp, and G.L. Swartzman, in preparation: Diel vertical migration and interaction of zooplankton and micronekton at a frontal region near the Pribilof Islands, Bering Sea. *ICES Journal of Marine Science*.
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- Stockwell, D.A., T.E. Whitley, S.I. Zeeman, K.O. Coyle, J.M. Napp, R.D. Brodeur, and A. I. Pinchuk, in preparation: Nutrient, phytoplankton, and zooplankton anomalies in the Eastern Bering Sea in 1997. *Fish. Oceanogr.*
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Presentations

- October 1996- Distribution of juvenile pollock relative to frontal structure near the Pribilof Islands, Bering Sea. PICES Annual Meeting, Nanaimo, BC. (R. Brodeur with M. Wilson, P. Stabeno, J. Napp, and J. Schumacher - Recipient of Best Paper Award).
- November 1996- *In situ* observations of the association between juvenile fishes and scyphomedusae in the Bering Sea. International Symposium on the Role of Forage Fishes in Marine Ecosystems, Anchorage, AK (R. Brodeur - poster).
- November 1996- Distribution of juvenile pollock relative to frontal structure near the Pribilof Islands, Bering Sea. International Symposium on the Role of Forage Fishes in Marine Ecosystems, Anchorage, AK (R. Brodeur with M. Wilson, P. Stabeno, J. Napp, and S. Salo).
- November 1996- Prey selection and food consumption by age-0 walleye pollock in nearshore waters of the Gulf of Alaska. International Symposium on the Role of Forage Fishes in Marine Ecosystems, Anchorage, AK (poster, R. Brodeur with L. Ciannelli).
- September 1997- Spatial and temporal variability in feeding and condition of age-0 walleye pollock in frontal regions of the Bering Sea. ICES Recruitment Symposium, Baltimore, MD (R. Brodeur with M. Wilson and L. Ciannelli).
- September 1997- Variation in groundfish predation on juvenile walleye pollock relative to hydrographic structure near the Pribilof Islands, Alaska. ICES Recruitment Symposium, Baltimore, MD (G. Lang with R. Brodeur, J. Napp, and R. Schabetsberger).
- February 1998- In situ observations of the habitat dependencies of juvenile fishes in the Bering Sea. Western Groundfish Conference, Monterey, CA (poster, R. Brodeur).
- February 1998- The 1997 Eastern Bering Sea shelf-wide coccolithophorid bloom: Ecosystem observations and hypotheses. Ocean Sciences Meeting (AGU/ASLO), San Diego, CA (poster, J. Napp with C. Baier, R. Brodeur, J. Cullen, R. Davis, M. Decker, J. Goering, C. Mills, J. Schumacher, S. Smith, P. Stabeno, T. Vance, and T. Whitledge).
- May 1998- Fronts and fish: Interannual and regional differences in frontal structure and effects on pollock and their prey. Oceanography Society Meeting, Paris, France (poster, R. Brodeur with M. Doyle, J.M. Napp, P.J. Stabeno, J.D. Schumacher, and M.T. Wilson).
- July 1998- Juvenile pollock distribution, growth and ecology in the Bering Sea. International Workshop on Ecosystems of the North Pacific Ocean, Seattle, WA. (R.D. Brodeur, M.S. Busby, J.M. Napp, and M.T. Wilson).

- July 1998- Biophysical factors that affect pollock survival and prey production over the southeastern Bering Sea Shelf. International Workshop on Ecosystems of the North Pacific Ocean, Seattle, WA. (J.M. Napp, C. Baier, A.J. Kendall, and J.D. Schumacher).
- August 1998- The role of pre-recruit walleye pollock in the Bering Sea and North Pacific Ecosystems. International Marine Science Symposium on Ecosystem Dynamics, Hakodate, Japan (R. Brodeur, Invited keynote presentation).
- February 1999- Are recent eastern Bering Sea ecosystem anomalies early evidence for climate change? What do records of zooplankton biomass and species composition tell us? American Society of Limnology and Oceanography meetings, Santa Fe, NM (Napp, J.M., Brodeur, R.D., Schumacher, J.D., Stabeno, P.J., and Jorgensen, E.M.).
- February 1999- Bioenergetics of age-0 walleye pollock in a frontal structure of the Bering Sea. American Society of Limnology and Oceanography meetings, Santa Fe, NM. (Ciannelli, L. and R. Brodeur).
- February 1999- Diel vertical migration, feeding selectivity, and prey distribution of juvenile walleye pollock at a productive frontal region in the Bering Sea. American Society of Limnology and Oceanography meetings, Santa Fe, NM (Schabetsberger, R., R. Brodeur, and J. Napp).

Outlook

We have successfully completed most of what we set out to accomplish in Phase I and actually accomplished a few additional things that we did not expect due to the unusual environmental conditions (e.g. coccolithophore bloom). Our work has led to a large number of publications either in press or preparation (see Appendix I). We are continuing many of the same lines of research in Phase II with the exception of analyzing growth rates using otoliths. Although we were partially successful in this aspect in Phase I, this method turned out to be too labor intensive and not sensitive enough for our purposes. In Phase II, we will collaborate with Dr. A.J. Paul of the University of Alaska, Seward, to examine somatic energy content in the different habitats as an indication of condition of the juveniles. We have samples from the same years and locations as the otolith collections so comparisons of the two methods can be made.

5.3 Low-temperature incubation of walleye pollock eggs (*Theragra chalcogramma*) from the Southeast Bering Sea region

Principal Investigator: Deborah M. Blood, Alaska Fisheries Science Center

Period of Research April 1997 to May 1998

Goal and Objectives

The goal was to determine temperature-specific development rates of southeastern Bering Sea walleye pollock eggs incubated at low temperatures (-0.6 to 3.8°C). These rates would be incorporated with similar data from the nearby Shelikof Strait area (Blood et al. 1994). Then I would construct a model of temperature-specific development rates for walleye pollock eggs over a broad range of temperatures (-0.6 to 7.7°C). One objective was to determine whether eggs would develop normally at low temperatures (as low as -1.5°C) recorded over the shelf region in 1995. Another was to examine the effect of light on development and hatching rates since walleye pollock eggs occur in the upper 20 m of the water column (Kendall in prep.). Finally, walleye pollock eggs from Shelikof Strait were incubated at low temperatures to compare their development and hatching rates with eggs from Bering Sea populations.

Project Description

Eggs were obtained from adult pollock collected northwest of Unimak Island near the 200 m isobath (Fig. 5.3.1) April 1997 and incubated in darkness at four temperatures (-0.6, 0.4, 2, and 3.8°C). A fifth group of eggs, incubated at 3.9°C, was exposed to a diel light cycle similar to conditions in the field at the time of collection (14 hr light, 10 hr dark) and at a level of approximately $45 \mu\text{M m}^{-2} \text{s}^{-1}$. This level is in excess of average levels typically found within the upper 20 m of the water column (Kendall et al. 1994). Eggs were sampled every 2 hr for the first 24 hr after fertilization, then every 4 hr until formation of the blastodisc, and every 8 hr from that point until all eggs had hatched. At each sampling time, 5-10 eggs from each temperature group were examined by microscope, assigned a stage according to those described in Blood et al. (1994), and preserved in 5% formalin. When eggs began to hatch, all newly hatched larvae were removed, measured, and preserved in formalin at each sampling period.

Eggs obtained from adult pollock in Shelikof Strait (Fig. 5.3.2) April 1998 were incubated at three temperatures (0.2, 1.8, 2.8°C). All eggs were incubated in darkness and sampled on the same schedule as above. Newly hatched larvae were measured at each sampling period for this group also.

Midpoints (in hours) of each of 21 stages were estimated for both the Bering Sea and Shelikof Strait eggs. With these midpoints and time of 50% hatch, a piece-wise least-squares linear regression model was derived for each group to estimate age (hours) of eggs at a specific stage incubated at any temperature within the limits of each experiment.

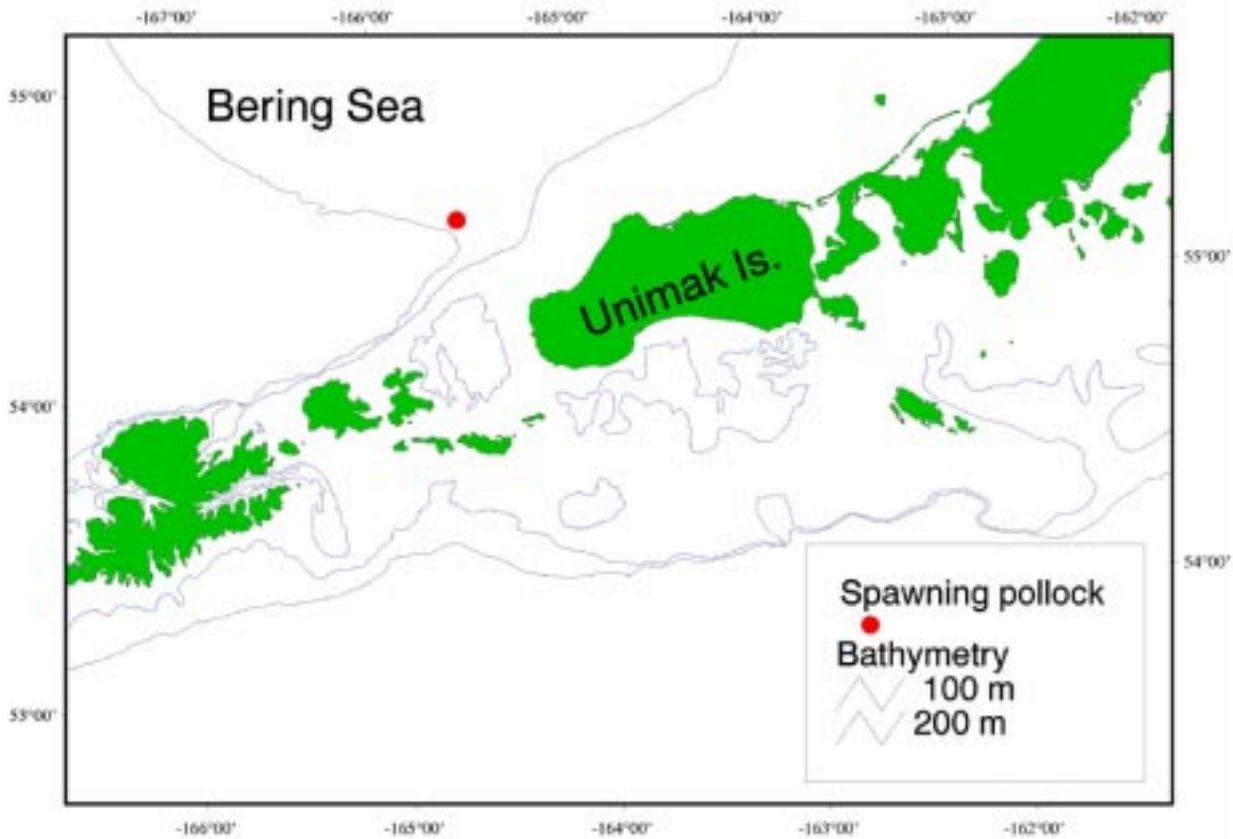


Figure 5.3.1 Location where spawning walleye pollock, *Theragra chalcogramma*, were collected in the Bering Sea during April 1997.

Results

I participated in the following cruises for onboard incubation of eggs:

MF97-04	Mar 28 - Apr 13, 1997
MF97-05b	May 3 - May 13, 1997
MF98-05a	Apr 6 - Apr 12, 1998
MF98-06	May 1- May 10, 1998

For the Bering Sea eggs, mortality was high for the first two weeks. This may have been the result of immaturity of the adult pollock. However, mortality dropped to negligible levels, leaving enough eggs to allow sampling during the incubation period and to adequately document 50% hatch in all treatments except those incubated at -0.6°C .

Development of embryos was normal for all temperatures except -0.6°C ; gross abnormalities included malformation of the tail, similar to that reported by Nakatani and Maeda (1984), and the absence of eyes. The pattern of hatch was similar for all eggs incubated under constant dark conditions; 50% hatch of eggs occurred approximately midway through the period of time required for all eggs to hatch. However, hatching of eggs incubated under diel light was delayed; 50% hatch occurred after 90% of the hatching period had elapsed (Fig. 5.3.3).

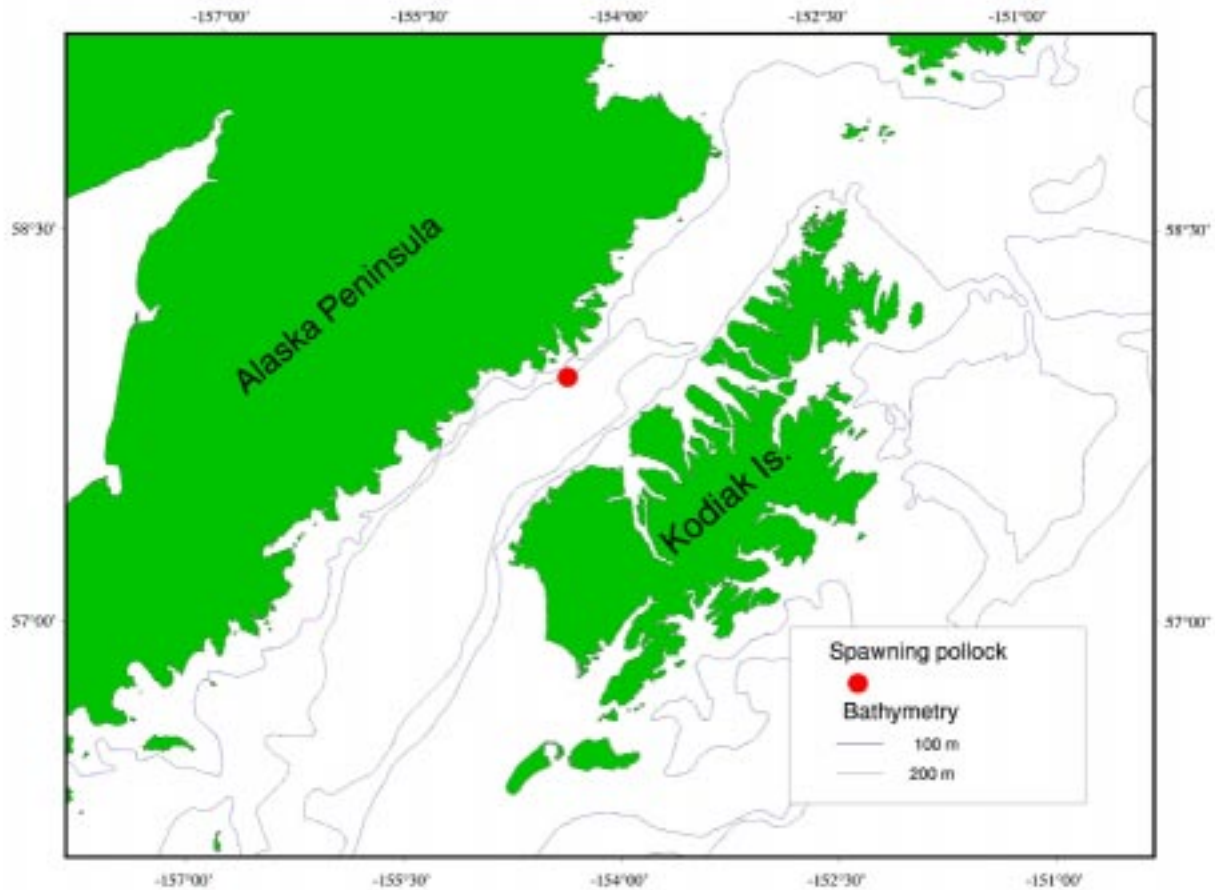


Figure 5.3.2 Location where spawning walleye pollock, *Theragra chalcogramma*, were collected in Shelikof Strait April 1998.

Development of Shelikof Strait eggs was normal at all temperatures. Eggs were obtained at the peak of the spawning season for this area and low mortality of the eggs during incubation allowed documentation of 50% hatch for all temperatures.

Data from the Bering Sea and Shelikof Strait egg incubations were used to develop two distinct models for temperature-specific development rates (Fig. 5.3.4). Equations for the models follow a similar format (Fig. 5.3.5), but three of the five parameters within the component predicting stages 7-21 are significantly different between the two models ($p < 0.05$). Also, when time to reach the midpoint of all stages from 7 to 21 was compared between the models, results were consistently higher (more time required) for the Shelikof Strait model at 1.8 and 2.8°C. Results were inconclusive for predicted times at 0.2°C (Fig. 5.3.6).

Mean length of the larvae at hatch, hatching pattern, and midpoint (point at which 50% of larvae had hatched) were compared for two similar temperatures: 0.2 and 1.8°C (Shelikof Strait larvae) and 0.4 and 2.0°C (Bering Sea larvae)(Fig. 5.3.7). For both the 0.2 versus 0.4°C and the 1.8 versus 2.0°C comparisons, hatching began earlier, midpoint of hatch was earlier, and overall mean length of larvae at hatch was higher for the Bering Sea group.

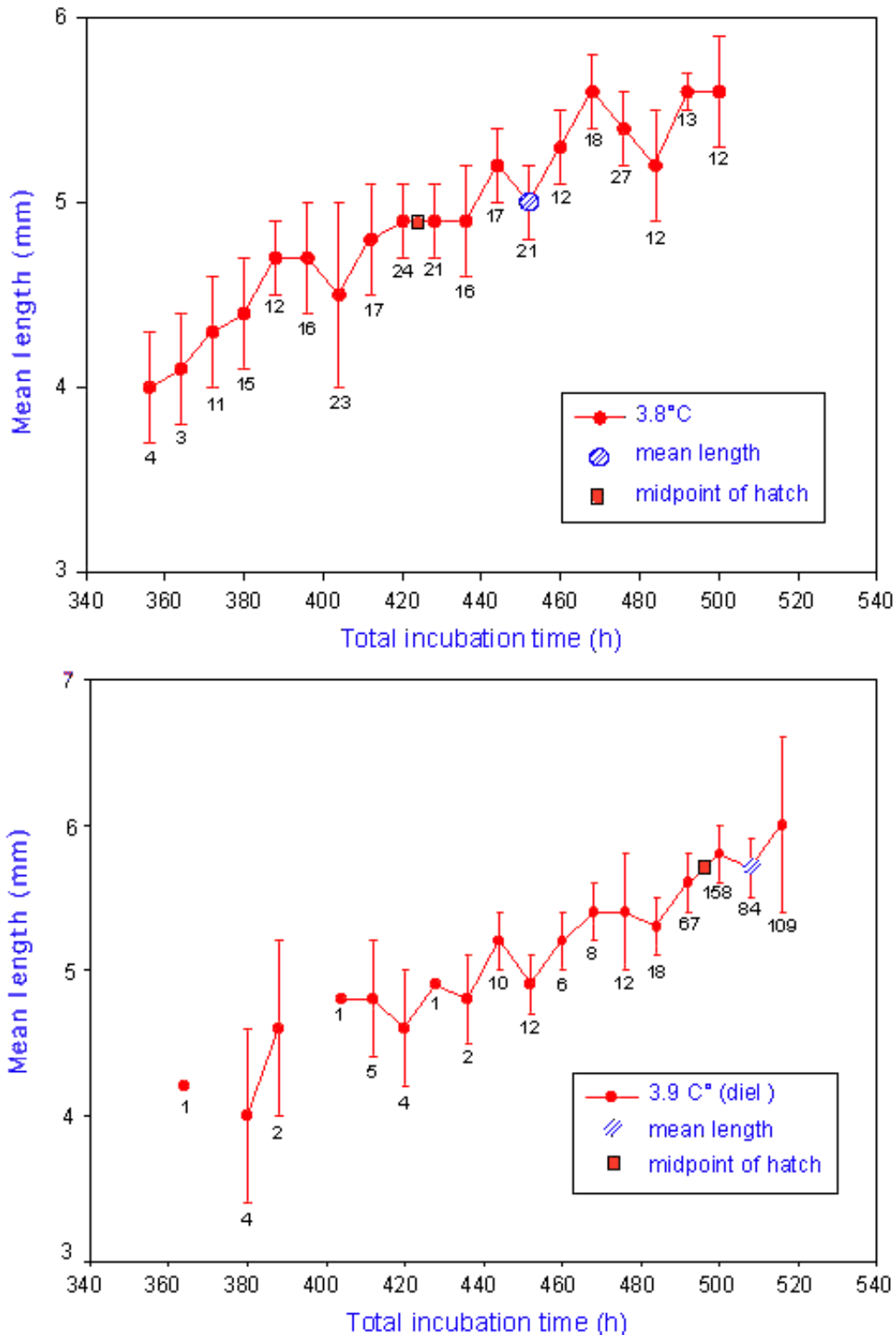


Figure 5.3.3 Mean hatch lengths at each sampling interval during the hatching period of Bering Sea *Theragra chalcogramma* eggs incubated at 3.8°C and 3.9 °C (diel treatment). Shaded circles indicate overall mean length of larvae at each temperature; yellow boxes indicate time at which 50% of eggs have hatched. Vertical bars are standard errors; numbers indicate sample size.

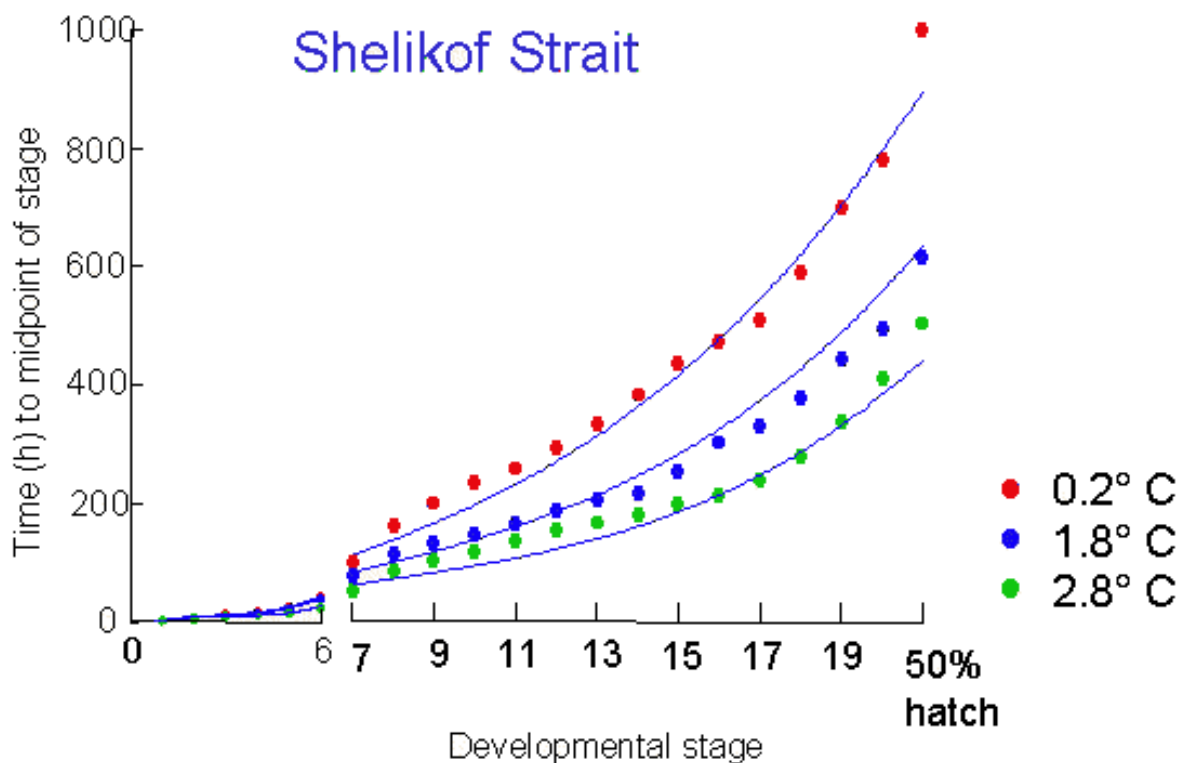
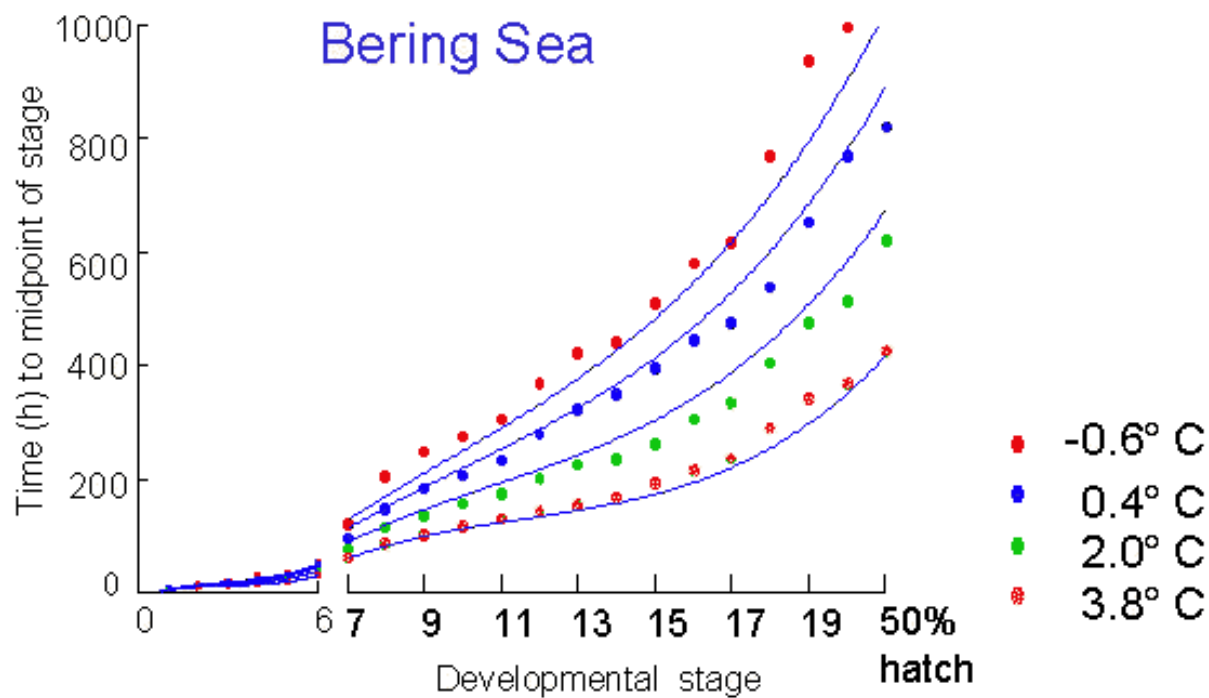


Figure 5.3.4 Time (h) to midpoint of stage of *Theragra chalcogramma* eggs from the Bering Sea (incubated at -0.6, 0.4, 2.0, and 3.8°C) and Shelikof Strait (incubated at 0.2, 1.8, and 2.8°C). Fitted lines are results of regression models; symbols are observed values.

Bering Sea

Component 1: stages 1-6

$$\text{age} = -10.6 + 19.167(\text{stage}) - 0.364(\text{stage})(\text{temperature}) - 5.129(\text{stage}^2) + 0.588(\text{stage}^3) - 0.011(\text{stage}^3)(\text{temperature})$$

Component 2: stages 7-21

$$\text{age} = -357.319 + 104.993(\text{stage}) - 6.946(\text{stage}^2) - 0.306(\text{stage}^2)(\text{temperature}) + 2.33(\text{stage}^3)$$

Shelikof Strait

Component 1: stages 1-6

$$\text{age} = -10.6 + 17.643(\text{stage}) - 0.061(\text{stage})(\text{temperature}) - 5.382(\text{stage}^2) + 0.662(\text{stage}^3) - 0.028(\text{stage}^3)(\text{temperature})$$

Component 2: stages 7-21

$$\text{age} = -52.288 + 27.669(\text{stage}) - 1.099(\text{stage}^2) - 0.412(\text{stage}^2)(\text{temperature}) + 0.1(\text{stage}^3)$$

Figure 5.3.5 Piece-wise regression model equations describing relation between time to midpoints of each stage of development and temperature for *Theragra chalcogramma* eggs from the Bering Sea (incubated at -0.6 to 3.8°C) and Shelikof Strait (incubated at 0.2 to 2.8 °C).

Whereas there are direct relationships between increasing temperature and both beginning of hatch and mean length of larvae at hatch, a temperature difference of 0.2°C between the Bering Sea and Shelikof Strait groups does not appear to be the sole reason for the difference in these parameters. Difference in the onset of hatch between the 3.8 and 3.9°C groups during the 1997 Bering Sea was only 8 hours. In contrast, commencement of hatch for the Shelikof Strait eggs lagged behind the Bering Sea eggs by 80 hours in the 1.8 versus 2.0°C comparison and by 96 hours in the 0.2 versus 0.4°C comparison. Blood et al. (1994) reported an increase in mean length of newly hatched larvae of only 0.4 mm over a temperature span of 3.9°C. In contrast, for the 0.2 versus 0.4°C comparison, mean length of Bering Sea larvae was 0.4 mm longer than that for Shelikof Strait larvae, and 0.9 mm longer for the 1.8 versus 2.0°C comparison. Comparing midpoint of hatch between the two groups, the midpoint was 24 hours earlier for Bering Sea eggs in the 1.8 versus 2.0°C comparison but was 224 hours earlier at colder temperatures (0.2 versus 0.4°C). The degree of difference between them indicates a delay in the hatching mechanism of Shelikof Strait eggs at the colder temperature.

Interannual variability of the ecosystem in the Bering Sea, specifically dramatically low ocean temperatures, could affect pollock survival. Ocean temperatures at Mooring 2 (Stabeno et al. In rev.), integrated over 11-55 m, varied from -1.5° to 2°C between 1995 and 1998 during the time period when pollock eggs would be present (Fig. 5.3.8). When pollock egg development times were estimated for each week at these temperatures, the incubation period varied as much as three weeks between the coldest year (1997) and the warmest (1998)(Fig. 5.3.9). Extending the incubation period by three weeks exposes the pollock eggs to increased risk of predation and

malformations from exposure to extreme low temperatures. Although pollock eggs are found throughout the water column, most are found within the top 20 m and may be exposed to temperatures colder than those mentioned previously. It is not known what the low temperature tolerances are for pollock eggs for short periods of time.

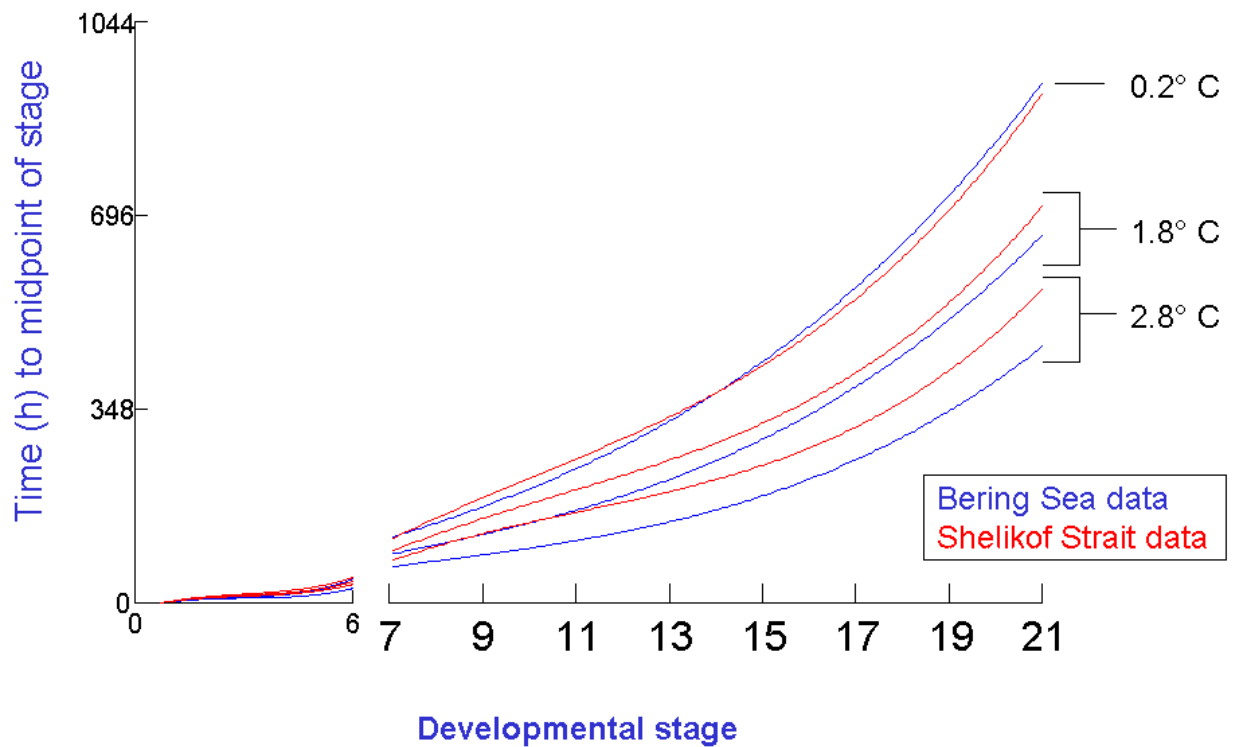


Figure 5.3.6 Comparison of time (h) to midpoint of stage of Bering Sea and Shelikof Strait *Theragra chalcogramma* eggs incubated at 0.2°, 1.8°, and 2.8°C as predicted by their respective regression models.

Outlook

Results of this research are yet to be published. Plans are for submission for publication by the end of the calendar year.

Possible future directions of research are:

1. Examine the effect of light on hatching of pollock eggs in the Bering Sea. Since light delays hatching until late in the incubation period, are larval lengths less variable in the Bering Sea in May than in Shelikof Strait? If there are many more larvae at the same size in the Bering Sea, availability of the correct size food may be more critical.
2. Is spawning on the Bering Sea shelf en masse such as in Shelikof Strait, or is it more protracted? Preliminary examination of stages of eggs found in large concentrations during April 1999 revealed a wide variation in egg ages, unlike the higher numbers of early stage eggs found in samples of high concentration in Shelikof Strait. Are the biological signals that guide the spawning population in Shelikof Strait weaker in the Bering Sea, thus leading to a protracted and erratic spawning season?

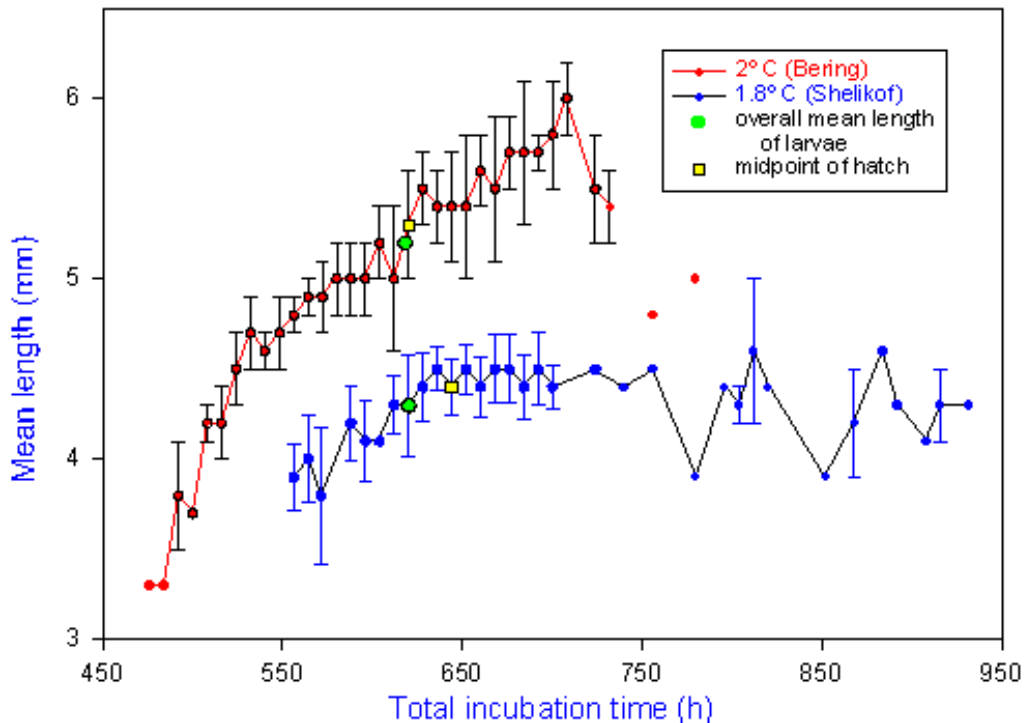
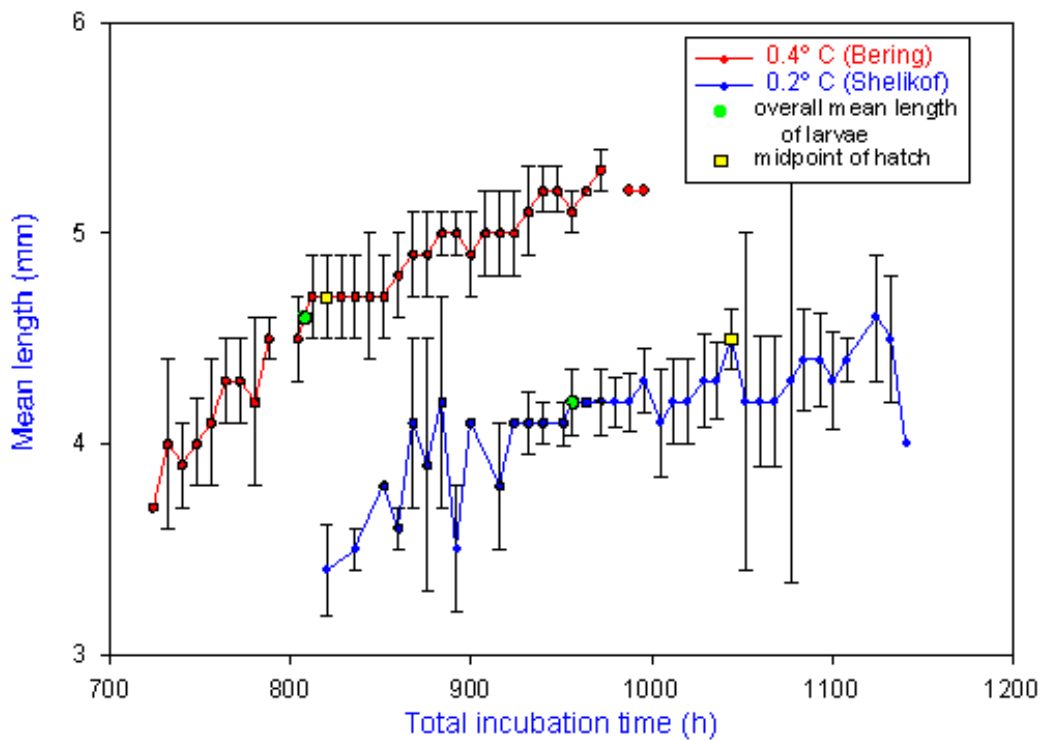


Figure 5.3.7 Comparison of mean length at hatch at each sampling interval for Bering Sea and Shelikof Strait *Theragra chalcogramma* eggs incubated at 0.4° and 0.2°C, respectively (upper panel), and 2.0° and 1.8°C, respectively (lower panel). Green circles indicate overall mean length of larvae at each temperature; boxes indicate time at which 50% of eggs have hatched.

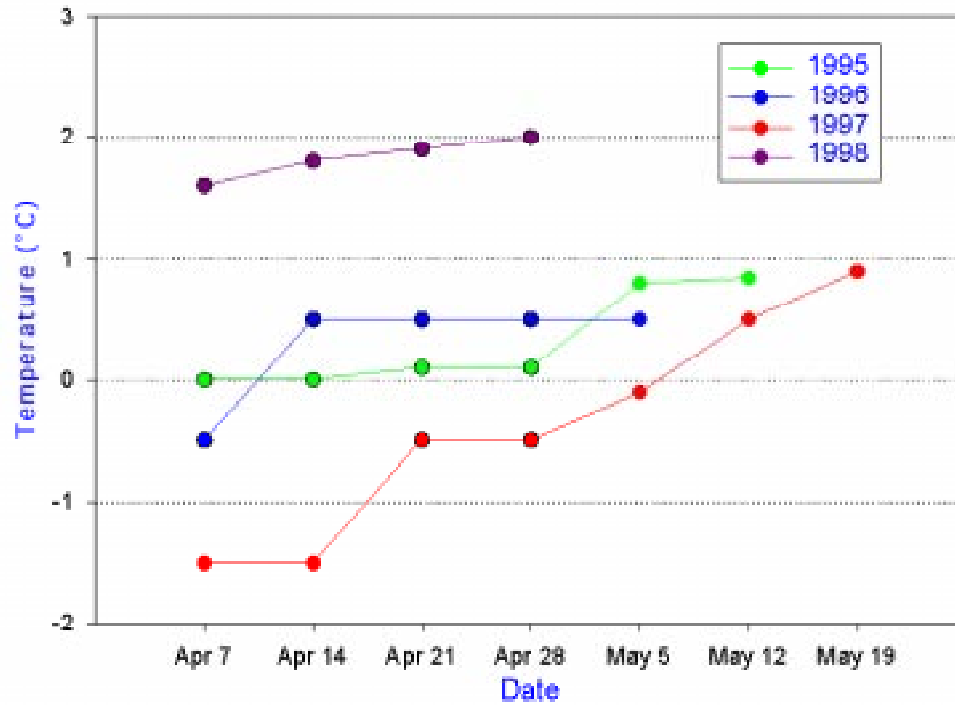


Figure 5.3.8 Weekly average ocean temperatures at Mooring 2 for April 7 - May 19, 1995-1998 (from Stabeno et al., in prep.). Temperatures are averaged for each week, beginning April 1 of each year, and integrated over 11-55m.

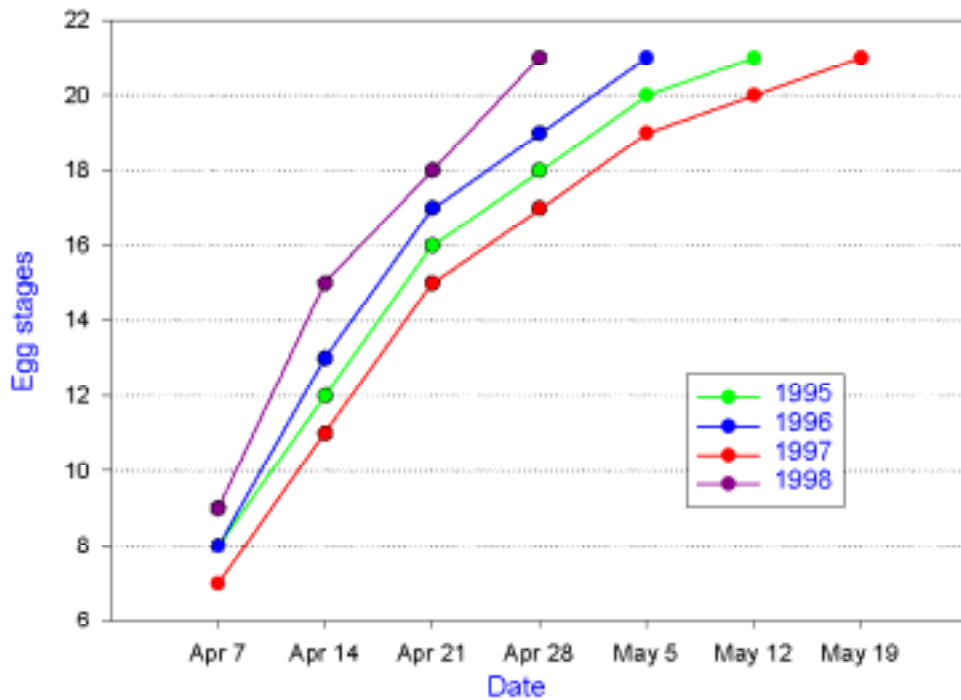


Figure 5.3.9 Stage of development for Bering Sea *Theragra chalcogramma* eggs for each of seven weeks after spawning as estimated by Bering Sea regression model and using temperatures from Figure 5.3.8 for the years 1995-1998. Assigned spawning date is April 1.

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6.0 RETROSPECTIVE STUDIES

6.1 Natural scales of variability in coastal marine ecosystems of the eastern Bering Sea

Principal Investigator: Robert C. Francis
University of Washington
School of Fisheries

Period of Research: October 1996 through September 1998 (as proposed) (This research was not completed because of project logistics problems.)

Goal and Objectives

The goal of this research was to provide information on the dynamics of fish populations as a reflection and component of the natural variability of the Northeast Pacific Ocean and the Southeast Bering Sea.

Objectives were to collect, process and analyze at least one set of cores (3m Kasten and 1m Box) from each of Skan Bay (Unalaska Island) and Herendeen Bay (Port Moller, Alaska Peninsula) during the summer of 1997, with a backup week of ship time during the summer of 1998.

Project Description

Effective management of a number of fishery resources of the Northeast Pacific and Bering Sea is hampered by uncertainties stemming from a poor understanding of the nature and causes of major changes in the marine ecosystem within which the fisheries are pursued. The essence of this problem is the vast scale in both space and time over which population changes occur. Strategies were developed by CalCOFI scientists to obtain insight into long time scale changes in fish populations. These methods use the accumulation of fish scales in bottom sediments to chronicle the dynamics of important pelagic fish populations over time periods from one to almost 20 centuries.

We showed from the Salmonid Fisheries Oceanography of the Northeast Pacific Ocean project we conducted from 1991 to 1994, that there are 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. We have obtained and initially analyzed cores from Effingham Inlet, Vancouver Island. Sediments are well laminated for some periods, numerous scales of several fish species are very well preserved in the sediments, and there are notorious long-term fluctuations in fish abundance.

We have felt all along that, in order to have a better understanding of the natural fluctuations of fish populations as indicators of coastal-climatic processes, we should replicate this coring study in several coastal ecosystems along the NE Pacific Coast including the Southeast Bering

Sea. Skan Bay and Herendeen Bay are likely anoxic because of low mixing with the surface and a high influx of rich organic material to the sediments. An existing box core from Skan Bay representing the period from 1960 to 1992 has been examined and shown to contain fish scales that agree well with deposition rates from cores in the Gulf of Alaska.

The Skan and Herendeen Bay cores will be separated into subsamples, partitioned into 2-cm sections, and sieved to remove fish scale and other remains from sediments. A detailed chronology of the upper 100 years will be established with lead and cesium isotopic analyses. Downcore (>100 years) samples will be taken at 50-year intervals and subjected to radiocarbon dating. We will explore the variance spectra for the dynamics of fish species with significant scale fluxes in the sediment samples.

Results

This project could not be carried out because of ship scheduling difficulties. Also, it was determined that the southeastern Bering Sea did not offer suitable sampling sites, after all. An attempt to analyze an existing Skan Bay core located at the University of Alaska was not realized.

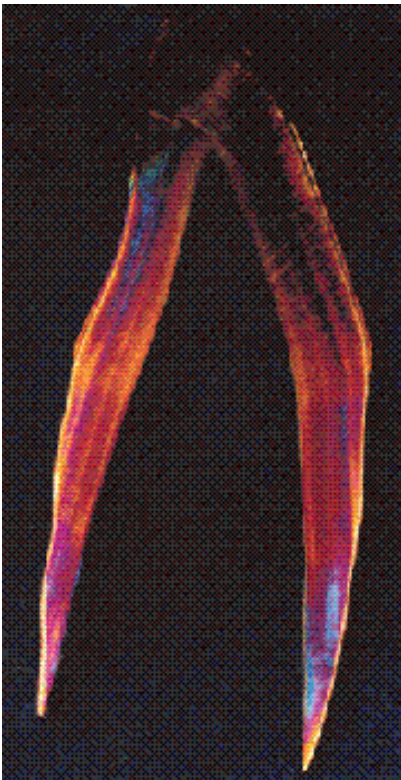
6.2 Historical trends in the number of foraging trips made by lactating northern fur seals

Principal Investigators: Jason D. Baker and Thomas R. Loughlin, NOAA/NMML

Goal and Objectives

The goal of this project was to establish whether there is a link between abundance of the primary prey of northern fur seals (*Callorhinus ursinus*) in the Bering Sea, juvenile walleye pollock (*Theragra chalcogramma*), and the number of foraging trips made by lactating female fur seals (an index of foraging success). Our objective was to determine the number of growth lines formed in teeth during a northern fur seal's birth year. These lines indicate the number of feeding trips made by the seal's mother. If a link between abundance of pollock and number of feeding trips is established, a long-term time series can be reconstructed on the mean number of trips made by female fur seals by examining teeth collected since the late 1940's on St. Paul Island. This time series would serve as an index of prey availability to fur seals in the Bering Sea over a period spanning several decades.

Project Description



According to recent diet studies, juvenile walleye pollock is the primary prey species of lactating northern fur seals from St. Paul Island, Alaska. Female northern fur seals make several day-long foraging trips from their breeding islands, periodically returning to nurse their pups. Variability in the duration and total number of trips females complete before weaning their pups likely reflects changes in prey availability in the Bering Sea during July-November. When prey is abundant, females presumably make shorter trips and therefore more total trips before weaning. The number of foraging trips made by female northern fur seals while rearing their pups can be estimated by counting growth lines in their offspring's teeth (Bengtson 1988; Baker 1991). Figure 6.2.1 shows a thin longitudinal section of a 3-year-old male's canine tooth. Annual growth lines are evident near the top of the tooth. Our strategy was to start by determining the mean number of trips made by females in years when the best data on juvenile walleye pollock in the Bering Sea are available. If we could establish that the number of trips made was indeed correlated with prey (pollock) abundance, we would proceed to expand the time series to include years when no prey surveys were conducted.

Figure 6.2.1 Longitudinal thin section of a 3-year-old male northern fur seal canine tooth photographed in polarized light.

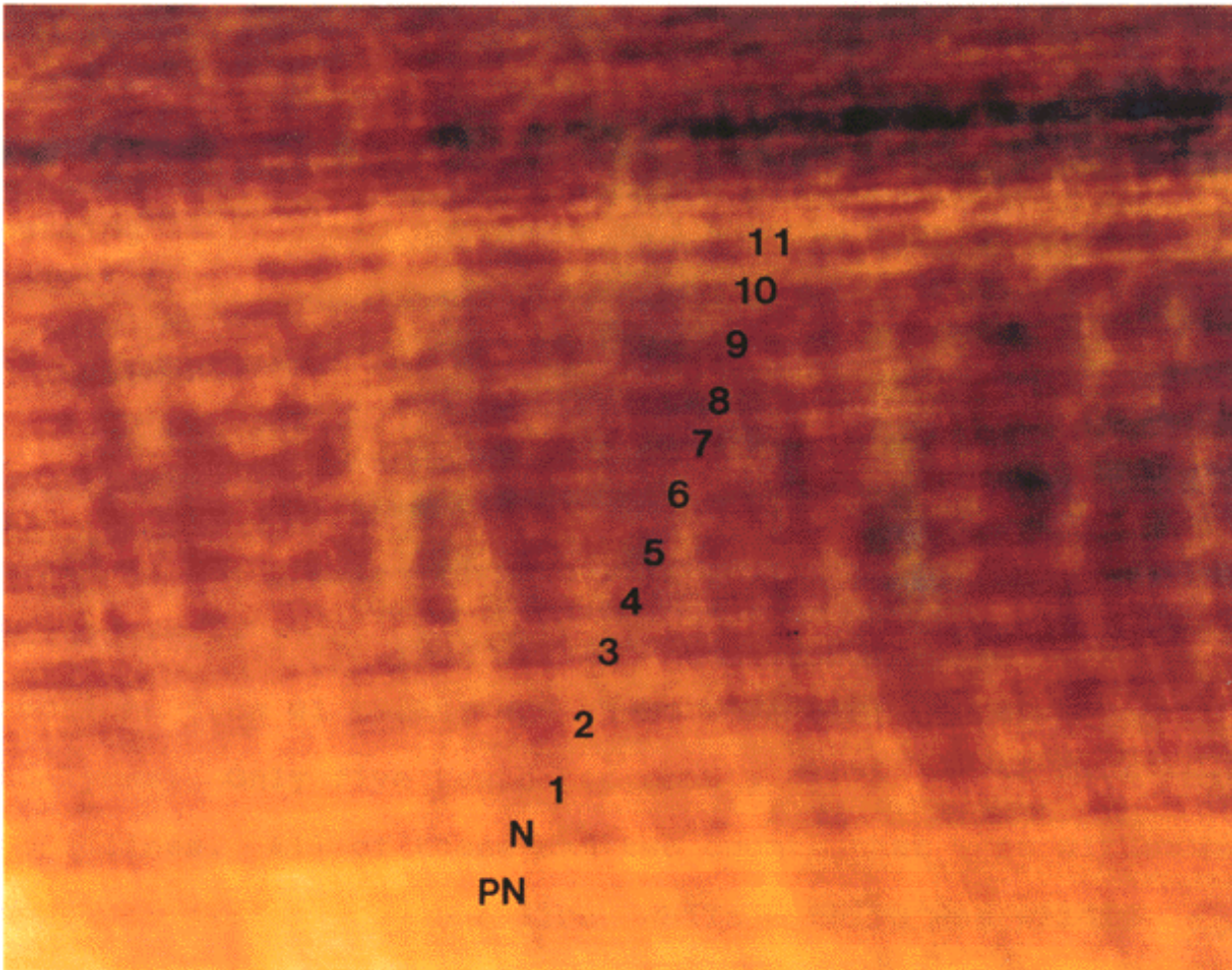


Figure 6.2.2 This image is a close up of nursing lines formed in the dentin during the first year of life. PN indicates pre-natally formed dentin. N indicates the neo-natal line that forms around birth. The lines numbered 1-11 indicate individual foraging trips made by this seal's mother.

The number of foraging trips made is estimated by counting "nursing lines" (Fig. 6.2.2) visible in the canine teeth of fur seals during the period when they are dependent on their mothers. The nursing lines form in the dentin due to the feeding/fasting schedule imposed on the growing pup by the mother's periodic absence on foraging trips. Growth lines in mammalian teeth are preserved for the life of the animal. We examined teeth from 2-3 year-old male northern fur seals that were killed either in the commercial skin harvest prior to 1985, or killed in the Aleut native subsistence hunt since then. Mean numbers of nursing lines were estimated from the teeth and compared with abundance estimates of juvenile walleye pollock in the area around St. Paul Island where females forage.

Results

We began by limiting our analysis to years when juvenile pollock abundance was estimated using both bottom trawl and hydroacoustic surveys. These surveys have been conducted

triennially beginning in 1979 (Traynor 1996, Traynor et al. 1990), and data were also available for 1978. Teeth from northern fur seals were available for six of these years (1978, 1979, 1981, 1982, 1991, and 1994). A total of 184 teeth, about 30 from each cohort, were processed and analyzed. The teeth were sectioned and the number of lines estimated independently by two researchers. Sections of poor quality in which nursing lines could not be counted were replaced in order to achieve equivalent sample sizes for each cohort.

We compiled estimates of age-0 and age-1 pollock abundance from research surveys and fishery data for 1978, 1979, 1981, 1982, 1991 and 1994 and compared them to the mean number of foraging trips completed by females between parturition and weaning: an index of foraging success (Table 6.2.1). Although the abundance of age-0 and age-1 pollock varied greatly among study years, there was no consistent relationship with the number of fur seal foraging trips (Fig. 6.2.3). In 1979, there was an enormous quantity of age-1 fish available and fur seals completed significantly more foraging trips that year. However, there were no similar peaks in the number of foraging trips in other years with high fish abundance (1978 and 1982). Most notably, juvenile pollock were scarce in 1994 but the number of foraging trips was average. While previous studies have shown that pollock is a primary prey species for lactating northern fur seals in the eastern Bering Sea, this study does not indicate a strong direct link between fur seal foraging success and trends in pollock abundance. Fur seals may benefit from years with extremely high pollock abundance, but they are not necessarily limited in years with moderate or low pollock abundance, as they rely on a variety of prey species.

Table 6.2.1 Abundance of age-0 and-1 walleye pollock in the eastern Bering Sea using various estimation methods. Based upon the relative magnitude of the estimates, annual relative abundance was categorized for each age class as "very small", "small", "medium", "large" and "very large". Corresponding estimates of the mean number of feeding trips made by lactating northern fur seals in the same years (estimated from offspring teeth) are also shown.

Year	Age-0 Pollock		Age-1 Pollock		Category		Mean # Trips
	Multi-species Model	Year-Class Strength	Direct Survey	Year-Class Strength	Age 0	Age 1	Nursing Lines
1978	N/A	17.9	N/A	7.5	very large	medium	12.8
1979	101	6.9	76.9	17.9	medium	very large	14.3
1981	125	3.6	N/A	7.5	medium	medium	11.9
1982	348	12.5	1.2	3.6	large	small	13.2
1991	58	3.6	3.2	6.2	small	medium	13
1994	N/A	1.6	1.7	1.4	very small	very small	13.2

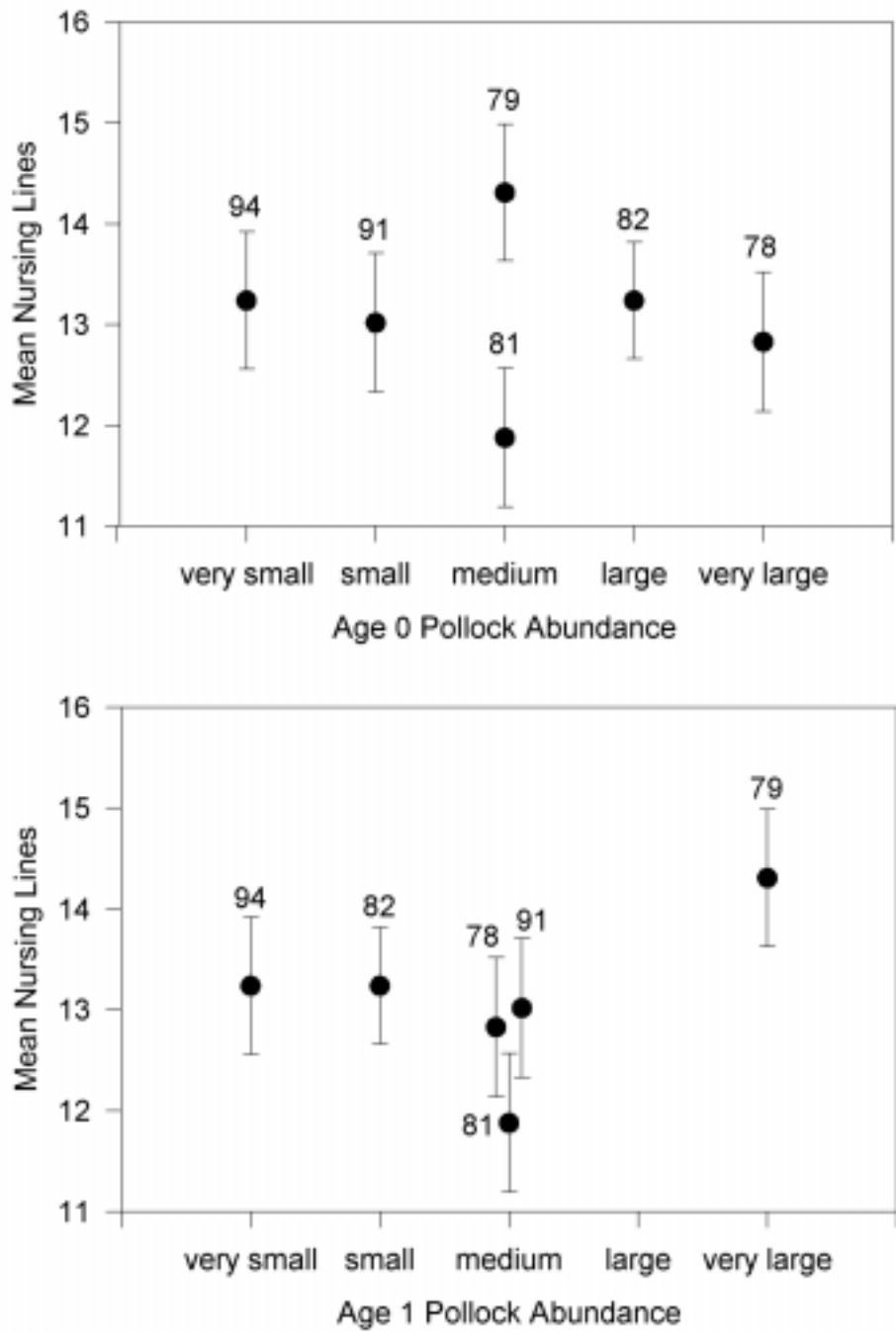


Figure 6.2.3 The mean number of foraging trips (mean nursing lines in pups' teeth) made by lactating female northern fur seals as a function of prey (walleye pollock) abundance at age 0 (top) and age 1 (below) shows no consistent relationship.

Products

Baker, J.D., and R.V. Caruso, in preparation: How influential is the abundance of juvenile walleye pollock in the Bering Sea on the foraging success of northern fur seals?

Outlook

Submission, revision and publication of the manuscript (above) is the final step to completion of this project. While no strong relationship between the abundance of juvenile pollock and fur seal foraging success was indicated, six years of data may have been too few to detect a noisy relationship. As more fisheries data accumulate and collection of fur seal teeth continues, this relationship can be explored more fully in the future. A further step, the construction of a long-term time series on fur seal feeding trips, would likely reflect foraging success of lactating northern fur seals, but may not reflect availability of juvenile walleye pollock.

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6.3 The role of atmospheric forcing on the cold pool and ecosystem dynamics of the Bering Sea shelf: A retrospective study

Principal Investigators

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Period of Research: August 1996 – September 1998

Goal and Objectives

Our goal is to understand the coupling between the physical and the biological environments of the eastern Bering Sea. We have hypothesized that short-term (interannual) climate fluctuations over the eastern Bering Sea shelf control oceanographic conditions, which in turn, regulate pollock abundance. We focused on the changes in atmospheric forcing and cold pool structure that have and continue to occur over the period ~1947-present with special emphasis on the "regime shift" in the mid-late 1970s. We have examined the influence of these changes on the biology, including fish populations and, to some extent, primary productivity. The relationships found are used to formulate a conceptual model of the physical processes regulating the cold pool, hence regional biology.

Project Description

Our approach consisted of gathering, organizing, collating and updating time series of atmospheric, oceanic and biological parameters, and then performing various analyses to identify temporal and spatial linkages between the atmosphere, ice, ocean and biology. The data sets were monthly mean, and finer scale, deviations from the mean time series over the last ~50 years. The atmospheric data included sea level pressure, air temperatures, Southern Oscillation Index and surface winds. The oceanic data included sea ice cover and sea temperatures (including sea surface temperatures and hydrographic casts). The biological data were more in the annual to multi-year time scale included fisheries data (especially pollock) and primary production.

Results

The general hypothesis of this retrospective study is that interannual climate variability strongly influences the ecosystem of the eastern Bering Sea. We separated our general hypothesis into three specific hypotheses:

3. oceanographic conditions over the eastern shelf are controlled by the short-term climate variability,
3. oceanographic conditions, in particular temperatures, modulate the abundance of fish populations such as pollock, and
3. climate variability is responsible for substantial fluctuations in timing, location and perhaps magnitude of primary productivity.

For hypothesis 1, the atmospheric component of the time series analysis included regional and global aspects. Variations in regional forcing of the Bering Sea were assessed using twice-daily analyses of lower-tropospheric structure (temperature, pressure and winds). The context for these variations was provided by analysis of larger-scale and longer-term aspects of the climate; namely fluctuations in the El Niño-Southern Oscillation (ENSO) and fundamental teleconnection modes such as the Pacific-North American (PNA) pattern. These fluctuations were analyzed using monthly deviations from the mean. The oceanographic conditions, including sea ice and cold pool, were assessed using weekly values for percent ice cover in the eastern Bering Sea, and monthly sea surface and annual shelf bottom temperatures.

To this point, all of the time series of ~50 years length have been, and will continue to be, collected, collated, processed and available through niebauer@sunset.meteor.wisc.edu. Time series include monthly mean wind, air and sea-surface temperature (SST), and percent ice cover from the Bering Sea, monthly mean sea-level atmospheric pressure over the North Pacific and northern hemisphere, and finally the Southern Oscillation Index from the South Pacific. We also gathered data to address the physical part of the "cold pool" hypotheses in our project, i.e., fluctuations in the temperature of the pool of cold water on the shelf bottom results from the severity of the previous winter's weather. About thirty years (1966-1998) of CTD profiles for the Bering Sea shelf have been collected, collated, and are available (chu@ims.alaska.edu), at the University of Alaska Fairbanks (UAF). Also available at the UAF web site are annual maps of bottom temperature (cold pool) from the CTD data.

In the late 1970s, there was a relatively strong and sudden change in the climate of the North Pacific region. As evidence of this change, Ebbesmeyer et al. (1991) point to effects in ~40 different variables for the North Pacific and Bering Sea. This "step in the Pacific climate", or "regime shift" as it has also been called, included the air-ice-ocean environment of the Bering Sea. At least a portion of the regime shift can be attributed to changes in the character of ENSO (Niebauer 1998). El Niño conditions occurred ~25% of time after the regime shift from 1978-1996 compared to ~16% before, while La Niña conditions only occurred ~9% of the time after the regime shift compared with ~19% before the regime shift. The dominance of El Niños compared with La Niña helps explain the relative warmth and less icy conditions in the Bering Sea since 1976.

On the other hand, the El Niños since 1976 have had a different impact on the sea ice in the Bering Sea than previous El Niños. Before the regime shift, the retreat of sea ice and below normal ice cover in the Bering Sea was typically associated with El Niño conditions which caused the Aleutian low to move eastward of normal, carrying warm Pacific air over the Bering Sea. Conversely, above normal ice cover was associated with La Niña conditions which caused the Aleutian low to move westward of normal, allowing cold Asian high pressure to move over the Bering Sea. However, since the regime shift, during El Niños, the Aleutian low has been moving even farther east causing winds to blow south to north over central Alaska and then from the east and north off Alaska resulting in ice advance for the Bering Sea. This results in the seeming contradiction of overall less ice associated with El Niños but with ice advance associated with El Niños.

Further results show that interannual variations in the wintertime atmospheric forcing are considerable (e.g., the standard deviation in the average net surface heat fluxes is 40 W m^{-2}). These variations are well correlated with the duration of sea ice, and in particular, the southernmost extent of the sea ice. The interannual variations in the latter have correlation coefficients of 0.64 and 0.72 with the winter-average net surface heat fluxes and meridional wind stresses, respectively. Striking interannual variations have also been documented in the atmospheric forcing during the spring and summer. Interannual variations in SST tendency during May through July are correlated about equally with the net surface heat fluxes (largely due to variations in low cloud cover) and a combination of the wind mixing and Ekman pumping. The latter are important because of their impacts on the depth of the mixed layer. Based on the net heat fluxes at the surface, and the fraction of these fluxes that go toward heating the mixed layer, estimates have been made in the rate of heating below the pycnocline. The years with a persistent cold pool (e.g., the early 1970s, 1995) typically had about 30 W m^{-2} less heating below the mixed layer than those without a cold pool. This result indicates the importance of the dynamics of the mixed layer and pycnocline for establishing the stratification that can insulate the cold pool from the summer heating.

Major effects of atmospheric forcing on the Bering Sea shelf include the ice and the cold pool, and they are related. The cold pool is the mass of subsurface water $<2^\circ\text{C}$ present in the middle shelf domain during summer. The water mass is formed and modified each winter and so varies in extent and magnitude each year. An evaluation was made by charting the eastern extent of the 2°C -isotherm in the southeastern Bering Sea shelf (the annual maps of shelf bottom

temperature are on the UAF web site mentioned above). Over the 40 years of available data, this eastern edge ranged from 170°W to 159°W. There appear to be two segments. There is a western portion that is colder (<-1°C) and more saline (>33.2 psu), ranging from the Gulf of Anadyr to 170°W and that has been present in each of the past 40 years. There is an eastern portion that may not form at all, as was the case in 1981 and 1989, or that may extend all the way into Bristol Bay to 159°W as it did in 1972, 1975, 1976, 1980 and 1982. The most frequent extent of the cold pool was to 163°W, with periods of a reduced cold pool in 1956-1958 and in 1978-1979, and wide interannual fluctuations in 1980-1982 and 1987-1989. The cold pool is closely linked to the seasonal ice formation; a correlation coefficient of 0.68 (p<0.01) has been found between winter ice extent and the following summer's cold pool volume (Wyllie-Echeverria 1995).

For hypothesis 2, fish populations were assessed with annual estimates. A southeastern shelf benthic trawl survey is performed every summer (1972-present) and allows analysis on no finer a scale than annually. Hydroacoustic surveys and mid-water trawls are performed triannually and were used to determine the relative position of young walleye pollock in the water column, particularly in relationship to the cold pool. Time series have been collected, collated and processed for walleye pollock (ages 1, 2 and 3 and older), yellowfin sole, arrowtooth flounder, and Pacific cod. Data are from benthic trawl surveys covering the eastern and central Bering Sea shelf since 1972, and each species contains 7,426 stations sampled during that time period (contact: tinawe@u.washington.edu).

The major goal of all our analyses was developing and refining conceptual and statistical models of atmosphere, ocean, primary production, and pollock links. The physical part of the model thus far reasonably well supported by our results is that oceanographic conditions are controlled by climate/weather fluctuations. This is how we think it works. During winters with a strong and eastward displaced Aleutian low (most often accompanying an El Niño), the Bering Sea shelf is warm and the cold pool is small. During winters with a weak and westward-displaced Aleutian low (most often accompanying La Niña), the Bering Sea shelf is cool and the cold pool is large. However, a climate-driven physical regime shift occurred on the Bering Sea shelf in the mid-late 1970s. Since the regime shift, El Niño driven Aleutian lows have moved so far to the east that winds actually come off Alaska and cause Bering Sea ice to advance as in 1998.

The related physical-biological model has the regime shift in the physical environment at least in part responsible for the sudden changes in fish populations on the Bering Sea shelf that occurred in the mid-late 1970s. The physical conditions occurring after the regime shift have persisted to some extent, but some of the biological response was short lived (for example, only about one pollock year class was strongly affected, although its effect on the pollock fishery has been felt for years). This model relates the physics and biology in that oceanographic conditions, particularly temperatures, limit the growth of some populations. In the case of pollock, the model works like this: In cold years with an extensive cold pool, pollock are forced off the shelf. Pollock recruitment is reduced because of lower egg hatch, and the concentration of adult pollock results in increased cannibalism. In warm years with a small cold pool, pollock recruitment is enhanced because of higher egg hatch, and the dispersal of pollock results in

decreased cannibalism. Within a year or so, the population catches up so that cannibalism balances egg hatch. This may have been the mechanism that caused the pollock increase over the regime shift.

A specific aspect of this model/hypothesis is that the distribution of both age-1 and pollock age 2 and older is predicted to be concentrated on the outer shelf during cool conditions (Wyllie-Echeverria and Wooster 1998). The abnormally large extent of sea ice in winter 1997 lead us to predict cool summertime conditions. Pollock sampled at stations with concentrations of at least 100 fish per hectare were indeed found to be distributed outside the cold pool and primarily on the outer shelf. Similar results occurred for age-1 and age-2 pollock.

In addition, during the years evaluated in this study (Table 6.3.1), on average, Pacific cod was concentrated in cooler waters, ~0°C. Higher catches of yellowfin sole were found in waters warmer than 0.3°C, adult pollock in waters warmer than 0.5°C, age-1 pollock in waters warmer than 0.8°C and arrowtooth flounder in the waters warmer than 1.3°C. These species were distributed in cooler waters during cool environmental conditions as predicted by the sea ice index, and in warmer waters during warm environmental conditions.

Table 6.3.1 Minimum bottom temperatures (°C) where the majority of each species were concentrated during cool , intermediate, or warm conditions on the southeastern Bering Sea shelf. Species evaluated were Pacific cod, yellowfin sole, adult pollock, age-1 pollock and arrowtooth founder.

Year	Shelf condition	Minimum bottom temperature (°C)				
		Pacific cod	Yellowfin sole	Adult pollock	Age-1 pollock	Arrowtooth flounder
1992	cold	0	-1	0	-1	0
1995	cold	0	0	0	0	0.5
1988	intermediate	0	0	0	-1	1.5
1990	intermediate	-1	0	0	-1	1
1991	intermediate	0	2	0	0	2
1994	intermediate	-1	-1	0	0	1
1989	warm	1	1	2	2	1
1993	warm	1	1	1	2	2.5
1996	warm	1	1	1	2	2.5

In the retrospective studies we have followed a number of variables of 2-4 decade duration and observed fluctuations on interannual and multi-annual scales. We were successful in predicting the size of the cold pool and adult pollock distributions based on the sea ice index for 1996 and 1997. However, the prediction failed in 1998 when the cold pool was smaller than predicted.

For hypothesis 3, primary production and productivity data sets were found to have been collected far less systematically (i.e., sporadically over the past 30 years) than either the physical or fish data. Some data are available from U.S. and Japanese cruises, the Processes and

Resources Of the Bering Sea (PROBES) project, OCSEAP and NSF sponsored ice edge cruises for several years starting in 1976, and from NODC. These data are still being located, collated and summarized and analyzed. Work that is farther along and very promising is a comparison of satellite derived productivity and production data, from color scanners such as SEAWIFS, with environmental factors for the past five years by L.J. Miller and Dave Eslinger of the University of Alaska Fairbanks. L.J. Miller's master's thesis of this analysis should be available shortly.

Products

Journal articles

- Niebauer, H.J., 1998: Variability in Bering Sea ice cover as affected by a regime shift in the North Pacific in the period 1947-96. *J. Geophys. Res.* 103: 27,717-27,737.
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Outlook

We have completed the milestones with the possible exception of hypothesis (3), that is, climate variability is responsible for substantial fluctuations in timing, location and perhaps magnitude, of primary productivity. The original scope of this hypothesis was probably too ambitious given the present productivity data set. We have explained some of the problems with productivity hypothesis above but one of us (HJN) is continuing to work with Dr. V. Alexander of U. of Alaska on this problem. It will be interesting to see how the last two summer's (1997 and 1998) abnormal coccolithophore blooms will aid in understanding the relationship between primary production and weather/climate. Again, as mentioned above, work that is very promising is a comparison of satellite derived productivity and production data, from satellite color scanners such as SEAWIFS, with environmental factors for the past five years by L.J. Miller and Dave Eslinger of the University of Alaska Fairbanks. L.J. Miller's master's thesis of this analysis should be available shortly.

One line of future research will include study of persistent interdecadal sea surface temperature (SST) patterns in the north Pacific, known as the North Pacific Oscillation (NPO) or Pacific Decadal Oscillation (PDO). It is being hypothesized that the interdecadal NPO can cause modulation of interannual ENSO teleconnections to the Aleutian low. It may be this type of interaction that caused the regime shift of 1977. Longer time series of ~100 years provide data through at least 3 interdecadal regime shifts in 1925, 1947 and 1977. This may be an important next step in understanding variability in the ocean-atmosphere-Aleutian low connection driving variability in the Bering Sea environment.

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6.4 A retrospective investigation into relationships between Southeast Bering Sea pollock recruitment and biophysical correlates

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Goals and objectives

The goals and objectives of this project were to develop a conceptual model of walleye pollock (*Theragra chalcogramma*) recruitment in the Bering Sea, to compile and analyze all relevant physical and biological factors governing variation in eastern Bering Sea walleye pollock recruitment, and to develop a predictive model to forecast pollock recruitment based on relevant biophysical factors.

Project Description

The project was designed to develop a forecasting model for eastern Bering Sea walleye pollock that combines relevant biological data with important environmental data. The project consisted of three stages, data compilation, model development and parameter identification, and recruitment forecasting. A conceptual model (Fig. 6.4.1) that follows the three-stage approach recommended by Hollowed (1992) and Tyler (1992) guided the project. Our approach began with an examination of temporal and spatial distributions of various life stages of walleye pollock, then related these to postulated key events in the life history that may influence survival. This important step reduced the environmental variables to a manageable subset and identified when they might affect survival. Next we examined spatial and temporal characteristics of biological distributions and related them to potential environmental influences. Finally, we compared time series of selected environmental variables with the time series of recruitment using a neural network modeling paradigm.

In our working conceptual model, most mortality takes place in the juvenile life stage, although mortality during the larval life stage could be important in some years. Two factors have been suggested as important mechanisms in regulating eastern Bering Sea pollock year-class strength. These are predation, primarily cannibalism of juvenile pollock by adult pollock (Laevastu and Favorite 1988), and environmental factors (Quinn and Niebauer 1995). Predation

on pollock is greatest in the first and second year of life, and cannibalism has been shown to be a significant source of predatory mortality (Livingston 1991, Wespestad and Quinn 1997)). It has been suggested that the intensity of cannibalism is primarily a function of the degree of spatial separation of adults and juveniles (Wyllie-Echeverria 1995; Wespestad *et al* in press).

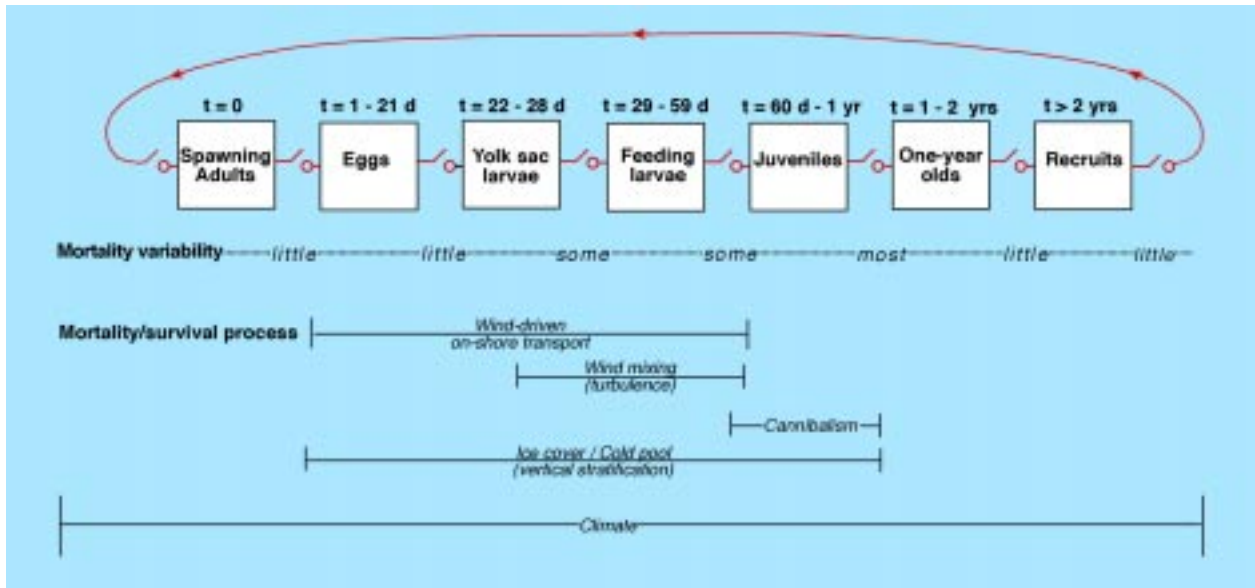


Figure 6.4.1 Working conceptual model of eastern Bering Sea walleye pollock survival at different life stages. Relative mortality, important environmental processes and the life stages that they affect are indicated.

Using the conceptual model, we tested a hypothesis that the degree of spatial separation/overlap of juvenile and adult pollock is determined by the influence of wind-induced passive transport during egg and larval stages (Wespestad *et al* in press). Strength of vertical stratification of the water column during the juvenile stage is likely to also be important. Water mass transport due to wind forcing (influenced by the location of the Aleutian Low-Siberian High) is the underlying mechanism separating adults and juveniles. However, wind forcing alone did not have strong predictive power. The wind-based model failed to accurately predict the 1996 pollock year-class. This indicated that the simple mechanistic model based on wind-driven transport did not fully capture all of the factors involved in regulating pollock survival. There exists a large body of environmental and biological data pertaining to Bering Sea climatology, oceanography, and biology. To systematically examine all of the data and to develop a predictive model that would capture important parameters, we decided to utilize a neural network model because it can be applied without the restrictions of traditional parametric statistical approaches.

One of the major outstanding questions of fisheries science concerns the existence of a relationship between the size of the breeding population (spawners) and their offspring (recruits) (Hilborn and Walters 1992). Typical parametric procedures like linear regression and correlation analysis require restrictive assumptions such as: errors are normally distributed, dependent and independent variables are measured without error, relationships are linear, data are not

autocorrelated. As biologists, we know these assumptions are not valid in marine systems. These methods also suffer from common restrictions. For example, standard multiple linear models do not allow interactions between variable unless they are pre-specified and of a particular multiplicative form. Also, functional relationships must be specified *a priori* before analysis proceed, and analytic methods do not deal well with gaps (missing values) in the data time series. In most circumstances these conditions cripple the ability of analysts to make sense of the data.

Neural networks, which are widely applied in other disciplines, are not very common in fisheries systems. However, neural networks deal effectively with the problems described above. First, they are very good at analyzing highly nonlinear systems. Second, they need long time series partitioned into learning, validation, and prediction segments. Further, they assume no *a priori* functional form between explanatory and response variables. Finally, they have superior predictive capability, and they are very flexible and require minimum assumptions.

Results

The following biological and physical data were compiled for analysis and development of an eastern Bering Sea pollock recruitment model.

Biological Data

The Bering Sea pollock spawning stock biomass data (Wespestad *et al.* 1997, Ianelli *et al.* 1998) was estimated as the abundance of 3-year-old pollock and the biomass of the mature adult component of the stock in the calendar year of the catch. The spawner biomass ran from 1964 to 1997. The recruitment series ran from 1964 to 1997, representing the 1961 to 1994 year-classes (Fig. 6.4.2). To match recruitment year-class and annual spawning biomass data points, recruitment values were lagged three years. For example, the estimate of the age-3 abundance in calendar year 1974, representing the 1971 year class, was matched with the 1971 spawning biomass estimate.

In our application we employed probabilistic neural networks to predict age-3 pollock recruitment. To use the technique, we had to classify the recruitment time series into recruitment states. We chose three: high, medium, and low using 33% (4.39 billion pollock) and 66% (6.73 billion pollock) percentile partitions (Fig. 6.4.3). Using the 33% and 66% percentile partitioning divided the data relatively equally so that approximately one third of the 30 available data points fell into each recruitment state. The even distribution of data over the three recruitment states assisted with neural network training. Recruitment state was arbitrarily scored as 1 for low, 2 for medium and 3 for high.

Physical Data

Physical data consisted of several atmospheric climatic indices and measures of the state of sea ice, water temperature and wind intensity around the Pribilof Islands. Data (Table 6.4.1) are presented as monthly averages, however, some of the input variables were normalized and expressed as deviations or anomalies from the long-term mean.

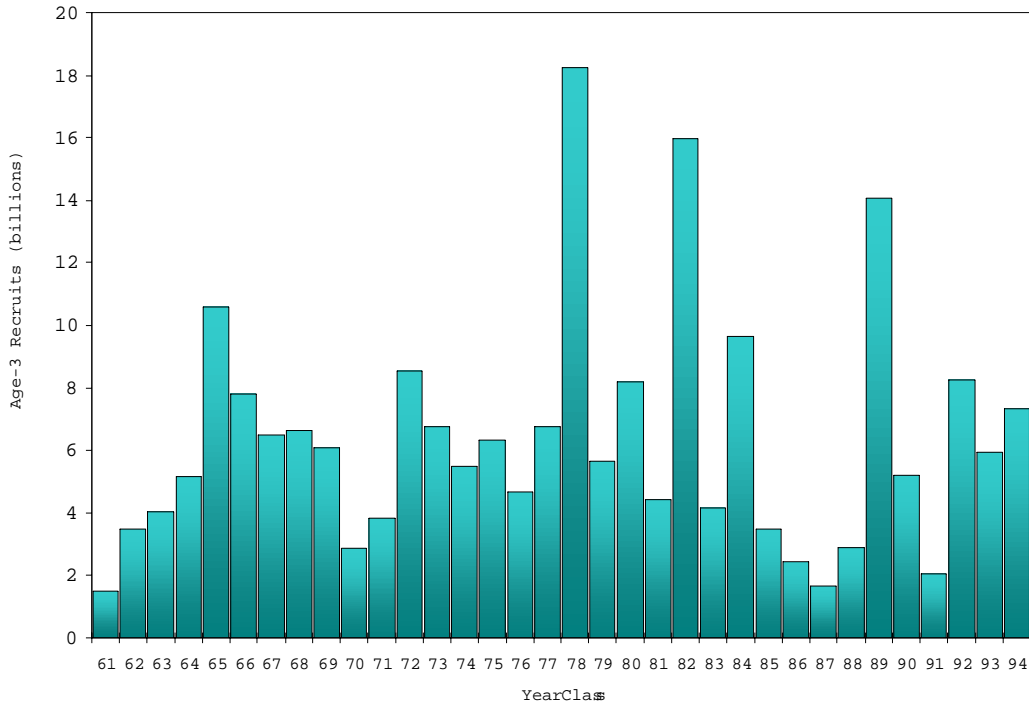


Figure 6.4.2 Recruitment time series for eastern Bering Sea pollock, 1961-1994.

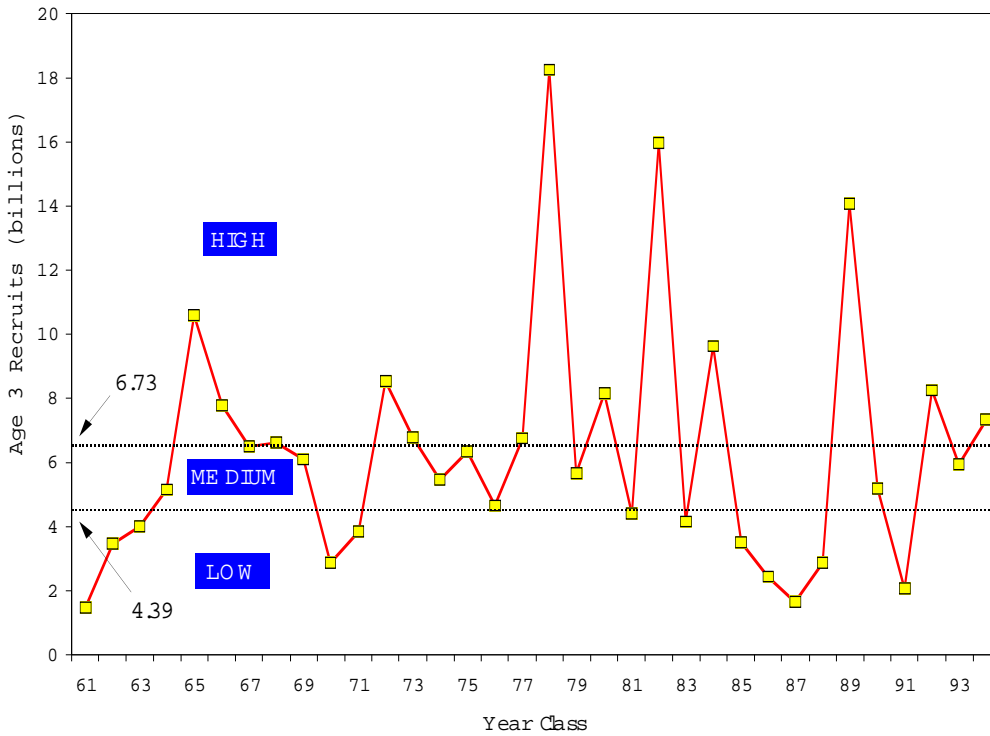


Figure 6.4.3 Eastern Bering Sea pollock recruitment time series and classifications.

Table 6.4.1 Biophysical data sources used in the analysis. Data for the physical variables are expressed as monthly means.

Variable	Description	Series Length
SB	Pollock spawner biomass (MMT)	1964-1997
AGE3	Abundance of age 3 pollock recruits (billions)	1964-1997
NPA	North Pacific sea level pressure deviations (mb)	1964-1997
PNA	Pacific North American Index	1964-1997
SOI	Southern Oscillation Index	1964-1997
PSA	Pribilof Islands SST anomalies (C°)	1964-1997
PTA	Pribilof Islands Air Temp anomalies (Pribilof I.) (C°)	1964-1997
PWA	Pribilof Islands (St. Paul) Wind speed, N-S anomalies (m/sec)	1964-1997
ICER	Eastern Bering Sea Ice (% Cover)	1964-1997
ICEA	Eastern Bering Sea Ice (% Cover) anomalies	1964-1997

Neural Network Model

Multilayer, feed-forward neural network models are multivariate statistical models which can be viewed as nonlinear regression models. Sometimes these are called multilayer perceptron (MLP) models (Sarle 1994). MLPs are general purpose, flexible, nonlinear models that can approximate virtually any function to any degree of accuracy. MLPs are especially useful in situations where there is little knowledge about the mathematical form of the relationship between independent and dependent variables.

Two types of feed-forward neural network models were explored, one to provide predictions of recruitment on an absolute scale, and one to predict recruitment on a classification basis. Ward Systems Group®™ Neuroshell Easy Predictor™ Release 2.0 and Neuroshell Easy Classifier™ Release 2.0 products were used to implement a predictor model based on General Regression Neural Nets (GRNN) and a classification model based on Probabilistic Neural Nets (PNN). For each type of neural net, two types of training were used: a nonlinear least squares optimization procedure and a genetic algorithm (Goldberg 1989, Davis 1991, Michalewicz 1992). The genetic algorithm is a derivative-free, “brute force,” stochastic optimization method that systematically searches the entire parameter space by mimicking the evolution of populations. In the genetic algorithm, several different possible solutions to a problem are generated. For each solution, the vector of parameters is encoded into “genes” and “chromosomes.” Each is tested for its performance (fitness) then a fraction of the “good” solutions are selected while others are eliminated (survival of the fittest). New (more fit) generations of possible solutions are created using the process of reproduction, crossover, and mutation. New generations are produced and evaluated until convergence is achieved. Genetic algorithms are very robust but the penalty for generalization is computational intensity. This is not much of a problem for relatively small problems implemented on fast computers.

Data Analysis

The preliminary step in the analysis was to examine the correlation between the suite of biological and physical variables with recruitment. Many of these input data were correlated to some extent and measured the same phenomena. Correlation is a simple, univariate, data analysis approach that does not consider multiple variable interactions. However, it is a useful beginning point for looking at possible associations. Subsequently, the modeling process consisted of the following steps:

- Select a neural network model
 - General Regression Neural Net (Specht 1991): prediction (GRNN)
 - Probabilistic Neural Nets (Specht 1988, 1990): classification (PNN)
- Select input rows for training (1965-1994)
- Select input variables
- Select output variable
 - Age 3 recruits when Generalized Regression Neural Network was used
 - Recruitment state when Probabilistic Neural Network was used
- Select training algorithm
 - Least Squares Optimization
 - Genetic Algorithm
- Apply trained network for prediction (1995-1997)
- Generate diagnostics

Due to the relatively small number of observations ($n=30$), the neural network models used in these analyses were restricted to two hidden neurons. When the genetic algorithm was selected, genetic training proceeded until 250 generations were created without an improvement in network performance. When the GRNN was being applied to the data, performance was measured using the R^2 statistic. The percent of the observed recruitment state observations correctly classified was the performance measure with the PNN. Different combinations of the input variables were applied to each neural network model. Guided by the correlation results, we chose an eight-input variable model. In addition, we also examined a more parsimonious three- and four-input variable model.

Recruitment predictions for the 1995-97 year classes were expressed in terms of recruitment state. Predictions from the PNN model were used directly, however predictions from the GRNN were on an absolute scale. To make these comparable to the PNN results, we converted the predictions (in absolute numbers) from the GRNN to recruitment state predictions by applying the cutoff values from Figure 6.4.3.

Different diagnostics were used to assess the importance of model input and output results. For PNNs, this included examination of the % classified correct, agreement matrices, or contingency tables, which show how the network's classifications compare to the actual data to which the network is applied. The percent of variation in the observed data explained by the model (R^2) was utilized with GRNNs to evaluate the various combinations of input parameters. The PNN and the GRNN models were not directly comparable based on intrinsic diagnostic or performance measures so the Schwarz's Bayesian Information Criteria (BIC) (Schwarz 1978,

Akaike 1983) was used to compare the performance of two alternative neural network models. BIC takes into consideration goodness-of-fit, parsimony and objectivity. The optimal model choice is the one with the smallest BIC value.

The RSS term for the BIC calculation was taken directly from the GRNN model. The PNN model, because of the probabilistic nature of its predictions, required intermediate calculations to derive the RSS term as follows. For each predicted year, the PNN gives the recruitment state prediction in the form of a probability vector (i.e., Pr[low recruitment], Pr[medium recruitment], and Pr[high recruitment]). The combined predicted recruitment for a year was calculated by multiplying the recruitment state probabilities by the score for the recruitment state (i.e., 1-low, 2-medium, 3-high) and summing them together. The SSQ was then calculated as the sum of the squared differences between observed and predicted recruitment state.

Other diagnostics we used included measures of sensitivity and specificity. Sensitivity can be thought of as the probability that the model will detect the condition when present. Sensitivity (true positives) equals 1 minus the number of false negatives. Specificity can be thought of as the probability that the network will detect the absence of a condition. Specificity (true negatives) equals 1 minus the number of false positives. Probabilities describe the chance that the set of inputs in that row will lead to a classification in each of the output categories. Also the importance of inputs were examined. The number associated with a variable indicates the relative significance of each of the input variables in the predictive model. These can be viewed much like the magnitude of a coefficient from linear regression. Higher values are associated with more important variables.

Best Fit Model and Explanatory Variables

The correlation analysis contained spawning biomass (SB) and six sets of monthly observations of physical environmental parameters as described in Table 6.4.1: ice coverage anomalies (ICEA), surface wind anomalies (PWA), air temperature anomalies (PTA), sea surface temperature anomalies (PSA), North Pacific air pressure anomalies (NPA), and the Southern Oscillation index (SOI). The variable that had the largest correlation with recruitment was the North Pacific Pressure Anomaly (Table 6.4.2). However, within the context of the conceptual model it had little predictive power, similarly for the Southern Oscillation index (SOI), the other broad area index. The extent of ice cover was inversely correlated with pollock recruitment, and the largest correlations were for the early and late part of the year. This likely relates to the fact that ice formation is retarded in warm years, and reflects the influence of the inflow of warm air from the North Pacific Ocean. Air temperature conditions, which were positively correlated with pollock recruitment, are also influenced by the inflow of warm air from the North Pacific. Wind anomalies were negatively correlated with recruitment, with largest coefficients occurring in June and the early winter.

Several model configurations were examined to determine the “best fit” model. To conform to the conceptual model, all models contained spawning biomass as an input variable. This variable needs to be included to maintain the biological integrity of the model. A summary of the model configurations is given in Table 6.4.3.

Table 6.4.2 Rank order of correlation coefficients for the major variables correlated with pollock recruitment.

Variable	Month	r	Variable	Month	r
NPA	May	0.51	PWA	Feb	-0.32
PWA	Jun	-0.45	PTA	May	0.32
PTA	Jan	0.41	ICEA	Dec	-0.31
PTA	Apr	0.39	ICEA	Aug	-0.31
NPA	Jul	0.38	SOI	Nov	-0.31
PTA	Sep	0.38	PTA	Dec	0.30
PWA	Jan	-0.37	ICEA	Feb	-0.30
PWA	Apr	-0.35	SOI	Dec	-0.30
NPA	Jun	0.34	PTA	Jun	0.29
ICEA	Oct	-0.34	SB		-0.19
ICEA	Mar	-0.33			

Table 6.4.3 Summary statistics from application of general regression (GRNN) and probabilistic (PNN) neural network models to the Bering Sea walleye pollock biophysical data set.

Method: Independent Variable Measurement	Training Algorithm	Number ¹ Variables	Number Parameters	% Classified Correct ²	R ²	BIC	Prediction		
							95	96	97
GRNN (Prediction): Age 3 Recruits	Neural	8	18		61.49	76.59	L	M	M
	Genetic	8	18		61.46	76.58	L	M	H
	Neural	4	10		19.47	57.48	M	M	L
	Genetic	4	10		48.16	58.36	L	M	M
	Neural	3	8		25.37	50.93	L	H	L
	Genetic	3	8		35.88	50.78	L	M	M
PNN (Classification): Recruitment State	Neural	8	18	86.67		54.56	L	H	L
	Genetic	8	18	76.67		54.59	H	H	M
	Neural	4	10	70.00		26.80	L	H	M
	Genetic	4	10	63.33		26.97	L	H	M
	Neural	3	8	76.67		19.93	L	H	M
	Genetic	3	8	70.00		20.66	L	H	H

¹--8 variable model - SB, PWAJan, PWAApr, PWAJun, PTAJan, PTAApr, PTASep, NPAMay

4 variable model - SB, ICEAMar, PWAApr, PTAMar

3 variable model - SB, ICEMar, PWAMay

²-- during training

Performance of the GRNN had R^2 values between 19 and 62%. PNN, the model that classified the data into the three levels of recruitment, had percent correct classification values between 63 to 87%. The eight input variable models had the highest performance measures. GRNN had R^2 values of about 61% for both neural and genetic training. PNN had an 87% correct classification for neural training and 77% for genetic training. Both GRNN and PNN eight input variable models estimated 18 parameters. Thus, these high performance characteristics came at the expense of estimating about one parameter for every two data observations. The large number of parameters estimated by these models are reflected in high BIC scores. For the GRNN, it was generally true that increased performance was directly related to the number of input variables submitted to the model. Differences in performance were minor in the PNN for the eight, four, and three variable input models. The best method of training varied between neural network models. GRNN seemed to perform better when trained with the genetic algorithm, while the PNN appeared to perform better using neural training (i.e., nonlinear least squares optimization).

The “best fit” model was defined as the most parsimonious set of variables that gave the best performance (lowest BIC). From Table 6.4.3 we can see that this was PNN using neural training that contained as input variables spawning biomass, March ice anomalies, and May wind anomalies. This correctly classified 23 data points out of 30 in the training data (76.67% correct) and misclassified 7 data points as shown in Table 6.4.4 below.

Table 6.4.4 Performance of the PNN model using three input variables.

	Actual “High”	Actual “Medium”	Actual “Low”	Total
Classified as “High”		4	1	15
Classified as “Medium”	1		0	7
Classified as “Low”	1	0		8
Total	12	10	8	30
True-positive ratio	0.83	0.60	0.88	
False-positive ratio	0.28	0.05	0.05	
True-negative ratio	0.72	0.95	0.95	
False-negative ratio	0.17	0.40	0.13	
Sensitivity	0.83	0.60	0.88	
Specificity	72.22%	95.00%	95.45%	

Note that there are six ways to misclassify a recruitment state. From a prediction point of view, the two most serious are to classify a low recruitment as high and/or to classify a high recruitment as low. We can see that the best model made this error two times out of seven misclassifications.

The relative weighting factors for this model (Fig. 6.4.4) showed that spawning biomass had the greatest influence on the model outcome and this was followed in rank order by March ice and May wind anomalies.

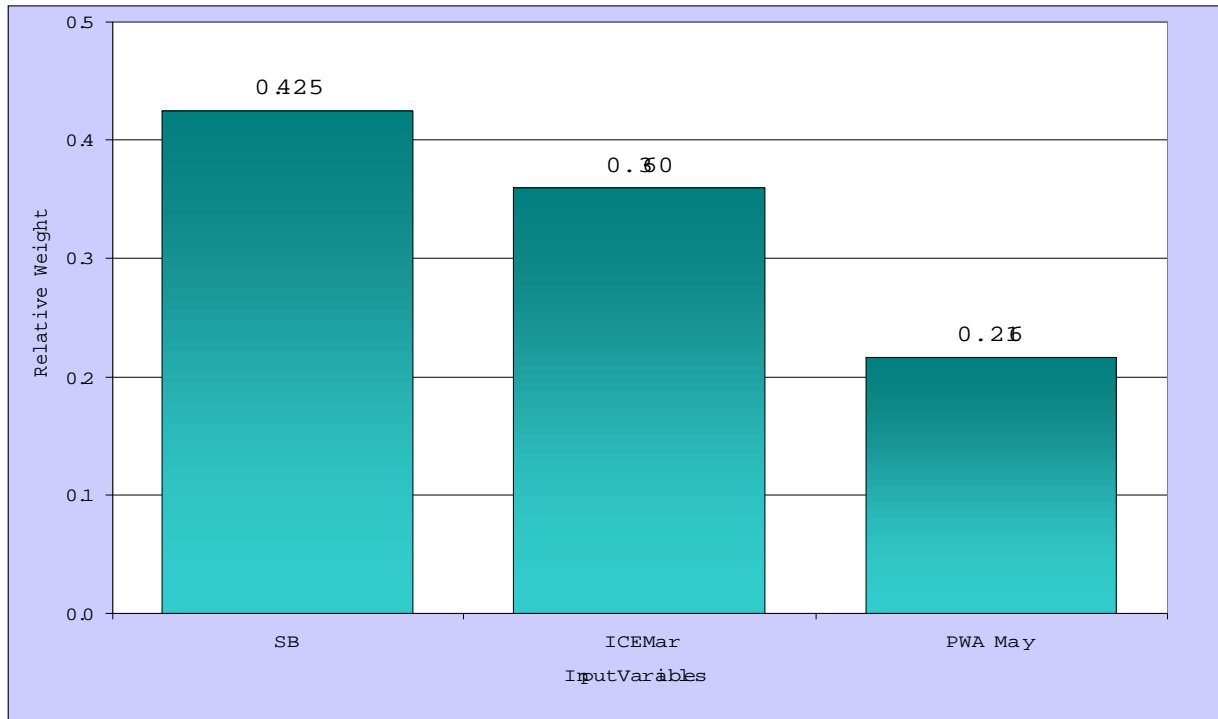


Figure 6.4.4 Relative weighting factors for the Probabilistic neural network using the neural training algorithm and spawning biomass (SB), March ice anomaly (ICEMar), and May wind anomaly (PWAMay) as input variables.

Predictive Power

Of the three year classes not included in the training data and predicted by the neural network models (1995-1997), only the 1995 year class had an actual recruitment observation to compare to the prediction. Information from trawl surveys indicates that the 1996 year class appears to be strong. We do not know the status of the 1997 year class.

With two exceptions, all neural network models predicted the 1995 year class to be low (Table 6.4.3). The GRNN had a tendency to predict the 1996 year class as medium while the PNN predicted high. Results for the 1997 year class from the GRNN was mixed, however the PNN predicted a more consisted medium.

The “best fit” neural network model incorporating spawning biomass, March ice, and May wind anomalies predicted the 1995 year class to be low, the 1996 year class to be high, and the 1997 year class to be of medium abundance. The prediction probabilities from this model (Figure 6.4.5) show, that for 1994, the probability for low was 0.98 and the probability for medium and high was 0.01. For 1996, the probability for high, medium, and low was 0.94, 0.05, and 0.01 respectively. For 1997, the probability was spread almost evenly between high (0.44) and medium (0.55), with low being 0.01. In general, the accuracy of the annual prediction degraded as the prediction moved further into the future. These predictions are in agreement with field observations.

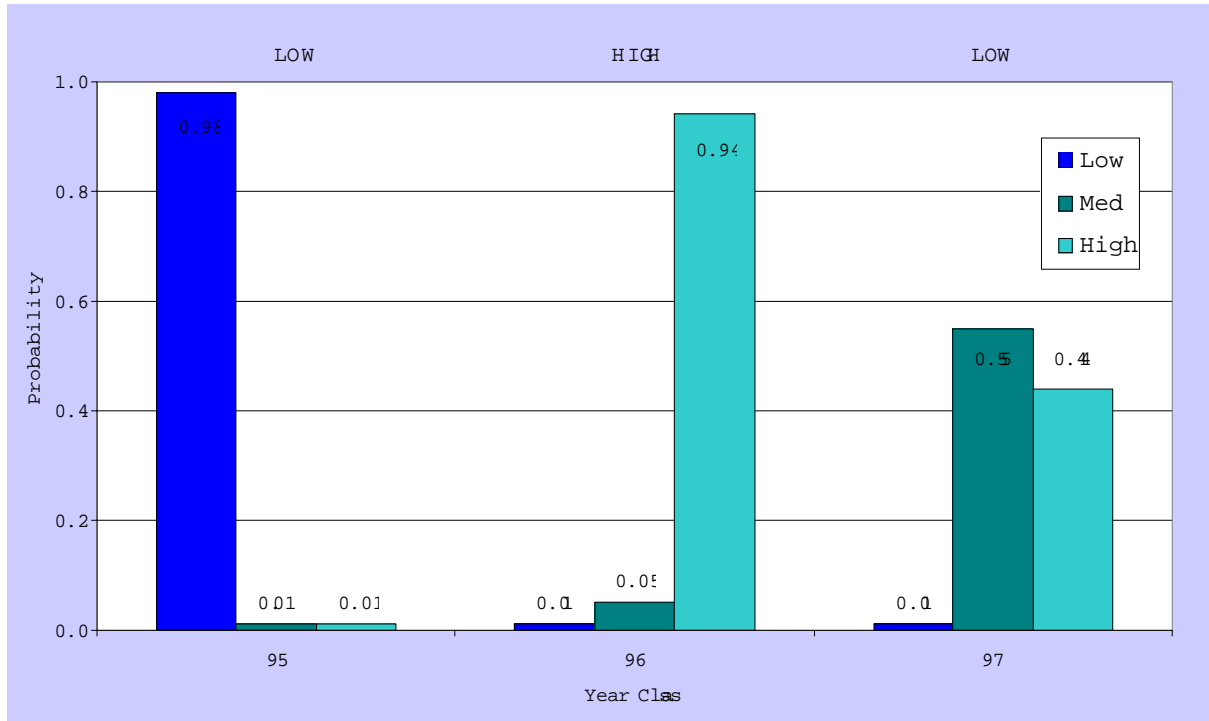


Figure 6.4.5 Probability of high, medium, and low recruitment for the 1995-1997 pollock year classes from the probabilistic neural network using the neural training algorithm and spawning biomass (SB), March ice anomaly, and May wind anomaly as input variables. Actual observed recruitment states are indicated at the top of the figure.

The variables that had predictive power fit within the conceptual framework model of how physical parameters influence pollock recruitment. It is encouraging to note that spawning biomass was an important factor in predicting recruitment in nearly all cases. Also, that wind during the spring months, the period when eggs and larvae are subject to surface drift, was an important predictor of recruitment. The role of temperature in prediction was not as clear cut as for other factors since temperature affects came into the model indirectly through the March ice variable. However, an examination of all possible combinations of wind and ice anomaly, holding spawner biomass constant, did show a maximum R^2 for March ice and May wind (Fig. 6.4.6).

Empirical curve fitting exercises do not impart any fundamental understanding of the underlying processes underlying recruitment. This is true for both nonlinear regression and neural networks. A major advantage of neural networks seems to be that they require few assumptions about error structure and functional relationships. Results of our analyses show that a better prediction is possible through the application of neural network models. Although, there does not appear to be a unique set of variables to predict recruitment, our results indicate that relative recruitment can be defined by the size of the spawning stock and a limited number of physical variables related to conditions during the early life history. The physical variables that produced relatively accurate predictions were all related to spring conditions. These were the extent of ice in March and the wind anomalies during May. Ice extent in March is a measure of the severity during the previous winter and correlates with the prevailing wind and air

temperature. In warm years the ice extent is limited and winds are predominately from the south and sea and air temperature warmer than in years when wind is primarily from the north and ice cover is extensive. Sea ice appears to be a valuable proxy for temperature in that it integrates temperature fluctuations through time. Variation in the intensity of the Aleutian Low is a very large-scale, high-latitude atmospheric circulation pattern (Overland 1981, Niebauer 1985). It has been observed in Asian and North American stocks that good survival occurs in warm years and in cold years survival is poor (PICES 1996). There also appears to be major coherence in year-class survival among the major North Pacific pollock stocks, suggesting a broad-scale, oceanic-wide forcing mechanism. It would be an interesting application to examine the total recruitment patterns from all stocks within the North Pacific Basin, especially to indices of broad-scale circulation, such as the NPA, PDO, and SIO, to determine if better classification and predictions could be obtained.

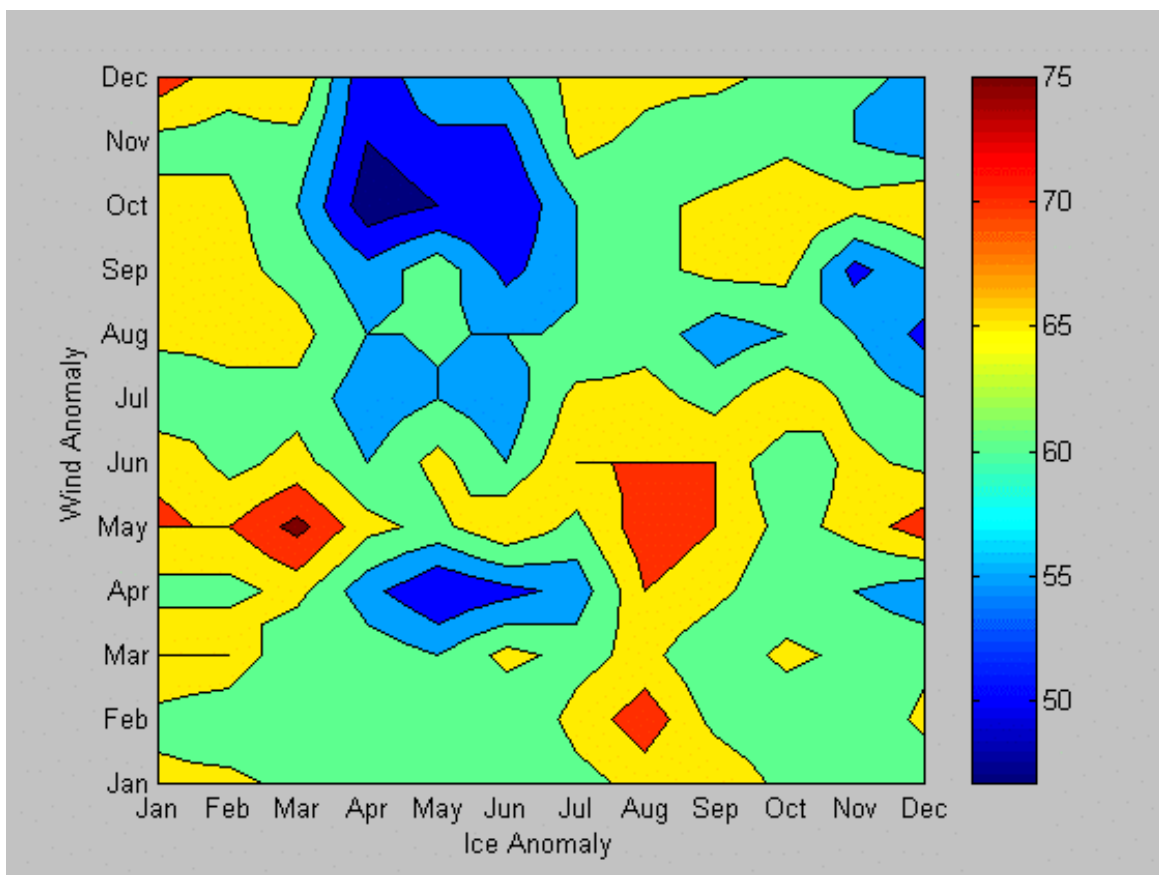


Figure 6.4.6 R^2 response surface for "best fit" PNN model holding spawning biomass constant and varying monthly ice and wind anomalies.

Our prediction of a weak 1995 year class, a strong 1996 year class and a moderate 1997 year class using the neural network model produced a better prediction compared to one obtained by a simple correlation to wind transport (Wespestad *et al.* in press) and one that appears to be borne out by trawl surveys.

In this application, the neural network model allowed us to explore a large number of environmental variables, thus expanding upon the previous simple descriptive model. The neural

network models provided a means of exploring input values consistent with our conceptual model, and to examine other input sets without *a priori* assumptions. These environmental-dependent models were found to be an improvement over pure biological (environment-independent) models.

Products

Models and data compilations

1. We developed a conceptual model of Bering Sea walleye pollock survival at different life stages describing relative mortality affecting each life stage and important environmental processes and the life stages that they affect. This model has proved extremely useful in several other Phase I SEBSCC projects.
2. We adapted a neural network model that is able to integrate biological and physical data sets and produce a forecast of the relative year class size of eastern Bering Sea pollock as well as a measure of the accuracy of the prediction.
3. We compiled all environmental data available for the eastern Bering Sea on a monthly basis that included ice coverage anomalies, Pribilof Island surface wind anomalies, Pribilof Island air temperature anomalies, Pribilof Island sea surface temperature anomalies, North Pacific air pressure anomalies, and the Southern Oscillation Index.

Journal articles published or submitted

Wespestad, V.G., L. Fritz, J. Ingraham, and B.A. Megrey, in press: On relationships between cannibalism, climate variability, physical transport and recruitment success of Bering Sea walleye pollock. *ICES Journal of Marine Science*.

Megrey, B.A. and V.G. Wespestad, submitted: Using neural networks to examine relationships between features of the environment and recruitment variation in bering sea walleye pollock. *Canadian Journal of fisheries and Aquatic Sciences*.

Megrey, B.A., 1996: On the relationship of juvenile pollock abundance to adult recruitment and linkages with the environment. In: *Ecology of Juvenile Walleye Pollock: Papers from the Workshop on the Importance of Prerecruit Walleye Pollock to the Bering Sea and North Pacific Ecosystems*, NOAA Tech Report NMFS 126.

Presentations at scientific meetings and seminars

Megrey, B.A., 1999: Untangling environment-recruitment relationships in North Pacific Pollock Stocks: Are artificial intelligence methods the answer? Invited speaker, AFSC/RACE Seminar Series, Time Series: New Methods, Fisheries and the Environment, March 9.

Megrey, B.A., 1998: Application of fuzzy logic to forecasting Alaska walleye pollock recruitment. Presented at the Seventh Annual PICES Science Meeting, October 14-25, Fairbanks, Alaska.

Megrey, B.A., 1997: Application of fuzzy logic to forecasting Alaska walleye pollock recruitment. Presented at the ICES International Symposium On The Role of Physical and Biological Processes in the Recruitment Dynamics of Marine Populations September 22-24, Baltimore, Maryland.

Megrey, B.A., 1997: Bering Sea walleye pollock recruitment. FOCI Seminar, October 2.

- Megrey, B.A., and V.G. Wespestad, 1998: Interannual variability in pollock from the contrasting environments observed during 1998, 1997, 1996 and before. Presented at the SEBSCC PI Meeting, October 24, Fairbanks, Alaska.
- Megrey, B.A., and V.G. Wespestad, 1998: Using neural networks to examine relationships between features of the environment and recruitment variation in exploited marine fish stocks. Presented at the International Workshop on the Application of Artificial Neural Networks to Ecological Modeling, December 14-17, Toulouse, France.
- Wespestad, V.G., 1997: Trends in North Pacific gadoid resources. Presented at the Groundfish Forum, London England, October.
- Wespestad, V.G., 1997: Environmental influences on recruitment variation in Bering Sea walleye pollock. Presented before the North Pacific Fisheries Management Council, December.
- Wespestad, V.G., L. Fritz, J. Ingraham, and B.A. Megrey, 1997: On relationships between cannibalism, climate variability, physical transport and recruitment success of Bering Sea walleye pollock. Presented at the ICES International Symposium On The Role of Physical and Biological Processes in the Recruitment Dynamics of Marine Populations, September 22-24, Baltimore, Maryland.
- Wespestad, V.G., and B.A. Megrey. 1998: On relationships between cannibalism, climate variability, physical transport and recruitment success of Bering Sea walleye pollock. Presented at the Seventh Annual PICES Science Meeting, October 14-25, Fairbanks, AK.

Outlook

We completed all of the objectives of our project. Our analysis was hampered by two restrictive assumptions. First, that spawning is fixed in time and space when we know this is not true. Hinckley (1987) showed that there was substantial temporal variation in pollock spawning in the Bering Sea. Also, the short time series available for analysis forced us to constrain the neural network architecture (i.e., models were restricted to only two hidden neurons) to maximize degrees of freedom. Monte Carlo simulations or the analysis of simulated data sets should be explored to overcome this problem.

The observed influence of environmental factors on recruitment does not appear to be unique to pollock. For instance, Rosenkrantz *et al.* (1998) also show a relationship between wind and year class strength of tanner crabs in the southeastern Bering Sea. The lack of a unique solution was disappointing, but not surprising, given the low correlation of the input values to recruitment, and the relatively small data set. Hare and Francis (1998) show that this is often an expected outcome in these situations. They note that when a large number of variables are being examined, a suite of possibly widely different models can provide almost the same statistical fit. It is also important to note that the models described herein still seem to be missing some important explanatory factors since, even in the “best fit” model, approximately 30% of the variation in recruitment was unexplained.

Further Research

In the Phase I SEBSCC study, we established that there is a significant statistical relationship between wind-forced surface transport and pollock year-class success. It is now apparent that spatial dynamics are an important part of the recruitment process of eastern Bering Sea pollock. Strong year classes appear to be transported long distances from the spawning grounds, and weak year classes appear to remain in the outer shelf domain, overlapping the distribution of adult pollock. The transport model parameters were included in the 1997 stock assessment of pollock for recruitment forecasting, and results were better than with conventional forecasts based solely on survey estimates of recruitment. Encouraged by these results, we developed a proposal for Phase II of SEBSCC titled "A Spatially-Explicit Biophysical Simulation Model of Pollock Recruitment." The goal of this proposal was to better define the relationship of pollock survival to environmental factors and predation through the use of coupled oceanographic and population dynamic models. We hoped to refine the basic conceptual model by including more spatial detail and additional physical and biological data. With greater model detail we hoped to incorporate a greater quantity of data and address at least two issues of importance to management. The Phase II model with simplified spatial dependence coupled to an age-structured life-history model would have allowed us to develop a better model of juvenile transport in the eastern Bering Sea. This model would have allowed us to investigate potential distribution patterns, their origin, the underlying physical dynamics, and the juvenile survival rate under predation and fishery rates of the various climatically forced transport trajectories. Unfortunately, the Phase II proposal was not funded.

We are also preparing data from 1998 and plan to forecast the 1998 year class with the neural network model. We know that 1998 was a very stormy year in the Bering Sea. Oceanic copepods and larval pollock were observed on the shelf and up against the west coast of Alaska. Preliminary information from field operations and examination of data indicate that strong onshore winds were prevalent in 1998. These conditions are consistent with our conceptual model and suggest that 1998 should be a strong year class.

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