Southeast Bering Sea Carrying Capacity (SEBSCC)

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The southeastern Bering Sea is a major ecosystem supporting bountiful economic resources. It boasts an abundance of high-latitude marine life and some of the busiest fishing ports in the United States. This ecosystem responds to changing conditions in ways that can be observed as fluctuations in abundance of commercial fish and shellfish, sea birds and marine mammals. At present, the southeastern Bering Sea ecosystem has a dominant pelagic species: the commercially fished walleye pollock (*Theragra chalcogramms*). Pollock is a nodal species, constituting an integral part of the region's food chain as both prey and predator. Understanding the ecology of this fish in the context of the overall ecosystem is a useful approach to developing methods to better manage living marine resources of the southeastern Bering Sea.

Southeast Bering Sea Carrying Capacity (SEBSCC), a project of the U.S. National Oceanic and Atmospheric Administration (NOAA) Coastal Ocean Program, is a six-year, interdisciplinary, regional ecosystem study. The study's goal is to increase understanding of the southeastern Bering Sea ecosystem, to document the role of juvenile pollock and factors that affect their survival, and to develop and test annual indices of pre-recruit (age-1) pollock abundance. SEBSCC builds on earlier research in the Bering Sea by programs such as the Outer Continental Shelf Environmental Assessment Program (OCSEAP), Processes and Resources of the Bering Sea Shelf (PROBES), and Bering Sea Fisheries-Oceanography Coordinated Investigations (BS FOCI). PROBES defined specific hydrographic regimes for the region: 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.

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?
3. How are pollock, forage fish, and apex species linked through energetics and life history? How important is cannibalism in the dynamics of pollock?
4. 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?
5. 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.

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. 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. A second, two-year research cycle is just beginning. Funded research for each cycle is identified in *Table 1*.

Monitoring

SEBSCC's monitoring program consists of broad-scale field surveys using ships, multi-disciplinary moorings, drifting buoys, and analysis of satellite data. 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 in February, to deploy moorings and measure late winter conditions; in April, to monitor the progress of the spring bloom; in June, to measure post-bloom conditions; and in 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. *Figure 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.

Figure 2 contains a schematic of a biophysical mooring. 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 1995. For example, *Figure 3* presents near-surface seawater temperatures from 1995 to 1998 from site 2. Note that August 1997 brought the highest-ever-recorded temperature in the region. Other

Table 1. SEBSCC research components: 1996-1998 and 1999-2000.

1996-1998

Monitoring
- Monitoring and development of biophysical indices
- Altimetric census of mesoscale eddy-like features

Process studies
- Origin and dynamics of nutrients on the shelf in relation to dominant physical and biological processes
- Isotopic and biomarker composition of sinking organic matter: indicators of food web structure
- Using optical measurements to explore the influence of mesoscale eddies on interaction of trophic levels
- Low-temperature incubation of walleye pollock eggs
- Habitat differences in frontal regions around the Pribilof Islands and their importance to juvenile pollock growth and survival

Modeling
- Circulation modeling
- Individual-based modeling of walleye pollock
- Spatial model of upper-trophic level interactions

Retrospective studies and synthesis
- High-resolution acoustic and juvenile pollock retrospective data analysis
- Retrospective study of the role of atmospheric forcing on the "cold pool" and ecosystem dynamics of the shelf
- Historical trends in the number of foraging trips made by lactating northern fur seals
- Retrospective relationships between Southeast Bering Sea pollock recruitment and biophysical correlates

1999-2000

Monitoring
- Monitoring and use of biophysical indices: phase II
- Currents and transfer processes between shelf and slope: a Lagrangian perspective

Process studies
- In situ monitoring of nitrate concentrations
- Origin of nutrients on the shelf in relation to physical processes and biological uptake
- Sinking organic matter and pelagic food webs
- Proximity of age-0 pollock, jellyfish, predators, and prey
- Habitat differences in frontal regions around the Pribilof Islands with respect to juvenile pollock growth and survival: phase II

Modeling
- Circulation modeling

Retrospective studies and synthesis
- Environmental influences on early life stages of walleye pollock during the late 1970's climate regime shift
- Climate regime shift of the 1970s: air-sea interactions crucial to walleye pollock
- Measures of ecosystem trends: an approach for synthesis and understanding

measurements from the mooring include 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 for the past two years.

Future monitoring efforts will continue occupation of site 2 with subsurface and surface moorings, site 6 with subsurface moorings, and transects as shown in *Figure 1*. Sediment traps will be maintained at site 2, and a nitrate sensor has been added to the biophysical mooring there.

Process-oriented studies

Nested within the broad-scale observations, SEBSCC conducts studies to investigate specific biological and physical processes. These include indicators of food web structure through the collection and stable isotope analysis of organisms and sinking organic matter, investigation of the origin and dynamics of nutrients, and exploration of the influence of mesoscale eddies on biological interactions. At higher trophic levels, the project has studied the effect of water temperature on the incubation of pollock eggs, and habitat differences for juvenile pollock in structural fronts around the Pribilof Islands.

The Pribilof survey occurs in the fall and has been conducted since 1994, having been started by BS FOCI. The 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, the occupation of Transect A, a survey line 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.

Figure 4 shows the distribution of nutrients and chlorophyll-*a* along the transect during 1995 and 1996. Nitrogenous nutrients (nitrate plus nitrite) were >1 μM below the thermocline in the stratified waters and throughout the water column in the transition and inner front area in both 1995 and 1996. Maximum chlorophyll-*a* concentrations (>4 μg l^{-1}) were found in surface waters just offshore of the region where nutrients were >1 μM. Moderate chlorophyll concentrations were measured in the stratified waters where nitrogenous concentrations were low. Some general conclusions may be inferred from the overall results of these surveys. There is high interannual variability. In general, the highest densities of juvenile pollock are at the front or inshore, but food density is highest offshore. The diet of juvenile pollock is highly variable, with copepods and euphausiids being the main prey at the front. The condition of juveniles (as measured by Fulton's K) is significantly higher offshore than in the coastal or frontal regions. This work will continue during SEBSCC's second research cycle.

Modeling

Modeling is a useful approach for understanding specific elements of the ecosystem, especially when models incorporate details of realistic biological/physical interaction and allow for data assimilation. Models also assist in the formulation and interpretation of field studies and provide context for integration of results. SEBSCC has three modeling components. One is a 3-dimensional, eddy-resolving circulation model of the southeastern Bering Sea. The circulation model is implemented as a free-surface, primitive equation, eddy-resolving model at 4-kilometer resolution with wind, heat flux, tidal, and subtidal forcing. 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. The model has simulated conditions through mid-May during 1995 and 1997. Simulations show considerable eddy activity in the Bering Sea basin, more so in 1995 than in 1997; abundance of eddies and strongest mixing near the shelf break and along the 100-m isobath; and a cold pool (an annual spring and summer feature of the bottom layer of the shelf having variable extent and duration) on the shelf in both years.

SEBSCC's two biological models are a spatially explicit individual-based model (IBM) of the early life stages of pollock and a spatial model of upper-trophic level interactions focused on pollock, their prey and predators. The IBM model tracks fish separately through space and time. It is probabilistic and mechanistic, adapted from a similar effort developed for the Gulf of Alaska, and includes detailed descriptions of processes that

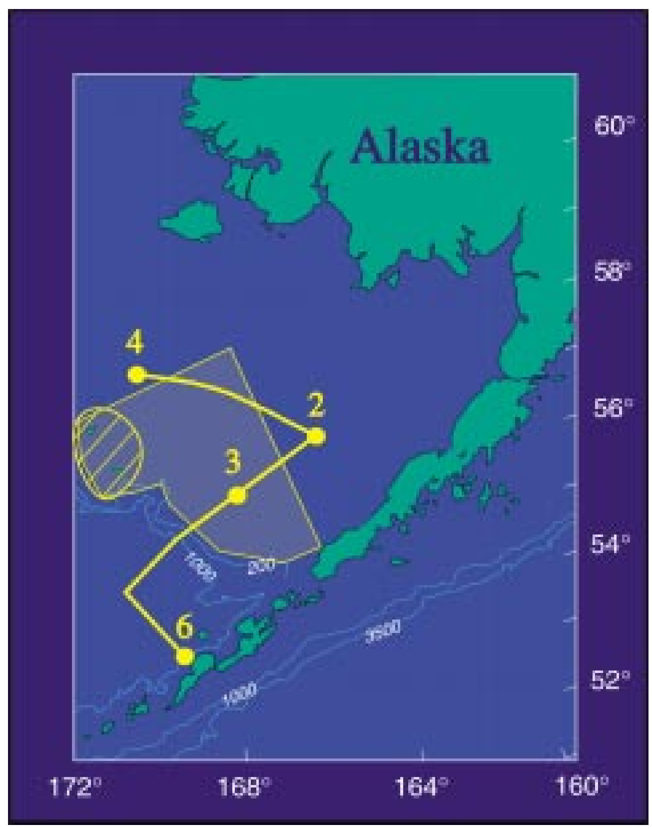

Fig. 1 The southeastern Bering Sea. The SEBSCC study area includes mooring sites 2, 3, 4, and 6; hydrographic, chemical, and biological sampling transects between moorings; a juvenile walleye pollock habitat (hatched area) around the Pribilof Islands; and a juvenile pollock survey area (shaded). Depths shown are in meters.

differ by life stage and affect survival. Some of its attributes are specification of habitat to set spawning depth and date and average food densities, depth distribution by life stage, and fish behavior. SEBSCC's spatial model of upper-trophic level interactions that spatial processes affecting the overlap and availability of juvenile pollock to predators, particularly, adult pollock, are important determinants of juvenile pollock survival. An intermediate product of the model's development is parameterization of 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

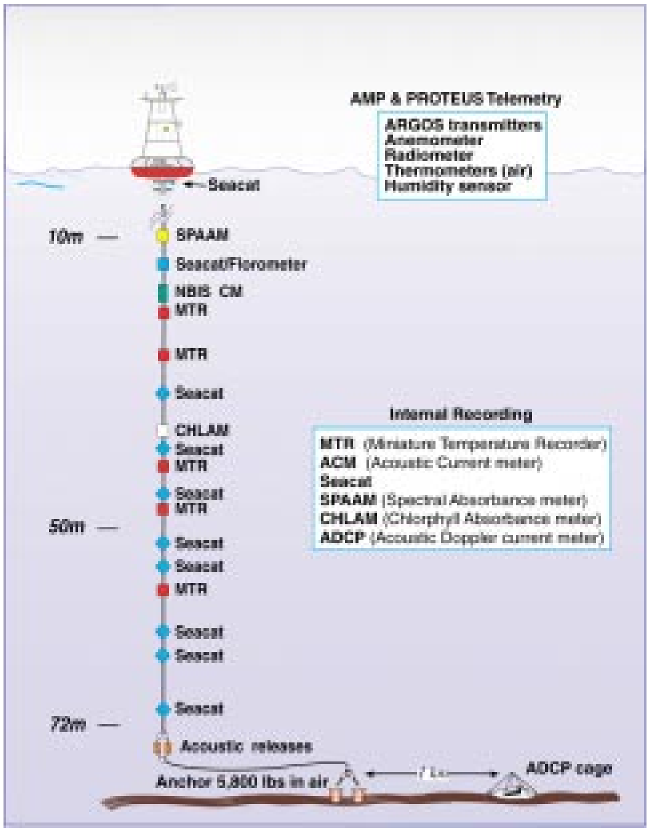

Fig. 2. The biophysical mooring deployed by SEBSCC at mooring site 2.

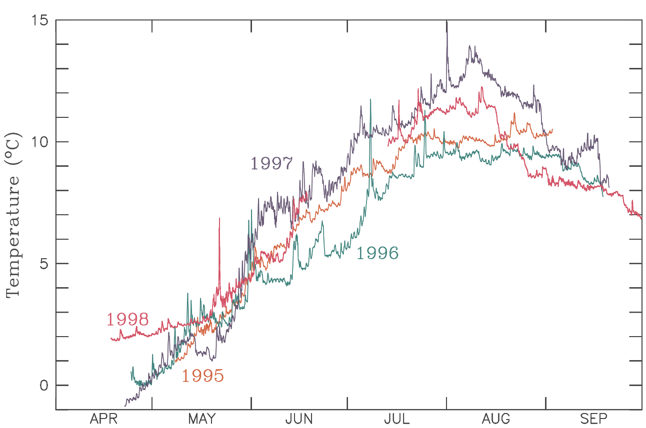

Fig. 3. Near-surface sea water temperatures (°C) measured at mooring site 2 from 1995 to 1998.

model will provide starting values of juvenile pollock abundance and estimates of prey suitability for the full spatial model.

Future refinements to circulation model forcing include specification of daily heat flux estimates and derivation of freshwater flux estimates from satellite-observed ice coverage. SEBSCC will couple the circulation, IBM, and spatial interactions models to allow numerical experiments examining the role of pollock in an ecosystem context and the role of the physical and biological environment in shaping trophic interactions involving pollock.

Retrospective analysis and synthesis

With this research technique, historical databases are used to investigate the biological and physical consequences of different biophysical domains and climate variability and to develop semi-quantitative conceptual models. SEBSCC has used hydroacoustic data to determine the distribution of juvenile pollock with respect to their predators and prey in frontal regions of the Pribilof Islands. Examination of spatial proximity between pollock and prey (plankton) patches suggests that when plankton biomass is low, fish tend to cluster around plankton patches. At high plankton densities, there is no consistent association. A small-scale spatial association was found between seabirds (murres and puffins) and their prey, large shoals of age-0 pollock. This association appears to depend on the size of the bird clusters, with larger clusters (>10-50 birds) always associated with food, and smaller clusters

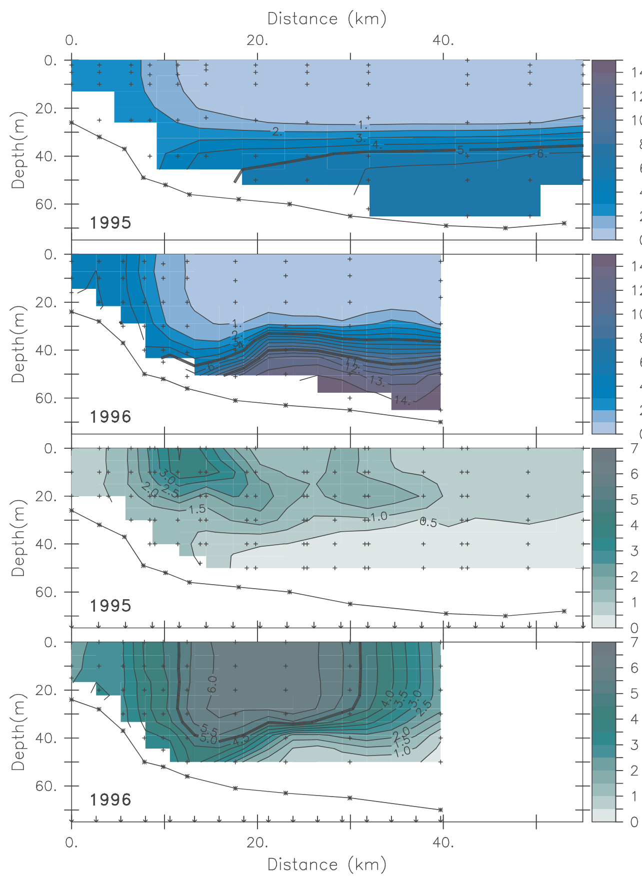

Fig. 4. Distribution of nitrogenous nutrients (μM of NO_2 and NO_3 combined) and chlorophyll-a (μg l^{-1}) along transect A.

not dependably so. In another study, historical trends in the number of foraging trips made by lactating northern fur seals did not correlate significantly with the abundance of their prey, pollock. An examination of biophysical correlates has led to the development of a conceptual model for pollock survival in the southeastern Bering Sea. Because pollock eggs and larvae over the southeastern Bering Sea shelf are found in the upper 20 m, the trajectory of their wind-driven transport during spring and early summer is important to their survival. Also, climate fluctuations and their role in the extent of seasonal sea ice and the resulting cold pool have been shown to affect the distribution of pollock on the shelf. Fishery surveys have shown that pollock tend to avoid the cold pool. An extensive cold pool forces juvenile pollock to share territory with cannibalistic adult pollock, and this is thought to reduce juvenile survival.

In the next research cycle, SEBSCC researchers will explore linkages between environmental influences, particularly air-sea interactions, and the early life stages of pollock during the regime shift of the 1970s. Also, the project will synthesize research results from SEBSCC and other studies using the guiding hypothesis that climate variability influences survival of young pollock by several interdependent biophysical processes. Features of the ecosystem that are candidate indices for the survival of juvenile pollock in the southeastern Bering Sea include:

- extent of sea 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;
- wind which influences the ecosystem through mixing and by advection as direct wind-driven flow;
- timing of storms that affect the intensity of stratification over the middle shelf and the depletion of nutrients in the cold pool;
- concentration of nutrients retained in the bottom layer of the middle shelf that are essential for prolonged production at the inner front;
- species composition of phytoplankton (e.g., rare coccolithophorid blooms);
- location, strength and stability of the Aleutian North Slope Current and Bering Slope Current system that influence advection of nutrients and pollock larvae onto the shelf; and
- increased presence of previously low abundance biota (e.g., jellyfish and coccolithophores).

Conclusions

SEBSCC has investigated with success the interannual variability in the southeastern Bering Sea from 1996 to 1998. SEBSCC's results coupled with information from the Inner Front Project allow some conclusions to be drawn about conditions over the slope and shelf. Extreme variation was observed in the climatology, physical oceanography and biology of the region during this period. Aspects of the environment in which variation of particular note occurred included: ice extent; storminess; insolation; sea surface temperature; thermal stratification; timing of the spring bloom; changes in phytoplankton community; blooms of the coccolithophore *Emiliania huxleyi*; abundance of euphausiids; timing of euphausiid mating on the inner shelf; and distribution, mortality, and shifts in reproductive success of seabirds. Contrasts between 1997 and 1998 are especially revealing. For more detailed information on some of the events mentioned below, see related articles on the status of the Bering Sea in *PICES Press 6*(1), *6*(2), *7*(1), and this edition.

In 1997, atmospheric conditions over the eastern Bering Sea during spring and summer included uncharacteristically light winds, warm temperatures and clear skies. These conditions resulted from forcing on multiple time scales: intra-seasonal, El Niño, Pacific Decadal Oscillation, and global climate warming. The atmosphere produced a strong effect on the physical oceanography, which 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. Despite the generally weak wind conditions, one strong wind mixing event did occur 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, and net phytoplankton production below the shallow mixed layer, reduced the reservoir of nutrients typically found throughout the summer in the lower layer, setting the stage for the switch from diatoms to a coccolithophore bloom. 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.

By contrast, 1998 was very different in forcing, yet it produced a similar coccolithophore bloom. From measurements in February 1998, the water over the shelf failed to mix to the bottom when sea ice was present. This lack of mixing allowed retention of some of the heat accumulated in the bottom layer from the previous year. Additionally, stronger than average atmospheric heat flux in late winter and early spring contributed to the warming of the shelf. The seasonal ice pack arrived and retreated early, spring temperatures in the southeastern Bering Sea were warmer than 1997, and there was much more storm activity. Storms that followed ice retreat 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. Circulation was abnormal as evidenced by detection 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 in 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 were in greater abundance, as opposed to 1997 when

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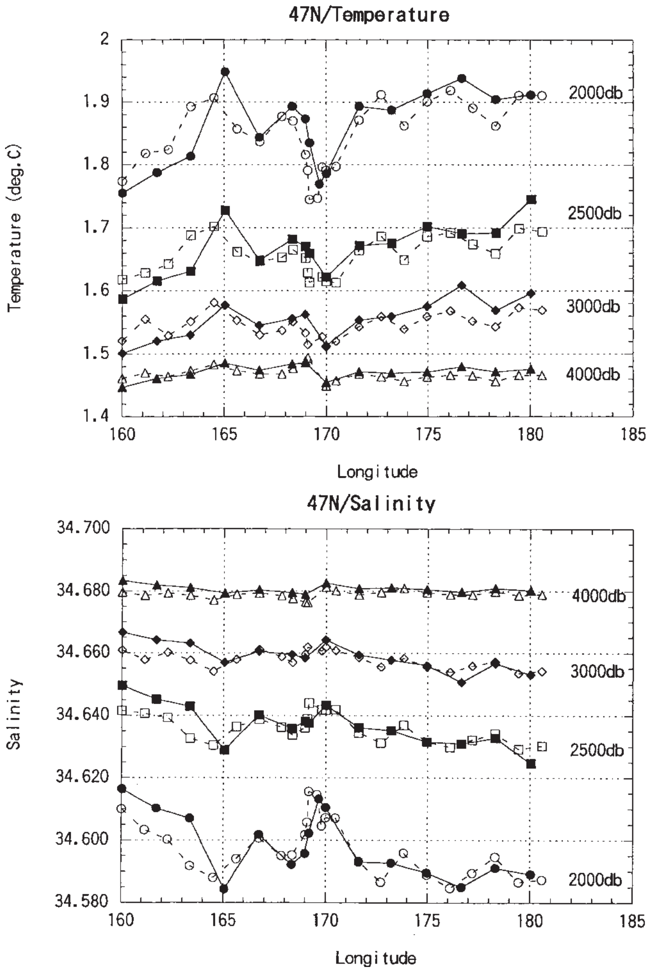

Fig. 6 Temperature (upper panel) and salinity (lower panel) along 47˚N at different depths. Solid lines with solid symbols are for R/V Shoyo's *observations in August 1997, and dashed lines with open symbols are for R/V* Thompson's *observations in August 1985.*

of 165˚E. Detailed analyses of the 1997 data are still being made. The whole P1 line will be revisited in June to September 1999, by the R/V *Kaiyo-Maru* of Japan Fisheries Agency and the R/V *Mirai* of JAMSTEC. Details of the changes will be learned soon by using observations of temperature, salinity, nutrients, and various tracers such as freons and ^{14}C.

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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 in 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 will not be known for several years until the young pollock mature into adult fish and are harvested.

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.