

NOAA ERL Special Report

Report on the FOCI International Workshop on Recent Conditions in the Bering Sea

Seattle, Washington, November 9–10, 1998

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Report on the FOCI International Workshop on Recent Conditions in the Bering Sea

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Executive Summary

Indications of unusual conditions in the Bering Sea during the summers of 1997 and 1998 included extensive die-offs of seabirds, rare coccolithophore blooms (a type of non-toxic, microscopic, marine plant), unanticipated low salmon runs, warm sea surface temperatures, and altered ocean currents and atmospheric conditions. These changes prompted NOAA Fisheries-Oceanography Coordinated Investigations (FOCI) scientists to convene an international workshop with more than 70 participants from a broad range of disciplines and geographic areas. This ecosystem is of particular concern because the eastern Bering Sea provides almost half of the fish and shellfish caught in the United States. The implications of these environmental changes on management of living marine resources was a prominent theme during the workshop on November 9–10, 1998, in Seattle, Washington.

At the workshop it was established that the springs and summers of 1997 and 1998 were in fact very unusual in a number of ways. The most direct human impact of these conditions was the unanticipated low returns of sockeye and chinook salmon. Although escapement goals of these fisheries were met, the low commercial and subsistence catches created considerable economic hardship. Atmospheric conditions over the eastern Bering Sea in spring and summer 1997 included light winds, warm temperatures, and clear skies. These caused a shallow mixed layer; nutrients above the pycnocline were quickly depleted, leading to the largest coccolithophore bloom ever seen in the area. The links between these events and the low salmon runs and other ecosystem anomalies such as the extensive seabird die-offs, remain unclear. Although spring of 1998 was much stormier than 1997, and stratification and the spring bloom were delayed, a coccolithophore bloom occurred again, as did low salmon runs.

It became apparent that the Bering Sea ecosystem is a complex and highly variable environment. Atmospheric forcing on several temporal scales (e.g., Pacific Decadal Oscillation, El Niño, Global Climate Warming) affects the physical oceanography of the area. In turn, marine forcing causes effects that cascade through the ecosystem, although we do not understand the exact mechanisms. The sum of all of these influences produces the conditions observed at any given time. Our understanding of this system is limited by lack of historical data.

Recommendations from the workshop included long-term monitoring of key physical and biological parameters at a number of locations in the eastern Bering Sea. Establishing the linkages between the physics and biology of the area will require effective interdisciplinary research in a variety of

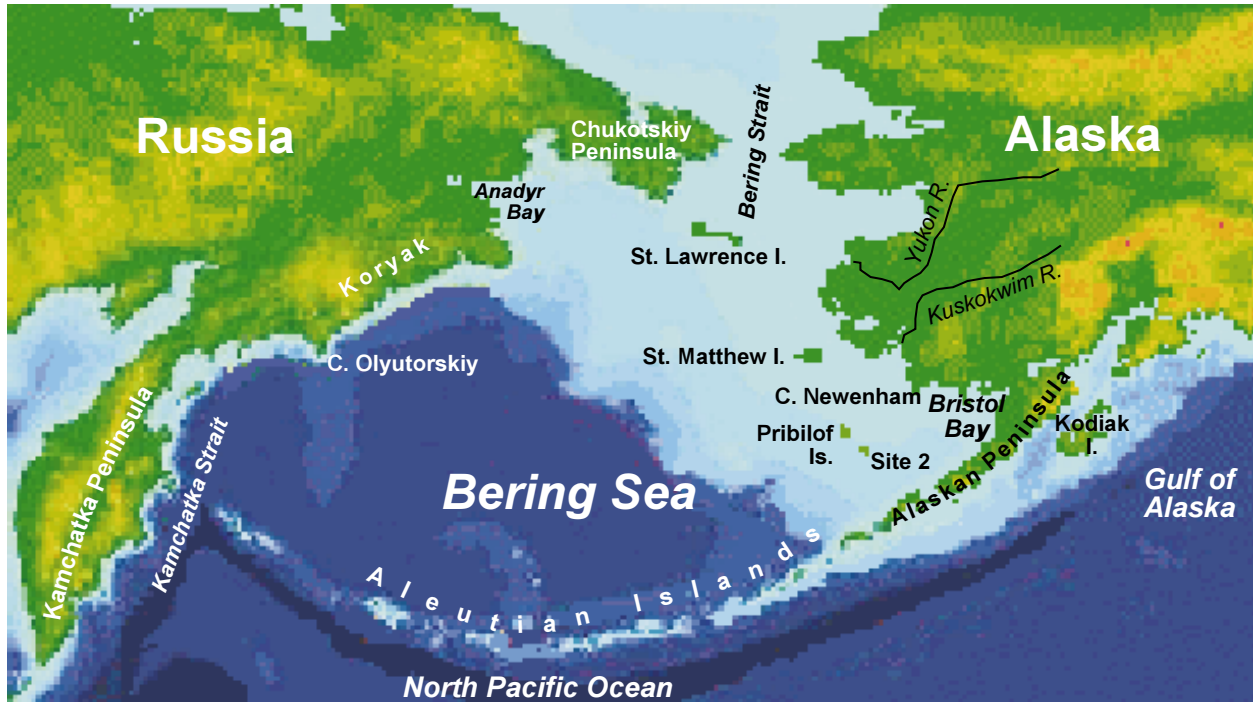


Figure 1: The Bering Sea.

modes: modeling, process-oriented, monitoring, and retrospective. Mechanistic understanding of the recruitment processes of a number of key species is needed. In some cases we have seen correlations between climatic trends and recruitment trends, but do not know the mechanisms responsible for the correlations. It is crucial to know the mechanisms because experience has taught us that correlations break down when the system is altered dramatically.

With our present level of understanding, we will not be able to predict events such as the unusual occurrences of 1997–1998. This will hamper effective management of living marine resources in this productive region.

Introduction

There were many indications of unusual conditions in the Bering Sea (Figure 1) during the summers of 1997 and 1998: extensive die-offs of seabirds, rare coccolithophore blooms, unanticipated low salmon runs, warm sea surface temperatures, and altered ocean currents and atmospheric conditions. In response to the occurrence of these anomalies, Fisheries-Oceanography Coordinated Investigations (FOCI) directors Drs. Arthur Kendall, Jr. (NOAA Alaska Fisheries Science Center [AFSC]) and Phyllis Stabeno (NOAA Pacific Marine Environmental Laboratory [PMEL]) convened a 2-day international workshop at the Sand Point NOAA facility, Seattle, Washington, on November 9 and 10, 1998.

The purpose of the workshop was to share information, integrate knowledge, suggest mechanisms, propose hypotheses, and outline future research



Figure 2: The eastern Bering Sea shelf is larger than California.

needs to address and understand changing conditions in the Bering Sea. This ecosystem is of particular concern because the eastern Bering Sea provides almost half of the fish and shellfish caught in the United States. Most of the catch comes from the continental shelf that borders Alaska's western coast, an area much larger than the state of California (Figure 2). Besides producing abundant fish and shellfish, this region also supports large numbers of resident and migratory seabirds and marine mammals. A prominent theme during the workshop was the implications of recent environmental changes on the management of these living marine resources.

Several thematic questions served as a focus for participants at the workshop, particularly the keynote speakers: In your field of expertise, how were conditions in the eastern Bering Sea during 1997 and 1998 different from usual? What mechanisms caused these anomalies? Is there evidence that unusual conditions will persist? What are the implications for the future of the ecosystem and its living marine resources?

The organizing committee for this workshop comprised Mr. Allen Macklin (PMEL): atmosphere and ocean physics; Dr. Jeffrey Napp (AFSC): lower trophic levels; Dr. Cynthia Tynan (Joint Institute for the Study of Atmosphere and Ocean [JISAO]): upper trophic levels, except fish; Dr. Richard Brodeur (AFSC): fish and fisheries.

Participants at the workshop included a member of the fishing indus-

try, representatives of fisheries and scientific management, various scientific disciplines, environmental organizations, and native Alaskan groups (Appendix A). From the agenda (Appendix B), the Monday session featured eight 20-minute keynote presentations detailing physical and biological observations made during the last 2 years and identifying linkages to other parts of the Bering Sea system and to global weather/oceanographic patterns. Following the keynote addresses, other attendees, including those from Canada, Japan, and Russia, had the opportunity to present findings. A reception featuring an address by a member of the fishing industry, Mr. Bart Eaton, Vice President of Trident Seafoods Corporation, was held Monday evening. Mr. Eaton stated that industry, as well as management, needs to be flexible in responding to the changing conditions of the resources in the Bering Sea. He also challenged scientists to find new ways for industry to assist with data collection.

On Tuesday morning, participants broke into two groups to discuss and answer the following questions:

- What are the physical-chemical-biological mechanisms causing the changes in the ecosystem observed in 1997 and 1998?
- What research is needed to better understand the origin and persistence of these changes?
- Given the large changes in the Bering Sea ecosystem, how do we manage marine resources in a fluctuating and highly variable environment?

Products from the workshop included a NOAA press release (12/30/98), this summary report with recommendations and endorsement of the draft Science Plan for the Bering Sea Ecosystem, and an Internet-based chat room to facilitate further discussion on the issues covered by the workshop.

Climate and Upper Ocean Physics

Contributors: P.J. Stabeno, N. Mantua, J.E. Overland, S.A. Macklin, and G. Weller

Atmosphere

The Bering Sea (Figure 1) is highly responsive to meteorological and climatological forcing. Local radiative warming and cooling, thermal advection, and wind mixing occur through processes associated with the progression of extra-tropical storms through the region. Storm tracks, frequencies, and intensities for the Bering Sea are affected by teleconnections to equatorial (e.g., El Niño-Southern Oscillation [ENSO]) and other climate forcing. Additionally, decadal-scale climate patterns, as demonstrated by various atmospheric indices (e.g., Pacific North American Index [PNA], Pacific Decadal Oscillation [PDO]) provide quasi-stable weather regimes. Finally, global warming may be a long-term climate trend affecting the Bering Sea region.

In 1997, the early summer (May–June–July [MJJ]) climate over the North Pacific Ocean and Bering Sea was uncharacteristically warm, windless, and cloud free. These benign weather conditions followed a relatively mild winter with anomalously low snow pack in much of western Alaska. A persistent pattern of anomalously high sea level pressure (SLP) (shown in the upper panel of Figure 3) over the Aleutian Islands and Bering Sea, with regions of anomalously low SLP to both the southwest and southeast of the Aleutians, contributed to these meteorological events. Such regions of high SLP anomalies are typically associated with anomalously fair weather, while low SLP cells are typically associated with anomalously stormy weather.

In contrast, meteorological conditions observed in the late spring–early summer of 1998 were characterized by frequent storms, strong winds, and relatively cloudy skies. The SLP anomaly patterns for MJJ 1998 (lower panel of Figure 3) were nearly opposite of those observed in the same calendar months of 1997. It is also interesting to note that in each of the past two summers, anomalous SLP and circulation patterns have been relatively strong (though very different) across the North Pacific. The anomalous weather during the past two spring and summer seasons has contributed to relatively large sea surface temperature (SST) anomalies as well. In MJJ 1997 extreme El Niño conditions were well underway in the tropics. The characteristic warming centered on the equator in the eastern and central equatorial Pacific was a dominating feature of Pacific SST anomalies (upper panel of Figure 4). Concurrent with equatorial warming, SSTs in the Northeast Pacific, Gulf of Alaska, and Bering Sea warmed at equally impressive rates. By MJJ 1998 the pattern of Pacific SST anomalies had changed dramatically (lower panel of Figure 4). The first signs of the transition from El Niño to La Niña conditions were evident as temperatures cooled sharply in the central equatorial Pacific. Likewise, North Pacific SSTs were markedly cooler in MJJ 1998 than they were in the same calendar months of 1997, with only small regions of slightly warmer than average temperatures in the eastern Bering Sea and coastal waters of the northeastern Pacific. Another

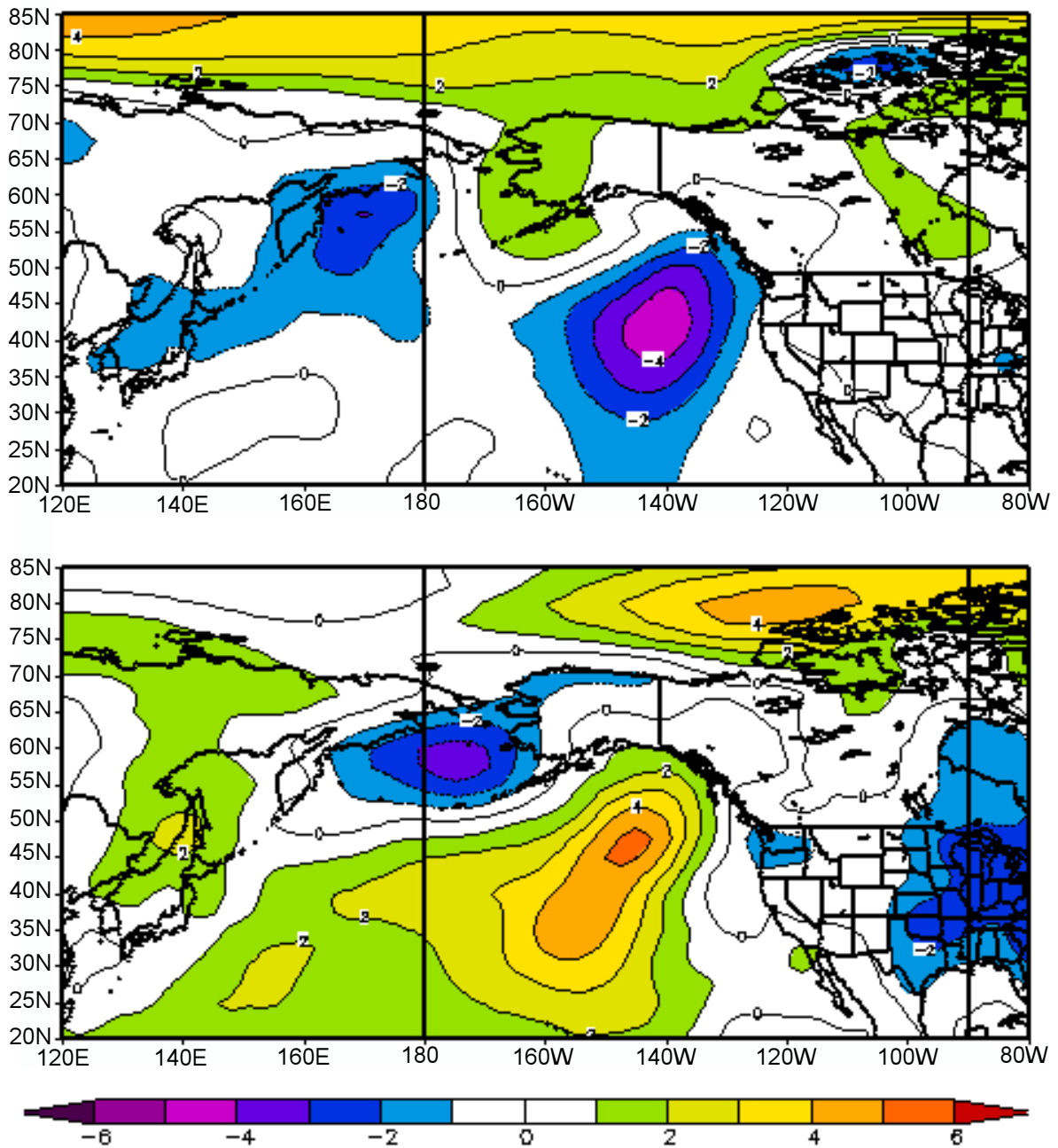


Figure 3: Sea level pressure anomalies, in millibars, during early summer 1997 (top) and 1998 (bottom).

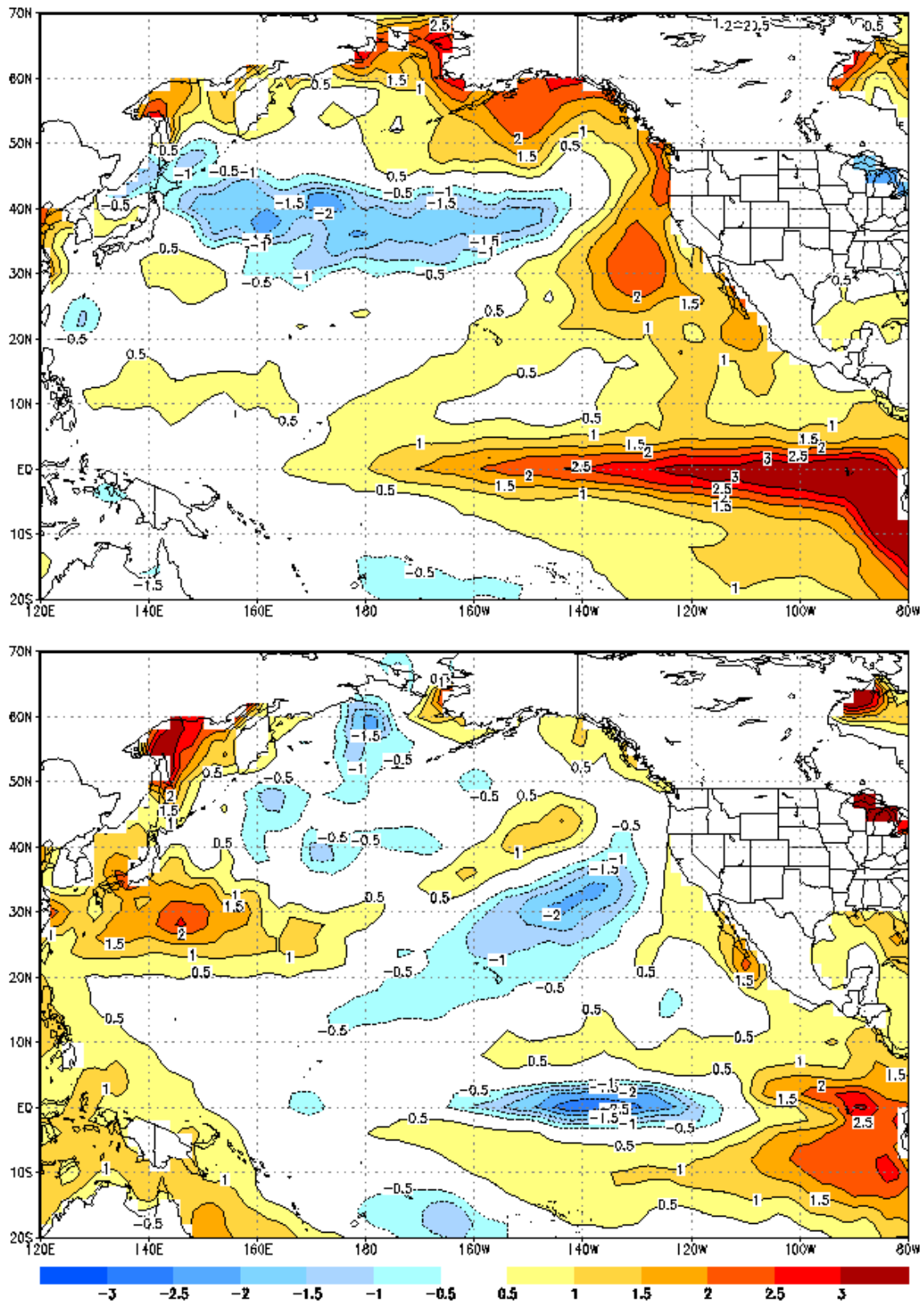


Figure 4: Pacific Ocean sea surface temperature anomalies, in degrees Celsius, during early summer 1997 (top) and 1998 (bottom).

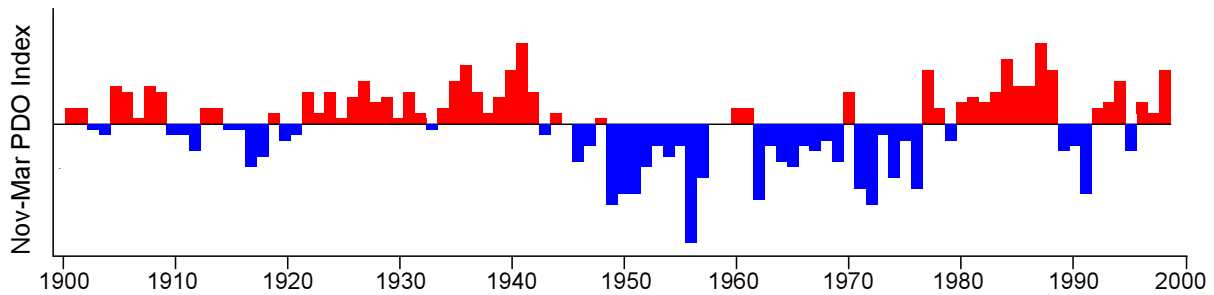


Figure 5: Time series of the Pacific Decadal Oscillation (PDO).

major change in upper ocean temperatures took place in the central and western North Pacific. Whereas SSTs were cooler than average in a wide band off the Asian coast in 1997, by MJJ 1998, SSTs had become 1 to a few degrees centigrade warmer than average in this same region.

What does the future hold? In the past few months, the trends toward anomalously cool SSTs in the NE Pacific and warm SSTs in the central North Pacific have continued. For most of the post-1977 period, PDO index values have been positive (Figure 5), indicating strong persistence of the “warm” (positive PDO) regime that appears to have favored such ecosystem features as high Alaska salmon production and low production of major crab and shrimp populations in the Bering Sea. From this index, there is no suggestion of a “regime shift” in the period since 1977. Given the strong likelihood that La Niña conditions will persist through the winter months of 1998–1999, it is also very likely that La Niña influences on North Pacific winter climate will favor the maintenance and possible amplification of negative PDO SST anomalies through (at least) the spring of 1999.

Beyond the spring of 1999, predicting North Pacific climate (both in the ocean and atmosphere) becomes much more problematic. The present day understanding of the PDO phenomenon is quite poor, especially when compared with the state of knowledge regarding ENSO. The synergy between observations, theory and modeling provided for rapid advances in understanding and predicting ENSO. Compared with our ability to monitor, understand, and predict ENSO variability, PDO science lags many years behind. Using the ENSO experience of the past two decades as a model, it seems of utmost importance to develop a comprehensive climate monitoring system for the North Pacific Ocean. The TOGA/TAO array in the equatorial Pacific has provided much valuable information to ENSO studies and predictive capability.

Long-term climate trends must also be taken into account in assessing impacts in addition to interdecadal and ENSO-related climate variability. From paleoclimatic evidence, it appears that present conditions are highly anomalous, and it seems very likely that we have already begun to see the greenhouse effect in the Arctic. Air temperature data show cooling in winter

in the western Bering Sea, while the eastern Bering Sea and Alaska show warming.

Ocean

The Bering Sea forms a buffer between the North Pacific and Arctic Oceans (Schumacher and Stabeno, 1998; Stabeno *et al.*, in press). It is also a region of extremes. Physically, it is divided into almost equal parts: a basin (maximum depth ~ 4000 m) and a broad (>600 km), shallow shelf on the eastern side (Figure 1). A defining characteristic of the Bering Sea is the presence of seasonal sea ice. From June through October the Bering is largely ice-free. Typically in November, sea ice begins forming in the polynyas and is advected southward by arctic winds. In extreme years most of the broad, eastern shelf is covered in ice; in weak years the sea ice does not extend south of 60°N . The melting ice freshens the water and lowers its temperature, contributing markedly to water properties over the shelf. Ice extent has changed markedly over the last 30 years. The ice extent was typically extensive from the early 1970s until 1976, reaching a peak in 1976, when it covered much of the eastern shelf for 2 months. After the regime shift in 1976, the extent and duration of ice over the shelf diminished. The most extensive ice coverage in recent years occurred in 1995, when ice covered much of the shelf for about a month. The ice extent in 1997 was also above average, arriving over the southern part of the shelf in March and retreating in early April. In contrast, the ice in 1998 arrived during January and retreated during February.

During winter, the water over the southeast shelf is usually well mixed to a depth of ~ 100 m, while during summer, three distinctive hydrographic regimes are evident (Figure 6), as described by the Processes and Resources of the Bering Sea Shelf (PROBES) project. The “coastal domain” (water depth <50 m) is well mixed or weakly stratified from a combination of tidal and wind mixing. The “middle shelf domain” (50 m $<$ water depth < 100 m) is two layered. An upper, wind-mixed layer is separated from a tidally mixed bottom layer by a strong pycnocline. The “outer shelf domain” is characterized by a wind-mixed surface layer and tidally mixed bottom layer separated by a region of finestructure with gradually increasing density. The coastal domain and the middle shelf domain are separated by the “inner front,” and the middle and outer shelf domains are separated by the “middle transition zone.” Support from the National Science Foundation’s Office of Polar Programs Inner Front project permitted a careful investigation of the dynamics and structure of the inner front during 1997 and 1998. During 1997, weak winds resulted in stratification extending the middle shelf domain coastward to a depth of ~ 30 m. In contrast, the strong winds of 1998 resulted in the coastal domain extending out to ~ 70 m until June, at which time the winds weakened and the more typical hydrographic regimes appeared.

A series of FOCI biophysical moorings have been deployed at a location near the center of the middle shelf domain (Site 2; Figure 1) for the last 4 years. These moorings were maintained with support from two NOAA Coastal Ocean Program (COP) regional projects: Bering Sea FOCI and Southeast Bering Sea Carrying Capacity (SEBSCC). This is the only location

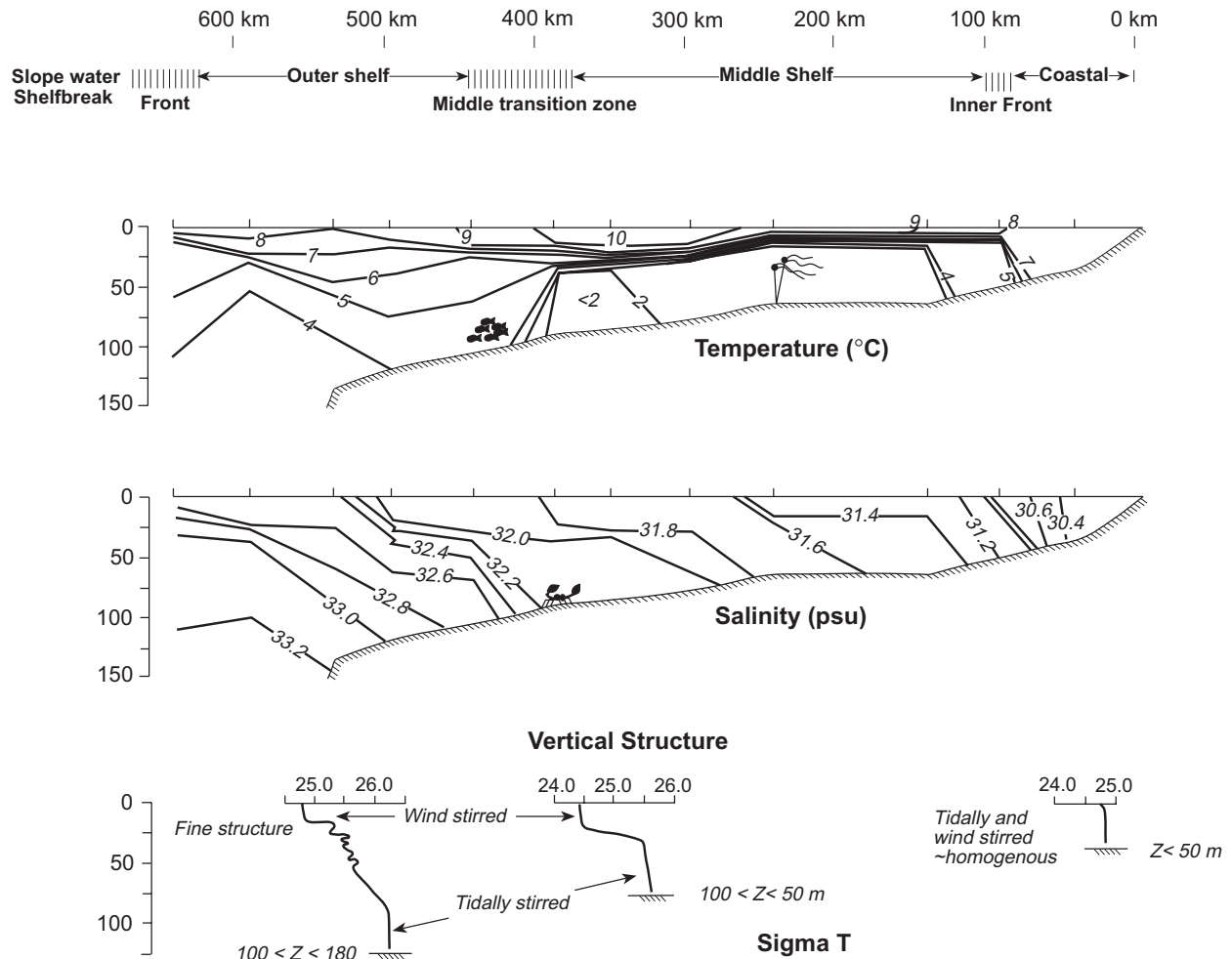


Figure 6: Hydrographic regimes of the southeastern Bering Sea shelf.

where long-term water column measurements have been made in the Bering Sea. In this discussion we will focus on this location, since it is ideal for examining direct warming of the water column in the spring and summer. The weak winds and cloud-free days of 1997 resulted in a shallow mixed layer with warm SST. The temperature (measured at 1–2 m below the surface; upper panel of Figure 7) shows a steady warming during each year, beginning in April with maximum temperatures occurring in late July or early August. The x's are historical temperature observations near this location dating back to 1962. The warmest temperatures ever recorded over the middle shelf occurred in 1997.

The wind forcing was at the opposite extreme in 1998 compared to 1997. In 1998, strong winds resulted in a well-mixed water column well into May. The water column did not stratify until June. In July the winds weakened, resulting in a shallow mixed layer (15 m) and warm near surface temperatures. The warm upper water temperatures in 1998 were thus a result of warmer than usual temperatures in April (the initial condition of the heating cycle) and shallow mixed layer in mid July. The warm temperatures

in April resulted from the atmospheric conditions in conjunction with ice cover. When ice was present over the southeastern shelf at site 2, the winds were weak, thus the cooling resulting from ice melt was limited to the upper 30 m. A reservoir of relatively warm water remained at depth. The storms of March and April stirred the water column, and the near-surface ocean temperature increased due to the mixing of warmer, deeper water. This is seen in the average vertical temperature at site 2 (lower panel of Figure 7). The average temperature (and thus heat content) of the water column in 1998 was higher than in 1997, and was similar to that observed in the warm years of 1978, 1979, and 1981. The implications of this for the coming year are not known, but it is interesting to note that in late November 1998, the Bering Sea is ice free and SSTs are above 6°C over part of the southeastern Bering Sea shelf. Thus the system enters the 1998/1999 winter season with higher than average heat content. To remove the heat and bring the system back toward its state in the early part of this decade will require above-average sea ice production and extended duration of arctic winds.

In addition to extremes that have occurred on the southeastern shelf, changes of transport through Bering Strait have occurred. Over the last several years, there appears to have been both a reduction in the total northward transport from the Bering Sea into the Arctic and in its salinity. Both changes could have repercussions on the Arctic Ocean, since Bering Strait is the only connection between the Pacific Ocean and the Arctic. The decrease in transport could be a result of changing wind directions or a decrease in the difference in the height between the Pacific and Arctic Ocean. The decrease in salinity resulted either from a decrease in the amount of sea ice (and hence a decrease in the amount of brine rejection) or a decrease in the salinity of the water on the shelf. There is some indication that over the last few years there has been a decrease in salinity over the southeastern shelf, but the variability of this signal is large.

Conclusions

Because observations have been limited over the years, it is difficult to determine whether recent extremes in the physical parameters of the Bering Sea are within the bounds of historical variability, the result of a decadal-scale regime shift, or due to global climate change. Much of our insight has been a result of the ~5-yr time series obtained from a single location over the Bering Sea shelf.

- Anomalously weak winds occurred over the Bering Sea in 1997, and unusually strong storms occurred during 1998.
- Above normal SSTs were observed during the summer of 1997 and 1998, with the warmest temperatures occurring in 1997, but the highest water column heat content during 1998.

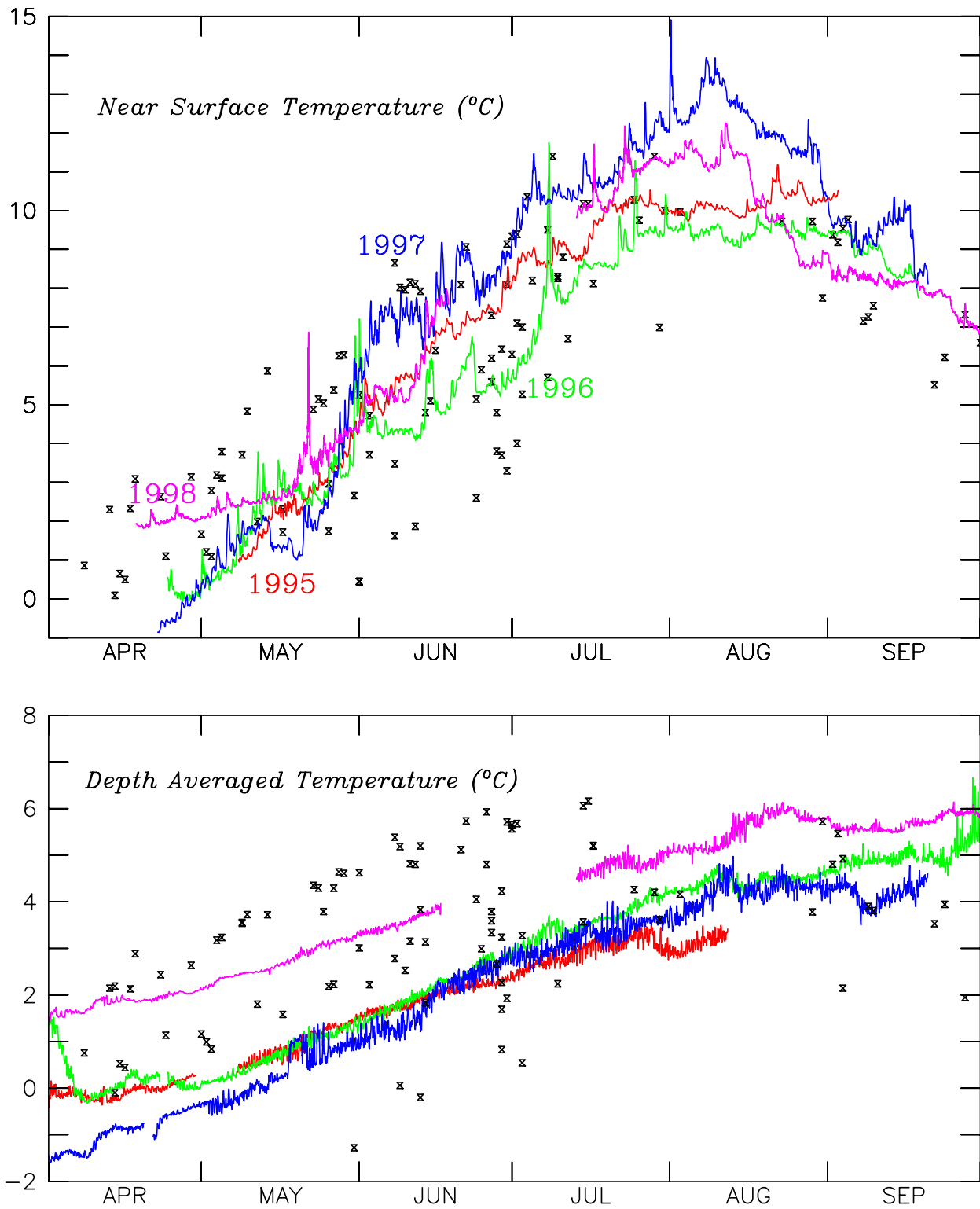


Figure 7: Near sea surface temperature (top) and depth averaged temperature (bottom) at mooring site 2.

Nutrients and Lower Trophic Level Response

Contributors: J.M. Napp, K.O. Coyle, T.E. Whitledge, D.E. Varela, M.V. Flint, N. Shiga, D.M. Schell, and S.M. Henrichs

Lower Trophic Level Studies

The eastern Bering Sea shelf is very large, larger than the state of California (Figure 2). To put past and present sampling into perspective, imagine a scientist using a butterfly net or empty soda bottle to sample water and animals from the state of California. All sampling is conducted at night or during periods of thick fog so that the scientist cannot see what is being sampled. In addition, the research “platform” is a tricycle, so the area sampled is relatively small. This example is analogous to scientists sampling the Bering Sea shelf from slow moving ships where the target organisms lie below the surface of the ocean and cannot be seen. Thus the community must recognize that many of our generalizations about plankton refer to specific areas and that a comprehensive examination of pattern and processes is lacking.

Nutrient Cycling and Phytoplankton Growth

During the late 1970s and early 1980s, PROBES provided a sketch of nutrient cycling, variability, and phytoplankton growth for the eastern Bering Sea (Whitledge *et al.*, 1986; Whitledge and Walsh, 1986). The annual nutrient cycle was carefully delineated over 4–5 years with regard to vertical structure along a single cross-shelf transect. Major events in the nutrient cycle are nutrient replenishment through advection (lateral) or wind-driven mixing (vertical), and utilization by phytoplankton. Careful observation of the spring phytoplankton bloom showed that the bloom started offshore and slowly progressed inshore, across the shelf. The peak in chlorophyll concentration started in mid-April offshore and by early June was observed over the coastal domain. Changes in the stability of the water column (Sigma-t) best explained this pattern. The annual cycle of nitrate (NO_3) follows phytoplankton dynamics. Nitrate was replenished over the shelf in late winter (March) by advection from the basin. Rapid decline of nitrate in the mixed layer was observed during the spring phytoplankton bloom. During the summer, phytoplankton growth was driven by regenerated nitrogen (ammonia [NH_4]) except when episodic wind mixing events replenished nitrate in surface waters. These events were shown to introduce $15\text{--}20 \mu\text{M m}^{-2}$ of new nitrate into the euphotic zone. This is probably the key to maintaining a summer population of diatoms.

During 1997 and 1998, different patterns of nutrient utilization with depth were observed. In 1997, stratification began early due to fewer storms than usual; 1998 was exactly the opposite, spring was extremely windy and the onset of stratification was delayed. Normally, uptake of nitrate by phytoplankton shows relatively large values at the surface, decreasing with depth. In 1997, however, the data clearly indicate that nitrate uptake increased

with depth and was maximal below the pycnocline. This resulted in depletion of nitrate (and silicate) from the water below the pycnocline (a nutrient reservoir). Thus more of the nitrate pool was available to phytoplankton production. In 1998 high nitrate uptake values at the surface were observed, but the wind mixing was so strong that light limitation prevented a large spring bloom (accumulation of plant biomass). The result was a slow, rather than rapid, decrease in nutrient concentration beginning in April through May and part of June. The consequence was the same as 1997: more of the nitrate pool was available to the phytoplankton. Preliminary calculations indicate that primary productivity calculated from nitrate disappearance during PROBES was 10–30% smaller than calculated for 1997 and 1998. The end result on system carrying capacity, trophic transfer, or the amount of the production retained in the water column is not known.

Comparisons of Recent Spring Blooms

The spring phytoplankton bloom is the dominant production event over the southeastern Bering Sea shelf. At FOCI's middle shelf domain biophysical mooring, continuous measurements of chlorophyll absorbance have been recorded (February–September) from 1995 to the present as part of a collaboration between NOAA and academic scientists (Oregon State University, 1995–96; Dalhousie University, 1997–98). These measurements provide insight into how interannual variability in weather affects the annual production cycle over the shelf (J. Cullen, personal communication). Briefly, 1995 was a heavy ice year, the bloom began early under the ice, and a large amount of chlorophyll accumulated in the surface waters before presumably settling to the bottom (Stabeno *et al.*, 1998). Surface nutrients were exhausted at the end of the bloom. In 1997 we observed a similar pattern, except the ice retreated rapidly and the maximum amount of chlorophyll was lower than in 1995. Sea ice did not extend onto the southeast shelf in 1996. Water column stratification and the spring phytoplankton bloom began much later in 1996 than either 1995 or 1997. In 1998 accumulation of chlorophyll also occurred very late (late May, early June). We interpret this to mean that phytoplankton growth and zooplankton grazing over the middle shelf domain were balanced for most of the spring, potentially resulting in less flux of phytoplankton to the benthic community.

Coccolithophore Bloom

During summer 1997, waters over large portions of the eastern Bering Sea shelf were turned chalky aquamarine by a bloom of coccolithophores (*Emiliania huxleyi*; Vance *et al.*, 1998; Sukhanova and Flint, 1998). This was the first confirmed report of a large-scale coccolithophore bloom in the eastern Bering Sea, although reflectance algorithms used with NASA's Coastal Zone Color Scanner (an ocean color remote sensing tool) suggest that smaller blooms may have occurred between 1978 and 1984 (Brown and Yoder, 1994). Phytoplankton species counts around the Pribilof Islands in the early 1990s

revealed low, non-bloom concentrations of *E. huxleyi* (M. Flint, personal communication).

Coccolithophores are small, flagellated photosynthetic cells (approx. 10 μm diameter) covered with calcareous plates that scatter light producing the aquamarine color. High reflectance and underwater light extinction are associated with coccolithophore blooms. By September of 1997, the bloom covered $2.1 \times 10^5 \text{ km}^2$ of the eastern Bering Sea shelf (Vance *et al.*, 1998). Coccolithophore cell densities around the Pribilof Islands in October were approximately $2.1 \times 10^6 \text{ liter}^{-1}$ and coccolithophores constituted 99.2% of the phytoplankton biomass (M. Flint, personal communication). Diatoms, not coccolithophores, dominate the normal fall community. The coccolithophore bloom returned in the early spring of 1998 and remained through the summer.

What caused the bloom and allowed coccolithophores to replace diatoms as the dominant summer and fall species? Nutrient uptake experiments conducted in 1997 indicated that diatom uptake responded much more to nitrate concentration than did uptake by communities dominated by coccolithophores (J. Goering, personal communication). The f-ratio (nitrate uptake/uptake of all dissolved inorganic nitrogen species) was 0.2–0.3 for the diatoms and about 0.1 for coccolithophores. During 1997 and 1998 ammonium concentrations were high on the shelf, nitrate and silicate were low, and the water temperature was anomalously warm. These conditions probably allowed the coccolithophores to outcompete the diatoms in 1997. We do not yet know what happened in 1998; ambient nutrient concentrations and nutrient uptake experiments are being analyzed.

Species of phytoplankton respond differently to the availability of nutrients and trace metals in the water column. In order to understand why extensive coccolithophore blooms have developed in the Bering Sea, it is important to identify which factors promote their growth. The coccolithophore *E. huxleyi*, isolated from Ocean Station “P” (OSP) in the subarctic Northeast Pacific Ocean, appears to grow equally well on different nitrogen sources, either ammonia or nitrate, in laboratory cultures (D. Varela, personal communication). However, when ammonium is added to nitrate-grown cells, the uptake rate of nitrate is dramatically inhibited and growth continues. Such behavior indicates that this coccolithophore may be growing on ammonium due to the constant availability of this nitrogen source from zooplankton excretion and remineralization. *E. huxleyi* can also grow in either high or low iron concentrations and adapts to low iron concentrations by reducing cell size. Therefore, there is no difference in sinking rates between cells in iron-replete or iron-stressed conditions because under lower iron concentrations the cells are smaller and sink more slowly. In contrast, the diatom *Actinocyclus* sp., also isolated from OSP, increases its sinking rate when under iron stress. In the laboratory, ammonia-grown diatom cells showed signs of energetic advantage over nitrate-grown cells when under iron stress. Thus, under the iron-limited scenario of the subarctic Northeast Pacific, diatoms may be growing on ammonium.

These laboratory results are in good agreement with field observations in the subarctic Northeast Pacific. Studies along a transect extending from the

continental slope off the southwestern corner of Vancouver Island (British Columbia, Canada) to OSP showed that most of the primary production is based on ammonia, and is due to small cells ($<5 \mu\text{m}$) well adapted to the low ambient iron levels. It is possible that nitrogen and iron limitation on the southeastern Bering Sea shelf would favor the growth of *E. huxleyi* over diatom species. At present there is no data on iron availability or limitation on the Bering Sea shelf.

Zooplankton

Zooplankton is an important link in the food web between primary production and apex predators (fish, seabirds, and marine mammals). There are many different types and forms of zooplankton. The key, when looking for system anomalies, is to examine types or species that might be sensitive, either through physiology (e.g., temperature) or life history, to the observed system anomalies. Many zooplankton taxa that are prey to fish, birds, and mammals (e.g., large copepods and euphausiids) have annual life cycles. Thus biological or environmental influences experienced by a population during one season may be observed both during that season, during subsequent seasons, and during the following year. For example, high predation on female zooplankters or severe conditions during spring may mean less reproduction and fewer juvenile zooplankton available during the summer as prey. Poor feeding conditions during the summer may impact those invertebrates that rely on lipid stores to make it through the long winter, thus decreasing the brood stock for the following year.

Each of the three distinct hydrographic regimes has its own zooplankton fauna (Cooney and Coyle, 1982; Vidal and Smith, 1986; Smith, 1991). The outer shelf domain is dominated by large oceanic copepods (*Neocalanus* spp.) and one euphausiid (*Thysanoessa inermis*). The zooplankton biomass of the middle shelf domain is dominated by a moderately sized copepod (*Calanus marshallae*) and another euphausiid (*T. raschii*), and the coastal domain is dominated by small copepods (*Acartia* spp. and *Oithona* spp.). Secondary production among the three regimes is highest in the outer shelf domain and lowest over the coastal domain. Primary production and grazing are usually balanced in the outer shelf domain, but are largely unequal in the middle shelf and coastal domains. Often the phytoplankton blooms sink to the bottom in the latter two domains, providing energy for a rich benthic community. Between each domain lies a front or transition zone. Secondary production at the shelf edge, another transition zone, is thought to be greater than that of the three domains due to persistent upwelling of nutrients to the euphotic zone (Springer *et al.*, 1996). Production at the inner front is currently being studied by the Inner Front project (G. Hunt, personal communication). Nearly continuous supply of nutrients plus active concentration of prey at these fronts appear to make the areas loci for apex predators such as seabirds and marine mammals.

Long-term (decadal and longer period) fluctuations in zooplankton biomass of the eastern Bering Sea have been noted. Zooplankton biomass was highest in the 1960s (800–900 mg m^{-3}) and decreased in the 1970s to 1980s

and again in the early 1990s to 200–300 mg m⁻³ (Sugimoto and Tadokoro, 1997). The same authors studied the relationship between long-term anomalies in summer zooplankton biomass and winter winds, summer phytoplankton, and Asian pink salmon catches. They concluded that predation pressure by salmon controls the year-to-year variability in summer zooplankton biomass, but bottom up control (winds to phytoplankton to zooplankton) was more influential than top down control on longer (decadal) time scales. A long-term increase in jellyfish biomass has also been noted for the eastern Bering Sea. Since 1990, jellyfish (*Scyphomedusae*) biomass in standard trawl surveys has tripled (Brodeur *et al.*, submitted). Jellyfish are carnivorous and increased biomass may mean increased predation on juvenile fish and increased competition with juvenile fish for zooplankton prey.

Interannual Variability in Zooplankton Abundance

First through Bering Sea FOCI and presently through SEBSCC, FOCI has been collecting samples for zooplankton biomass and community composition in larval and juvenile pollock habitat on the southeastern Bering Sea shelf. Collections are made in the winter, spring, and fall. Recent springtime abundance and stage composition of *C. marshallae* over the middle shelf domain show a pattern that may reflect interannual variability in water temperature and timing of the spring bloom (Figure 8). Note that *C. marshallae* nauplii are consumed by larval fish, and copepodites are important dietary components of age-0 fish. The highest abundances and earliest spawning (deduced from the early appearance of young developmental stages) was during 1995, the year with the coldest water temperatures and the earliest spring bloom (J. Napp and C. Baier, personal communication). Springtime abundances in 1996 and 1997 were comparable, but the appearance of young developmental stages was latest in the warm year (1996) when the spring bloom was delayed. Analysis of FOCI 1998 samples (also a warm, late bloom year) is ongoing. Japanese researchers report that summer zooplankton biomass in 1998 was neither anomalously high nor low (N. Shiga, personal communication). The extremes in recent years are not directly comparable to a published comparison of zooplankton from PROBES: 1981 was warm and calm, while 1980 was cool, but stormy (Smith and Vidal, 1986).

Following cohorts of *C. marshallae* to the end of summer, FOCI has found that if the year starts with relatively more females and copepodites, then relatively more are found in that year class at the end (J. Napp, personal communication). When the years were ranked by abundance of *C. marshallae* sampled around the Pribilof Islands during September, the rank order of the years was 1995, 1997, and 1996 (highest to lowest). The exception to this was the 1996 year class. Both 1996 and 1997 began the years with approximately the same abundance of *C. marshallae*, although reproduction began much later in 1996. In 1996, however, relatively high abundances of age-0 pollock were found over the southeastern shelf (Wilson and Brodeur, 1998), so low abundances of *C. marshallae* may also have been due to predation by age-0 pollock (N. Shiga, personal communication). Thus at this

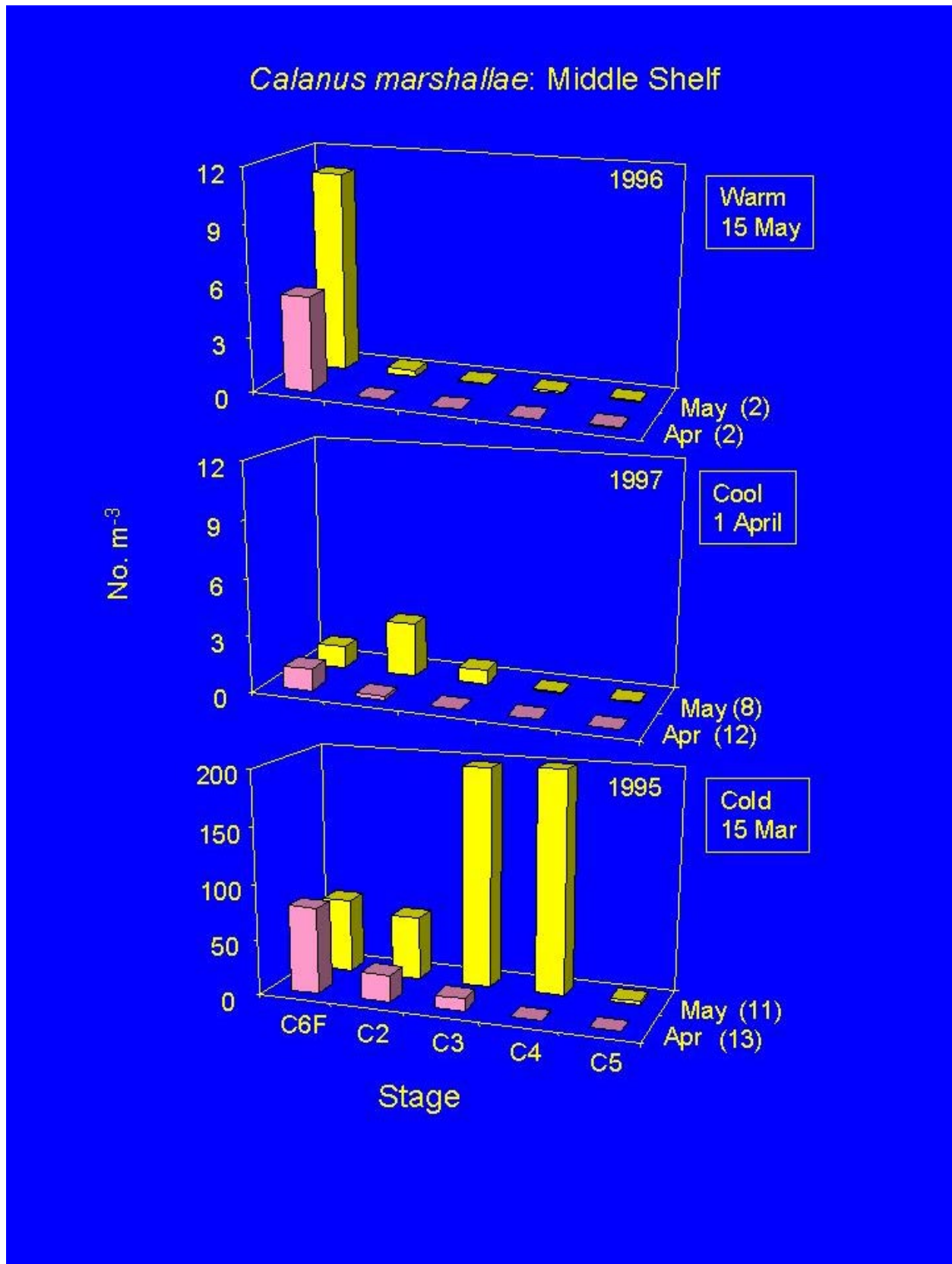


Figure 8: Spring abundance and stage composition of *C. marshallae* over the middle shelf domain.

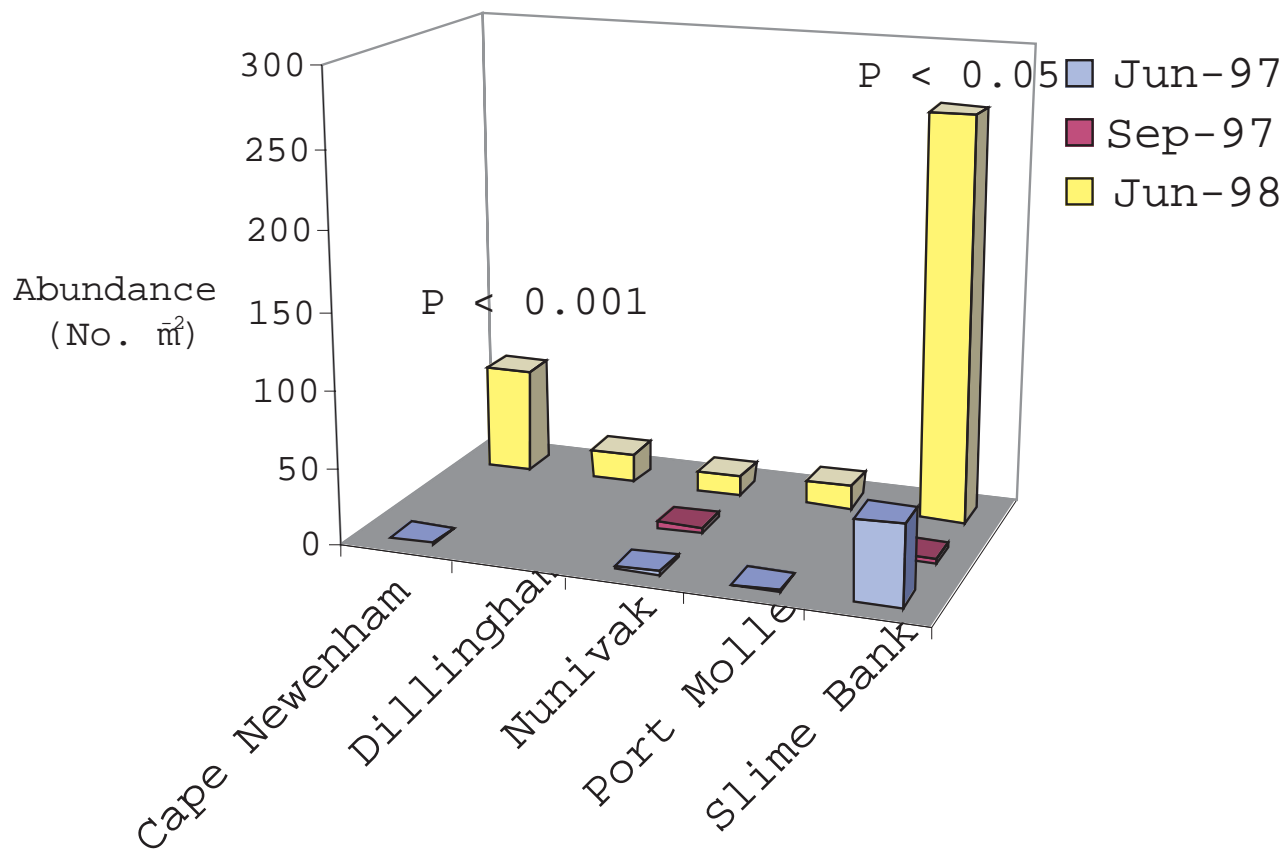


Figure 9: Densities of adult euphausiids in and around the inner front region.

point in our analyses, we do not see either a sharp increase or decrease in abundance of one of the dominant zooplankton species of the middle shelf domain, the one most affected by the anomalously high water temperatures and coccolithophore bloom.

The most notable distinction between 1997 and other years in zooplankton abundance and distribution were the significantly lower densities of adult euphausiids in and around the inner front region (Inner Front project, K. Coyle, personal communication; Figure 9). Short-tailed shearwaters, a migratory sea bird that relies on surface swarms of euphausiids for food, suffered high mortalities during the summer of 1997 (G. Hunt, personal communication). Those shearwaters surviving to the end of summer had broadened their diet to include squid and juvenile fish. Interestingly, adult plus juvenile euphausiid abundance measured around the Pribilofs (including the inner front) in 1997 by SEBSCC (Napp, unpublished; Brodeur, unpublished) was higher than that measured in either 1995 or 1996. Investigators from the Inner Front project and SEBSCC are currently comparing their zooplankton data sets for anomalies in biomass, distribution, and community composition that may be attributed to recent environmental anomalies.

Conclusions

- Interdecadal variations in zooplankton biomass in the southeastern Bering Sea are controlled by physics and phytoplankton concentration.
- Sea ice and wind mixing affect the timing and magnitude of the spring phytoplankton bloom.
- The abundance of selected zooplankton taxa appeared to respond to variations in the timing and magnitude of the spring bloom.
- Interannual differences in the distribution of zooplankton (as prey for apex predators) are important.
- In the fall of 1997, euphausiid prey for diving seabirds existed around the Pribilof Islands, but not in the coastal domain or inner front adjacent to the mainland. This resulted in massive mortalities for short-tailed shearwaters.
- In the summer of 1998, age-0 pollock and oceanic zooplankton were found at the inner front, suggesting large-scale, shoreward transport of animals from at least the outer shelf domain.

Living Marine Resources (Groundfish, Salmon, and Crabs)

Contributors: R.D. Brodeur, G.H. Kruse, P.A. Livingston, G. Walters, J. Ianelli, G.L. Swartzman, M. Stepanenko, and T. Wyllie-Echeverria

The most visible sign of unusual fisheries events in the Bering Sea was the surprisingly low return of sockeye salmon to Bristol Bay in 1997 and 1998. This is the world's largest wild sockeye fishery. Actual catch was 49% and 47% of that forecast in 1997 and 1998, respectively. Although salmon escapement goals were met for this stock, there were substantial economic hardships incurred and subsistence harvest needs were not met. The State of Alaska has taken emergency measures to ease the hardships. In addition, salmon runs to the Yukon River, Kuskokwim River, and several other river systems, were well below predicted levels (Kruse, 1998). The Yukon River chum run was weak in 1998, and the commercial catch (about 4% of the mean catch since 1974) was restricted to bycatch in the early chinook salmon openings. Anecdotal evidence suggests the fish that did return to the Yukon River were smaller than normal, which is somewhat unusual for a small run of salmon. Larger than average fish are usually associated with low returns. The decrease in abundance and size was noted across several groups, which suggests that the causative factor was likely to be of marine origin (Kruse, 1998). Despite these shortfalls in the Bering Sea, returns of pink salmon in the Gulf of Alaska were generally strong. The statewide catch of pink salmon (104 million) was the fifth highest ever. Taken together, the total commercial catch of Alaska salmon was 150 million fish, which was the eighth highest ever recorded. The mixed returns may indicate that some regional factor associated with the Bering Sea, such as increased temperatures, more predation, or reduced food availability, may be affecting these fish. Marine factors affecting survival are generally thought to be the most important during early marine life, whereas later, marine factors can have significant impacts on growth. However, at this point in time, we are unable to disentangle the contributions of early marine conditions from the unusual ocean conditions of the last 2 years on reduced salmon runs in 1997 and 1998. So, we cannot yet tell if the impacts of the last 2 years will carry over into future return years, even if ocean conditions return to normal in 1999.

Groundfish stocks in the eastern Bering Sea are surveyed each summer by the AFSC, and stock assessments are provided annually to the management agencies. From results of the most recent (1998) assessments, there do not appear to be any anomalies observed in the distribution patterns of the dominant fish species that could be associated with the unusual ocean conditions in 1997 and 1998. Long-term trends in biomass and recruitment for some species have been assessed. For example, yellowfin sole, rock sole, flathead sole, and arrowtooth flounder show a recent increase in adult biomass due mainly to good year classes in the late 1980s and early 1990s. In contrast, other species, such as Pacific cod, Alaska plaice, and Greenland turbot have had few or no recent strong year classes and have been declining in biomass

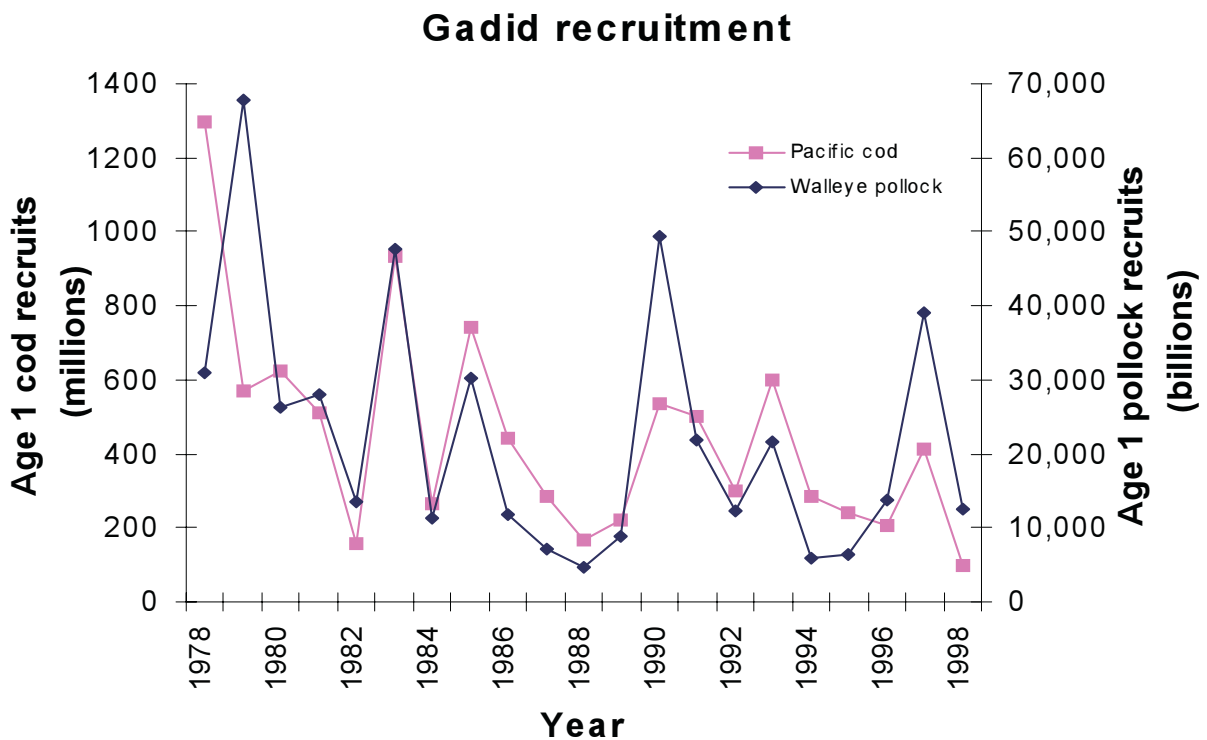
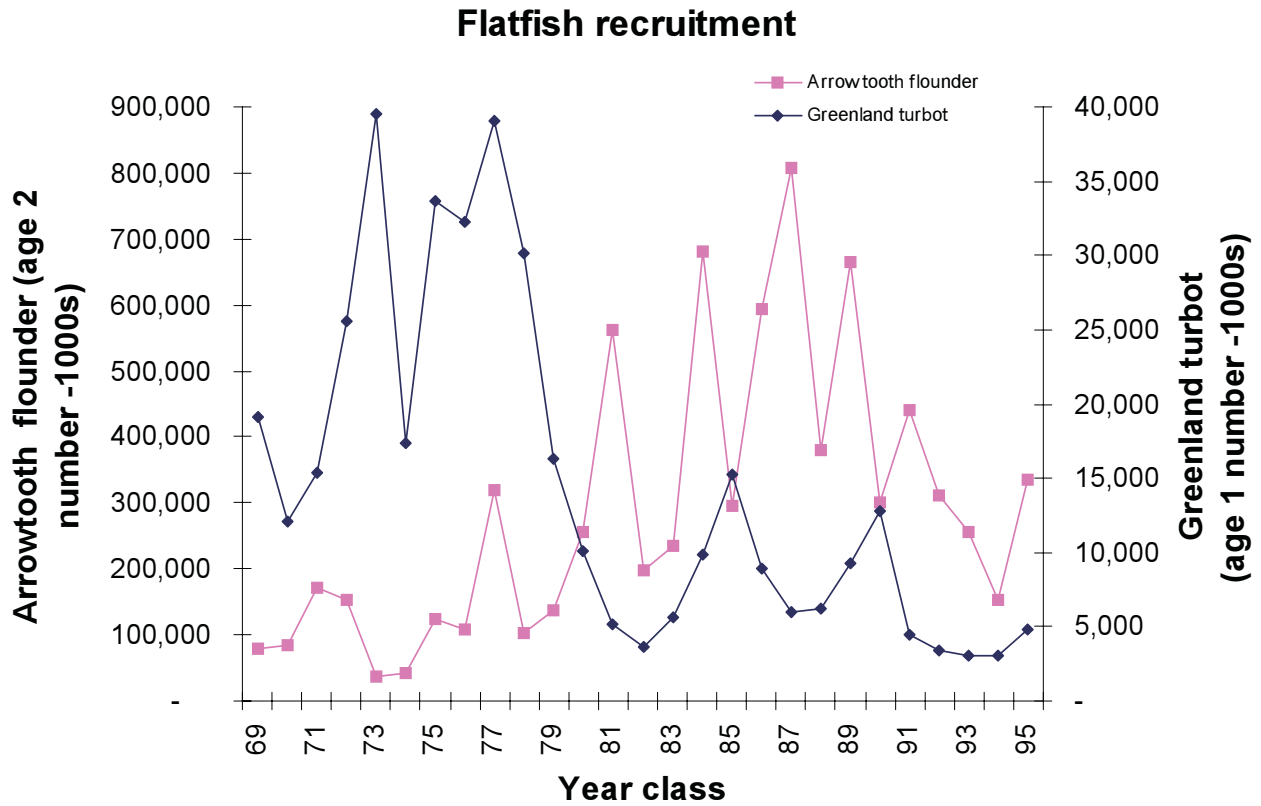


Figure 10: Recruitment trends of some Bering Sea groundfish (arrowtooth flounder, Greenland turbot, walleye pollock, and Pacific cod) from the 1998 groundfish stock assessments.

throughout the 1990s. Walleye pollock show strong pulses of recruitment and the biomass has fluctuated over the last 35 years. The 1996 year class appears to show the most recent above-average recruitment. This strong year class was detected in age-0 surveys of walleye pollock conducted in mid-summer in cooperative surveys with Japanese scientists (Wilson and Brodeur, 1998). An interesting observation is that the recruitment of some flatfish species vary out of phase with each other (e.g., Greenland turbot and arrowtooth flounder, yellowfin sole and rock sole), whereas recruitment of gadid stocks (walleye pollock and Pacific cod) vary roughly in phase (Figure 10). The various groundfish have been classified into trophic guilds based on their dietary preferences. The inshore benthic infauna consumer guild (soles and plaice) have shown a general increase since 1979, while the fish and crab consumer guild (sculpins, cod, skates, and halibut) have been declining since 1988.

Trends in forage fish (herring, capelin, eulachon, juvenile cod, and juvenile walleye pollock) abundance also have been documented by AFSC summer surveys. Most of these forage fishes have declined over the last 5 years. Although the catch rates in 1997 were not particularly low, 1998 had fairly low catches for all species but pollock. Both surface and bottom temperatures measured during the survey showed that 1994 and 1995 were relatively cold years, while 1996 through 1998 were warmer than average. The cold pool was very extensive in 1995, extending well into Bristol Bay.

Fishery data collected by NMFS observers are very extensive. Length, weight, and age are determined for a large number of pollock each year. These data are routinely used in stock assessments for Bering Sea pollock and can be used to evaluate how average growth in weight changes over time and age. Results indicate that the annual average weights-at-age from the fishery are highly variable (Figure 11). Based on analyses of growth by cohort from 1996–1997 (e.g., average weight increase of 4 year-old pollock in 1996 compared to 5 year-olds in 1997), pollock growth during this year was considerably lower than average. This may reflect changes in the distribution of the fishery, differences in optimum temperature regimes for pollock growth, or possibly shifts in prey availability and consumption. Analyses are ongoing to see if lower than average growth persisted through 1998.

In addition to interannual variability, there is a consistent pattern of weight increase with age. The average annual growth decreases from ages 4 to 6, and then appears to increase again with older ages. Preliminary examinations of bottom-trawl survey estimates of average weights-at-age suggest a similar pattern is also present from those samples. This would indicate that the pattern is not due to the target age-classes of the fishery.

In recent years, Russian research surveys have been conducted throughout the Bering Sea to assess the abundance and distribution of various age classes of pollock and other fish. During the warm summer and autumn of 1996, a significant part of the mature eastern Bering Sea pollock population, including the very abundant 1992 year class, inhabited the area to the northwest of the Pribilof Islands. In the warm spring of 1997, most of the western Bering Sea pollock spawned on the northwestern Russian shelf. Juvenile pollock were extremely abundant (5.3×10^9 fish) in Anadyr Bay and extended southward along the Koryak coast to Cape Olyutorskiy in the

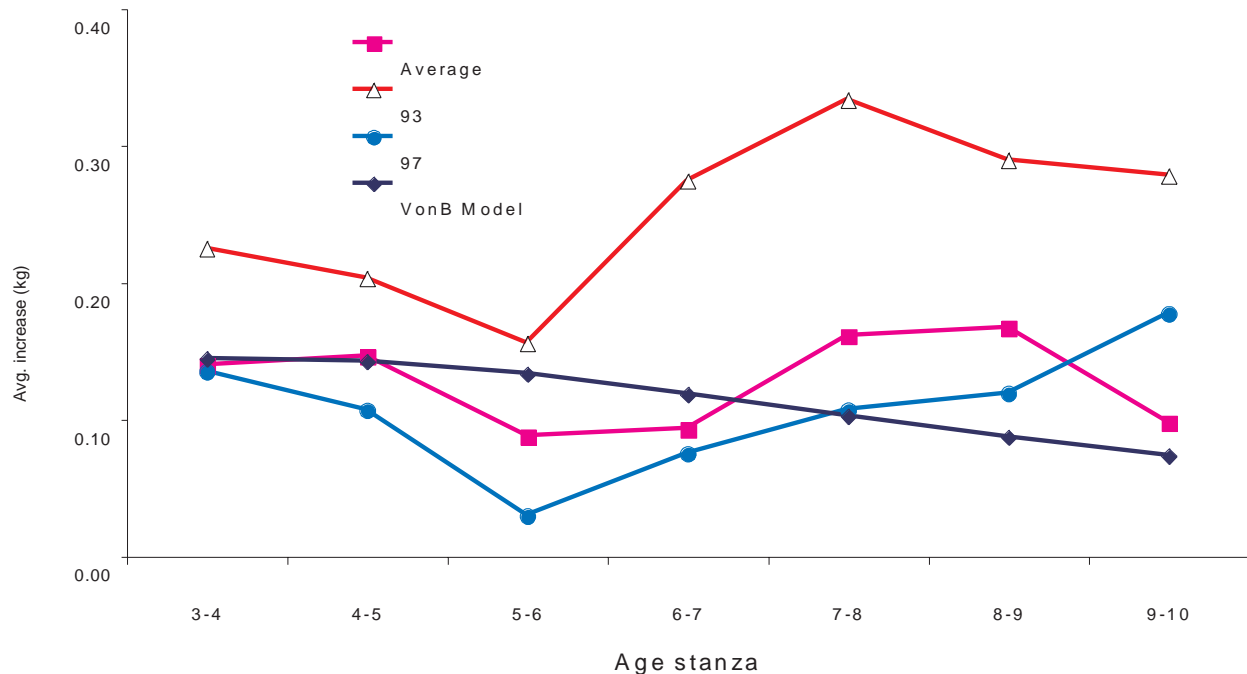


Figure 11: Eastern Bering Sea pollock average individual growth by year as observed from the fishery. The VonB model represents expected growth increases from a von Bertalanffy curve.

latter half of the year. During the following winter, however, most of the 1997 year class juveniles were distributed under the ice for about 5 months. In 1998 (a cold year), the abundance of this year class was not very high, possibly reflecting the negative influence of this long habitation under the ice.

Acoustic backscatter images at 38 and 120 kHz were compared for the years 1994–1997 from a survey in mid-September of each year in the Pribilof Island region of the Bering Sea. Both fish and plankton can be seen in the images. The plankton patches were indicated by increased backscatter at 120 kHz over 38 kHz, as predicted from geometric modeling of backscatter from zooplankters. The comparison showed the 4 years to be quite different. In particular, 1997 appeared to have extremely low fish biomass, and fish shoals were small and distributed throughout the water column. Plankton biomass appeared to be large. In contrast, 1996 had extremely high fish biomass throughout the water column. Plankton biomass, although possibly obscured by the high fish density, appeared to be low. The cold years of 1994 and 1995 had intermediate fish biomass, with fish shoals restricted to above or close to the thermocline throughout the day. Plankton biomass during the daytime was found near the bottom. The low catches of juvenile pollock around the Pribilof Islands in 1997 were also substantiated by low catches in trawl collections during the summer and fall in this area (Wilson and Brodeur, 1998; Brodeur, unpublished data). Given other reports (Coyle, Stepanenko) that large numbers of young-of-the-year pollock were found in other areas of the Bering Sea, it is possible that currents were not favorable

that year for juvenile pollock to be transported to the Pribilof Islands, which generally have been an important pollock nursery area.

Distributions of age-1 walleye pollock were compared from data collected during NMFS bottom trawl surveys during 1996, 1997, and 1998. Age-1 pollock from hauls with more than 100 kg ha⁻¹ were distributed differently among these 3 years. During 1996 high concentrations of age-1 fish were landed from 25 stations, no catch occurred at 179 stations, and the largest catch was 11,537 kg. During 1997, age-1 fish were landed from 21 stations, no catch at 189 stations, and the largest catch was 1,214 kg. During 1998, high numbers of age-1 pollock were landed at only 8 stations, no catch at 84 stations, and the largest catch was 656 kg. It appears that age-1 pollock have decreased in abundance over this time period and in 1998 were more spread out with smaller catches over a larger area. This would be predicted from a smaller cold pool area. Food of age-1 pollock varied from 1996 to 1997, with euphausiids being more important in 1996 and mysid shrimp in 1997. *Metridia* sp. were taken as prey in 1996 but not in 1997, while crab megalopae were taken only in 1997. Mysids may indicate feeding closer to a benthic food source in 1997, although pelagic copepods were the dominant prey item in both years.

The major crab fisheries in the Bering Sea have also shown dramatic fluctuations over the last several decades. Factors operating during early life history are thought to be most important to determining year class success. So, the potential effects of ocean conditions during 1997 and 1998 will not be realized until those year classes are recruited to the surveyed stocks 6–8 years in the future. It is too early to predict what the effects of the recent anomalous conditions might have been on crab recruitment, but studies of stock and environmental trends (Zheng and Kruse, in press) and detailed analyses of recruitment processes for select individual stocks (Rosenkranz *et al.*, 1998) shed some light. Long-term trends tend to indicate that some Alaskan crab stocks show poorer recruitment during periods of strong Aleutian lows and warmer sea surface temperatures. This is opposite to the relationship shown for salmon, herring, and most groundfish (Zheng and Kruse, in press). This pattern appears to hold for Bristol Bay red king crabs. Nearly all Bering Sea king crabs and Tanner crabs showed consistent downward trends in year class strength during the early 1970s. However, Bering Sea crab trends since the late 1970s have been very stock specific. Bristol Bay red king crab recruitment continued to steadily decline until a relatively strong 1990 year class (consistent with a strong Aleutian low) and appears to have since returned to low recruitment levels. Tanner and snow crab year classes in the early 1980s were strong, but recruitment of Tanner crabs have since declined sharply while snow crab year classes continued strong through the 1980s. Two blue king crab stocks experienced increasing recruitment from brood years in the late 1970s to early 1980s and were relatively stable through the late 1980s. From these disparate recent stock trends, it is apparent that no one climate or ocean factor accounts for all the variability in crab recruitment. In the case of eastern Bering Sea Tanner crabs, it is suggested that higher productivity and favorable wind conditions promoting transport to offshore nursery areas are both important variables in recruitment success

(Rosenkranz *et al.*, 1998). Mild temperatures experienced by maturing adult Tanner crabs also seem to favor stronger year classes through an effect on reproduction.

In summary, it is too early to fully assess the impacts of the anomalous oceanographic conditions during 1997 and 1998 on groundfish recruitment and other aspects of their life history. Future research needs include:

- additional sampling for pre-recruit stages and forage fishes to track their abundance trends and map their habitat
- more information on maturity, age, and weight-at-age
- identification of climate conditions linked to recruitment and growth of groundfish.

Seabirds and Marine Mammals

Contributors: C.T. Tynan, G.L. Hunt, Jr., E.H. Sinclair, and C. Pungowiyi

Seabirds and Marine Mammals

The extreme weather events of 1997 and 1998 influenced the survival and trophic ecology of marine birds in the southeastern Bering Sea by changing the distribution, abundance, and availability of prey resources. For the period 1997 and 1998, three sources of information on the ecology of marine birds in the southeastern Bering Sea were available. Vern Byrd of the U.S. Fish and Wildlife Service, Alaska National Maritime Refuge monitoring program provided information on the reproductive ecology of seabirds nesting on the Pribilof Islands. SEBSCC and Inner Front projects supported study of prolonged production, trophic transfer, and processes at Bering Sea inner fronts. Finally, Vivian Mendenhall of the U.S. Fish and Wildlife Service, Office of Migratory Bird Management, assembled reports of dead seabirds observed floating or washed ashore along the coasts of Alaska and the Russian far east.

On the Pribilof Islands, the U.S. Fish and Wildlife Service obtained data on the reproductive success of nesting kittiwakes (*Rissa tridactyla*, and *R. brevirostris*) and murre (*Uria lomvia*, and *U. aalge*). Kittiwakes are surface-foraging members of the gull family and are limited to obtaining food from the upper 25 cm of the water column. Murres, in contrast, are pursuit-diving members of the auk family, and can dive to almost 200 m. Thus murres are able to reach prey at almost any depth on the southeastern Bering Sea shelf. In general on the Pribilof Islands, the two species of murres show a higher average rate of reproductive success and less interannual variation in reproductive success than the two species of kittiwakes. This is presumably because kittiwakes are sensitive to the vertical distribution of prey in the water column, whereas the deep diving murres can access the entire water column and can seek alternative prey at depth if preferred prey are not available.

During both 1997 and 1998, the Inner Front project obtained data on the distribution, abundance, mortality, and trophic ecology of short-tailed shearwaters (*Puffinus tenuirostris*) over the middle shelf and coastal domains of the southeastern Bering Sea, particularly in the vicinity of the inner front. Short-tailed shearwaters nest in southeastern Australia and migrate to the Bering Sea, where they forage from May until October. In the Northern Hemisphere, these birds take a wide variety of prey. However, in the shelf regions of the southeastern Bering Sea and Bristol Bay, previous studies have shown that between 80% and 100% of their diet has consisted of adult euphausiids which they capture in the upper water column to depths of as much as 35 m.

At the Pribilof Islands in both 1997 and 1998, kittiwake reproductive success was at or above the long-term mean, whereas murre reproductive success was considerably below the mean. This unexpected finding may have been influenced by the presence of the dense coccolithophore bloom

near the islands. These minute plant organisms are covered with calcium carbonate plates and reflect light. Objects close to the surface are highlighted by this bright background. Bioluminescent organisms at the surface, such as lantern fish eaten by kittiwakes, would be conspicuous at night if their flashes were reflected by the coccolithophores beneath them. Thus the surface foraging of the kittiwakes may have been enhanced by the presence of the coccolithophore bloom. In contrast, within and below the coccolithophore bloom, ambient light levels were greatly reduced and scattering of light was enhanced. These effects of the bloom would decrease the ability of murrelets to see and pursue their prey deep in the water. Thus, the poor reproductive performance of murrelets nesting on the Pribilof Islands in 1997 and 1998 may have been caused by a decreased ability of murrelets to obtain prey at depth.

In June 1997, short-tailed shearwaters were fat and were feeding on small near-surface patches of adult euphausiids, despite a general lack of widespread, epibenthic layers of euphausiids in the coastal domain. In late August and early September 1997, shearwaters were, for the most part, emaciated and often seemed lethargic in their reactions to the approach of the research vessel. Their diets included juvenile euphausiids, as well as squid and fish, an unexpectedly broad diet that suggested that the more usually taken adult euphausiids were unavailable in the shallow waters of the coastal domain.

During summer and fall 1997, unusually high numbers of seabirds, most notably short-tailed shearwaters, died in the eastern Bering Sea and in parts of the Gulf of Alaska. Starting in early August, unusually high numbers of shearwaters washed ashore along the south side of the Alaska Peninsula, along the shores of the southeastern Bering Sea and Bristol Bay, on at least some of the Aleutian Islands, and in the northern Bering Sea at St. Lawrence Island, and along portions of the Chukotskiy Peninsula of Russia. Within our study areas, about 163 carcasses were seen floating, and on the basis of the number seen per unit area searched, we estimate that about 191,500 dead shearwaters were afloat during our surveys, about 10% of all shearwaters present in our study areas. Starvation was the apparent cause of mortality. Many of the shearwaters that we collected were underweight, lacked lipid reserves, and had lost a significant proportion of their flight muscle mass.

The die-off of shearwaters in 1997 was more widespread than the coccolithophore bloom. Thus, although the dense bloom may have impaired shearwater foraging, overall some other factor(s) must have influenced the availability of prey. In 1997, an early spring bloom followed by a secondary utilization of nutrients below the pycnocline resulted in a shutdown of new production by the end of May. This lasted until storms in fall resulted in vertical mixing of nutrients. Consequently, there would have been little new production to support grazing by euphausiids. Additionally, the exceptionally warm surface temperatures found throughout the eastern North Pacific Ocean in 1997 may have influenced the distribution of euphausiids. Elsewhere, euphausiids have been found to cease surface swarming when water temperatures were excessive. Either of the above factors may have resulted in the euphausiids' retreat to the deeper waters of the middle shelf domain,

where they were present in dense, epibenthic layers and unavailable to shearwaters.

In June 1998, shearwaters were of lighter mass than they were in June of 1997, apparently because euphausiids, present in extensive, near-bottom layers in the coastal domain, were late in beginning their mating swarms, and few near-surface patches were available to the shearwaters. By August and September 1998, shearwaters exhibited lower body masses than they did in 1997. Nevertheless, there was no evidence of unusual levels of mortality in 1998.

How lightweight birds in 1998 avoided starvation is not clear. In the eastern Bering Sea in 1998, sea surface temperatures were cooler and spring production was more prolonged than in 1997. This prolonged production supported euphausiids and the prey of juvenile fish through at least June. In fall 1998, shearwaters collected in the southeastern Bering Sea had more fish and squid in their stomachs than was true in past seasons. In particular, in the middle shelf domain and near the inner front southwest of Cape Newenham, shearwaters fed on age-0 walleye pollock that were present in great abundance. It is possible that this switch to juvenile fish provided sufficient nutrition for shearwaters to avoid starvation, but insufficient energy density to permit weight gain.

An additional factor that may be influencing the availability of euphausiids to shearwaters is the possibility of competition with baleen whales. In the late 1980s near the Pribilof Islands, and in both 1997 and 1998 in the coastal and middle shelf domains, whales were observed foraging in the vicinity of feeding shearwaters. In most of these instances, the shearwaters were taking euphausiids, although in one case their prey was juvenile pollock. C. Tynan (personal communication) has also reported aggregations of large whales foraging in the vicinity of feeding shearwaters. It is likely that since the 1970s there has been an increase in the number of whales on the Bering Sea shelf. The impact of their foraging on the availability of food to other predators in this ecosystem has yet to be evaluated.

Cetaceans

Coastal and oceanic warming associated with El Niño can produce redistributions of many marine species, including cetaceans. During the summer of 1997, Pacific white-sided dolphins, a temperate species generally confined to the Gulf of Alaska and regions further south, were observed in outer Bristol Bay. Although there have been sightings of this species in other years in the Bering Sea, their presence in 1997 may have been linked to the warm water anomalies. Redistributions of large whales may also have occurred.

Large baleen whales migrate long distances to forage in the productive waters of polar and subpolar regions during summer. As such, they are important indicators and integrators of the regional productivity and biomass of their principal zooplankton prey (euphausiids and copepods). In the Bering Sea, migratory baleen whales have historically tracked the “green belt” areas of high productivity along the shelf-edge region (Springer *et al.*, 1996). However, during a July 1997 survey of cetaceans, high densities of

large baleen whales were observed on the middle shelf domain, in and near the coccolithophore bloom (Tynan, 1998a). The middle shelf domain now appears to support the highest baleen whale biomass in the southeastern Bering Sea (Tynan, 1998b). It is important to determine whether these redistributions reflect the anomalous warming of 1997 and 1998, or whether the movements of whales signal a much longer-term change in the regional productivity and trophic structure of the Bering Sea ecosystem.

Northern fur seals, which breed during the summer on the Pribilof Islands, were infected with a fungus, possibly *Trycophytum*, that caused the loss of guard hair. Although the condition has been observed in pinniped populations in more southern regions, such as along the coast of California, this is the first recorded outbreak of the infection in Bering Sea seals. The outbreak appears to be associated with the warm water anomalies of 1997 and 1998. Up to 15% of the females appear to have been infected. The longer-term effects on the thermoregulatory ability of the seals is unknown.

Conclusions of Working Groups

Compilers: T. Wyllie-Echeverria, E.D. Cokelet, and S.A. Macklin

During the second day of the workshop, participants divided into two discussion groups (Appendix C) to explore three questions that served as themes for the workshop. Drs. James Schumacher and Tina Wyllie-Echeverria served as facilitator and rapporteur, respectively, of one group, while Drs. Alan Springer and Edward Cokelet filled similar roles for the other group. The collective responses of the two groups are presented here on a question-by-question basis.

1. What are the physical, chemical, and biological mechanisms and interactions causing the changes in the ecosystem observed in 1997 and 1998?

Climate change in the Bering Sea is difficult to detect because of large year-to-year variability that can mask a more gradual trend. Nevertheless, it seems that the meteorological conditions of the winter and spring-summer seasons have changed between the 1980s and the late 1990s in Alaska. For 1977 through 1989, there was a major warming with a strong Aleutian low directing warm air from the Pacific toward Alaska. In the 1990s, the low shifted westward, and high pressure set up over the state circulating cold arctic air southward over the Bering Sea. Winters have become slightly colder with more ice, and summers warmer with clearer skies. There has also been a trend toward more frequent El Niños in the 1990s.

Three conditions reinforced one another in 1997 and 1998: (1) a persistent positive North Pacific weather pattern anomaly with associated high pressure over Alaska and low over Siberia, (2) an El Niño-reinforced high pressure over Alaska beginning in April 1997—somewhat earlier than usual for El Niño onset, and (3) strong blocking ridges in May of both years. However, there were also differences between the two years. The spring of 1997 was benign with lower than average winds and sunnier days; whereas spring 1998 had stormy weather.

The physical oceanic conditions on the southeastern Bering Sea continental shelf differed between 1997 and 1998. Southward ice extent was above average in 1997 and below average in 1998. Both summers had warmer-than-average temperatures, but for different reasons. In 1997 the water was warmed by increased sunshine and lack of wind mixing. In the intervening winter, cold water at the freezing point did not mix to the bottom as normally occurs, and spring 1998 commenced with warmer water that heated to higher temperatures in late summer. Perhaps this carry-over of warm bottom water from the previous summer is a mechanism for climate change. Spring 1997 winds forced only weak onshelf flow, as verified by satellite-tracked drifting buoys that showed sluggish onshore and alongshore flow. Spring 1998 brought strong onshelf flow in the upper few meters of the water column and strong northward flow of 15–20 cm s⁻¹ along the 50-m isobath where 3–5 cm s⁻¹ is the norm. This pushed warm water northward, reinforcing the warm start from the preceding winter. Kamchatka Strait

is the primary outlet from the Bering Sea. The transport (5.5 Sv) of the Kamchatka Current was only about half its usual magnitude in 1998.

In the summers of 1997 and 1998, the nutrient reservoir below the pycnocline on the southeastern Bering Sea shelf was depleted, contrary to the PROBES observations of the 1970s. In 1997, the retreating sea ice was followed by a phytoplankton bloom that stripped the nutrients from the surface layer. A strong May storm mixed the shelf to 50 m, providing a second bloom. Then weak winds and increased sunlight caused a shallow mixed layer below which new phytoplankton growth occurred, stripping the nutrients from the bottom layer. In 1998, the ice may have retreated too early to trigger a bloom. Stratification remained weak well into June due to storms, and net phytoplankton growth was low and balanced by zooplankton grazing. Net new production continued over a longer period of time, ultimately consuming the nutrients in the entire water column.

Primary production in 1997 and 1998 may have been higher than normal on the southeastern shelf because the entire nutrient pool was utilized. Sediment trap observations of the carbon flux owing to new production during 1997 were high ($\sim 300 \text{ mg C m}^{-2} \text{ d}^{-1}$), thus supporting the conjecture.

Unusual coccolithophore blooms covered large areas of the shelf both years as shown by chalky, aquamarine water in SeaWiFS satellite real-color images. These calcium-carbonate-rich phytoplankton are favored over silicate-based diatoms when ammonium concentrations are high (due to zooplankton grazing and nutrient recycling) and silicate concentrations are low due to depletion by diatoms. Water temperatures above 10°C , as observed, favor the coccolithophore *E. huxleyi* over *Phaeocystis*, another often-dominant phytoplankton. Preliminary sediment trap analyses from a single location do not show coccoliths in zooplankton fecal pellets, implying that they were not preyed upon. Diatoms were present in the traps, but conclusions about relative abundance remain open. Water samples from October 1997 show that coccolithophores comprised 98% of the phytoplankton biomass.

Isotopic-ratio measurements in whale baleen indicate a long-term drop in primary production near Bering Strait. D. Schell hypothesizes that reduced flow through the strait leads to less onshelf flow, lower nutrient flux (replenishment), and less productivity.

No consistent picture emerges for zooplankton on the southeastern shelf, but the measurements are sparse. Euphausiid abundance was low at the inner front in 1997, but very high over the middle shelf domain near the Pribilof Islands. It is puzzling that oceanic copepods were pushed into the inner front ($\sim 50 \text{ m}$) in June 1998, but that onshore flow was low that year. Pollock larvae were located more to the north in 1997 than in the early 1990s, and their growth rate was low. Larval concentrations were high across the middle shelf in 1998.

Pollock hydroacoustic and trawl survey data for 1997 were not too different from other years on the shelf (N. Williamson, personal communication). In September 1997, there were strikingly fewer age-0 pollock in close proximity of the Pribilofs than observed since 1994 (G. Swartzman, personal communication).

Sockeye salmon returns were lower than expected in 1997 and 1998 in Bristol Bay, but escapement goals were met. Yukon chinook salmon runs also were low, and the fish were small and late returning. Low runs also were reported for the southern side of the Alaskan Peninsula and Kodiak Island. Salmon in some river systems fared better. Russia had unexpectedly high salmon runs. Returning fish were being stripped of their roe and bulldozed back into the sea due to processing under-capacity.

Scientists find it difficult to imagine how the numbers of returning adult salmon could be affected by environmental conditions in the Bering Sea. The fish returning to Bristol Bay were not emaciated or diseased, although they were smaller than average. However, it is probable that salmon smolts heading out to sea would be affected by climatic conditions. Those effects would be noted in 2 to 3 years when the salmon returned to spawn. Thus, for salmon returning in 1997 and 1998, perhaps conditions in 1994 to 1996 should be investigated. Similarly, salmon returns in 1999 to 2001 may be affected by the recent anomalies.

We do not yet know enough about the ecosystem and its workings to surmise any conclusions about the co-occurrence of coccolithophore blooms, bird die-offs, low salmon runs, increased whale sightings, etc.

2. What research is needed to better understand the origin and persistence of these changes?

Participants felt that both top-down and bottom-up approaches are useful in understanding the Bering Sea ecosystem. It is helpful to begin with atmospheric forcing and its affects on the ocean environment, then to consider the consequences of the basic biology of animals. The key to understanding broad-scale changes in this ecosystem seems to lie in our understanding of temperature, winds, and sea ice variability. Monitoring programs incorporating moored and drifting instruments and knowledge gained from local users of the Bering Sea combined with retrospective studies help direct future questions and place the present situation in a long-term context. Multidisciplinary, process-oriented studies are necessary and should focus on specific questions of a regional nature to attain understanding of interactions among species and their environment. Emphasis should be placed on knowledge of individual species' life histories and how those species interrelate to other key species. We need to understand *E. huxleyi*, its role in the carbon budget, and how it differs from another small cell that is abundant in the summer, *Phaeocystis* sp. An iterative process where we return to retrospective investigations using the knowledge gained through process work may provide clues to key hypotheses. Additionally, modeling may help predict how key species will respond to hypothesized environmental conditions.

Communication is vital to progress in science. Besides established methods of communication, participants suggested establishing a chat room as part of the Bering Sea and North Pacific Ocean theme page (<http://www.pmel.noaa.gov/bering/>) to facilitate information exchange on a timely basis.

The recently drafted Science Plan for the Bering Sea Ecosystem (avail-

able from the theme page at <http://www.pmel.noaa.gov/bering/pages/inter-agency/>) was recognized as an accurate and timely guide to research needs. Specific research recommendations from this workshop include:

- Measure the system over the next 3 years to capture critical evidence to support or reject claims of a climatological regime shift that may be occurring in the Bering Sea. This opportunity was missed before, and may not recur for decades.
- Establish process-oriented research to determine intervening pathways between atmospheric forcing and ecological response.
- Monitor ocean circulation and water properties at more locations for longer time periods to establish baseline values. Biophysical drifters and moorings are needed. Additional sites in the outer shelf and coastal domains between the Pribilof Islands and St. Matthew Island are needed to expand the present FOCI measurement area.
- Provide more observations of the flow through the Aleutian Islands' passes to determine the balance of heat and salt in the Bering Sea basin.
- Consider the flow through Kamchatka and Bering Straits. The oceanic flow into the Bering Sea enters through a variety of passes, but exits through just these two constrictions. They would make natural pulse points to measure the effect of climate on the mean flow field over long time periods.
- Monitor Bering Strait flow and its connection with onshelf nutrient flux and primary production in the region.
- Couple physical measurements with those of primary and secondary productivity.
- Determine the specific fate of primary production. How do variations in biomass, production, and species composition affect the transfer of energy to apex predators?
- Investigate whether recently observed changes are propagating through the entire trophic pyramid.
- Increase the sampling frequency. Provide more cruises to capture the spring and summer production pulses and food web dynamics. Shore-based sampling from smaller vessels in the Pribilofs and along the northern Alaskan Peninsula should be considered. A mosaic of regions and ecological steps should be constructed and sampled at key points and times.
- Study predator-prey relationships. They are important to the ecosystem at all levels.

- Research connections between the pelagic and benthic communities.
- Learn more about forage fish (myctophids, capelin, eulachon, sand lance) and squid.
- Determine the reason(s) for dramatic increases in jellyfish population.
- Monitor salmon and environmental conditions along the northern side of the Alaskan Peninsula in late summer and early fall.
- Establish when year-class strength is set for different Bering Sea salmon stocks. Could it be when smolts migrate along the Alaskan Peninsula in May to August?
- Investigate the relationship between salmon in the eastern, central, and western Bering Sea.
- Study the movement of juvenile pollock on the basin scale.

3. Given the large changes in the Bering Sea ecosystem, how do we manage marine resources in a fluctuating and highly variable environment?

Managers need a broad, simple rule by which to manage. It is the researchers' challenge to understand species responses in a variable environment and be able to predict large-scale consequences. Because species have evolved in this variable environment, it was suggested that human management of its resources also be flexible. Harvesters need to be able to switch between targeted species not only as seasons vary, but as populations vary interannually. This would require a more flexible, integrative management policy. At the governmental level, official policies and mechanisms should be established to exchange scientific data and manage the international pollock fishery (Russia, USA, donut hole, etc.).

Recommendations

Recent events have demonstrated how quickly and dramatically the Bering Sea ecosystem responds to changes in established weather patterns. These patterns are the result of decadal and shorter-term variations in the atmosphere. Participants of the workshop emphasized the scientific and socio-economic value of the Bering Sea ecosystem. The recommendations below seek a more complete understanding of the ecosystem so that potential changes may be forecast and distributed to all stakeholders (e.g., as is done with El Niño forecasting). The recommendations are consistent with those in the recently published Draft Science Plan for the Bering Sea Ecosystem sponsored by NOAA, Alaska Department of Fish and Game, and the U.S. Department of the Interior.

- Design and immediately implement a long-term ecosystem observing system to continually document the state of the system and observe future changes. System components would include information obtained from scientific observing systems, industry, and Native Alaskans.

- Begin a comprehensive synthesis of our knowledge of the ecosystem. Components would include paleo-oceanographic data, anthropological data, results of prior research projects, and traditional knowledge.
- Assemble integrated teams of scientists and stakeholders to determine how the Bering Sea ecosystem operates. Teams would conduct process-oriented research to determine how changes in physical forcing, biological production, biomass, and species composition affect the transfer of carbon from lower trophic levels to living marine resources and protected species.
- Design, assemble, and test analytical, numerical, and conceptual models that seek to examine critically our knowledge of how the system operates. The long-term goal for the models is accurate forecasting of system response to physical and biological perturbation.
- Build tools (and collaborative relationships) that facilitate communication among ecosystem stakeholders (industry, Native Alaskans, representatives of state and federal agencies).
- Design and implement flexible resource management strategies that can quickly interpret and incorporate relevant information about resources and changing conditions into management decisions.

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Appendix B: Agenda

Monday, November 9, 1998

9:00 am	Welcome	Dr. Arthur Kendall, Jr. and Dr. Phyllis Stabeno
9:15 am	Pacific climate in 1997–98: El Niño? PDO? or another animal from the climate zoo?	Dr. Nathan Mantua University of Washington
9:45 am	Temporal variability of water properties and currents over the eastern Bering Sea shelf	Dr. Phyllis Stabeno NOAA/Pacific Marine Environmental Laboratory
10:15 am	Bering Sea nutrient dynamics: Then and now	Dr. Terry Whitledge University of Alaska Fairbanks
10:45 am	Break	
11:15 am	Southeastern Bering Sea zooplankton: Known patterns and potential anomalies	Dr. Jeffrey Napp NMFS/Alaska Fisheries Science Center Dr. Kenneth Coyle University of Alaska Fairbanks
11:45 am	Responses of marine birds to unusual condi- tions in the southeastern Bering Sea, 1997 and 1998	Dr. George Hunt, Jr. University of California Irvine
12:15 pm	<i>Lunch</i>	
1:30 pm	Redistributions of cetaceans in the southeast- ern Bering Sea relative to anomalous oceanog- raphic conditions during the 1997 El Niño	Dr. Cynthia Tynan University of Washington
2:00 pm	Implications of recent climate changes on salmon and crabs in the Bering Sea	Dr. Gordon Kruse Alaska Department of Fish and Game
2:30 pm	Bering Sea groundfish abundance and re- cruitment trends	Ms. Patricia Livingston NMFS/Alaska Fisheries Science Center
3:00 pm	<i>Break</i>	
3:20 pm	International Perspectives:	
	Nitrogen and iron effects on the physiology of a coccolithophore and a diatom from the oceanic Northeast Pacific	Dr. Diana Varela University of British Columbia
	Coccolithophorids in phytoplankton of the Pribilof region of the Bering Sea	Dr. Mikhail Flint Shirshov University Russian Academy of Sciences
	Lower trophic conditions coupling with the recent warm sea surface temperature in the southeastern Bering Sea shelf in summer	Dr. Naonubo Shiga Hokkaido University
	Walleye pollock distribution and spawning in the eastern and western Bering Sea	Dr. Mikhail Stepanenko TINRO

4:00 pm	Voluntary Presentations:	
	Marine mammals	Mr. Caleb Pungowiwi
	Age-1 pollock	Dr. Tina Wyllie-Echeverria
	Sediment trap and zooplankton stable isotopic composition	Dr. Susan Henrichs
	Weather	Dr. Jim Overland
	Northern fur seal pelage condition	Ms. Beth Sinclair
	Zooplankton-fish acoustic comparison	Dr. Gordie Swartzman
	Climate change impacts	Dr. Gunter Weller
	Coccolithophores in the 1970s and 1980s?	Ms. Tiffany Vance
	TOPEX/Poseidon-ERS2 sea surface height anomalies	Dr. Ned Cokelet
5:30 pm	<i>Reception</i>	
6:00 pm	Keynote Address	Mr. Bart Eaton, Vice President Trident Seafoods Corporation
7:00 pm	<i>Adjourn</i>	

Tuesday, November 10, 1998

8:10 am Coffee

8:30 am Instructions for Discussion Groups Organizing Committee

8:45 am Discussion: As assigned

What are the physical, chemical, and biological mechanisms and interactions causing the changes in the ecosystem observed in 1997 and 1998?

What research is needed to better understand the origin and persistence of these changes?

Given the large changes in the Bering Sea ecosystem, how do we manage marine resources in a fluctuating and highly variable environment?

11:00 am *Break*

11:30 am Discussion Group Reports Rapporteurs

12:30 pm Closing Comments

12:45 pm *Adjourn*

Appendix C: Discussion Group Assignments

Group 1 (Oceanographer Room)

Schumacher, J.—*Facilitator*
Wyllie-Echeverria, T.—*Rapporteur*
Aagaard, K.
Bernard, E.
Bond, N.
Bretschneider, D.
Chythlook, M.
Cyr, N.
Frost, K.
Goering, J.
Hare, S.
Helle, J.
Hermann, A.
Hollowed, A.
Hunt, G.
Ianelli, J.
Kendall, A.
Low, L-L.
Macklin, A.
Mathieson, O.
Napp, J.
Shiga, N.
Tynan, C.
Varela, D.
Warren, B.
Weller, G.
Whitledge, T.

Group 2 (Rooms A and B)

Springer, A.—*Facilitator*
Cokelet, N.—*Rapporteur*
Adkinson, M.
Baduini, C.
Bailey, K.
Brodeur, R.
Byrd, V.
Coyle, K.
Flint, M.
Henrichs, S.
Kruse, G.
Livingston, P.
Mordy, C.
Overland, J.
Pungowiyi, C.
Schell, D.
Sinclair, B.
Speckman, S.
Stabeno, P.
Stepanenko, M.
Stockwell, D.
Swartzman, G.
Tocco, C.
Walker, T.
Walter, B.
Williamson, N.
Wright, B.