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Climate Change in the Southeastern Bering Sea and Some Consequences for its Biota

J. D. Schumacher, N.A. Bond, R.D. Brodeur, P.A. Livingston, J.M. Napp and P.J. Stabeno

INTRODUCTION

Dramatic changes are occurring throughout the Arctic (Weller *et al.* 1997). The systematic modification in wintertime climate of Alaska and the Bering Sea that occurs in 1976-1977 illustrates the magnitude and nature of these changes. Among the effects documented are a step-like increase of nearly 2° C in air temperature (Bowling 1995), an ~5 percent decrease in sea ice extent (Niebauer 1998), and decreases in sea-ice thickness (Wadhams 1995). Many local residents around the Bering Sea have also noted changes in ice thickness and strength (Gibson and Schullinger 1998). Over longer time scales, the extent of glaciers has decreased markedly. Permafrost temperatures measured in bore-holes in northern Alaska are 2 to 4°C warmer than they were 50 to 100 years ago (Lachenbruch and Marshall 1986). Discontinuous permafrost has warmed considerably and is thawing in some locations (Osterkamp 1994). For the Bering Sea region (Figure 2-1), the warming may reflect a natural multi-decadal cycle (regime shift) superimposed on a warming trend due to the greenhouse effect. Given our limited understanding of the Earth climate system, the latter mechanism provides compelling reasons for legitimate public and management concern over future changes resulting from increased concentrations of greenhouse gases (AGU Report 1999).

Substantial natural and human induced variability occurs in the ecosystem of the eastern Bering Sea which includes some of the most productive fisheries on Earth (NRC Report 1996). Besides lucrative crab, halibut and salmon fisheries, most of the world catch of walleye pollock (*Theragra chalcogramma)* occurs here and these resources represent 2 to 5 percent of the world's fishery production and ~50 percent of the U.S. fishery production (NRC Report 1996). The Bering Sea is home to at least

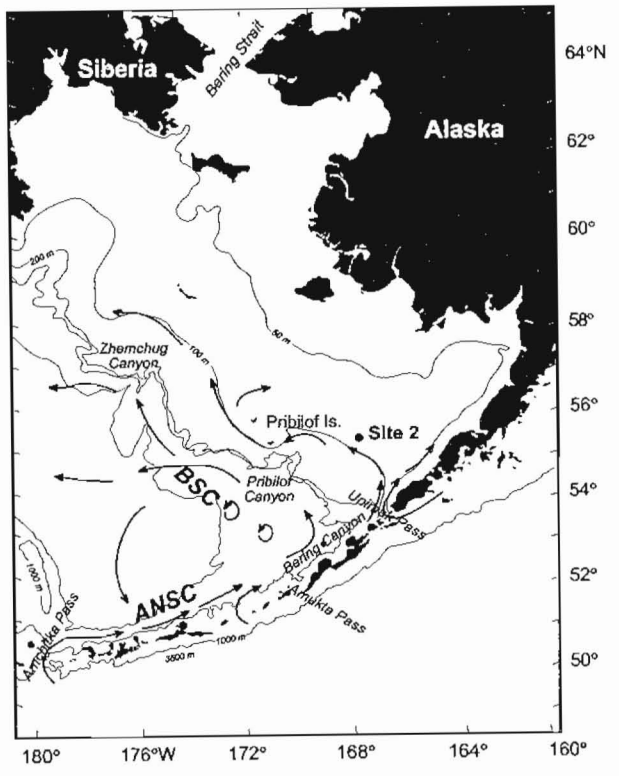

Figure 2-1. Eastern Bering Sea showing geographic names and the location of the Fisheries-Oceanography Coordinated Investigations (FOCI) moored biophysical platform (Site #2). Also shown is a schematic of the mean circulation. BSC= Bering Slope Current; ANSC= Aleutian North Slope Current

450 species of fish, crustaceans and mollusks; 50 species of seabirds; and 25 species of marine mammals. Walleye pollock is a nodal species in the food web (NRC Report 1996) with juveniles providing the dominant prey of fishes, seabirds, and marine mammals (Springer and Byrd 1989, Livingston 1993, Brodeur *et al.* 1996). In the past, climate variations altered species composition and at present may be reducing carrying capacity (Kruse 1998, Napp and Hunt 2001). Such changes impact sustained ecosystem health and should dictate management of human activities and utilization of this rich ecosystem.

Changes forecast for the Bering Sea due to warming (US GLOBEC Report 1996, Weller *et al.* 1997, Schumacher and Alexander 1999) include decreases in storms (mixing energy), the supply of nutrients and sea ice extent/thickness and an increase in sea surface temperature. Physical conditions observed during 1997 fit these predictions well. During 1998, some conditions continued to be abnormal. It is early to tell whether these conditions will persist or transition back to those characteristic of the historical record. Nevertheless, it is clear that recent changes in the physical environment had immediate and profound consequences on biota. The complex mechanisms that link physical and biological elements preclude precise prediction of ecosystem changes, but it is likely that major evolutions will occur. Below, we update previous work on biophysical processes (Incze and Schumacher 1986) and use recent conditions to suggest mechanisms and biotic responses. We conclude with a brief discussion of management concerns and a scenario for potential future ecosystem change.

THE BIOPHYSICAL ENVIRONMENT

Recent results germane to biophysical mechanisms in the southeastern Bering Sea include: refinement of our understanding of the Bering Slope and Aleutian North Slope Current (Stabeno *et al.* 1999, Reed and Stabeno 1999) and the potential importance of these to fish stocks (Reed 1995), discovery of eddies over the outer shelf (Reed 1998) and slope (Schumacher and Stabeno 1994) and suggestions of their biological importance, discovery of a mean flow across the shelf (Reed and Stabeno 1996, Reed 1998), observations from moored instruments of the ice-associated phytoplankton bloom without water column stratification and the role advection has on stratification (Stabeno *et al.* 1998), determination of the critical nature of timing of sea ice melt and wind mixing to bloom dynamics (Stabeno *et al.* 2001), clarification of the relationship between inner front dynamics and prolonged production (Hunt *et al.* 1999), the potential influence that wind drift, currents and cannibalism have on recruitment of pollock (Wespestad *et al.* 2000) and the importance of warm season climate (Overland *et al.* 2001).

The southeastern Bering Sea consists of oceanic and shelf regimes. Within the latter regime, three distinct domains exist, characterized by contrasts in water column structure, currents and biota (Iverson *et al.* 1979a, Coachman 1986, Schumacher and Stabeno 1998). These are the coastal (<50 m deep, weak stratification), middle shelf (50 to 100 m deep, strong stratification), and outer shelf (100 to 200 m deep, mixed upper and lower layers separated by slowly increasing density). The domains provide unique habitats for biota. For example, the zooplankton community in the two shallower domains is comprised primarily of small copepods and euphausiids whereas, in the outer shelf domain and oceanic region, large copepods dominate (Cooney and Coyle 1982, Vidal and Smith 1986).

The Oceanic Regime is influenced by the Alaskan Stream flowing through Amchitka and Amukta Pass, producing the Aleutian North Slope Current (ANSC) (Reed and Stabeno 1999). The ANSC provides the main source of the Bering Slope Current (BSC) which exists either as an ill-defined, variable flow interspersed with eddies and meanders, or as a more regular, northwestward flowing current (Stabeno *et al.* 1999). Shelf/slope exchange likely differs depending upon which mode is dominant. The importance of these currents to dissolved or planktonic material is threefold: they can provide transport from oceanic (including an important spawning region for pollock) to shelf waters, their inherent eddies may temporarily provide habitat that favors survival of larvae (Schumacher and Stabeno 1994) and temperature characteristics that are poteutially important to fish stocks (Reed 1995). Eddies are also common in waters just seaward of the shelf break (Schumacher and Reed 1992) and exist even in the region between 100 and 122 m (Reed 1998). Transport of high concentrations of pollock larvae onto the shelf by eddies occurs (Schumacher and Stabeno 1994).

The amount of sea ice cover depends on storm tracks (Schumacher and Stabeno 1998) and varies by > 40 percent about the mean (Niebauer 1998). Ice advection and melting play a critical role in fluxes of heat and salt and generation of both baroclinic flow and the cold pool located over the middle shelf domain (Schumacher and Stabeno 1998, Wyllie-Echeverria and Wooster 1998). The positive buoyancy from melting ice initiates both baroclinic transport along the marginal ice zone and stratification. Cooling and mixing associated with ice advance help to condition the entire water column over the middle shelf domain (Stabeno *et al.* 1998). With seasonal heating, the lower layer becomes insulated and temperatures often remain below 2.0°C (Reed 1995). The area of this cold pool varies by ~2.0 x 10^5 km^2 between maximum and minimum extent. A spring bloom of phytoplankton is associated with the sea ice and accounts for 10 to 65 percent of the total annual primary production (Niebauer *et al.* 1995). Ice and the cold pool both influence distributions of higher trophic level biota (Ohtani and Azumaya 1995, Wyllie-Echeverria and Wooster 1998, Brodeur *et al.* 1999b).

RECENT ANOMALIES

Recently, the Bering Sea exhibited a host of noteworthy physical and biological conditions (Kruse 1998, Vance *et al.* 1998, Tynan 1998, Badnini *et al.* 2001, Napp and Hunt 2001, Hunt *et al.* 1999, Stabeno *et al.* 2001): the first recorded major coccolithophorid blooms (1997, 1998 and 1999), large die-off of shearwaters (1997), salmon returns far below predictions (1997 and 1998), the unusual presence of whales over the middle shelf (1997 and 1998), unusually warm summer sea surface temperatures (1997 and 1998), and a decrease in the onshore transport of slope water (1997). It is instructive to consider these events in the context of the historical records.

Changes in the regional environment are related to the state of the entire North Pacific/Arctic climate system. Much of the variance herein is accounted for by a few modes. Particularly systematic effects appear to be linked to the El Niño-Southern Oscillation (ENSO) on 2 to 7 year time scales and associated with the Pacific Decadal Oscillation (PDO) (Mantua *et al.* 1997) on decadal to multi-decadal time scales. In brief, both ENSO and the PDO impact the Bering Sea during winter through their positive correlation with the strength of the Aleutian Low (Figure 2-2).

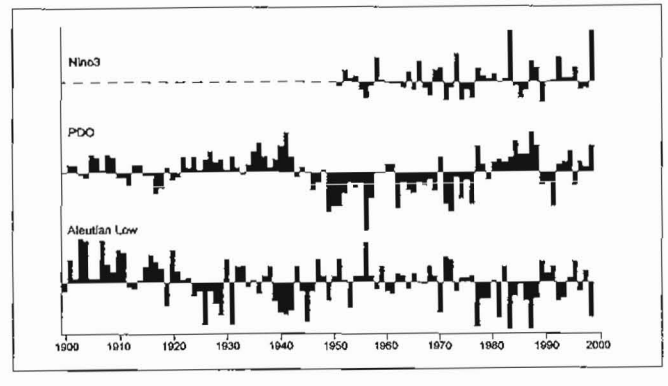

Figure 2-2. Atmospheric indices for the North Pacific and Bering Sea: an index of ENSO (the NINO3 index), the PDO (after Mantua *et al.* 1997) and the Aleutian Low (from Stabeno *et al.* 2001).

The Aleutian Low is important to the Bering Sea through its impact on surface winds (advection and mixing of the npper ocean and production/advection of ice) and heat flux (mixing and ice formation). The time series of both the ENSO and PDO indices show a marked change between 1976 and 1977, the well known "regime shift" (eg., Trenbberth and Hurrell 1995, Hare and Mantua 2000). While the anomalies were less extreme than during the 1970s, the Aleutian Low has undergone significant recent variations between bemg weaker than normal in 1995, stronger than normal from 1996 through 1998 and then weaker than normal in 1999. As noted below, this contributed to substantial differences in timing and persistence of ice cover.

Sea ice characteristics represent an integrated measure of winter atmospheric forcing. An index of sea ice developed for Site #2 (Figure 2-3) shows that the most extensive ice years coincided with a strong negative PDO (Figure 2-2). Sea ice arrived as early as January and remained as late as mid May. Between 1979 and 1981, ice was largely absent. Beginning in the early 1990s, ice again became more common, althongh not to the extent observed in the early 1970s. Even though ENSO and the PDO are the best understood and potentially predictable components of the climate

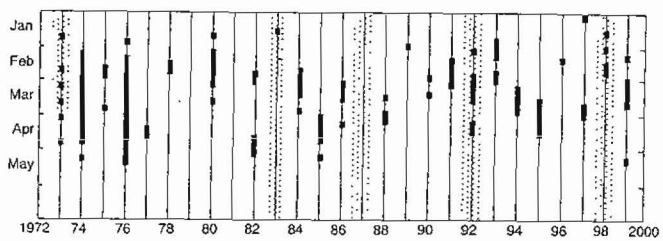

Figure 2-3. The persistence of ice cover at the position of Site #2 is indicated by the dark bars. The shaded areas indicate periods when an El Niño was occurring on the equator (after Stabeno *et al.* 2001).

variability for the Bering Sea in winter, they do not actually account for much of the interannual fluctuation in sea ice cover: ENSO accounts for only ~7 percent of the variance (Niebauer 1998). To illustrate the variability in sea ice extent over the

Bering Sea shelf, we divided the ice observations into three subsets according to generally agreed upon short-term climate regimes (Figure 2-4): the 1972 –1976 cold

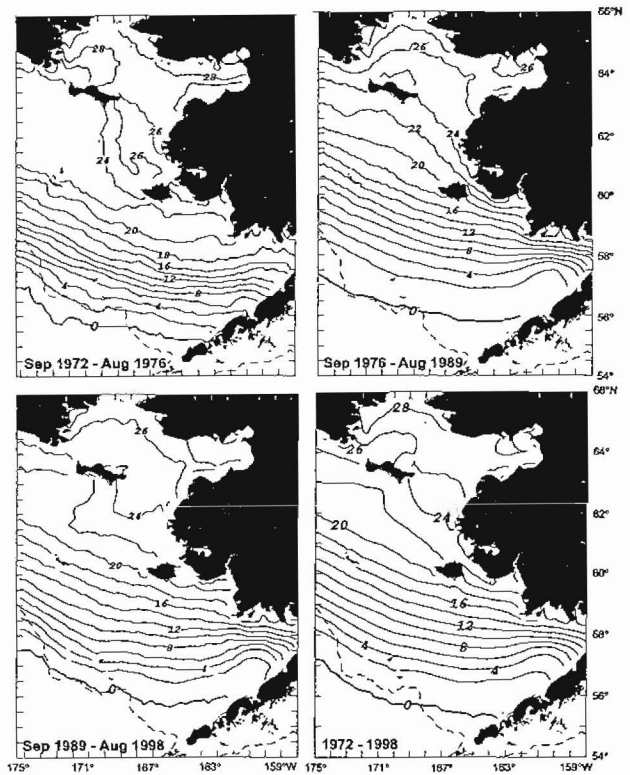

Figure 2-4. Contours of the number of weeks that sea ice was present over the Bering Sea shelf shown as the average ice coverage during. a) 1972-1976, b) 1977-1988, c) 1989-1998, and d) 1972-1998 (from Stabeno *et al.* 2001).

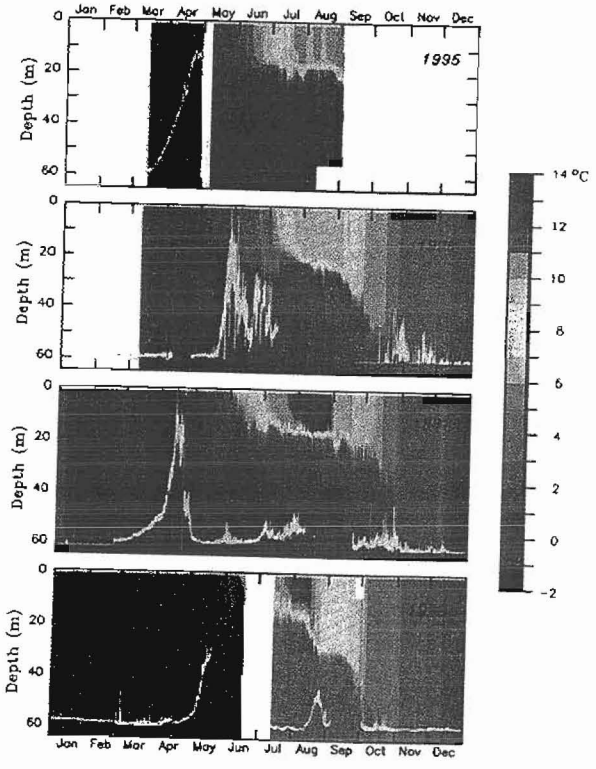

Figure 2-5. Time-series of water temperature and chlorophyll/fluorescence (llm) collected at Site #2. The coldest temperatures indicate the presence of ice (from Stabeno *et al.* 2001.

period, the 1977–1988 warm period, and the 1989–1998 weaker cold period, to characterize the temporal variability in the spatial pattern of sea ice (Stabeno *et al.* 1999). During the first period, ice covered the shelf out to and over the slope and remained around St. Paul Island for more than a month. During the later years of this period, ice did not extend as far seaward and its residence time was typically 2 to 4 weeks less than during the cold period. The differences between the two latter regimes are more subtle, but still evident. Along 59°N, there were 2 to 4 weeks more ice during the 1989 –1998 period than during 1977–1988.

Until recently, studies of the causes and implications of climate variations for the North Pacific and Bering Sea have focused almost exclusively on the winter season. Interest and awareness is growing, however, in warm season climate variations. While these may not be as large as those during winter, they can stand out above background atmospheric conditions (Trenberth *et al.* 1998) and can impact the upper ocean and its biota. For example, the unusually warm SSTs in the eastern Bering Sea (summer 1997) were ascribed mainly to atmospheric anomalies associated with the concurrent strong El Niño (Overland *et al.* 2001). This type of research is in its infancy, but we now have new tools, in particular ~40-year long data sets (e.g. the NCEP/NCAR [National Centers for Environmental Prediction/ National Center for Atmospheric Research] atmospheric reanalysis) for estimating aspects of atmospheric forcing (e.g. radiative effects) that were formerly unavailable. Preliminary results using these data indicate that the eastern shelf is experiencing a trend toward sunnier summers. The consequence is that about 20 watts/m^2 of additional heating has occurred during recent years as compared with 30 to 40 years ago. This is a substantial change and may be attributed to a positive feedback between sea surface temperature and cloud cover. We expect rapid progress in identifying and understanding the variability in the warm season climate of the Bering Sea.

Temperature records from 1995 into 1999 (Figure 2-5) illustrate the seasonal cycle typical for the southeastern middle shelf. In January, the water column is well mixed. The coldest temperatures typically occur in February or early March with the arrival of sea ice. This condition persists until buoyancy is introduced to the water column either through ice melt or solar heating. Generally, this stratification develops during April. The water column exhibits a well defined two-layer structure throughout the summer consisting of a 15-25 m wind mixed layer and a 35-40 m tidally mixed bottom layer. Deepening of the mixed layer by strong winds and heat loss begins as early as mid August, and by early November the water column is again unstratified.

During 1997 through 1999, variations in winds resulted in dramatic changes in the structure and function of the ecosystem. The timing and duration of the transition

from winter to spring and summer conditions dictated whether there was an ice associated bloom (1997) or prolonged primary production by diatoms (1998). In 1997, moderate winds resulted in average ice cover that persisted into April; in 1998 weak winds with a more southwesterly component resulted in minimal ice cover of brief duration; whereas in 1999, northerly winds resulted in less extensive ice cover than occurred in 1997, but it remained over the southeastern shelf into May.

In 1997, ice was present when adequate light existed to support an ice-related bloom. In 1998, however, ice departed prior to the existence of sufficient light levels and as a consequence a bloom occurred in May/June when stratification of the water column occurred. The strength and stability of the inner front was also modified by the prevailing wind conditions. Weak winds in spring and summer 1997 resulted in a broad, diffuse front with undetectable nitrate to 60 m depth and few nutrients entering the upper mixed layer. In contrast, the strong storms of spring and the lack of an ice-edge bloom in 1998 resulted in a slow draw down of nutrients. During 1999, the stability of the front permitted events of vertical mixing/upwelling to supply nutrients to the upper mixed layer throughout summer, supporting prolonged production. Interannual variation in the shelf production regimes was reflected in the body condition of migrant short-tail shearwaters (*Puffinus tenuirostris*) which starved in fall 1997, were emaciated but survived in fall 1998, and were of healthy body mass in 1999 (Badiuni *et al.* 2001, Hunt *et al.* 1999).

BIOLOGICAL TRENDS

The relative importance of bottom-up and top-down processes in controlling production in marine ecosystems continues to be debated (Micheli 1999). In addition to losses to natural predators, human harvests of living marine resources in the eastern Bering Sea have averaged over 1.6 million metric tons in the period from 1979 to 1998 (Figure 2-6), with the majority of the catch consisting of pollock. Harvest rates of pollock and other resources have been relatively conservative over the last twenty-five years, with exploitation rates (catch/mature biomass) of 20 percent or less (Livingston *et al.* 1999). Despite these conservative exploitation rates, a variety of species in diverse trophic groups has shown either long-term increases or decreases in abundance while others have shown cyclic fluctuations in abundauce over the last two decades (Figure 2-7).

Total biomass in the inshore benthic infauna consumer trophic guild is higher than two decades ago. Within this guild, rock sole and predatory starfish biomass have increased, yellowfin sole and Alaska plaice have decreased, and crabs have shown two periods of fluctuations in abundance, with recent trends indicating several crab species are now at very low abnndance and three stocks have been placed in the

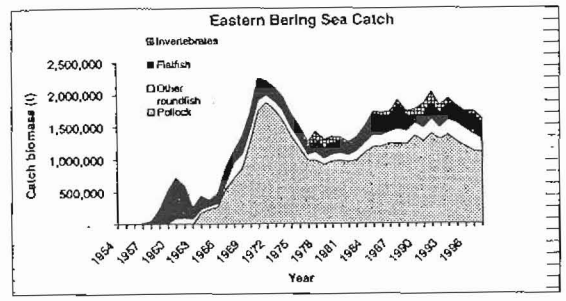

Figure 2-6. Catch biomass of pollock, other roundfish, flatfish, and invertebrates in the eastern Bering Sea from 1954 to 1998.

overfished category. Offshore pelagic fish consumers are dominated in biomass by walleye pollock, which have undergone at least two periods of fluctuation and are now at a lower abundance level than in the 1980s. Several lines of evidence suggest continnation of the long term pattern of increasing arrowtooth flounder abundance and decreasing Greenland turbot abundance. Arrowtooth flounder abundance may now be leveling off. Northern fur seal and piscivorous bird populations declined in the late 1970s and early 1980s but have also leveled off. Crab/fish consumer's biomass is generally declining although skate and halibut biomass within that group is higher in the 1990s than in the 1980s.

Several lines of evidence suggest that the overall production or allocation of resources has changed over the last few decades. The fact of smaller than average adult salmon returning to western Alaska has been linked to changes in ocean conditions that influence growth and survival (Kruse 1998). Decreases in the numbers of seabirds breeding on the Pribilof Islands since the mid 1970s point to a recent change in the carrying capacity of the middle shelf region (Hunt and Byrd 1999). Zooplankton biomass in this region appears to have declined in the early 1990s relative to the mid 1980s (Figure 2-8). Marked increases in jellyfish and rebounding populations of planktivorous marine mammals (Tynan 1998) may put further pressure on food resources (zooplankton) used by larval and juvenile fishes (Brodeur *et al.* 1999a). As noted by Napp and Hunt (1999), if food to apex predators becomes limiting, then climate indnced perturbations that affect production and availability of zooplankton may have an even greater effect on the structure of trophic webs than was observed in 1997.

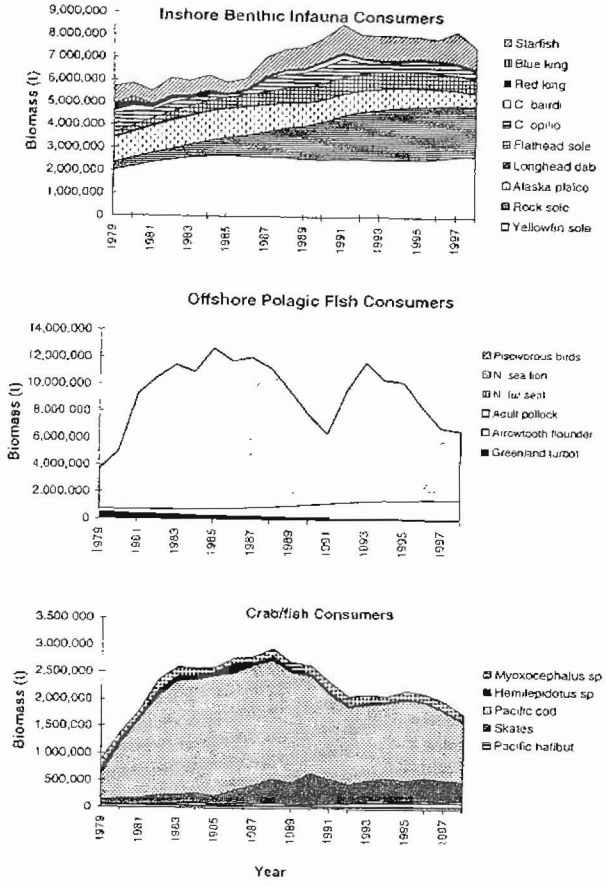

Figure 2-7. Biomass trends of three major trophic guilds in the eastern Bering Sea from 1979 to 1998.

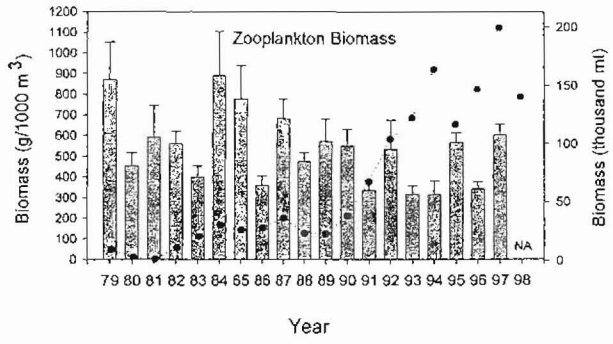

Figure 2-8. Biomass of zooplankton in the Eastern Bering Sea. The bars represent mesozooplankton collected by NORPAC nets (see Sugimoto and Tadokoro 1997) and the circle-and-dash lines represent the biomass of large medusae (in thousand metric tons) collected in standard trawl surveys (modified from Brodeur *et al.* 1999a). All error bars are errors of the mean.

There are indications that the population changes of fish, marine mammals and marine birds in the last twenty years were caused, at least in part, by environmentally driven recruitment changes (Hollowed *et al.* 1998, Kruse 1998, Rosenkranz *et al.* 1998, Springer 1998, Zheng and Kruse 1998). Different species may respond to environmental changes that occur at either interannual or decadal scales. The biomass trends seen in eastern Bering Sea species may be due to decadal or interannual forcing of their prey. Understanding the responses of species to climate forcing is progressing rapidly in this ecosystem. Predicting future climate states and developing fishery management strategies that take changing climate into account must now make similar advancements.

BIOTIC RESPONSES

Identifying and understanding mechanisms that transfer climate change via the ocean to biota (Figure 2-9) is essential if we are to understand ecosystem dynamics (Francis *et al.* 1998). Fluctuations in the physical environment can impact the

ecosystem through both changes in the nutrient-phytoplankton-zooplankton sequence (i.e., bottom-up control) and/or by altering habitat resulting in changes in abundance and/or composition of higher trophic level animals (i.e. top-down control). Sugimoto and Tadokoro (1997) hypothesize that for the eastern Bering Sea, top-down control may be responsible for year-to-year fluctuation of zoo- and phytoplankton biomass, while bottom-up control is the mechanism responsible for longer period (decadal) variations.

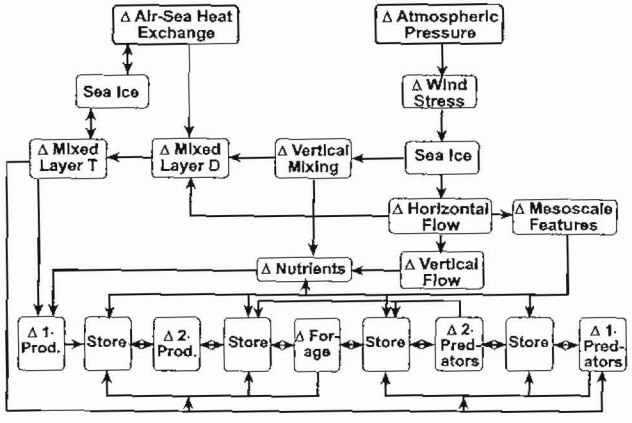

Figure 2-9. Pathways of influence of climate changes in the biological environment (after Francis *et al.* 1998). We have added ice which couples atmospheric phenomenon to the ocean thereby effecting biota in a bottom-up mode. The presence of ice also directly influences distributions of marine mammals exerting an aspect of top-down control. Note that the presence of a coccolithophorid bloom also has direct influence on light penetration, hence on primary production and success of visual feeders.

Sea ice is a feature not present in more temperate ecosystems. Sea ice and its interannual variation has marked ramifications for both the physical and biological environment. As the climate over the Bering Sea warmed, changes occurred in sea ice, the ocean itself and biota. Distributions of marine mammals (Tynan and DeMaster 1997) and fish (Wyllie-Echeverria and Wooster 1998, Brodeur *et al.* 1999b)

as well as survival of age-1 pollock (Ohtani and Azumaya 1995) respond to the extent of sea ice itself and to its associated cold pool. The substantial increase in jellyfish biomass over the eastern shelf of the Bering Sea may be linked to climate change through ice cover (Brodeur *et al.* 1999a). The extent, timing, and persistence of ice cover can dramatically alter time/space characteristics of primary production (Niebauer *et al.* 1995, Stabeno *et al.* 1998), and secondary production as food for larval fishes (Napp *et al.* 2000).

Recent results support the belief that interannual and decadal changes in the environment (e.g., using temperature and wind-drive transport) play a significant role in standing stock variability. For example, water temperature has been implicated as an important regulating factor of salmon production in Alaskan waters (Downton and Miller 1998, Kruse 1998, Welch *et al.* 1998). In the southeastern Bering Sea, wind-drive advection of surface waters containing planktonic stages of pollock (Wespestad *et al.* 2000) and Tanner crabs (Rosenkranz *et al.* 1998) accounts for some of the observed fluctuations in year-class strength. In these studies the mechanism which links advection to year-class strength is predation. The advection models use wind-drift of the planktonic stages either to or away from regions where strong predation pressure exists. In the case of marine mammals and seabirds, climate effects appear to be mediated through the food web, although in some cases the links may be direct (Springer 1998).

Coccolithophorid blooms have been observed in the eastern Bering Sea since 1997 under different environmental conditions (Hunt *et al.* 1999). Why this happened and what the implications are for the future is not known. Perhaps coccolithophores will replace the small flagellates that normally dominate in summer. It is likely that favoring another trophic level between primary producer and consumer (i.e., microzooplankton (Nejstgard *et al.* 1997) will affect ecosystem dynamics (Napp and Hunt 2001). Attenuation and scattering of light by whole cells and detached liths alters submarine light fields (Voss *et al.* 1998), influencing competition among phytoplankton species and affecting the quality and quantity of light for subsurface visual predators (e.g. diving seabirds). Dense concentrations of coccolithophores also alter regional biogeochemical cycles making large positive contributions to calcite and dimethylsulfide production (Matrai and Keller 1993, Brown and Podesta 1997).

Changes in the ecosystem occurred which emphasize the importance of biological interactions. During the regime shift of the mid-1970s, the physical system experienced significant changes. Atmospheric conditions which had favored strong winds from the north, extreme ice cover and an extensive cold pool became those

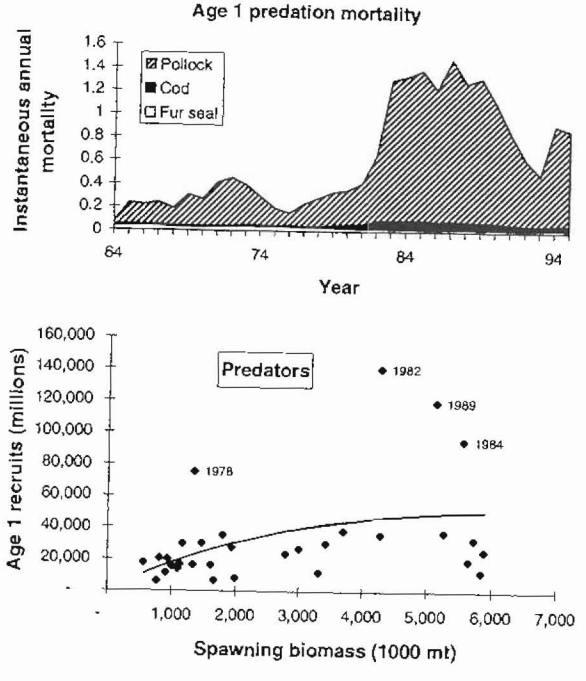

Figure 2-10. Predation mortality of age-1 walleye pollock from 1963 to 1995 estimated by the eastern Bering Sea pollock population model with predation by adult pollock, Pacific cod and northern fur seals (top). Estimates of age-1 recruitment of pollock recruits versus pollock spawning biomass from the pollock population model with predators and the fitted Ricker stock recruitment curves (bottom) (from Livingston and Methot 1998.

experienced significant changes. Atmospheric conditions which had favored strong winds from the north, extreme ice cover and an extensive cold pool became those

which generated minimal ice cover and magnitude/extent of the cold pool. During winter and spring of 1977-1978, a set of environmental conditions occurred that promoted development of the extremely large 1978 year class of pollock. The role of cannibalism in influencing population dynamics resulting from the strong year class has been examined (Livingston and Methot 1998). Age-1 pollock mortality due to cannibalism increased in the mid-1980s due to the influence of the large 1978 year class attaining the adult, more cannibalistic size (Figure 2-10). Predation models suggest that the recruitment of subsequent year classes was reduced by cannibalism which played a large role in reducing the number of juvenile pollock that eventually recruited to the fishery (Livingstou and Methot 1998). Model results also indicate the possibility of two different spawner-recruit relationships, one for average to cold years and one for warmer years. The authors hypothesize differential survival of pollock in cold versus warm years may initially be due to differences in weather mediated transport of surface waters that separates age-1 pollock from cannibalistic adults (Wespestad *et al.* 2000). These results highlight the importance of studying biotic interactions in order to pinpoint which life history stage of a population is most influenced by abiotic and biotic factors. Because of the interplay between predation and climate factors, it is possible that a year-class as large as the 1978 year-class will not be observed again until there is a combination of a relatively low adult population and winter/spring conditions favoring larval survival.

MANAGEMENT CONCERNS

Many issues surround management of human use of shell fish and fin fish stocks in the Bering Sea. Activities associated with these industries can impact the ecosystem through many pathways, including: overfishing, altering trophic pathways, waste from by-catch, habitat destruction, benthic disturbance and marine debris. These threats to maintaining a healthy ecosystem are compounded by variations in climate that can cascade through the ecosystem. In this region where indigenous peoples abound, issues such as subsistence harvest jurisdiction, and the lack of involvement of local communities in resource management decisions add crucial concerns. These human factors play out on Earth's natural variability which itself has already been impacted by greenhouse gasses (AGU 1999). Part of the solution to this complex challenge is to attain an understanding of the mechanisms which dictate ecosystem vitality and health. We have provided only a few examples of changes in ecosystem dynamics of the eastern Bering Sea and have suggested that these are mainly due to climate change. We must continue discovering how mechanisms causing natural fluctuations function in order to have a reliable basis for managing human impact on various populations (Livingston *et al.* 1999). To make further advances in our understanding of how this ecosystem functions requires a greater effort monitoring and conducting process-oriented investigations of both physical and biological

parameters. This will allow identification of the important fluctuations and elucidation of the mechanisms by which changes in physical phenomena are transferred to biota. In addition, this would permit the development of more complete knowledge of the life histories of the central species in the ecosystem and clarify the role of biological mechanisms such as predation. Long-term monitoring programs appear to be the most direct way to establish causal mechanisms responsible for inducing ecosystem change.

THE NEXT DECADE

Prediction through mechanistic understanding is the goal of many applied sciences (e.g. Schumacher and Kendall 1995). Using our increasing knowledge of processes important to the functioning of the Bering Sea ecosystem, we speculate here about what might happen if the majority of years within the next decade resemble environmental conditions observed during spring and summer of 1997.

From a mechanistic view, the reduction of on-shelf transport during 1997 stands out as a fundamental process, regulating production on the shelf. This transport is important for supplying inorganic nutrients, heat and salt (thereby affecting stratification) to the shelf. Assuming that, in the next decade, there is a decrease in shelf flux of nutrients, together with weaker stratification, a reduced influence of sea ice and warmer water temperatures, we envision the following changes. Annual primary production will decline and the spring phytoplankton bloom (in the absence of ice) will also be of lower magnitude but longer duration. This will favor planktonic rather than benthic production. In addition, those zooplankton species that are temperature, rather than food limited, may initially have higher rates of production under a warming scenario. Predation by invertebrates, mammals, and seabirds also has an important role in structuring marine ecosystems. In recent decades, marine mammal populations have been protected from harvest. As their population sizes increase, we expect to see increased inter- and intra-specific competition for food. In 1999, sightings of dead beach-cast Pacific gray whales increased (Rugh *et al.* 1999) with scientists hypothesizing that inadequate food resources in their traditional summer feeding grounds (northern Bering and Chukchi seas) was the cause. Under limiting food resources, prey switching (increasing diet breadth) can be expected. Recent examples include hypothesized use of sea otters by killer whales, *Orcinus orca*, (Estes *et al.* 1998) and diet breadth expansion in planktivorous short-tailed shearwaters (*Puffinus tenuirostris*) when adult euphausiids were not available (Baduini *et al.* 2001). Increased competition for planktonic prey such as euphausiids may also explain the recent decline in size at maturity of Bristol Bay sockeye salmon (Kruse 1998). A decrease in the presence of sea ice in the southeastern Bering Sea and under ice phytoplankton blooms may

reverse the recent dramatic increase in scyphomedusae (jellyfish) which prey on zooplankton.

We emphasize that these speculations form, in part, a test of our knowledge of structuring mechanisms of the Bering Sea ecosystem. They are based on observations of its previous states. It is possible that multiple stable points exist for this resource-rich ecosystem. Formulation of hypotheses and collection of observations designed to test them is an essential part of increasing and refining our knowledge.

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3

Contemporary State and Factors of Stability of the Barents Sea Large Marine Ecosystem

G.G. Matishov, V.V. Denisov, S.L. Dzhenyuk

INTRODUCTION

The Barents Sea Large Marine Ecosystem is at the highest latitude among the LMEs of the World Ocean. It is situated within the European part of the Arctic shelf, completely to the north of the Northern Polar Circle (Figure 3-1). The area of the Barents Sea is 1424 km^2, the volume of the water is 316 thousand km^3, the average depth is 222 m (Atlas 1980).

The Barents Sea is well known as one of the most productive ocean areas. An intensive fishery has been conducted here from the beginning of the twentieth century by Russia (the Soviet Union from 1922-1991), Norway and some other European countries. Together with significant stocks of marketable fish (cod, herring, capelin, plaice and many others) it is rich in such resources as invertebrates (shrimps, mussels, crustaceans etc.), sea algae, many species of sea mammals and birds. The coastal zone of the Kola Peninsula is a prospective area for the artificial breeding of valuable fish species and for the organization of a recreational fishery.

For a relatively long period, the state of the Barents Sea ecosystem was determined only by the natural factors. However, the rapid growth of the fishing industry in the second half of the twentieth century became the most important factor influencing the quantitative and qualitative composition of the marine biota. The overfishing of certain fish species led to a population dominance in the fishery by less valuable and profitable species. In general, the exhaustion of the Barents Sea caused the expansion of the Soviet fishery fleet in 1970-80s to the distant ocean areas of the North-East and Southern Atlantic, the Southern Pacific, and the Antarctic. Only in the last decade, due to the changing geopolitical situation and to the strengthening of protective measures, has the role of the Barents Sea as the leading fishery basin been restored to a great extent.

At the same time, the development of other branches of the economy, such as the oil and gas industries, has begun on the Barents Sea shelf. Two large offshore projects have already started and several more oil and gas structures are prospective for future exploitation. New ports and industrial enterprises are projected for the Barents Sea