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Regime shift theory: A review of changing environmental conditions in the Bering Sea and Eastern North Pacific Ocean

by

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ABSTRACT

Multi-decadal changes in patterns of physical phenomena and populations of marine biota occur in the Bering Sea and Eastern North Pacific Ocean. The most marked physical manifestation of these changes is a variation in modes of atmospheric pressure patterns known as a “regime shift”. The physical mechanisms that generate regime shifts are hypothesized to include such primary driving forces as the lunar-nodal tide, variations in solar radiation and changes in the North Pacific circulation that affect air-sea exchange of heat and momentum with the Aleutian Low atmospheric pressure pattern. Secondary effects include interactions among upper atmosphere pressure patterns. The cause for the variations in these pressure patterns, however, is not known. The changes in atmospheric pressure fields together with their attendant winds, moisture and momentum, transfer energy throughout the oceanic environment. These fluctuations greatly influence such phenomena as variations in the extent of sea ice, transport of nutrients into the euphotic zone, water column temperature and turbulence. Changes in these aspects of the ecosystem, in turn, influence biota both through the nutrient-phytoplankton-zooplankton feeding sequence and by directly affecting biological rates and behavior. Changes in the physical environment, however, do not explain all the variations in populations. Clearly, biological interactions are also important, as are the impacts of human intervention. While our understanding of natural changes and their impact on the ecosystem is growing, many of the mechanisms that link physical to biological processes and the life histories of many species are not yet known. As our understanding of how marine populations respond to regime shifts grows, we will be able to use such knowledge toward sustaining the health and productivity of the ecosystem.

INTRODUCTION

Features and phenomena of the Earth undergo natural changes. Most of these exhibit a somewhat cyclic or repeating behavior. Seasonal and interannual signals in physical phenomena are marked throughout the ecosystem of the eastern North Pacific and Bering Sea. On seasonal time scales primary production by phytoplankton reaches a maximum during spring and fall blooms and then declines, animals migrate to and from this region and physical features like sea ice, water column structure/temperature and currents fluctuate. Dramatic changes also occur year-to-year. These include all of the physical phenomena above, as well as the die-off of marine birds, the presence of marine biota associated with warm water, and unusual phytoplankton blooms (Vance et al., 1998; Hunt et al, 1999). Recent research (e.g., Minobe, 1999; Hare and Mantua, in press) shows that atmospheric variations on multi-decadal time scales (typically 10 – 70 years) cause significant alterations throughout the physical environment. These changes, known as regime shifts, also are seen in the biological environment mainly as changes in community composition and/or biomass of a given species. Understanding such changes has importance for management of human interactions with the ecosystem.

For proper management of man’s use of the sea’s many treasurers, we must change our attitude toward the ecosystem and develop a better understand of natural variations. The Food and Agricultural Organization of the United Nations states that (FAO, 1995): "The wealth of aquatic resources was assumed to be an unlimited gift of nature. However, with increased knowledge and the dynamic development of fisheries after the Second World War, this myth has faded in face of the realization that aquatic resources, although renewable, are not infinite and need to be properly managed if their contribution to the nutritional, economic and social well-being of the growing world's population is to be sustained.” It has long been known that humans impact their environment. "Man did not weave the web of life; he is merely a strand of it. Whatever he does to the web, he does to himself." (Chief Seattle, 1854). The reality that the sea provides a finite set of gifts is dawning on man. Over-fishing on George’s Bank provides an example of how man can alter an ecosystem. During the 1960s, fishing depleted stocks of commercially valuable ground fish species. In response, species (including sharks and skates) which are less valuable became the dominant biomass. In addition to human impacts, large natural fluctuations in the abundance of marine species also exist. Studies of fish scales deposited in anaerobic sediments off California (Figure 1, from Baumgartner et al., 1992) provide an example of a natural fluctuation that occurred long before human intervention.

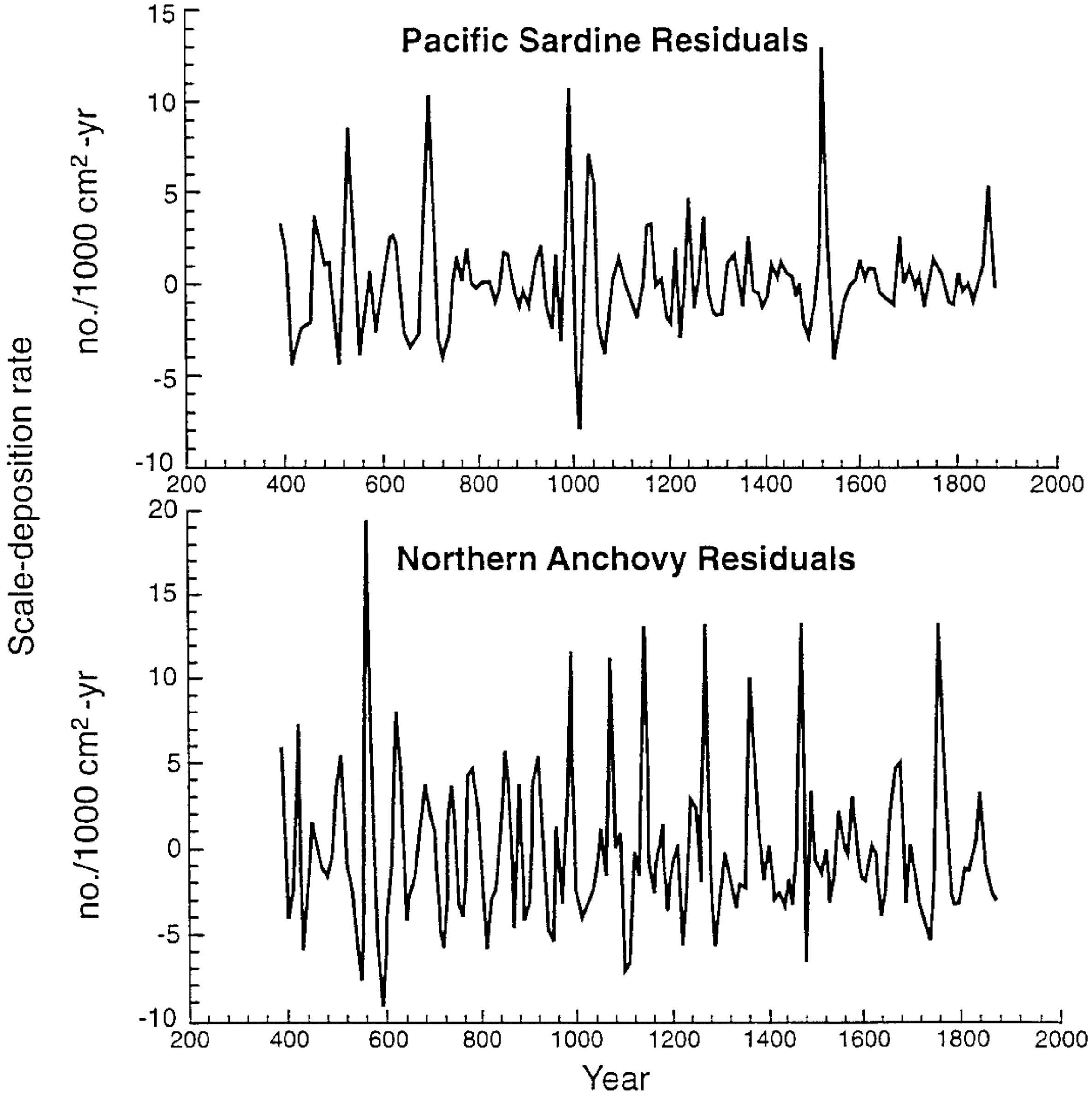


Figure 1. Index of changes in fish abundance of Pacific sardine and northern anchovy based on fish scale deposition rate in an anoxic basin. The fluctuations demonstrate that natural variability exists in marine populations independent of human intervention. (From Baumgartner et al., 1992).

In this paper the focus is on natural fluctuations in the ecosystem. I first present a review of the potential causes for regime shifts in the atmosphere. Following this, I provide a conceptual framework for how atmospheric changes are transferred through the sea ice-ocean realm and hence potentially influence biota. I conclude with a suggested strategy for proper management of human use of the gifts from the eastern North Pacific and Bering Sea.

CAUSES OF REGIME SHIFTS

Mechanisms hypothesized to be responsible for regime shifts for the north Pacific were presented by Ware (1995). Results from more recent investigations supports Ware’s conclusion that there are four candidates that can explain the origin of regime shifts. These are: 1. changes in solar activity (e.g., Van Loon and Shea, 1999), 2. the lunar-nodal cycle of the moon (Royer, 1993), 3. atmospheric interaction between high-latitude atmospheric pressure patterns (Wooster and Hollowed, 1995; Overland et al., in press), and 4. an air-sea interaction between North Pacific circulation and the Aleutian Low (Latif and Barnett, 1994; Barnett et al., 1999).

Fluctuations in solar activity have variable amplitudes and phases. Solar activity is indexed by sunspots, or for a more quantitative measure, by solar emissions at a wavelength of 10.7 cm (Hill and Jones, 1990). Dominant short periods for solar flux include a band that ranges from 7 to 17 years (average 11.1 years) and the 22-year Hale cycle. Solar activity has been correlated with temperature and pressure in the atmosphere over the North Pole (Labitzke and van Loon, 1988; Figure 2, Van Loon and Shea, 1999). Ice extent off the east coast of Canada (Hill and Jones, 1990) also correlates with solar activity. Solar activity is a potential forcing mechanism for decadal period oscillations of the coupled air–ice–sea system in the northern hemisphere (Ikeda, 1990). While solar activity is correlated with many phenomena on Earth, the belief that fluctuations in solar energy cause variations in meteorological and biological phenomena is controversial. Opposition to such hypotheses centers on the small magnitude of the solar flux variation (~0.1% or ~ 2 watts/m^2 at sea level). For solar activity to cause the observed atmospheric phenomena requires either reinforcement of the solar variation by positive feedback from the sea (Ikeda, 1990) or mechanisms not yet known.

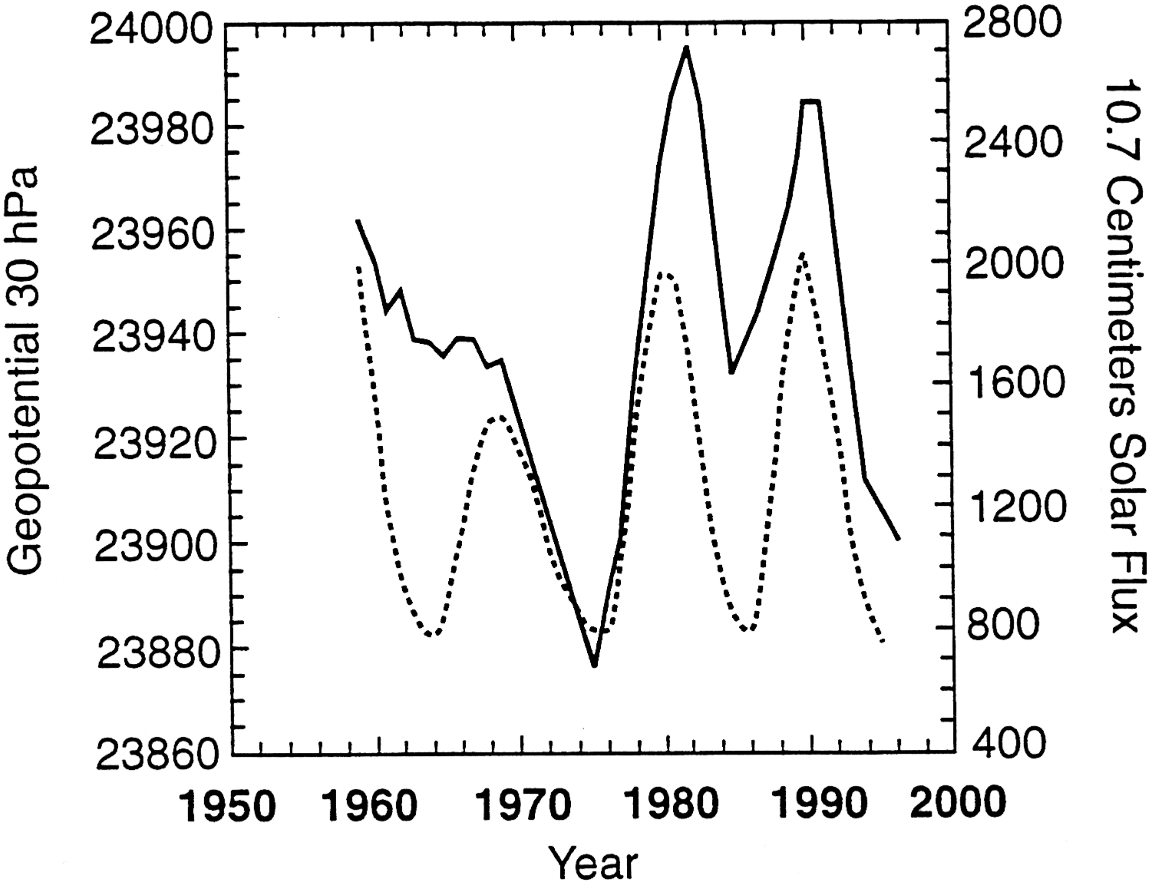


Figure 2. Changes in solar flux and the accompanying change in the height of an atmospheric pressure surface (correlation coefficient = 0.72). Spectral maxima occur roughly every 7-17 years (with an average of 11 years) and 22 years. (From Van Loon and Shea, 1999)

The moon exerts a pronounced gravitational influence on the ocean's tidal heights and currents over periods ranging from less than a day to multi-decadal. The changing position of the moon with respect to the plane of the Earth's equator (18.6-year period lunar-nodal tide) generates variations in tidal mixing. This may force decadal changes in coastal water temperatures off the east and west coast of North America (Loder and Garrett, 1978). An ~17-year spectral peak occurs in air temperature records from southeast Alaska and other high latitude locations and has been linked to enhanced mixing due to the lunar-nodal tide (Figure 3, Royer, 1993).

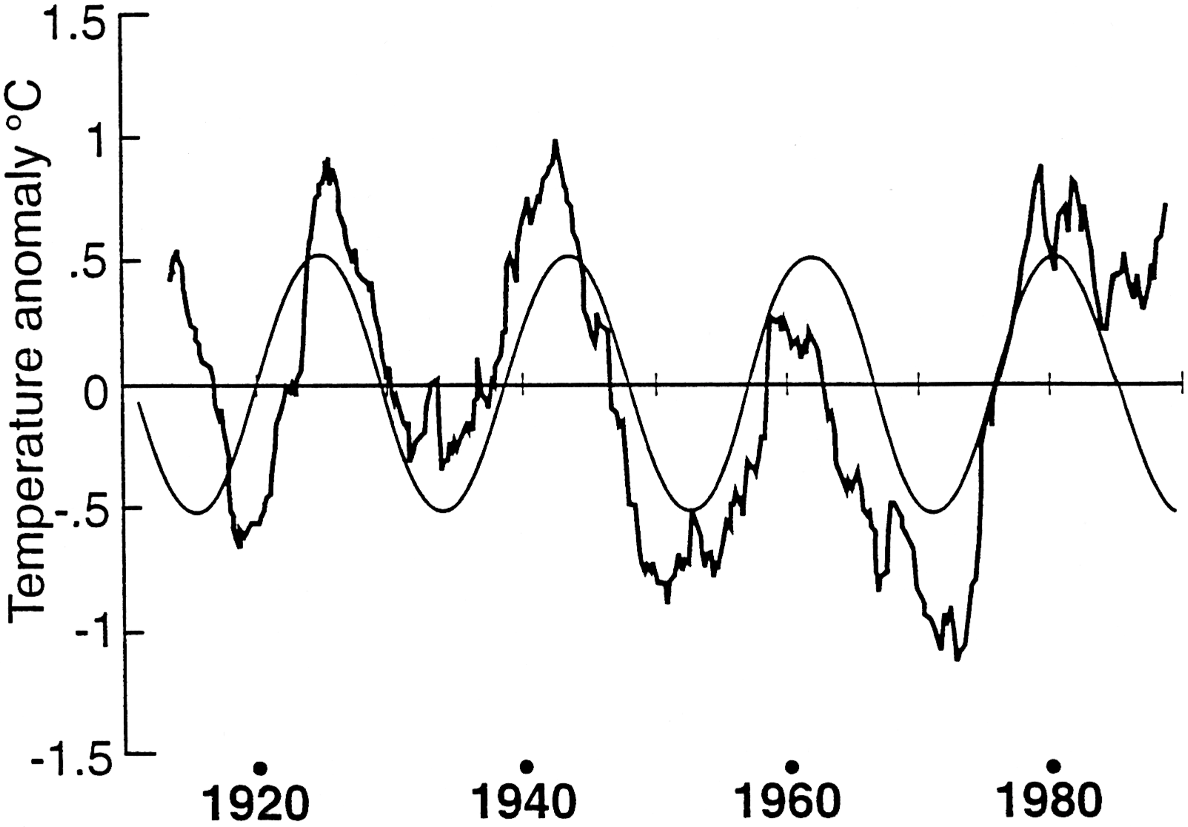
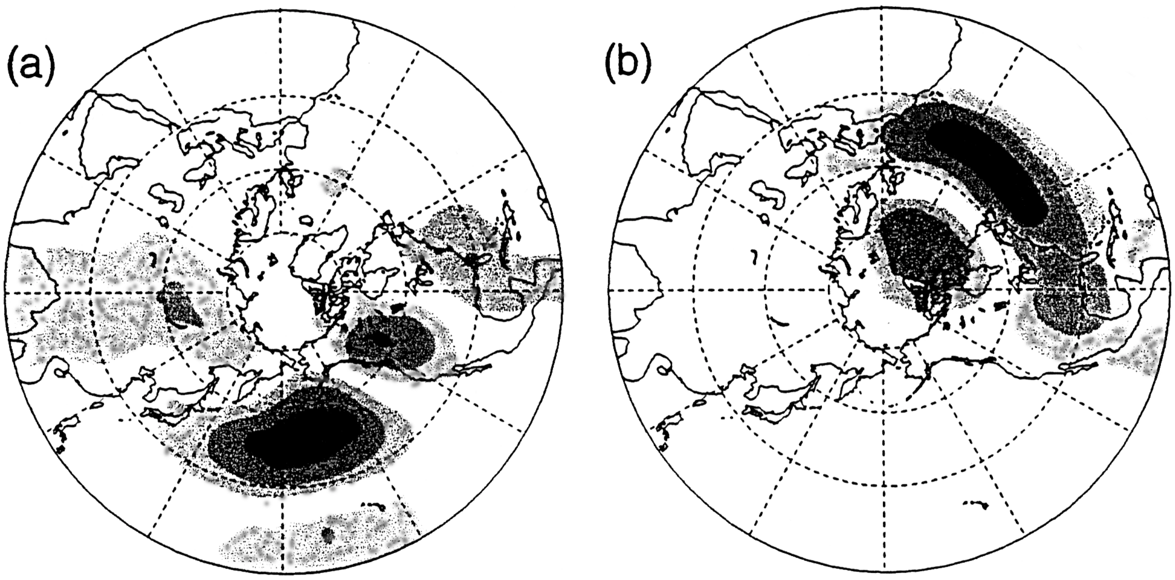


Figure 3. Changes in the lunar-nodal tide and the accompanying signal in air temperature at Sitka, Alaska. Anomalies in the air temperature measured at Sitka (five-year averages, dark line) with "best fit" 18.6-yr lunar tidal signal superimposed (smooth curve). (From Royer, 1993)

A major feature of the surface atmospheric conditions over the North Pacific and Bering Sea is the frequent passage of low-pressure centers along the Aleutian Island chain. This results in the feature known as the Aleutian Low which appears in spatial representations of hemispheric pressure patterns such as the Pacific-North America (PNA: Figure 4). A substantial (37%) amount of the total variance of the Aleutian low is on times-scales greater than 5 yr. (Overland et al., in press). These authors note that "No single tropospheric teleconnection pattern is sufficient to capture the variance of the Aleutian low. The Aleutian low covaries primarily with the PNA pattern but also with the Arctic Oscillation." Much attention has been given to the El Niño-Southern Oscillation (ENSO) and its potential role in altering conditions in the North Pacific and



Pacific North American (PNA)

North Atlantic Oscillation (NAO)

Figure 4. Examples of spatial patterns of atmospheric pressure fields: (a) The Pacific North American (PNA) pattern and (b) The North Atlantic Oscillation. The dark shading represents a value less the mean and the lighter shading indicates a higher value. The region in panel (a) over the central North Pacific Ocean indicates the low-pressure feature called the Aleutian Low.

Bering Sea (e.g., Wooster and Hollowed, 1995). A correlation between ENSO and an index of ice cover over the eastern Bering Sea shelf, however, only accounts for 7% of the total variance (Niebauer, 1998) and the mid-latitude decadal variability in the atmosphere can be explained without the ENSO processes (Barnett et al., 1999).

Time series of atmospheric pressure exhibit regime shifts. For example, a parameter called the North Pacific Index (Figure 5, from Minobe, 1999) shows strong interannual variations superimposed on longer period regimes of mean high or low pressure. During a regime with high pressure, a given year's low can be less than values during a low-pressure regime and visa-versa. The period of the regimes in this series varies between 20-28 years. A recent study (Yasuda et al., 1999) shows a similarity between the abundance of Japanese sardines and regime shifts as indexed by the NPI. The NPI pattern has phases similar to those noted for solar activity. The similarity of phases of these two mechanisms makes it difficult to determine what role each of them play in causing regime shifts.

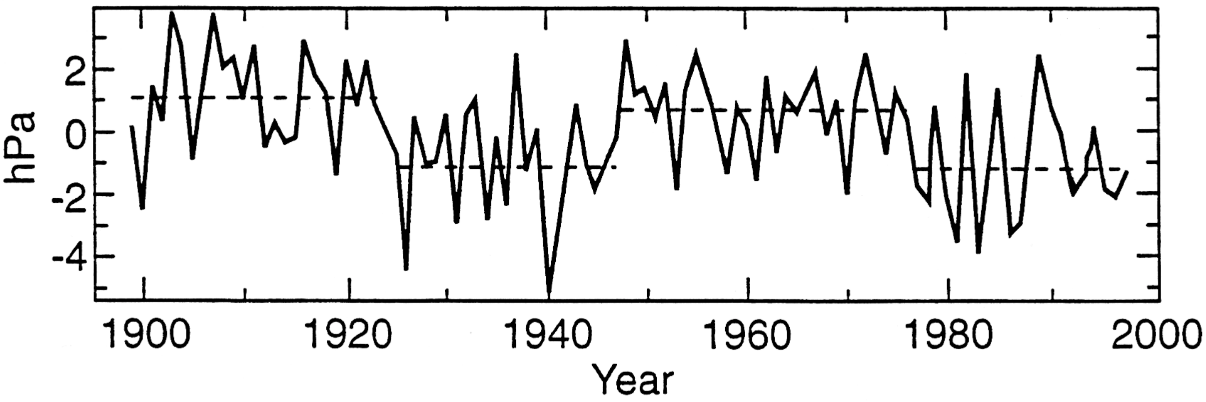


Figure 5. Example of an atmospheric pressure index (North Pacific Index or NPI) that allows the spatial pattern to be presented as a time series. To create the index, one calculates the mean surface air pressure over a large area of the North Pacific Ocean and then subtracts the many-year average of that parameter. The NPI averaged over winter-spring (Dec.-May) seasons (solid curve), and the respective averages for 1899-1924, 1925-1947, 1948-1976 and 1977-1997 (dashed lines). These periods indicate regime shifts. (From Minobe, 1999)

Ocean dynamics may play a significant role in multi-decadal period fluctuations in atmospheric features. Feedback of heat and moisture from the ocean to the atmosphere is important in model simulations of decadal variability in the Pacific Ocean (Barnett et al., 1999). Oceanic circulation features such as the Kuroshio Extension and the Alaskan Gyre undergo long period fluctuations in transport. In the northeast Pacific Ocean, upper waters of the North Pacific Current tend to follow two patterns: either a northward current along the west coast of Canada that flows into the head of the Gulf of Alaska and becomes a southwestward flow along Kodiak Island and the Alaskan Peninsula, or as a southward current off the west coast of North America. These two modes are depicted in surface current simulations and may have marked implications for biota (Figure 6, from Ingraham et al., 1998).

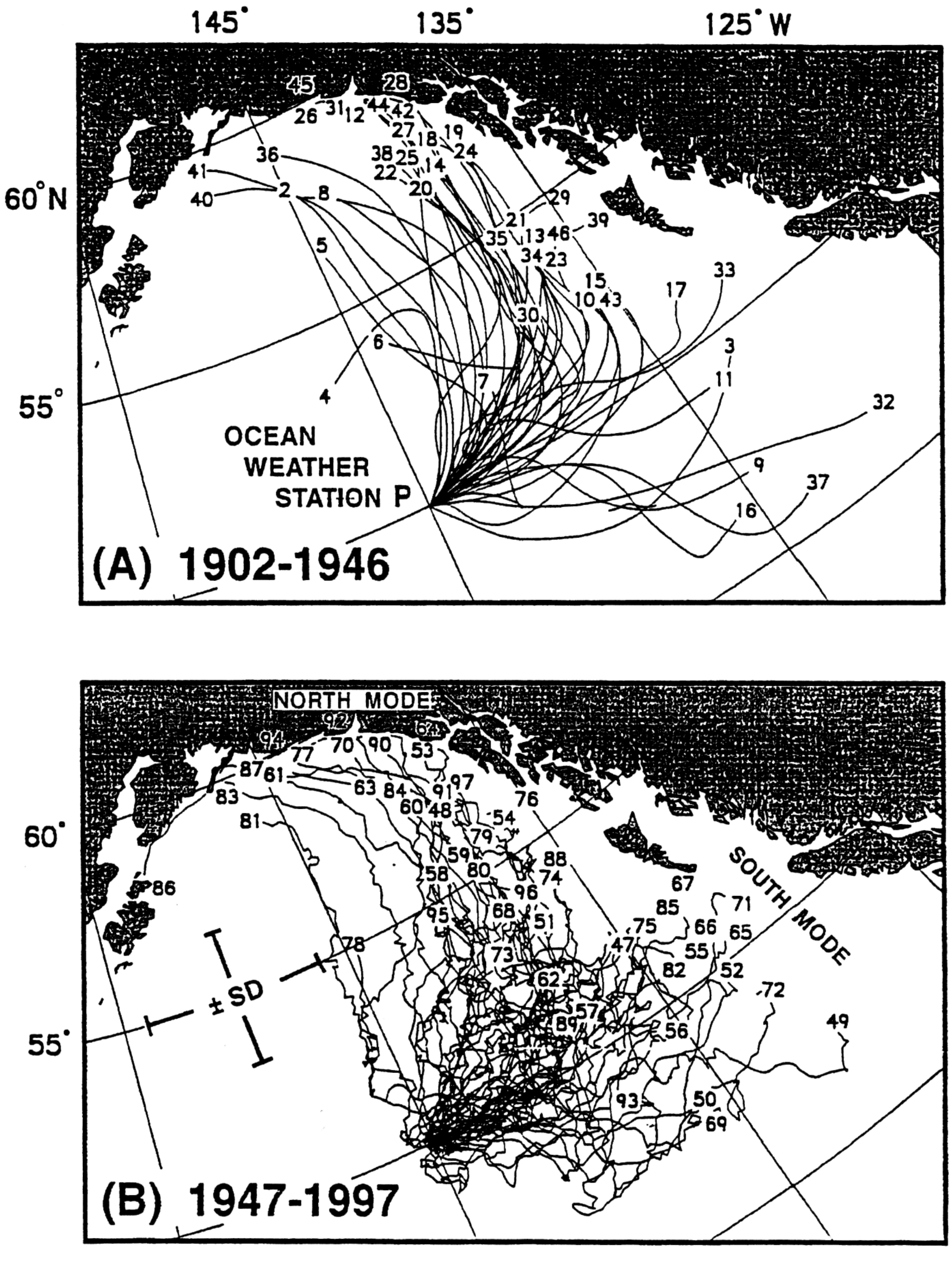


Figure 6. The modes of the North Pacific Current that influence transport of salt, heat and moisture flux. Such changes alter air-sea exchanges between oceanic waters and the Aleutian Low. The lines represent ninety-day trajectories (December 1 – February 28) of surface water starting from ocean station PAPA (45 ° N, 145 ° W). A simulation model using daily sea-level pressure to generate surface winds created the trajectories for each given winter (noted by the number at the end of the trajectory). (From Ingraham et al., 1998)

THE INFLUENCE OF CLIMATE CHANGE ON THE ECOSYSTEM

A recent review of the impact of climate change on the ecosystem of the Bering Sea (Schumacher et al., submitted) supports the conclusion of Francis et al. (1998) that we must identify and understand mechanisms that transfer climate change via the ocean to biota if we are to understand ecosystem dynamics. Fluctuations in the physical environment can impact the ecosystem through changes in the nutrients which affect phytoplankton and zooplankton (i.e., bottom-up control), and/or by altering habitat resulting in changes in abundance and/or composition of higher trophic level animals (i.e., top-down control). For example, Sugimoto and Tadokoro (1997) hypothesize that for the eastern Bering Sea, top-down control may be responsible for year-to-year fluctuation of zooplankton and phytoplankton biomass, while bottom-up control is the mechanism responsible for longer period (multi-decadal) variations.

The highly varying sea ice cover (Figure 7) has a profound influence on both the physical and biological environment of the Bering Sea (Schumacher et al., submitted). As the climate over the Bering Sea warms, changes occur in extent of 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., 1999a) 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 of bottom water which occurs during summer over the eastern shelf. A substantial increase in jellyfish biomass over the eastern shelf of the Bering Sea since 1989 may be linked to climate change through ice cover (Brodeur et al., 1999b). The extent, timing, and persistence of ice cover can dramatically alter the timing and location of primary production (Niebauer et al., 1995: Stabeno et al., 1998), and secondary production which creates food for larval fishes (Napp et al., in press).

Interannual and decadal changes in physical features other than sea ice also 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

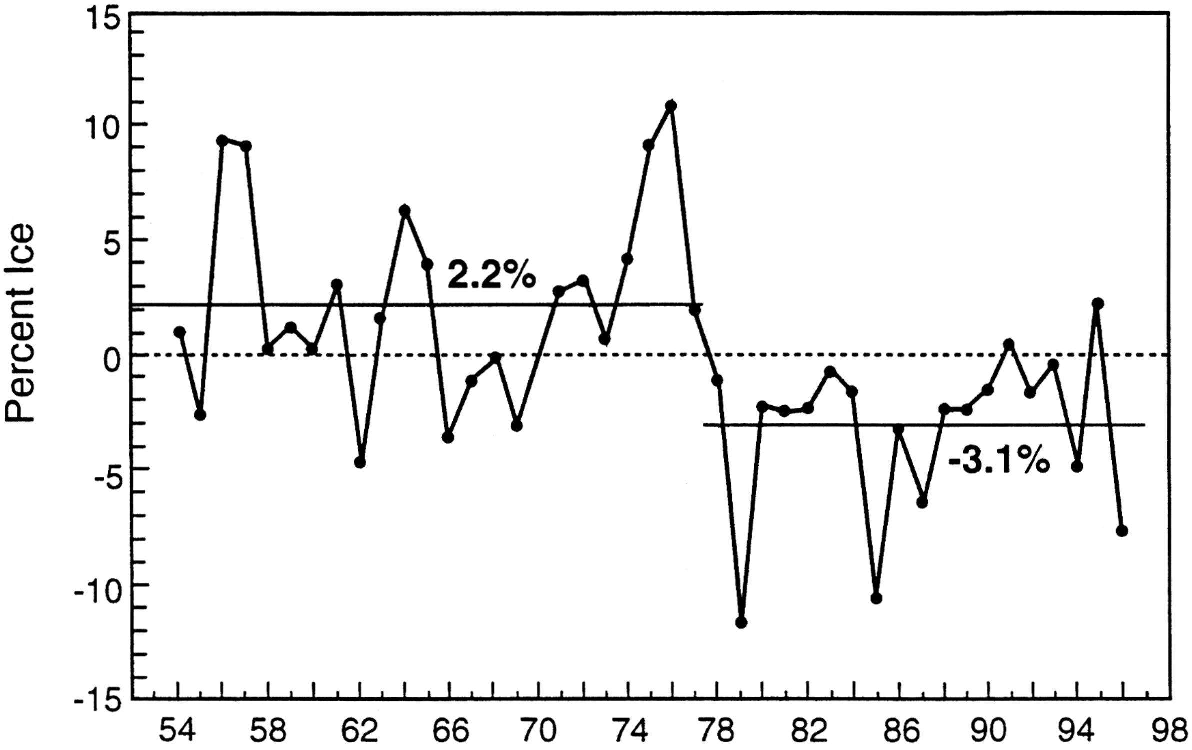


Figure 7. Winter-averaged (November-March) percent ice cover anomalies for the Bering-Chukchi Seas for the period 1954-1996. Average anomalies for the periods 1954-1977 and 1977-1996 are also shown. (From Niebauer, 1998)

and Miller, 1998; Kruse, 1998; Welch et al., 1998). In the southeastern Bering Sea, wind-driven advection of surface waters which contain planktonic stages of pollock (Wespestad et al., in press) and Tanner crabs (Rosenkranz et al., 1998) accounts for some of the observed fluctuations in year-class strength of theses organisms. In these studies the mechanism which links advection to year-class strength is predation. Planktonic stages are transported either to or away from regions where strong predation pressure exists. Marine mammals and seabirds appear to be affected by climate changes through the food web, although in some cases the links may be direct (Springer, 1998).

Francis et al. (1998) developed a conceptual model of the pathways through which climate variations affect biota. With the addition of sea ice (Figure 8, from Schumacher et al.,

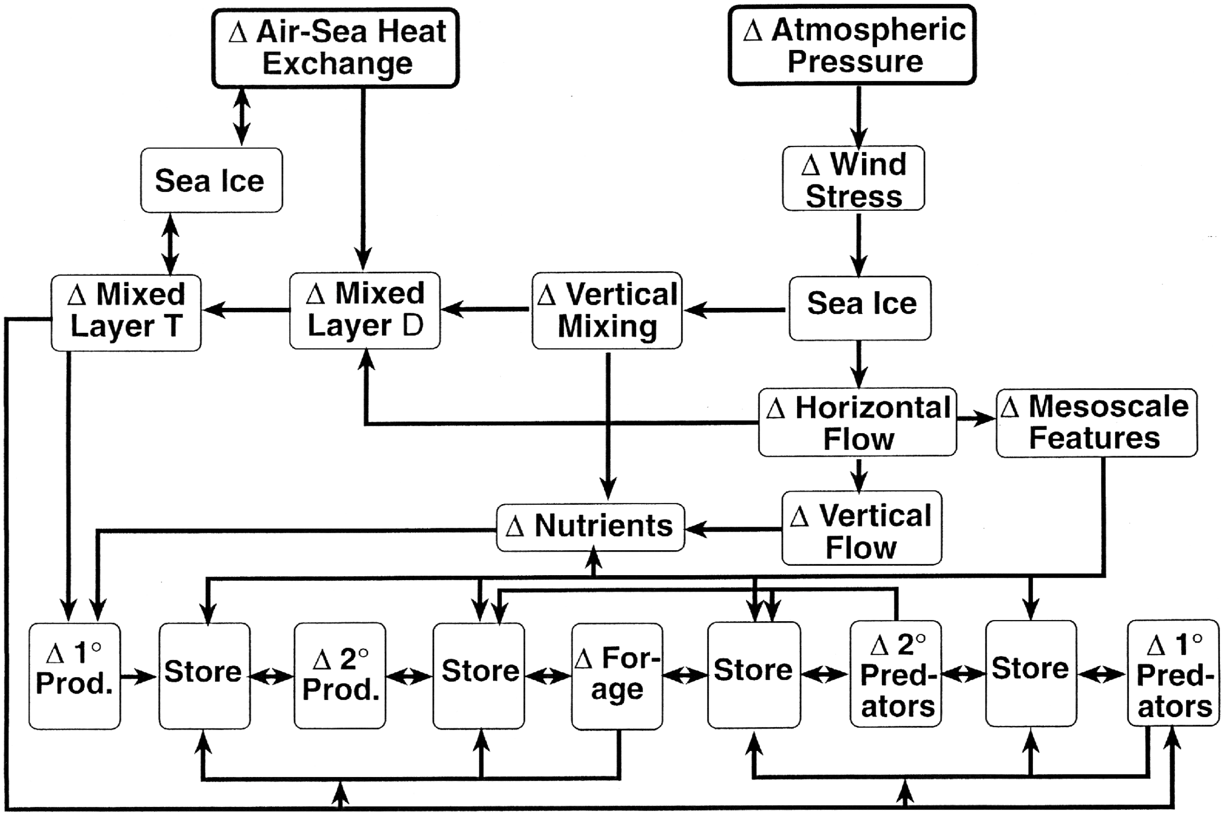


Figure 8. A conceptual representation of the pathways that connect changes in climate to the biological environment (After Francis et al., 1998). Sea ice has been added to account for this marked feature of the Bering Sea.

submitted), this model can be partitioned into atmospheric, ice-ocean and biological components. Hare and Mantua (in press) provide an extensive set of indices for the North Pacific and Bering Sea ecosystem, including representatives from each of the components of the pathway model. Their results indicate that regime shifts occurred in all components, including: summer zooplankton biomass, annual salmon catches, annual recruitment time series for the major commercially exploited groundfish populations, etc. Their analysis of a composite of 100 environmental time series clearly shows that the two regime shifts occurred and that the 1988-1989 shift was less marked than the 1976-1977 shift.

An index of primary production over the time period of the two most recent regime shifts is not available. Stabeno et al. (in press) clearly show, however, that the timing of primary production is intimately connected to the presence or lack of sea ice and sea ice extent is related to regime shifts. An index of nutrients also is not available. Little is known about how the supply of nutrients varies on multi-decadal time scales; however, it is likely that the transport of nutrients onto the shelf responds to atmospheric-oceanic forcing that respond in some manner to regime shifts.

CODA

Atmospheric phenomena in the North Pacific Ocean and Bering Sea undergo systematic changes whose amplitudes and phases are not constant. While several candidates for driving mechanisms exist, research is needed to clarify their roles before any form of predictability can be attained. The changes in atmospheric features are transferred through the linked air-ice-ocean system to biota. The mechanisms that link physics to biology and the rates of change, however, are poorly known. It is clear that regime shifts can have a marked impact on biota. Some of the vital aspects of biology (e.g., biological interactions and life histories), however, are either poorly known or not known at all.

To address the voids in our knowledge requires a long-term commitment to well focussed research. Providing information to management and policy makers should be paramount. Frequent monitoring is extremely useful and provides the most direct means of establishing measurers of the ecosystem. In this way, baselines can be established so that variations from theses can be recognized. The standard surveys (e.g., those conducted by the National Marine Fisheries Service in the eastern Bering Sea) must be maintained and where necessary expanded. Direct measurers of the fish stocks particularly those of commercial value are vital toward developing an understanding of the ecosystem. Observations of currents, salt and heat content and biological factors collected by moored instruments are few and far between, yet their utility is great. For example, an array of moored instruments over the shelf of the southeastern Bering

Sea has provided invaluable information regarding sea ice influence on interannual variation in the physical environment and its impact on primary production (Stabeno et al., 1998; Stabeno et al., in press). Such arrays also provide background time series of observation for studies that seek to elucidate biophysical processes. The regional peoples are another source of knowledge. Hundreds of villages surround the Bering Sea and their peoples have lived off the gifts of the ecosystem for generations. The knowledge of the Elders provides a great, yet mainly untapped library of wisdom regarding this ecosystem.

Proper management requires treating the ocean with respect and gratitude for her gifts. Individual, corporate or national greed has no place in this paradigm. By following proper management, however, we can ensure that a bountiful ocean will be available for all future generations. To develop understanding of the ecosystem and to establish healthy policies requires we must coordinate research and management conducted by all peoples from Pacific Rim countries and responsibly implement strategies indicated by the results. This path can ensure that fishing mortality does not dominate the natural fluctuations in recruitment to commercial fisheries. This is not only our moral responsibility, it is mandated by Federal law in the United States (Magnuson Fisheries Management Conservation Act, 1976) and proposed in the Code of Conduct for Responsible Fisheries (FAO, 1995).

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