ECOSYSTEM INDICATORS AND TRENDS USED BY FOCI

NORTH PACIFIC REGION

Recent indicators suggest that the climate of the North Pacific region is changing. Scientists think this may have started as early as 1989 when the Arctic Oscillation (AO) changed phase. However, the most significant change is the cooling of coastal waters of the Pacific Northwest and Alaska since 1997-1998 when the Pacific Decadal Oscillation (PDO, see below) probably switched phase. With coastal cooling have come shifts in marine abundance, e.g., West Coast salmon that were suffering declines in abundance early in the 1990s appear to be recovering, while Alaska salmon abundance is waning. The following sections discuss some of FOCI's climate and pollock abundance indicators in light of climate change.

Interannual variability of atmospheric forcing

The winter magnitude and position of the Aleutian Low explain much of the interannual variability of atmospheric forcing and physical oceanographic response of the North Pacific Ocean and Bering Sea. The Aleutian Low is a statistical feature formed by averaging North Pacific sea level pressure for long periods. Because this is a region of frequent storms, the averaged pressure pattern describes a closed-cell, low-pressure area over the North Pacific, much like an individual storm on a weather map. The amplitude and location of the Aleutian Low have a strong bearing on weather and ocean conditions in the region and are correlated with other climate indices such as ENSO (El Niño Southern Oscillation), AO, and PDO. A strong Aleutian Low (low pressure) is accompanied by strong winds that drive warm water from the central Pacific into the coastal regions of Alaska and the Pacific Northwest. Conversely, when the Aleutian Low is weak (higher pressure), winds are weak and coastal sea surface temperatures cool.

A measure of the strength of the Aleutian Low is the North Pacific Index (NPI, Fig. 1). It is the sea level pressure over the North Pacific averaged for January through February. The index contains strong decadal variability. For example, there is a shift from high to low values of the index in 1925, a return to high values in 1946, and a shift back to low in 1977. If the data are smoothed, secondary shifts appear (one and a half secondary shifts for each major shift) such as in 1958 and 1989. In the past two years, NPI values have been higher, indicating a weaker Aleutian Low. Consequently, wind-driven advection of warm water from the central North Pacific into the coastal regions of Alaska and the U.S. Pacific Northwest has diminished, and local processes play a larger role in determining ocean temperature near the coast.

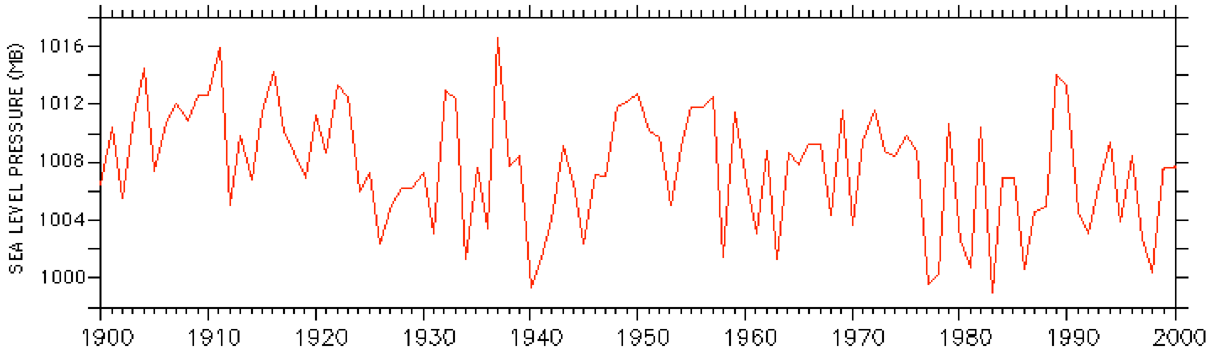
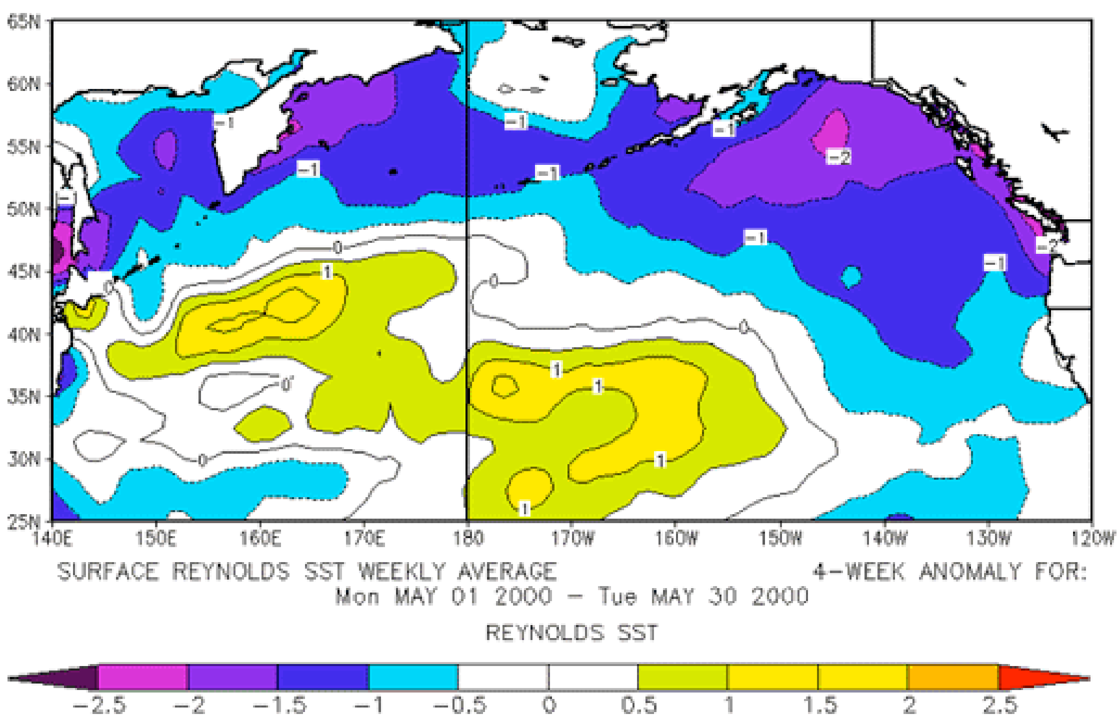


Figure 1. The North Pacific Index (NPI) from 1900 through 2000 is the sea-level pressure averaged for January through February.

Figure 2 shows the averaged monthly anomaly of sea surface temperature for the North Pacific during May 2000. Note the relative cooling of the coastal waters. This signature is indicative of a recent change in the PDO (see next section). The cooling began in 1998 associated with the La Niña, but has persisted in the NE Pacific whick is taken as an indicator of a change in the PDO. Ocean temperatures throughout the North Pacific continued to cool during June relative to long-term climatology.

Figure 2. The pattern of sea surface temperature anomalies for May 2000 shows a return to cool coastal waters with



warmer central Pacific waters.

Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) Index (Fig. 3) is defined as the leading principal component of North Pacific monthly sea surface temperature variability. The PDO is a long-lived, El Niño-like pattern of North Pacific Ocean climate variability. Two main characteristics distinguish PDO from ENSO. First, 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months. Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. Several independent studies find evidence for just two full PDO cycles in the past century: "cool" PDO regimes prevailed from 1890-1924 and again from 1947-1976, while "warm" PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990s. Some researchers have identified a cold phase starting in 1989, others point to 1997. Beginning in early 2000, it became apparent that a shift had occurred from changes in ocean temperature (Fig. 2) and distribution of salmon and other marine species. A weaker Aleutian Low (Fig. 1) certainly is associated with this change. Major changes in northeast Pacific marine ecosystems have been correlated with phase changes in the PDO.

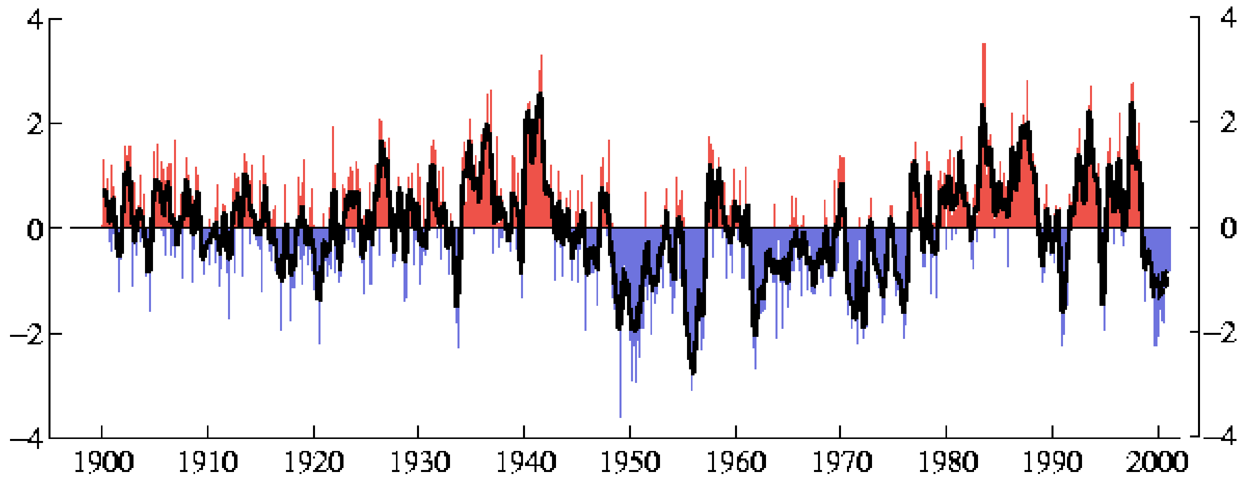


Figure 3. Monthly and smoothed (black line) values of the Pacific Decadal Oscillation (PDO) index, 1900-2000 (updated from Mantua et al. 1997).

Warm eras bring enhanced coastal ocean biological productivity in Alaska and inhibited productivity off the west coast of the contiguous United States, while cold PDO eras produce the opposite north-south pattern of marine ecosystem productivity. Causes for the PDO are not currently known. Even in the absence of a theoretical understanding, PDO climate information improves season-to-season and year-to-year climate forecasts for North America because of its strong tendency for multi-season and multi-year persistence. From a societal perspective, recognition of PDO is important because it shows that "normal" climate conditions can vary over time periods comparable to a human's lifetime.

WESTERN GULF OF ALASKA

Seasonal rainfall at Kodiak

Patches of larval walleye pollock have been located within mesoscale eddies. For early larvae, presence within an eddy may be conducive to survival. Eddies in Shelikof Strait are caused by baroclinic instabilities in the Alaska Coastal Current (ACC). The baroclinity of this current fluctuates with the amount of fresh water discharged along the coast. A time series of Kodiak rainfall (inches) is a proxy for baroclinity and thus an index for survival success of species such as walleye pollock that benefit from spending their earliest stages in eddies. Greater than average late winter (January, February, March) precipitation produces a greater snow pack for spring and summer freshwater discharge into the ACC. Similarly, greater than average spring and early summer rainfall also favor increased baroclinity after spawning. Conversely, decreased rainfall is likely detrimental to pollock survival. A pollock survival index based on precipitation is shown in Figure 4. Although there is large interannual variability, a trend toward increased survival potential is apparent from 1962 (the start of the time series) until the mid-1980s. Over the last 15 years, the survival potential has been more level. Are the lower values of the last two years commensurate with a phase change of the PDO?

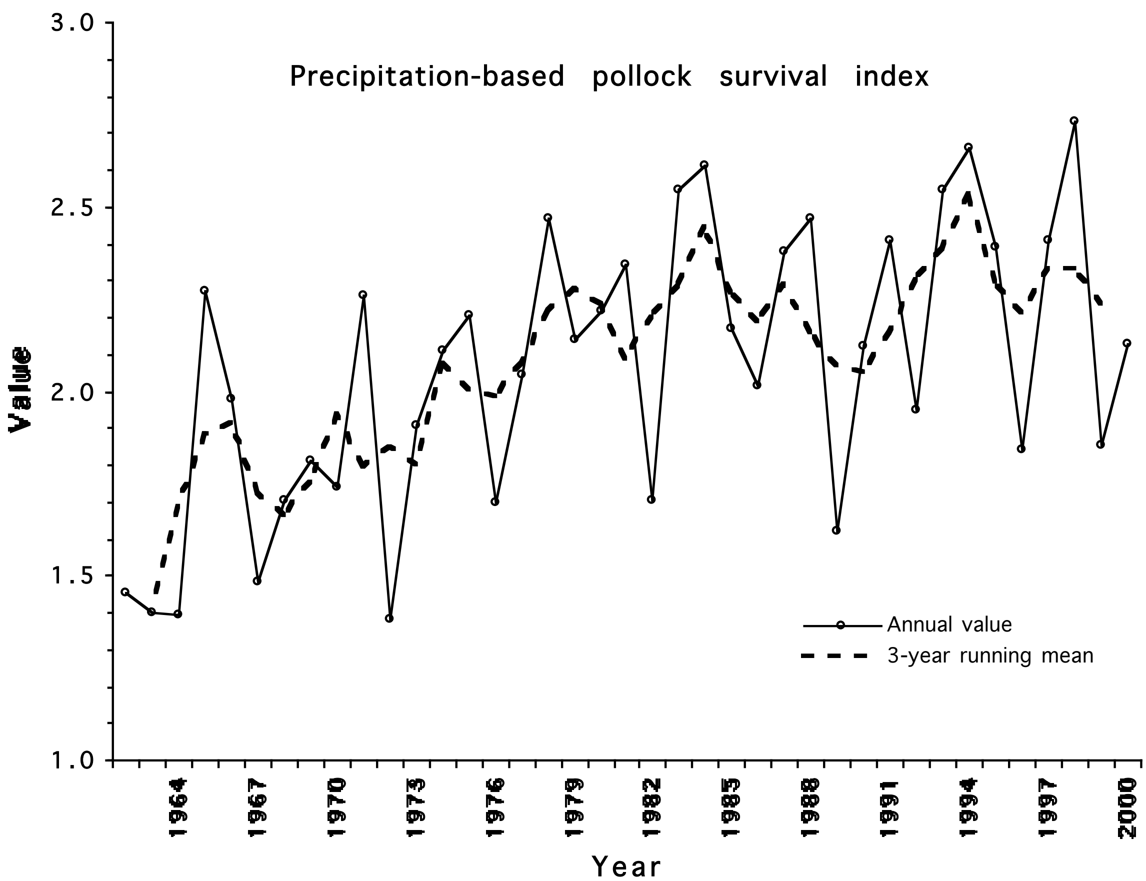


Figure 4. Index of pollock survival potential based on measured precipitation at Kodiak from 1962 through 2000. The solid line shows annual values of the index; the dashed line is the 3-year running mean.

Wind mixing south of Shelikof Strait

Another survival index relates to first-feeding pollock larvae, a key survival stage when baby fish have exhausted their yolk sacs and need to capture food. Possibly because increased turbulence interferes with larvae's ability to feed, strong wind mixing events during the first-feeding period are detrimental to survival of pollock larvae. A time series of wind mixing energy (W m^{-2}) at [57°N, 156°W] near the southern end of Shelikof Strait is the basis for a survival index (Fig. 5) wherein stronger than average mixing before spawning and weaker than average mixing after spawning favor survival of pollock. As with precipitation at Kodiak, there is wide interannual variability with a less noticeable and shorter trend to increasing survival potential from 1962 to the late 1970s. Recent survival potential has been high. Monthly averaged wind mixing in Shelikof Strait has been below the 30-year (1962-1991) mean for the last three January through June periods (1998-2000). This may be further evidence that the

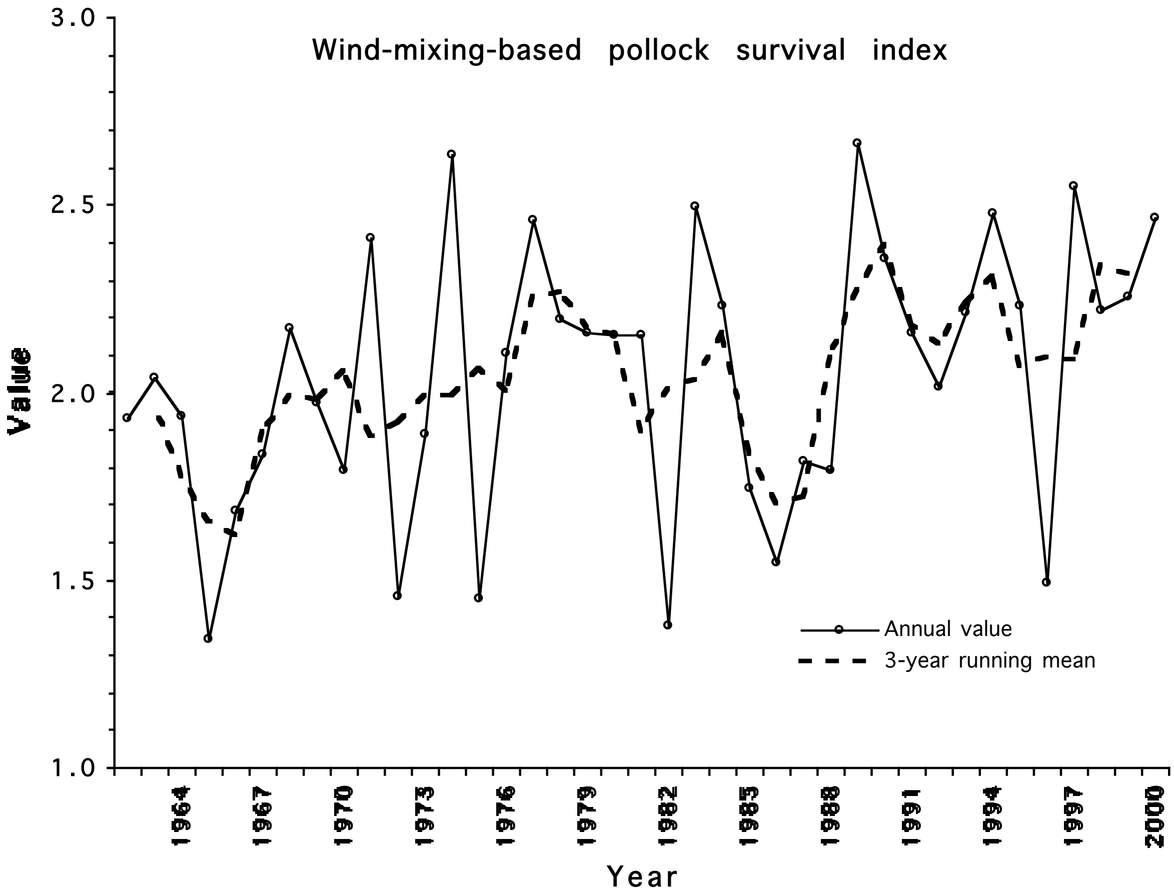


Figure 5. Index of pollock survival potential based on estimated wind mixing energy at a location south of Shelikof Strait from 1962 through 2000. The solid line shows annual values of the index; the dashed line is the 3-year running mean.

North Pacific climate regime has shifted in the past few years.

EASTERN BERING SEA

Sea ice extent and timing

The extent and timing of seasonal sea ice over the Bering Sea shelf plays an important role, if not the determining role, in the timing of the spring bloom and modifies the temperature and salinity of the water column. Sea ice is formed in polynyas and advected southward across the shelf. The leading edge continues to melt as it encounters above freezing waters. The ice pack acts as a conveyor belt with more saline waters occurring as a result of brine rejection in the polynyas and freshening occurring at the leading edge as the ice melts. Over the southern shelf, the timing of the spring bloom is directly related to the presence of ice. If ice is present in mid-March or later, a phytoplankton bloom will be triggered that consumes the available nutrients. If ice is not present during this time, the bloom occurs later, typically during May, after the water column has stratified.

The presence of ice will cool the water column to -1.7°C. Usually spring heating results in a warm upper mixed layer that caps the water column. This insulates the bottom water, and the cold water (<2°C) will persist through the summer as the “cold pool.” Fish, particularly pollock, appear to avoid the very cold temperatures of the cold pool. In addition the cold temperatures delay the maturing of fish eggs and hence affect their survival.

Figure 6 shows the presence of ice over the southeastern shelf between 57° and 58° N during the last 28 years. The figure is divided into three panels, each representative of a climate regime: 1972-1976 ice conditions occurred during a cold PDO phase, 1977-1989 during a warm PDO and AO phase, and the years hence which seem to be in an intermediate regime reflecting a warm PDO and a cold AO. The possible change in the PDO that may have occurred about 1997 is reflected in the extreme ice conditions observed in 2000. During the first regime ice was common over this part of the shelf. In the warm period thereafter, ice was less prevalent. Since then, ice has been more persistent but not as extensive as it was prior to 1977. Recently, 2000 had the most extensive seasonal sea ice pack since 1976. There appears to be a slight reduction in ice cover during El Niño years, but the relationship is weak.

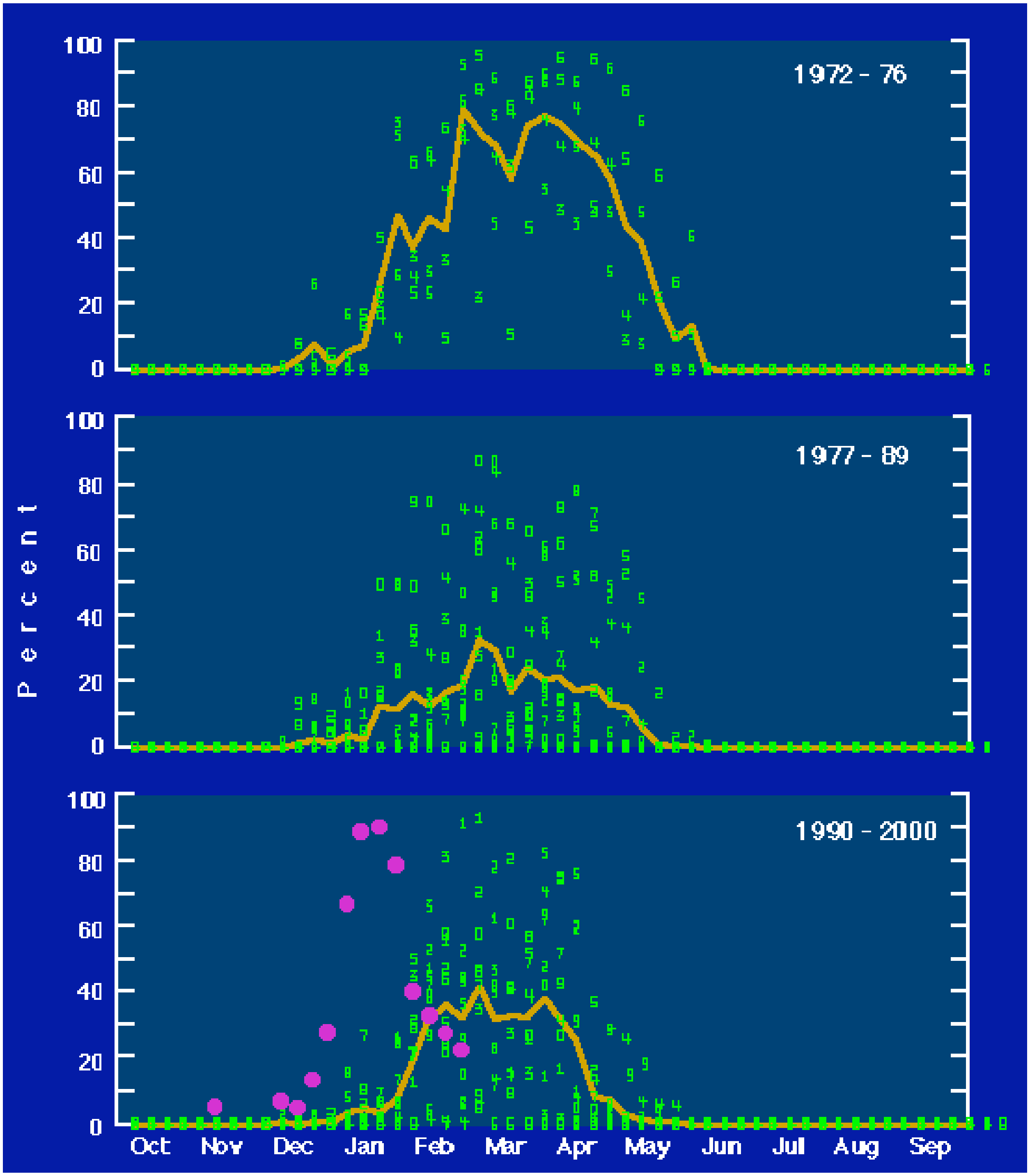


Figure 6. Percent ice concentration over the southeastern Bering Sea shelf between 57° and 58° N from 1972 through 2000. The pink dots in the lowest panel are for 2000.

Mooring 2: The cycle in the middle shelf

The cycle in water column temperatures is similar each year. In January, the water column is well mixed. This condition persists until buoyancy is introduced to the water column either through ice melt or solar heating. The very cold temperatures (shown in black in Fig. 7) that occurred in 1995, 1997, 1998 and 1999, resulted from the arrival and melting of ice. Shelf temperature during 1999 was the coldest, well below 1995 and 1996, and approaching the cold temperatures of the negative PDO phase of the early 1970s. During 1996, ice was present for only a short time in February, however no mooring was in place. A phytoplankton bloom occurs with the arrival of the ice pack in March and April. If ice is not present during this period, the spring bloom does not occur until May or June, as in 1996 and 1998. Generally, stratification develops during April. The water column exhibits a well defined two-layer structure throughout the summer consisting of a 15 to 25-m wind-mixed layer and a 35 to 40-m tidally mixed bottom layer (the cold pool if temperatures are sufficiently low). Deepening of the mixed layer by strong winds and heat loss begins in August, and by early November the water column is again well mixed.

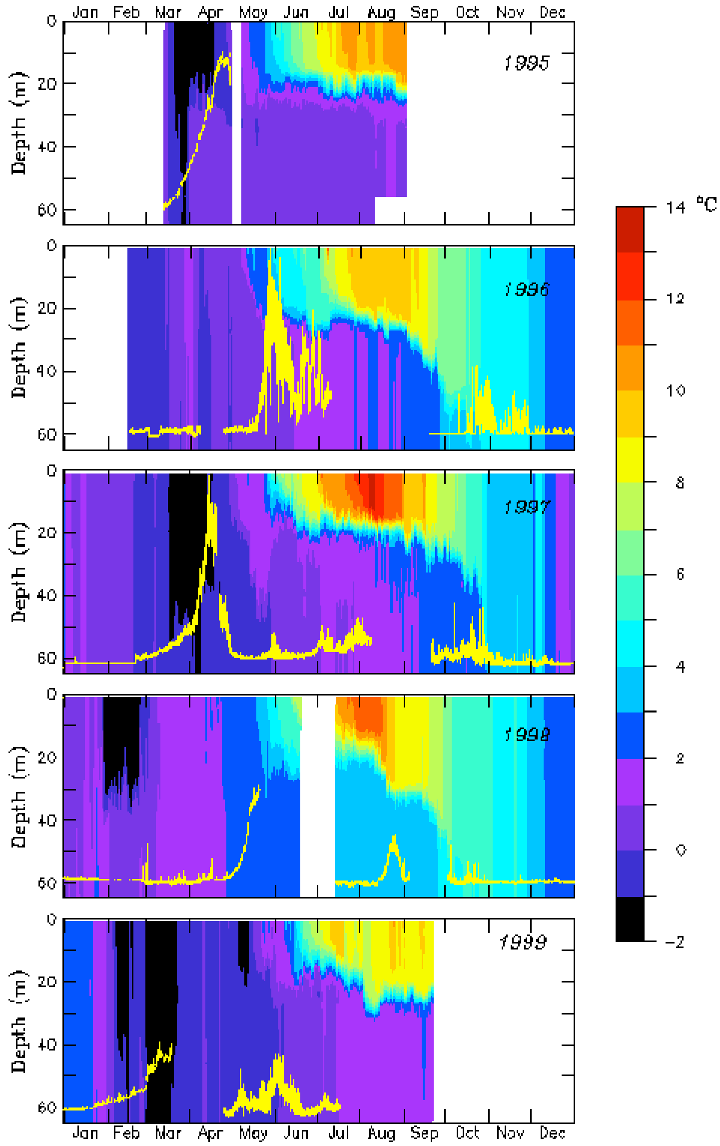


Figure 7. Ocean temperature (°C) as a function of depth (m) and time (month of year) and fluorescence as a function of time measured at mooring site 2 during 1995 through 1999.

The depth of the upper mixed layer and the strength of the thermocline contribute to the amount of nutrients available for primary production. A deeper upper mixed layer makes available a greater amount of nutrients. In addition, a weak thermocline (more common with a deeper upper mixed layer) permits more nutrients to be "leaked" into the upper layer photic zone and thus permits prolonged production. The temperature of the upper layer influences the type of phytoplankton that will flourish. For instance, warmer sea surface temperatures (>11°C) during 1997 and 1998 may have supported the coccolithophorid bloom.

Timing of the last spring storm

One of the striking features of the atmosphere during 1997 and 1998 was a change in the timing of the last storm and strength of summer mixing over the eastern Bering Sea. This ecosystem is particularly sensitive to storms during May. The spring bloom strips nutrients from the upper layer, and the stability of the water column isolates nutrients in the lower layer. Thus mixing and deepening of the upper mixed layer by storms in mid to late May provide important nutrients for continuation of blooms into summer. June and July storms are less effective mixers because they are weaker and the thermocline has strengthened. May storms also lessen the density difference between the two layers (entraining denser water into the upper layer), thus permitting subsequent minor mixing events to supply nutrients into the photic zone. From 1986 to 1996, the weather during May was particularly calm; during May 1999, winds were again light. By contrast, May of 1997 and 1998 were characterized by strong individual wind events (Fig. 8). These storms presented a pathway for greater nutrient supply, more prolonged primary production, and weaker stability of the water column than observed between 1986 and 1996 and in 1999. In addition to

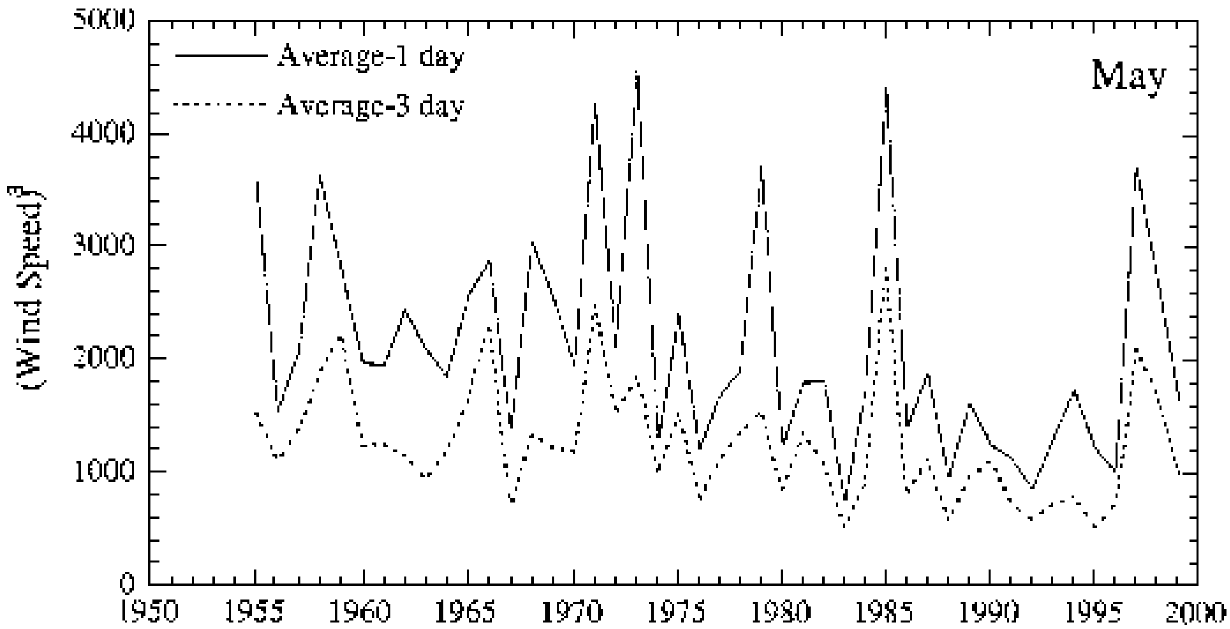


Figure 8. Cube of wind speed (proportional to wind mixing energy) measured at St. Paul, Alaska. The solid line is the daily average; the dashed line is the 3-day average.

stronger winds in May, the summers of 1997 and 1998 had the weakest mean wind speed cubed (a measure of mixing energy) since at least 1955. This allowed for a shallow mixed layer and thus higher sea surface temperatures. A pattern of late spring storms and weak summer winds could change the phytoplankton community. If production is prolonged into summer, the total productivity of the shelf could be enhanced, thereby affecting higher trophic levels.

Cross shelf advection

Each spring and summer over the Bering Sea shelf, approximately half the nutrients are consumed. These nutrients apparently are replenished during winter and early spring. Cross shelf advection moves nutrient-rich basin water onto the shelf. A reduction of onshelf flow will reduce the available nutrients and thus productivity of the shelf. Understanding and monitoring the mechanisms that induce cross shelf flow are critical to management of the Bering Sea's living resources.

During the last ten years, FOCI released more than 100 satellite-tracked drift buoys in the Bering Sea. Prior to 1996, drifters deployed in the southeastern corner of the Bering Sea typically revealed persistent northwestward flow along the 100-m isobath, with cross shelf flow occurring intermittently. In 1997, 1999 and 2000, flow along the 100-m isobath was weak or nonexistent, and there were no occurrences of onshelf flow. Flow patterns in 1998 are less well known as no drifters were deployed that year. Indices of onshelf flow and strength of the 100-m-isobath flow are derived from trajectories of the satellite-tracked drifters. Such indices are important in determining changes in flow patterns, particularly if there has been a climate regime shift as some scientists believe occurred in 1997.