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REPORT OF THE STUDY GROUP ON FISHERIES AND ECOSYSTEM RESPONSES TO RECENT REGIME SHIFTS

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TABLE OF CONTENTS

Executive Summary

Request for Advice

The North Pacific Marine Science Organization (PICES) received a formal request for advice from the United States government in October 2003. The request asked for scientific advice on the implications of the 1998 regime shift for North Pacific fisheries. Following the strong 1997-1998 El Niño, the North Pacific climate underwent a rapid and striking transition, the persistence of which suggests that a regime shift had occurred. Previous regime shifts have had serious implications for ecosystems, and consequently for fish populations and the fishing industry. As such, the National Marine Fisheries Service requested scientific advice from PICES that addresses six specific questions:

1. Has the North Pacific shifted to a different state or regime since the late 1980s?
2. What is the nature of the new state?
3. What are the ecosystem responses?
4. How long can the shift be expected to last?
5. Is it possible to predict when the regime will shift back, and what indicators should be used to determine when it happens?
6. What are the implications for the management of marine resources?

This is the first such formal request for scientific advice made to PICES and represents a new direction for the Organization. PICES was formed in 1992 to provide a forum for scientists from throughout the North Pacific to compare observations and ideas. During these years, PICES has focused on environmental variation and impacts on marine ecosystems and has organized symposia addressing ocean–climate regimes and regime shift impacts on marine resources. At its first annual meeting in 1992, in Victoria, Canada, PICES sponsored an international symposium on climate variability and fish production (R.J. Beamish (*Editor)*. 1995. Climate Change and Northern Fish Populations. Canadian Special Publication of Fisheries and Aquatic Sciences **121**: 739 pp.). In a 1999 symposium held in Vladivostok, Russia, numerous papers identified a strong possibility that a regime shift had occurred in 1989 (S.R. Hare, S. Minobe, and W.S. Wooster (*Editors*). 2000. The Nature and Impacts of North Pacific Climate Regime Shifts. Progress in Oceanography **47**: 99–408). A conference held in La Jolla, United States, in 2000, focused specifically on climate regimes, ecosystem consequences and impacts on fisheries (S.M. McKinnell, R.D. Brodeur, K. Hanawa, A.B. Hollowed, J.J. Polovina, and C. Zhang (*Editors*). 2001. Pacific Climate Variability and Marine Ecosystem Impacts from the Tropics to the Arctic. Progress in Oceanography **49**: 1–639). Most recently, at a workshop in Victoria, Canada, in 2003, a PICES Working Group recognized that a simple two-state system was not a sufficient representation of regime variability. Thus, the scientists of PICES have considerable expertise on ocean–climate regimes, and this topic is of current active research within the Organization and its member nations.

Study Group on Fisheries and Ecosystem Responses to Recent Regime Shifts

The PICES Science Board established a 20-member Study Group on Fisheries and Ecosystem Responses to Recent Regime Shifts (FERRRS) to provide a response to the United States government's request for advice. The Study Group was chaired by Jacquelynne King (Canada) and was comprised of PICES scientists from Canada (William Crawford, David Mackas, Gordon McFarlane, Jacob Schweigert), People's Republic of China (Qi-Sheng Tang, Jin-Ping Zhao), Japan (Akihiko Yatsu), Republic of Korea (Suam Kim), Russian Federation (Victor Lapko), the United States of America (Harold Batchelder, Jennifer Boldt, Anne Hollowed, Alec MacCall, Nathan Mantua, James Overland, Jeffrey Polovina, Franklin Schwing) and PICES *ex-officio* members (Alexander Bychkov, Stewart McKinnell, Ian Perry).

Provision of Advice

The Study Group met February 9–10, 2004, in Victoria, Canada, to organize activities and to outline a report which would provide the background material necessary to prepare responses to the six questions posed in the request for advice. At a three-day workshop held June 14–16, 2004 in Seattle, U.S.A, the background material was reviewed by the Study Group and answers to the six questions were formulated.

This report is the result of the collaborative effort of the Study Group to collate scientific information in support of its responses to the above questions. In addition to the Executive Summary, the report is organized by sections which contain the scientific information that was reviewed by the Study Group and used to prepare its advice. Section 1 (Decadal-scale Climate Events) provides information on climate–ocean indices and basin-scale events related to questions 1, 2, 4 and 5. Section 2 (Coherent Regional Responses) summarizes the ecosystem responses to recent regime shifts in support of answers to questions 2 and 3 and discusses potential indicators (question 5). Detailed descriptions of the observed regional responses to the 1998 basin-wide shift are provided in Appendices 1–5. Section 3 (Implications for the Management of Marine Resources) outlines the conceptual framework for the provision of scientific advice and the development of resource management policy, given impacts of regime shifts on ecosystems and fish productivity (question 6).

Regimes and Regime Shifts

Around 1977, several zooplankton, invertebrate and fish populations throughout the North Pacific underwent a rapid (within a couple of years) change in distribution, productivity (particularly year class success) and abundance. For many species the change was substantial and unexpected. Most noteworthy was the fact that the changes, or shifts, observed in marine ecosystems were evident on such a large geographic scale, mainly the whole North Pacific, and that the changes were not short-lived, but in fact, persisted for a decade. The post-1977 period is broadly characterized as a period of good fish productivity. The co-occurrence of these shifts in ecosystems (across all trophic levels and including non-exploited fish species) around the North Pacific suggested that the ecosystems were responding to a common factor, namely changes in climate or ocean conditions. In fact, rapid and substantial shifts in climate and ocean systems, such as the Aleutian Low pressure system and sea surface temperatures and salinities, did occur around 1977.

It was in the 1990s that this issue of rapid and substantial shifts in climate, ocean conditions and ecosystems became a hot topic of interest to marine scientists. As a result, there has been much research on this topic, and climatologists, oceanographers, marine ecologists and fishery scientists have all contributed to the development of the concept of what are now commonly referred to as regimes and regime shifts. A list of suggested reading on regime shift research is provided in Section 4.

Though the concept of regimes and regime shifts is now a widely accepted paradigm in the marine sciences, a rigid definition of the term "regime" or "regime shift" has not yet been adopted. A regime is a period of several sequential years (often a decade or more) in which the state, or characteristic behavior, of the climate, the ocean conditions or an ecosystem is steady. It does not preclude year-to-year differences, but overall, the state of the system over the decades (*i.e.*, decadal-scale) can be described as persistent, steady, or "locked in". A regime shift refers to a relatively rapid change (ocurring within a year or two) from one decadal-scale period of a persistent state (regime) to another decadal-scale period of a persistent state (regime). As noted above, 1977 is a year in which the climate, ocean conditions and ecosystems of the North Pacific underwent a rapid and substantial shift which resulted in changes that persisted for a decade. As such, 1977 is referred to as a regime shift year. The period from 1977–1988 is referred to as a regime. In 1989, another regime shift occurred and a new regime period began.

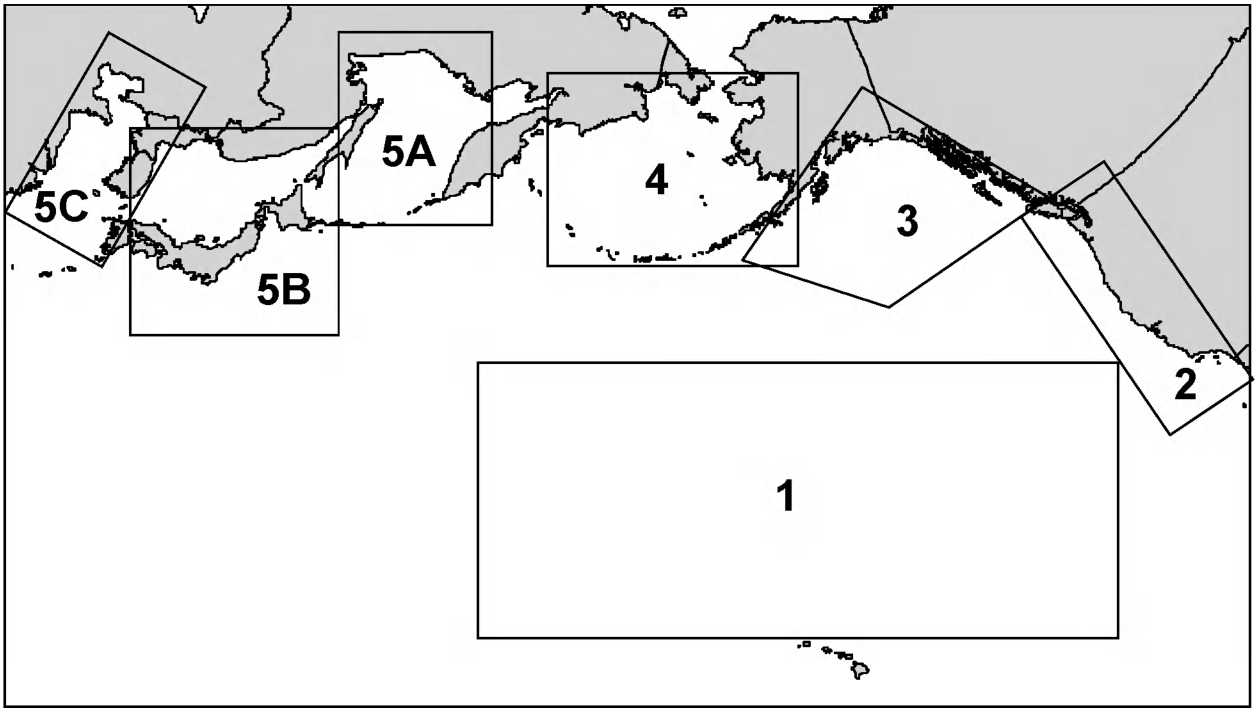
Since ecosystems respond to changes in climate and ocean conditions (and not *vice versa*) and long-term data sets are available for climate and ocean factors, several climate and ocean indices have been developed and used to identify years in which regime shifts have occurred. It should be noted that this had led many scientists to use the terms "climate regime" or "climate–ocean regime" when referring to regimes. A widely used oceanographic index for the North Pacific is the Pacific Decadal Oscillation index (PDO) which tracks the dominant spatial pattern of twentieth century sea surface temperature variation across the North Pacific. For example, one phase of the PDO represents an overall cooling in the central subarctic Pacific and a warming along the northeastern coastal areas, while the alternate phase characterizes an overall warming in the central region and a cooling in the northeastern region. This east–west pattern in PDO is referred to as the classic PDO mode. Since 1989, a different pattern has emerged which is a north–south pattern. This pattern is being referred to as the Victoria Mode since it was first characterized at a workshop in Victoria, Canada. Other commonly used indices include the Aleutian Low Pressure Index (ALPI) and the North Pacific Index (NPI), both of which measure the intensity of the winter Aleutian Low pressure system, and the Arctic Oscillation index (AO) which is a measure of sea level pressure in the Arctic.

Scientific literature reports that regime shifts occurred in 1925, 1947, 1977 and 1989. Regime shifts are not confined to the last 100 years. Paleo-ecological records show that regime shifts have occurred throughout the centuries but that the durations of detectable regimes have diminished from lengths of 50–100 years to 20–30 years and even to 10 years in most recent history. The identification of years in which a regime shift has occurred is often a topic of debate, since there are seasonal components to climate and ocean conditions, and the time it takes for biota to respond to changes in their environment is often lagged by a few years. Another factor impeding the definitive identification of regime shift years is the lack of long-term data sets that span several decades or more. Different studies employ different criteria for identifying regime shifts, but some common aspects include:

- a synchronous and substantial change in the state of the climate and ocean conditions across a large geographic area, such as the whole basin of the North Pacific; as a result, changes would be evident in most climate and ocean indices;
- synchronous changes in ocean conditions and biota at regional scales; as such, changes would be evident in most ecosystems;
- changes in species' productivity, abundance, or distribution evident in a large number of species, across all trophic levels.

Major Regions of the North Pacific

The North Pacific can be divided into five major regions, or ecosystems: the central North Pacific which includes the transition zone and the Hawaiian Islands; the California Current System from California up to northern Vancouver Island; the Gulf of Alaska from northern Vancouver Island to the start of the Aleutian Islands, including the central Gulf region; the Bering Sea and Aleutian Islands; the western North Pacific which includes the Sea of Okhotsk, the Tsushima Current region, Kuroshio/Oyashio Current region, the Yellow Sea and the East China Sea.



Designation of the five regions of the North Pacific for which information on oceanic conditions and ecosystems were compiled and reviewed: (1) central North Pacific, (2) California Current System, (3) Gulf of Alaska, (4) Bering Sea and Aleutian Islands, and (5) western North Pacific comprised of (A) Sea of Okhotsk, (B) Tsushima Current region and Kuroshio/Oyashio Current region and (C) Yellow Sea and East China Sea.

Response to the Request for Advice

Q1. Has the North Pacific shifted to a different state or regime since the late 1980s?

Yes, based on North Pacific climate and ocean indices, there were regime shifts in 1989 and in 1998. Not all North Pacific ecosystems have responded to the 1998 regime shift, however, there is growing evidence that most regional ecosystems have responded in varying degrees to this shift. The 1998 regime shift had the greatest impact in the most southerly regions (*i.e.*, the central North Pacific and the California Current System), less of an impact in the Gulf of Alaska, and little impact in the Bering Sea.

Q2. What is the nature of the new state?

Overall, the new regime since 1998 has a north–south pattern in variability. For example, in the eastern North Pacific, surface waters have cooled in the southern regions, but this effect diminishes northward, and surface waters have continued to warm in the northernmost regions. The dominant atmospheric pressure systems over the North Pacific (the Aleutian Low and the North Pacific High) have intensified which has resulted in greater upwelling-favorable winds along much of the western United States, and greater downwelling-favorable winds off Canada and southeast Alaska. The opposite gradient has occurred in the western North Pacific.

It is important to note that regimes are defined as decadal-scale (at least 10-year) periods, yet there are only 5 years of data available since 1998 with which to assess the new state. In addition, an El Niño event in 2002–03 has complicated the characterization of the new state. Some of the notable oceanographic responses to the 1998 regime shift include:

Central North Pacific – warmer, thicker upper water layer

- abrupt warming of surface waters
- increased sea surface heights
- deepening of the thermocline

California Current System – return to less stratified, cooler conditions

- cooling of coastal waters
- enhanced southward transport of water and organisms
- decreased stratification
- deepening of the thermocline

Gulf of Alaska – return to cooler, stormier conditions

- increased storm intensity
- deepening of mixed layer depth

Bering Sea and Aleutian Islands – no apparent regional response

- continued increase in surface water temperatures
- sea ice extent has continued to diminish

Western North Pacific – pattern of responses opposite to the eastern North Pacific

- harsher winter conditions in the Sea of Okhotsk
- more sea ice in the Sea of Okhotsk
- continued warming of surface waters in southern regions

Q3. What are the ecosystem responses?

Not all North Pacific ecosystems have responded to the 1998 regime shift, however, there is growing evidence that most ecosystems are responding to this shift. The 1998 regime shift had the greatest impact in the California Current System, less of an impact in the Gulf of Alaska, and virtually no impact in the Bering Sea. ***In the southern region of the eastern North Pacific and in the northern region of the western North Pacific, biological production has improved.***

Ecosystem responses to regime shifts are most quickly detectable in lower trophic levels, such as phytoplankton, zooplankton and invertebrates because they reproduce quickly, which makes changes in their population abundance apparent shortly after a regime shift has occurred (usually within a year). However, because these species also respond to year-to-year environmental changes, several years are required in order to distinguish regime changes from interannual variation. In fish populations, the response to regime shifts may not be immediately apparent since any changes in egg, larval or juvenile survival that affect population abundance will often not be measured until that year class is old enough to be caught in surveys or in fisheries. This lag time can range from 2–3 years for fish such as Pacific herring or Pacific sardine, and up to 15 years for some rockfish species. Surveys directed to larval or juvenile fish can be used to detect changes in fish populations sooner, but these types of surveys are not conducted in most regions.

As with regional oceanographic conditions, the biota, or ecosystem communities, of different regions have different responses to regime shifts. Specific ecosystem responses to the 1998 shift include:

Central North Pacific – decreased productivity throughout the food web

- northward shift in the low chlorophyll surface waters (Transition Zone Chlorophyll Front)
- decrease in the survival of monk seal pups in the northern atolls of the Northwestern Hawaiian Islands
- eastward shift in the summer albacore tuna troll fishing grounds from predominately oceanic waters to coastal waters, indicating a shift in tuna distribution

California Current System – increased productivity

- increase of phytoplankton biomass in both amount and seaward extent
- increase in zooplankton biomass throughout the California Current System and a return of community composition to mid-1980 patterns
- improved groundfish reproductive success since 1999
- improved Pacific salmon marine survival since 1999
- largest observed, since 1984, year class of Pacific hake in 1999

Gulf of Alaska – increased productivity in some areas

- increased primary production in British Columbia
- increased Pacific salmon marine survival in British Columbia
- increase in shrimp abundance in northern Gulf of Alaska in 1998–2001
- strong year class of pollock, Pacific cod and sablefish in 1999

Bering Sea and Aleutian Islands – unchanged productivity conditions

- no detected ecosystem response to the 1998 regime shift

Western North Pacific – variable productivity changes, with some increases in northern regions and no apparent responses in southern regions

- increase in Sea of Okhotsk zooplankton biomass
- evidence of changes in the near-surface fish community with Japanese sardine, previously a dominant species, being replaced by herring, capelin and Japanese anchovy
- marked decrease in walleye pollock biomass in the Sea of Ohkotsk, but still remaining the most abundant species
- no detected ecosystem response to the 1998 regime shift in the southern regions.

Q4. How long can the shift be expected to last?

Earlier regimes have lasted 20 or 30 years, but most recent regimes have lasted only about 10 years. Although one might reasonably expect the current regime to last a decade or more, ***it is currently not possible to reliably predict when a regime will end because we currently lack a good understanding of the mechanisms involved in regime shifts***.

Q5. Is it possible to predict when the regime will shift back, and what indicators should be used to determine when it happens?

The phrase "shift back" implies that for climate, ocean systems and ecosystems there are only two possible states. It is important to note that regimes are not characterized by only two possible states. As such, a regime shift will not necessarily imply a shift back to a previously observed state. ***It is currently not possible to reliably predict when a regime shift will occur*** because the multiple physical and ecological processes that cause regime shifts are presently not understood. Research must continue to investigate the mechanisms and triggers for regime shifts. However, ***it is possible to detect regime shifts soon (*ca.** *5 years) after they have occurred*.

Because they have proven to be reasonable indicators of past regime shifts, ***existing climate and ocean indices should continue to be used as indicators of changes in climate and North Pacific Ocean conditions***. Research must continue to develop and test new indicators such as sea surface height and ocean color from satellites. These may be very reliable indicators because they integrate many processes of ecological importance (thermal structure, circulation, primary production), and satellite technology makes these fields consistently and regularly available.

Monitoring programs to develop indices that are more directly related to the productivity of fish populations should be a high priority. Research should continue on identifying the mechanisms by which climate change produces an ecosystem response. This research is critical if we are to efficiently and quickly recognize the climate signals that cause shifts in marine populations that are of interest to resource managers.

Q6. What are the implications for the management of marine resources?

Including the effects of regime shifts in the management of marine resources is critical to sustaining their productivity. There are numerous examples globally of the undesirable consequences of failing to detect or acknowledge climate impacts on fish populations. ***Agencies need to develop policies with explicit decision rules and the subsequent actions to be taken when there are preliminary indications that a regime shift has occurred. These decision rules need to be included in long-range policies and plans.***

Stock assessment advice should indicate the potential consequences to stock viability of alternate management strategies under different levels of recruitment that would be expected in different regime periods.

Ecosystem changes in response to natural disturbances provide opportunities for some species to persist when there is competition for limited resources. In managed systems, where harvest is controlled, ecosystems will continue to shift and evolve in response to environmental disturbances. The key responsibility for managers is to recognize that human exploitation may exacerbate the effects of these natural disturbances. Managers should also recognize that the lifespan of species may have evolved in response to decadal patterns of variability. Short-lived species are able to rapidly expand and re-colonize regions when favorable environmental conditions occur. In contrast, long-lived species may rely on having several years to produce young, which allows their populations to endure long (decadal) periods of poor ocean conditions. These survival strategies require different management responses.

In the case of short-lived species that exhibit a short lag time in their recruitment responses to climate shifts, stock assessment scientists have a high probability of detecting the processes that influence production. Assessment scientists must incorporate these processes into their assessment advice. Stock projections can be conducted using best estimates of 5- to 10-year climate regimes to directly incorporate environmental forcing in advice to managers. Minimum stock size thresholds may be the best protection for short-lived species. It might mean that there are prolonged periods when no directed harvest is possible.

In the case of long-lived species, the response of the spawning stock biomass to regime shifts will be slower. For these species, annual recruitment is only a fraction of the spawning stock biomass, and longevity ensures a relatively long reproductive cycle, enabling populations to endure prolonged periods of unfavorable environmental conditions. In addition to minimum stock size thresholds, maintaining a diverse age-structure in spawning stock biomass should be a paramount management goal for long-lived, late-maturing species.

Overall Recommendations

Given the importance of regimes to ecological systems, we provide four recommendations for incorporating regime shift concepts into fishery management activities:

1. accept the regime concept for marine ecosystems – a wealth of historical evidence suggests regime shifts are a natural and recurring part of marine ecosystems;
2. develop and maintain a comprehensive observational program to monitor state changes in climate, ocean systems and ecosystems;
3. develop climate indices to aid ecosystem monitoring efforts, and support research efforts into linking those climate indices to predictable parts of the climate system (*e.g.*, variability in the El Niño Southern Oscillation);
4. make use of integrated stock assessments, wherein various future regime scenarios can be evaluated to assess the vulnerabilities of fisheries and ecosystems, and to conduct risk analyses for different management strategies.

1. Decadal-scale Climate Events

Lead Author: Franklin Schwing

Contributing Authors: Harold Batchelder, William Crawford, Nathan Mantua, James Overland, Jeffrey Polovina, and Jin-Ping Zhao

Summary

Statistical analyses of Pacific Ocean and atmosphere fields for the twentieth century have revealed spatial patterns that remain steady for 10 or more years (regimes), then shift to another pattern within a few years (regime shifts). The new pattern could be the "reverse" of the previous one (a phase change, where anomalously cool regions turn warm, warm regions become cool, etc.*), or a totally new spatial pattern. Thus North Pacific regime shifts project onto multiple spatial patterns, and in some cases are manifested as phase changes in these patterns.*

Around 1989, the atmospheric forcing of the North Pacific underwent a sharp change indicative of a shift to a new spatial pattern (not simply a phase change in a spatial pattern) from that which had dominated since 1977. Anomalies in sea surface temperature evolved rapidly to a state with a spatial pattern that did not reflect the classic two-phase mode of the Pacific Decadal Oscillation. The new spatial pattern had a north–south distinction with sea surface temperatures remaining warm in the California Current System, but cooling in the Gulf of Alaska and Bering Sea. In 1998, this pattern changed phase and since then the dominant temperature pattern has featured moderately warm anomalies in the central and western regions, substantially cooler anomalies in the California Current, slightly warmer anomalies in the eastern Gulf of Alaska and extremely warm anomalies in the Bering Sea.

The decadal-scale variability documented by ecosystem and climate observations is also found in paleo-records, suggesting that regime shifts are a natural feature of North Pacific climate and marine ecology. Mechanisms for regime shifts are not known, and the statistical properties of observed climate indices can be reproduced by different models, each with different mechanistic assumptions. Sudden shifts in atmospheric forcing are linked to rapid changes in upper ocean conditions. The North Pacific climate forcing interacts with the dominant physical processes in each region, which leads to different regional responses in both ocean state and ecosystem structure.

Forecasts of interdecadal North Pacific climate and associated ecosystem shifts are now impractical because we lack well-validated models and a mechanistic understanding for interdecadal climate variations. However, given the importance of regimes to ecological systems, we provide four recommendations for incorporating regime shift concepts into fishery management activities:

1. *accept the regime concept for marine ecosystems – a wealth of historical evidence suggests regime shifts are a natural and recurring part of marine ecosystems;*
2. *develop and maintain a comprehensive observational program to monitor state changes in climate, ocean systems and ecosystems;*
3. *develop climate indices to aid ecosystem monitoring efforts, and support research efforts into linking those climate indices to predictable parts of the climate system (*e.g.*, El Niño–La Niña Southern Oscillation);*
4. *make use of integrated stock assessments, wherein various future regime scenarios can be evaluated to assess the vulnerabilities of fisheries and ecosystems, and to conduct risk analyses for different management strategies.*

1.1 Introduction

This section is organized as follows. First, the recent physical conditions of the North Pacific are described. We consider this to be the atmospheric forcing and ocean conditions since 1998, when a broad-scale climate regime shift in the North Pacific appears to have occurred (Schwing and Moore 2000; Bograd *et al.* 2000; Peterson and Schwing 2003; Bond *et al.* 2003). Next, we describe changes over the past several decades (the reasonable course of available observational data), to place the recent state of the North Pacific in the context of historical temporal and spatial patterns related with their characteristic time scales. A brief discussion of longer-term proxy climate records (*e.g.*, sediment cores and tree rings) is also included. From this large-scale description of decadal climate variability, we describe distinct aspects of decadal change in its major coastal ecosystem regions. Finally, a discussion of potential mechanisms by which climate variability and regime shifts may occur is offered, both as a status report of our current level of understanding and to set the stage for future projections of the region's climate state. These are based on the body of climate research that includes a broad range of data analyses and a spectrum of simple to complex models.

1.2 Basin-scale Patterns

Present state of the North Pacific

Because climate variability, including regime shifts, is due to global processes, the signals of this variability often have a coherent basin-wide pattern in the North Pacific. In turn, regional and local coastal processes modulate larger-scale changes. Regionally distinct surface (wind and heat fluxes) and buoyancy (freshwater inflow) forcing interact with topography to create regional differences in seasonal conditions, and in the timing, location, and strength of characteristic regional-scale processes and features such as fronts, upwelling plumes, and eddies. Climate forcing interacts with each process differently, leading to unique regional responses in both ocean state and ecosystem structure. We initially describe recent conditions in the greater North Pacific, and subsequently place regional differences in this context.

In the mid-1970s, the Pacific climate shifted rapidly and dramatically, with the North Pacific becoming dominated by anomalously low sea level pressures (SLPs) (Fig. 1.1, top left panel). Changes in atmospheric conditions – principally surface fluxes of heat and momentum associated with the changes in the atmosphere – contributed to a pattern of unusually warm, upper-ocean temperatures throughout the northeastern Pacific, a pattern now recognized as the positive phase of the Pacific Decadal Oscillation (PDO) (Mantua *et al.* 1997). Around 1988, the atmospheric forcing of the North Pacific underwent another sharp change. The winter Aleutian Low pressure system switched to a weaker-than-normal state (positive anomaly). However, atmospheric forcing maintained anomalously weak upwelling along the North American west coast. Sea surface temperature (SST) anomalies evolved rapidly to a state that did not resemble the PDO SST pattern. SSTs remained warm along the west coast, but switched to cool anomalies in the Gulf of Alaska (GOA) and Bering Sea. The Northwest Pacific reversed from a negative to positive SST anomaly.

From 1999–2002, the dominant SST anomaly pattern in the North Pacific featured moderately warm anomalies in the central and western regions, extremely warm anomalies in the Bering Sea, and cooler than normal ocean conditions east of the dateline and north of about 40°N (Fig. 1.1, bottom panels). SST anomalies in the eastern GOA were weakly positive during this period. This pattern of ocean temperature anomalies has been consistent throughout the upper 200 m of the water column. Climate changes in 2002–03 (likely linked to the 2002–03 tropical El Niño event) disrupted the SST anomaly pattern seen in the previous 4 years, yet this pattern remained relatively robust below the mixed layer (Fig. 1.2). As will be discussed later, the dominant pattern of SST variability in 1990–2002 was fundamentally different from the PDO pattern that captured much of the interdecadal SST variance from the 1950s through to the 1980s.

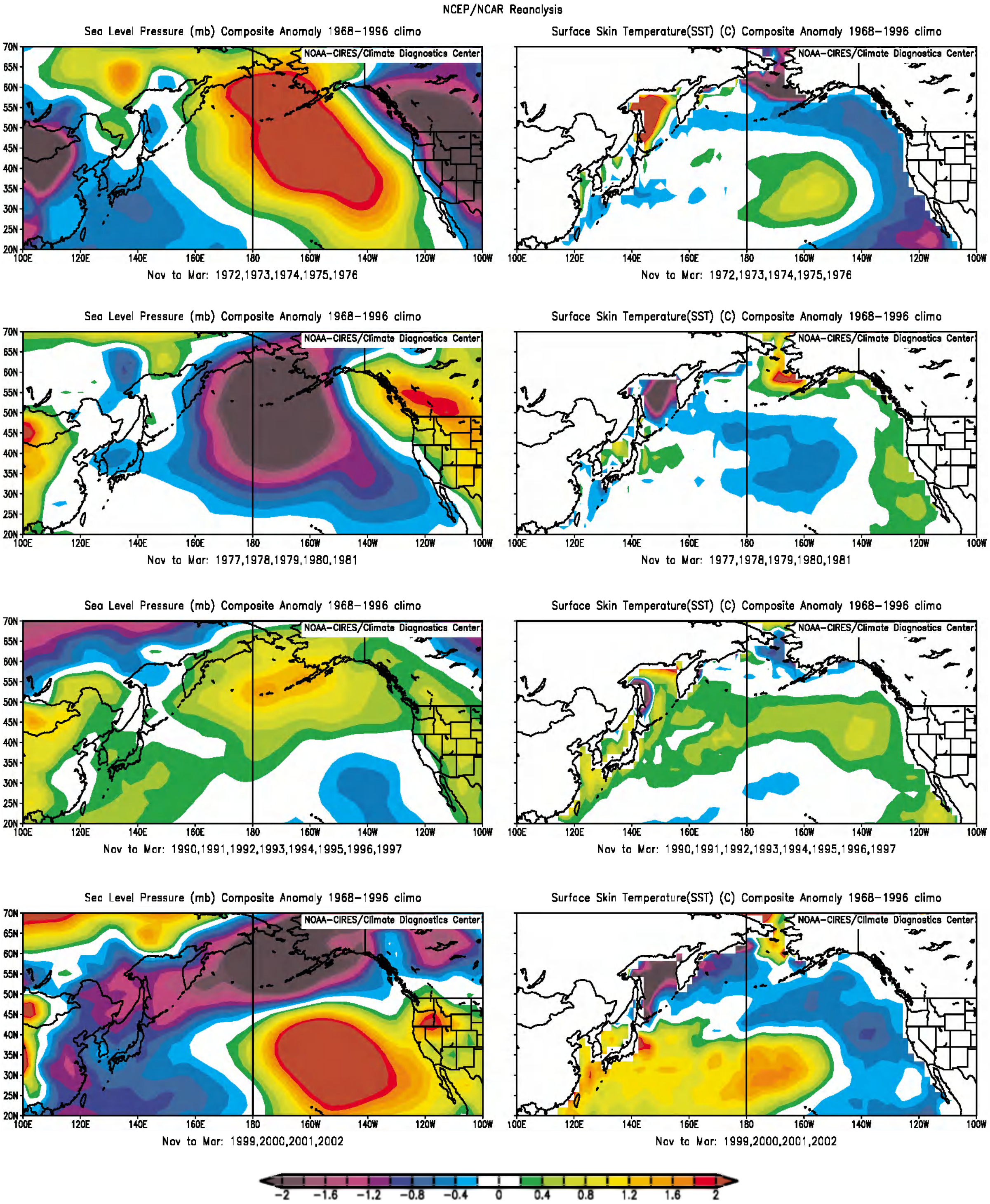


Fig. 1.1 Composite of mean winter (Nov–Mar) anomalies of sea level pressure (left side) and sea surface temperature (right side) for: 1972–76 (top panels), 1977–81 (second panels), 1990–97 (third panels), and 1999–2002 (bottom panels). After the 1977 regime shift (second panels), the whole North Pacific was dominated by low sea level pressures (intense Aleutian Low) and warm surface temperatures throughout the Northeast Pacific. The 1998 regime shift (bottom panels) has resulted in a reintensification of the Aleutian Low and the North Pacific High pressure systems and cooler waters in the eastern North Pacific.

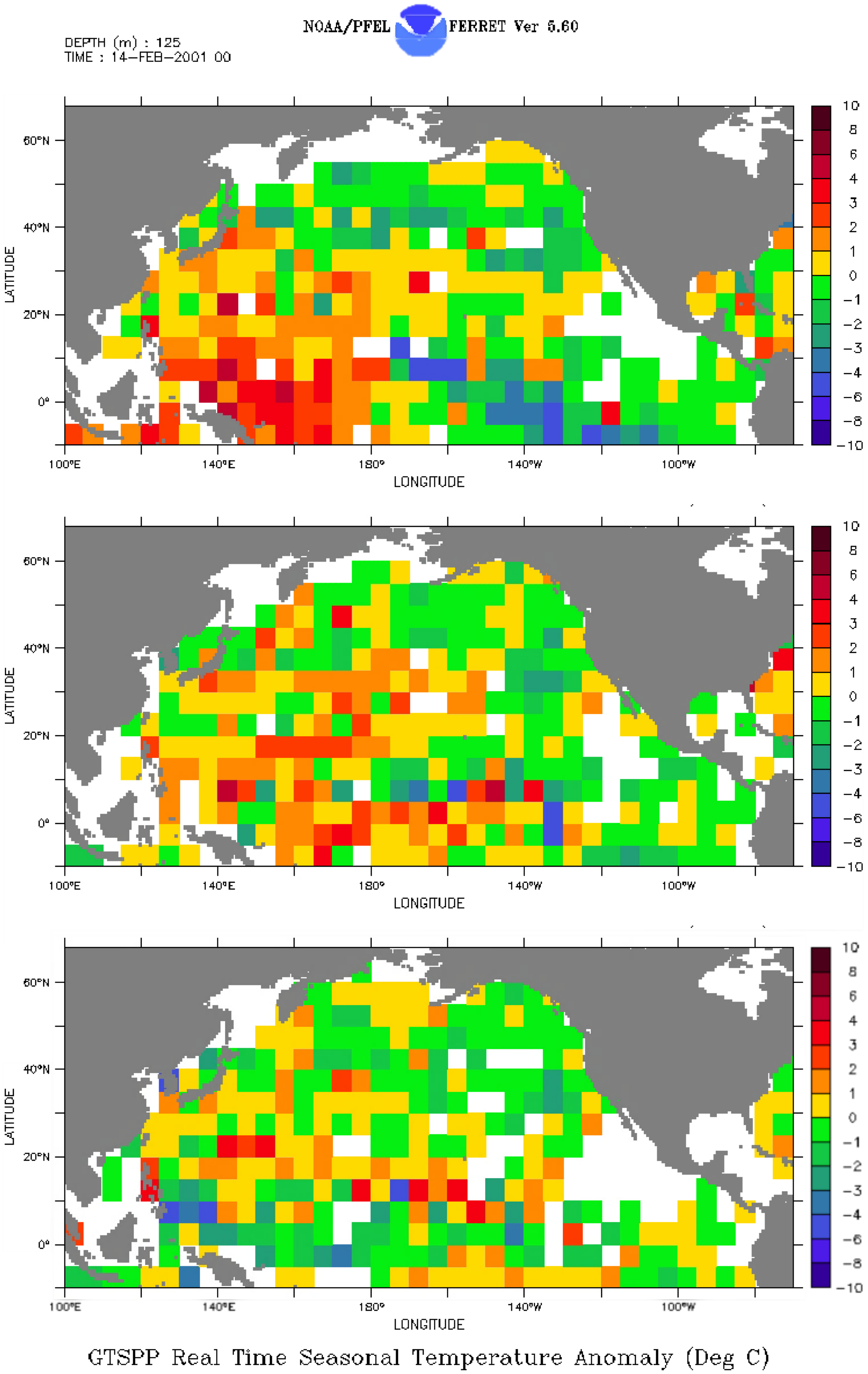


Fig. 1.2 February anomalies of 125 m depth ocean temperature (°C) for 2000, 2001, and 2002 (top to bottom). This subsurface temperature pattern has persisted into 2004 despite the disruption of similar surface temperature patterns due to the 2002–03 El Niño event.

Previous studies indicate that the upper ocean in the North Pacific is strongly coupled with atmospheric forcing (Polovina *et al.* 1994, 1995; Miller *et al.* 1994; Miller and Schneider 2000; Parrish *et al.* 2000; Huang and Liu 2001). Thus it is no surprise that the atmosphere also has exhibited a distinct pattern since 1998 that differs dramatically from prior years (Peterson and Schwing 2003; Bond *et al.* 2003). The dominant atmospheric forcing features over the North Pacific – the Aleutian Low and North Pacific High – were both intensified from the long-term mean (Fig. 1.1). The surface wind stress pattern included intensified cyclonic (counter-clockwise) winds about the Low as well as anti-cyclonic winds about the High, and stronger-than-normal eastward stress across much of the central North Pacific. From a coastal perspective, this resulted in greater upwelling-favorable winds along much of the western United States, and greater downwelling off western Canada and southeastern Alaska. In addition to the local, direct influences on coastal conditions by wind-driven ocean processes like upwelling, this shift in large-scale atmospheric forcing contributes to changes in the magnitude and nature of the boundary currents (*e.g.*, the California and Alaska Currents), including source water mass characteristics, the biological effectiveness of coastal upwelling, and the formation of biologically-important ocean features such as eddies.

Sea surface height (SSH)

From a basin-scale perspective, it appears that the dominant climate mode of the North Pacific changed in the late 1980s, leading to new ocean temperature and circulation anomaly patterns. The physical organization of the upper ocean since 1998 has had a relatively distinct character from the long-term mean. This may be a first criterion for defining this period as a distinct climate regime. Later in this section we will compare this pattern to conditions in the available observational record (50–100 years), and to the objectively determined modes of the North Pacific system over that historical time frame. The relatively short duration of the instrumented record – relative to the multi-decade time scale of regime shifts – along with the present lack of a mechanistic understanding for decadal climate variations, will be shown below to be a limitation.

Sea surface height (SSH) estimated with satellite altimetry is a useful indicator of temporal and spatial changes in large-scale ocean transport and vertical structure, especially changes in the depth of the thermocline, which may have important ecosystem implications. While these satellite-based series are short (1992 to the present), they provide a useful integration of the North Pacific variability. In particular, the mid-latitudes experienced an abrupt warming, and deeper thermocline from 1999 through 2002 that appeared to be reversing in early 2004. However, in the eastern and northern North Pacific a drop in SSH in 1999 has persisted through the present, suggesting a regime shift, although conditions may be returning to baseline levels in the eastern North Pacific. Furthermore, regional differences show that while the 2002–03 El Niño was weak in the equatorial region, it was relatively strong in the eastern North Pacific.

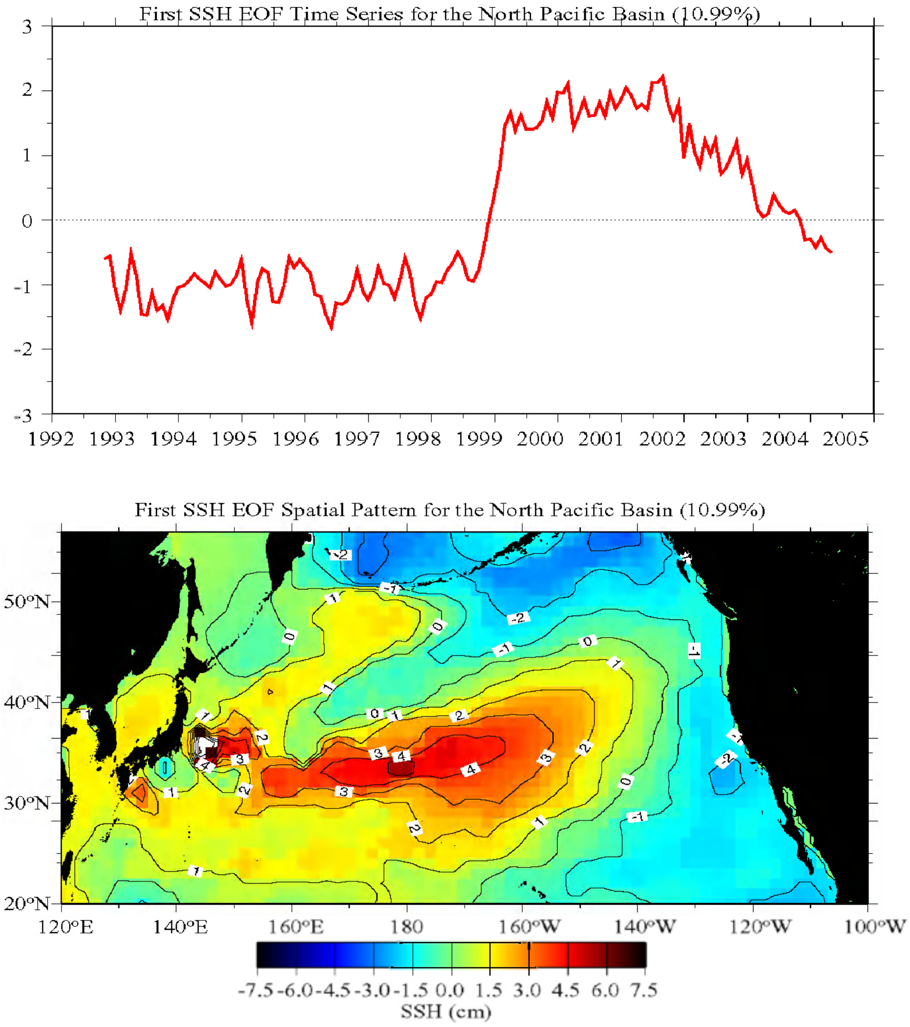
The leading empirical orthogonal function (EOF) mode of SSH for the entire basin highlights the North Pacific clockwise circulation, and accounts for about 11% of the total variance. This indicator identifies an abrupt increase in SSH in the central North Pacific in 1999 (Fig. 1.3). This represents an increase in heat content, stratification, and depth of the top of the thermocline, and a likely increase in Kuroshio Extension transport and in the clockwise basin flow. The change persisted for several years, but by 2004 conditions returned to baseline levels, perhaps reflecting the impact of the strong 1999 La Niña rather than a regime shift (Fig. 1.3).

To capture important regional dynamics in SSH, the first SSH EOF is shown for four regions of the North Pacific (Fig. 1.4). In the equatorial region, the first SSH EOF captures 36% of the monthly SSH variation with a spatial dipole pattern where the eastern and western Pacific vary in an opposite manner (Fig. 1.4a). This SSH EOF is basically an El Niño indicator but, because it is based on SSH rather than SST or atmospheric pressure, it better describes changes in vertical structure and geostrophic transport than the more traditional indices. During the strong 1997–98 El Niño, the SSH in the western tropical Pacific dropped by as much as 28 cm and in the eastern tropical Pacific, rose by 28 cm. However, the 2002–03 El Niño had a much weaker impact on equatorial SSH.

The next regional indicator, the first SSH EOF from the mid-latitude region, defined as 20°–45°N latitude, captures 11% of the monthly SSH variation (Fig. 1.4b). It is virtually identical to the first EOF for the entire basin (Fig. 1.3).

The third regional indicator is the first SSH EOF from the eastern North Pacific (20°–60°N latitude) and explains 28% of the monthly SSH variation (Fig. 1.4c). This indicator shows a sharp and more persistent change in SSH in 1999, interrupted by the relatively strong mid-latitude 2002–03 El Niño. The drop in SSH in the California Current indicates a shoaling of the top of the thermocline.

The fourth regional indicator is the first SSH EOF for the GOA and Bering Sea (north of 45°N latitude) and explains 21% of the monthly SSH variation (Fig. 1.4d). SSH in this region declined more gradually than in the eastern North Pacific, beginning in 1999. This was minimally impacted by the 2002–03 El Niño and persists through 2004.


First SSH EOF Time Series for the North Pacific Basin (10.99%)

First SSH EOF Spatial Pattern for the North Pacific Basin (10.99%)

Fig. 1.3 First sea surface height (SSH) empirical orthogonal function (EOF) time series and spatial pattern for the North Pacific. An abrupt change is evident in 1999 and characterizes a rise in SSH in the central North Pacific. This rise represents an increase in heat content, an intensification in stratification and a deepening of the thermocline.

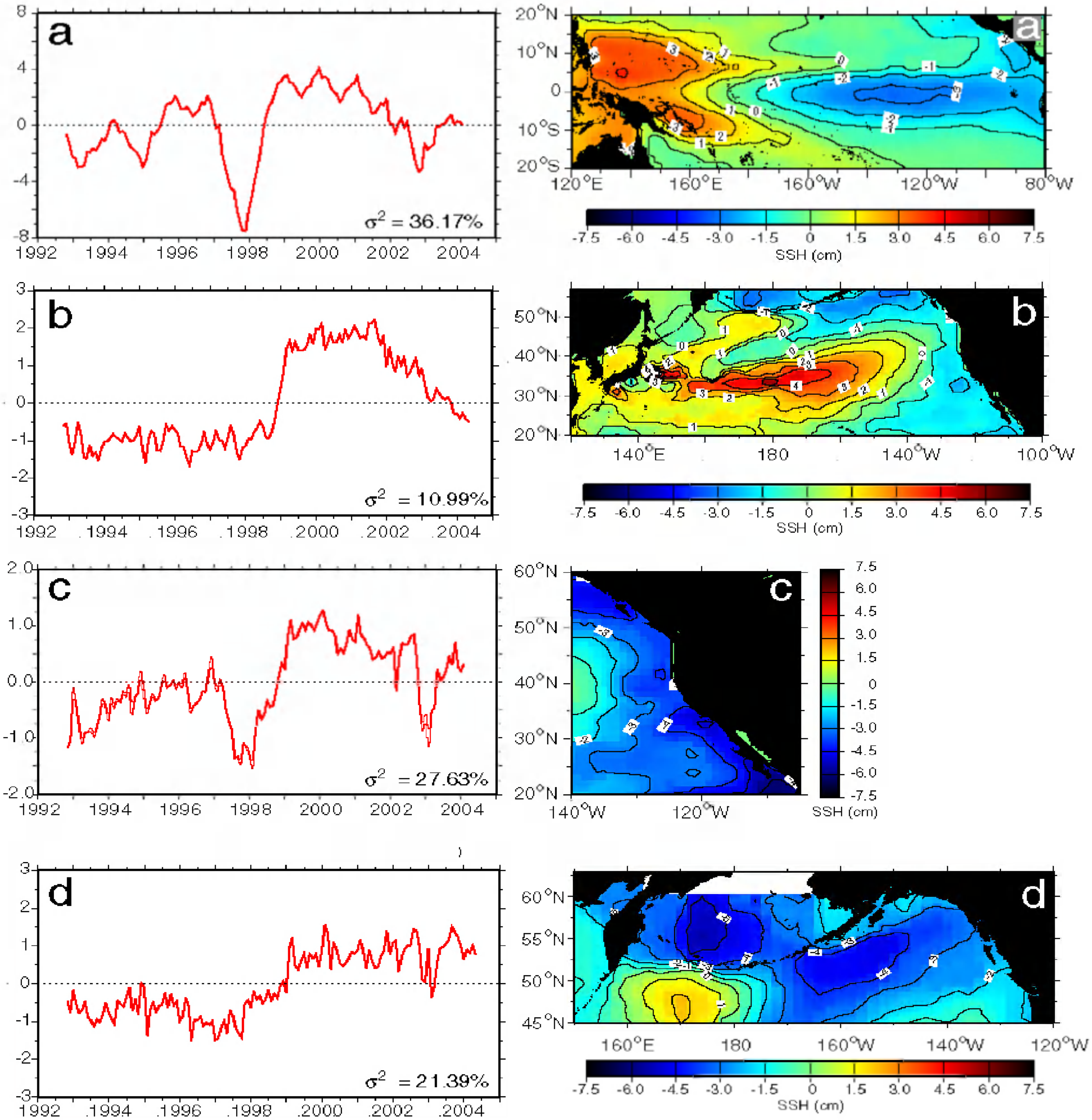


Fig. 1.4 First sea surface height (SSH) empirical orthogonal function (EOF) time series and spatial patterns for the North Pacific regions: (a) equatorial, (b) mid-latitude, (c) eastern and California Current, and (d) northern, including the Gulf of Alaska and Bering Sea. Following the 1998 regime shift, all regions exhibited a sharp change in SSH: the central and western mid-latitude North Pacific underwent a sharp rise; the eastern and northern North Pacific underwent a sharp decline. The 2002–03 El Niño event disrupted these patterns in each of the four regions shown here, but only the mid-latitude North Pacific (panel b) has not returned to pre-El Niño conditions.

Comparing the first two EOF modes of SSH for the Northeast Pacific (25°–60°N, east of 160°W) details the recent evolution of the California and Alaska Currents (Fig. 1.5). The first EOF shows the North Pacific and Alaska gyres changing out of phase over time. In 1998, the northward Alaska Current and southward California Current both strengthened rapidly. This reversed again during the 2002–03 El Niño. The second SSH EOF indicates the entire coastal sea level rising rapidly during the 1997–98 El Niño, then declining steadily. The implication of this indicator is that the California Current has been gradually increasing from 1999 until at least late 2002, while the Alaska Current declined during this period.

Individual years since 1998 display significant interannual differences. The most notable is the impact of the 2002–03 El Niño, which created warm anomalies in the upper mixed layer along most of the North American west coast. However, this degree of interannual variability is typical for the instrumented record of the North Pacific, and is apparent within previously defined climate regimes. There is some evidence that aspects of ecosystem structure are relatively insensitive to these year-to-year physical perturbations, compared to the apparent dramatic shifts associated with interdecadal regime shifts, although this remains an important interaction for further study.

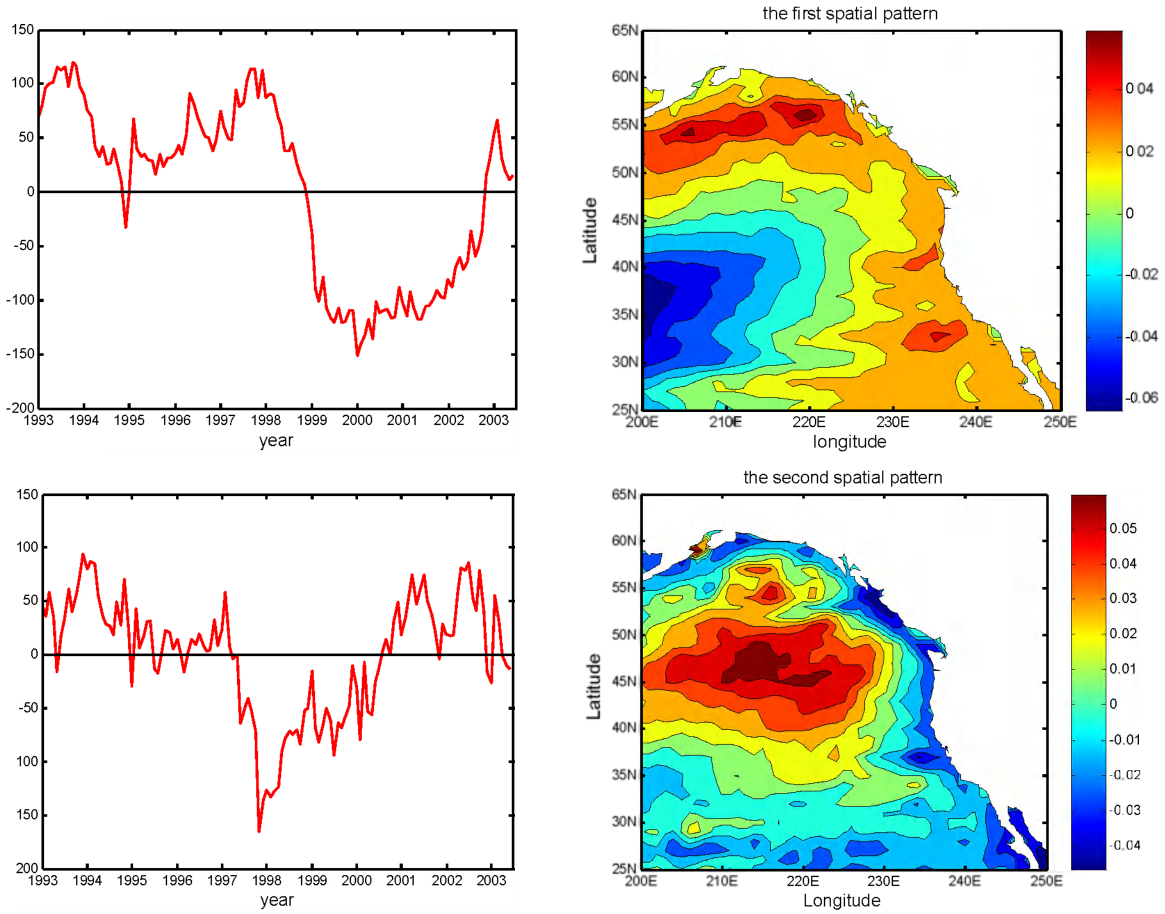


Fig. 1.5 First and second sea surface height (SSH) empirical orthogonal function (EOF) time series (left panels) and spatial pattern (right panels) for the Northeast Pacific. The first EOF shows the North Pacific and Alaska gyres changing out of phase over time. In 1998, the northward Alaska Current and southward California Current both strengthened rapidly. This reversed again during the 2002–03 El Niño. The second SSH EOF indicates the entire coastal sea level rising rapidly during the 1997–98 El Niño, then declining steadily. The implication of this indicator is that the California Current has been gradually increasing from 1999 until at least late 2002, while the Alaska Current declined during this period.

Impact of atmospheric pressure systems on temperatures in the Northeast Pacific

Much of the decadal variability in North Pacific Ocean conditions is explained by overlying wind patterns; persistent winds over many years set up an ocean state that can shift within a year should the winds change. The shift can be sudden, as observed in 1998–99, partly due to release of wind energy stored in the ocean and held in place by persistent winds. The thermal and momentum inertia of the ocean can store energy from atmospheric shifts, in essence retaining a long memory of past climate changes. In these ways, the extratropical North Pacific is coupled with, and shares, the features of the El Niño response of the equatorial Pacific Ocean.

Figure 1.1 explains some of the recent unusual features of the North Pacific. The left panels show persistent SLP anomalies in winter for a series of years, which represent the large-scale atmospheric forcing of the upper ocean; the right panels show the SST anomalies for the same periods. The winds of 1972–76 represent the cold phase of the PDO, with cool winds blowing from the northwest or, more likely, weaker winds blowing from the southeast along the west coast of North America. These conditions cooled the waters along Line-P (a line of regularly occupied oceanographic stations from Juan de Fuca Strait to 50°N, 145°W, Figs. 1.6–1.7). Stronger upwelling-favorable winds in summer contributed to cooler coastal temperatures (Fig. 1.1, top panels). In addition, the effect of the 1972–73 El Niño did not extend far northward along the west coast, so this El Niño created barely a blip in Line-P temperatures.

Following the 1976–77 El Niño, the winter Aleutian Low shifted to the warm phase of the PDO, which lasted almost to the end of the 1980s (Fig. 1.1, second panels). The pressures of 1977–81 winters display this pattern, almost the reverse of the cool phase that preceded it. During this period the warm winter storm winds from the south were accelerated, warming waters along Line-P. Tropical El Niño events often deepen the Aleutian Low further, increasing the winds even more. For this reason, the warm phase of the PDO enhances El Niño warming in the GOA. Weaker upwelling led to warm SST anomalies along the west coast.

In the 1990s, a new atmospheric pattern developed, referred to here as the "Victoria" pattern. SLP anomalies identify simultaneously a weak Aleutian Low and a weak North Pacific High, rather than the PDO pattern of a single SLP anomaly over the entire North Pacific. The SST anomaly pattern was also different from the PDO pattern. Weak upwelling winds resulted in warm coastal SSTs off the mainland United States. Upper ocean temperatures along Line-P were elevated while SSTs in the Bering Sea and GOA were slightly cooler than normal, possibly because of stronger northerly winds from the Arctic.

Following the strong 1997–98 El Niño, North Pacific SLP anomalies reversed again. The winters of 1999–2002 experienced higher than normal pressure in the North Pacific High (Fig. 1.1 bottom panels). Much of the GOA saw a deeper Aleutian Low, centered closer to the Aleutian Islands than in the previous cool phase. This mode of circulation has been observed previously, but it was unusually strong in this period, and represents the positive phase of the Victoria pattern.

The anomalous winds from the south and the effects of the 1997–98 El Niño contributed to warmer waters far to the north. Along the North American west coast, sea level heights in this winter were at record levels, exceeding those of the 1982–83 El Niño. Sea levels dropped within a few days at the end of February 1998 all along the Canadian and United States west coast, and did not return to the highs of the previous winter. This quick response indicates that persistent winds build up pressure gradients in the ocean that can be quickly released as the anomalous winds die out.

The west coast waters of North America shifted rapidly in late 1998, cooling dramatically as northerly winds led to extremely strong upwelling (Schwing and Moore 2000). Open ocean upwelling during winter cooled waters in the GOA. The waters likely flowed out, away from the center, and eventually sank below warmer waters in summer. Crawford *et al.* (in press) have shown that in the winter and spring of 2002 the anomalously cold waters at 120 m depth between the North Pacific High and Aleutian Low flowed almost due east, creating the record cold temperatures on deep coastal waters noted earlier. The large-scale impacts of this atmospheric pattern may have included a stronger North Pacific Current flowing toward the coast, suggested by SSH anomalies (Fig. 1.4b,c), which brought more subarctic water into the California and Alaska Currents.

SST anomalies of the Victoria mode faded in 2002–03, possibly in conjunction with the tropical El Niño, and North Pacific SLPs featured an anomalously intense Aleutian Low, a pattern that is associated with both El Niño winters and the warm phase of the PDO. Anomalously strong winds from the south along the North American coast created warmer near-surface coastal waters, but this warming failed to penetrate below 100 m depth, leaving cold anomalies along Line-P at 100 to 150 m below the surface.

Climate indices

Large-scale climate indices are useful integrators or proxies of environmental variability important to ecological conditions. There are several climate indices that help identify the historical interdecadal variability of the North Pacific, and support the idea of abrupt climate shifts toward different states. A fundamental conclusion from these indices is that no single index can adequately relate the complexities of climate variability in the diverse physical and ecological regions of the North Pacific. This is particularly true when relating climate to marine populations and ecosystem structure, since physical–biological coupling is likely to be non-linear, and the biological response integrates many physical signals from a number of time and space scales and sources.

The leading pattern of twentieth century North Pacific SST variability, the PDO, has exhibited significant interdecadal variations over the past century. Minobe (1999) used wavelet analysis of the PDO index and an index for the Aleutian Low to identify enhanced spectral power at periods around 15–25 (~bidecadal) and 50–70 (~pentadecadal) years. The pentadecadal time scale was evident in both spring and winter PDO and Aleutian Low indices, and was suggested to provide the basic time scale for proposed PDO-related regime shifts in North Pacific climate in the 1920s, 1940s, and 1970s.

Figures 1.6 and 1.7 show how subsurface temperature anomalies at depth vary over time compared to three climate indices: the PDO, the Multivariate El Niño–Southern Oscillation (ENSO) Index (MEI) by Wolter and Timlin (1998) that describes El Niño and La Niña activity in the tropical Pacific, and the Northern Oscillation Index (NOI) by Schwing *et al.* (2002a) that captures aspects of both interannual and decadal variability in the extratropical Northeast Pacific. Figures 1.6a–c all reveal a shift in the late 1970s from a cold to warm regime. The warm regime lasted until the late 1980s, with warming at depth beginning in the early 1970s, prior to the abrupt shift in SST. The cold episode of the late 1980s is La Niña (Fig. 1.6c), and is followed about 2 years later by cold waters at 100–150 m depth along Line-P. The PDO was cold throughout most of these 3 years. Both the PDO and MEI shift to their cold phase after 1998, but the cold temperature anomalies along Line-P, which appear near the surface in 2001, take a few years to reach subsurface regions.

Figure 1.7 illustrates temperature anomalies in the same manner along line-P, but for winter temperatures in the upper 100 m, and without the NOI. In this case the MEI and PDO climate indices align in time with changes in Line-P temperatures. Interestingly, the El Niño events of the 1970s had little impact on Line-P temperatures, likely due to the presence of a cold phase of the PDO. The cold anomaly has persisted at 120 m in the 2003–04 winter.

In summary, Figures 1.6 and 1.7 show that the upper 50 to 100 m of the ocean west of southern Vancouver Island respond quickly to El Niño and decadal changes, but cooling of subsurface water at 100–150 m follows La Niña events by 1 to 3 years. The mechanisms linking upper ocean temperature variability at Line-P with ENSO and PDO variability are presented later in this report.

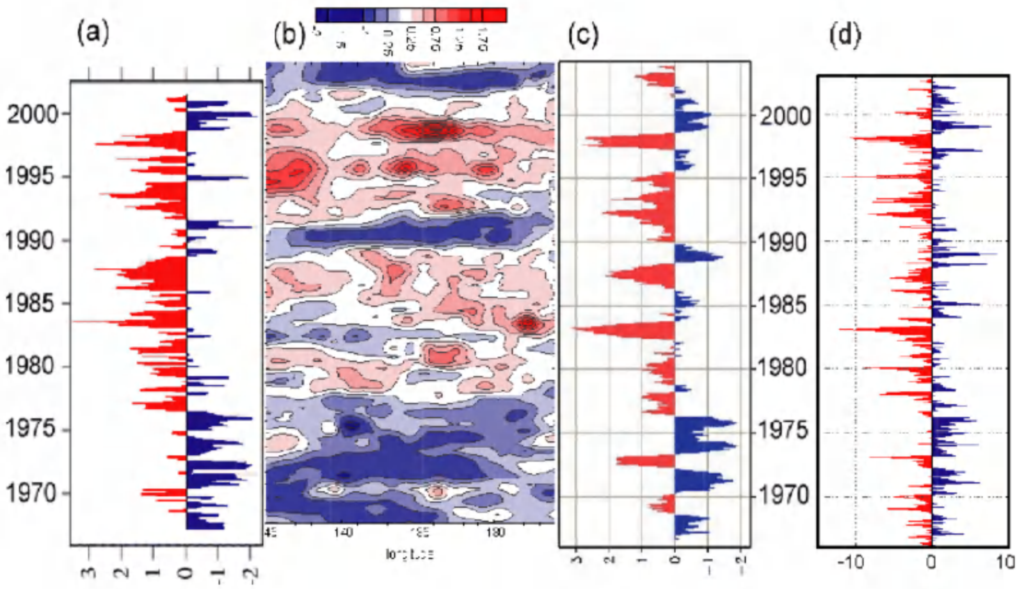


Fig. 1.6 (a) Standardized Pacific Decadal Oscillation (PDO). Red denotes Warm phase; blue denotes Cool phase. (b) Summer temperature anomalies (100–150 m depth averaged). Temperature contours represent the deviation of this vertical average from the temporal mean over the years plotted. Horizontal axis represents distance along Line-P; vertical axis is date. (c) Multivariate El Niño–Southern Oscillation (ENSO) Index (MEI). Red denotes El Niño conditions; blue denotes La Niña. (d) Northern Oscillation Index (NOI). Red denotes El Niño and decadal-scale warm conditions; blue denotes La Niña and other cooling conditions. Subsurface temperatures can vary over time with both decadal-scale variability related to regime shifts and interannual variability related to El Niño and La Niña events. Subsurface cooling appears to lag surface La Niña events by 1 to 3 years.

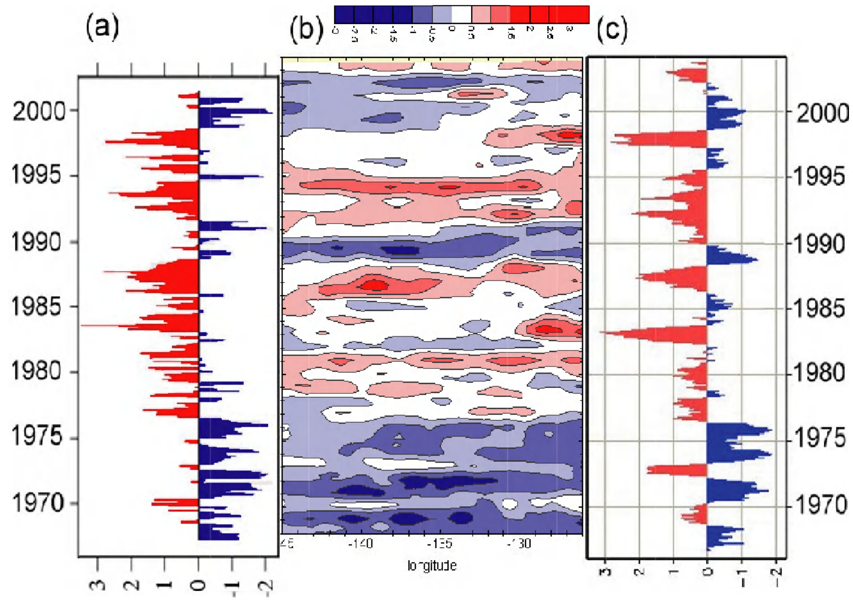


Fig. 1.7 (a) Pacific Decadal Oscillation (PDO) as in Figure 1.6. (b) Winter ocean temperature anomalies averaged over the upper 100 m depth. Otherwise as in Figure 1.6. (c) Multivariate ENSO Index as in Figure 1.6. The upper ocean waters can respond quickly to interannual (El Niño–La Niña) and decadal changes in the atmosphere. Surface ocean temperature variations do not always reflect subsurface anomalies (*cf.* Fig. 1.6).

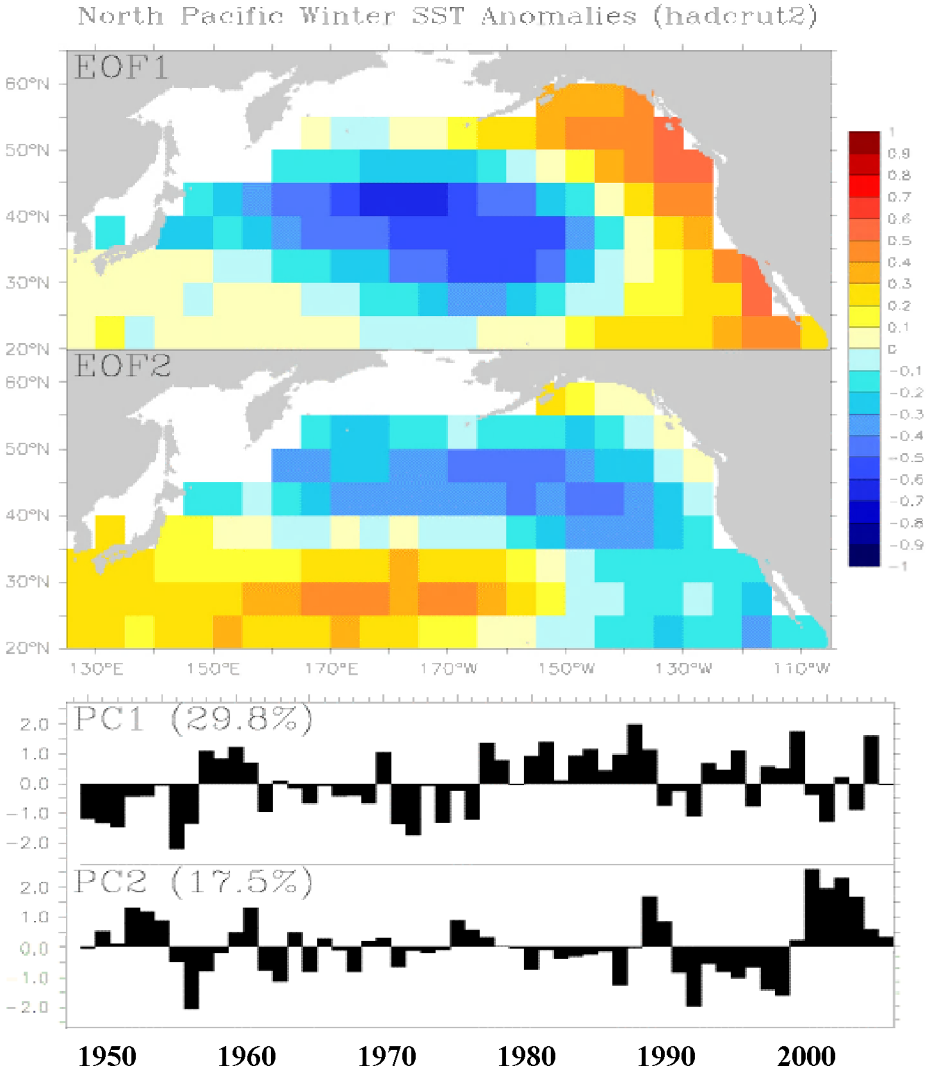


Fig. 1.8 Principal component analysis of North Pacific winter (November–March) sea surface temperature (SST) fields north of 20°N, for 1950–2003. The first empirical orthogonal function (EOF1) (top panel) corresponds to the Pacific Decadal Oscillation (PDO) pattern and its time evolution is given by principal component 1 (PC1). The evolution of the second empirical orthogonal function (EOF2) pattern shows large magnitudes since the 1990s, with a shift to large positive values for 1999–2002 (PC2) (from Bond *et al.* 2003). The classic mode of the PDO (EOF1 and PC1) has two phases (positive and negative) of its east–west spatial pattern and has been the dominant classification of regimes until 1989. The second pattern (EOF2 and PC2) is a north–south spatial pattern that is referred to as the Victoria mode. The 1989 regime shift was a shift to this spatial pattern, and the 1998 regime shift was a shift in the phase of this pattern.

While atmosphere and ocean conditions in the California Current System (CCS) region since 1998 have been similar to the cool, high biological productive state influenced by an anomalously strong North Pacific High prior to the mid-1970s (Peterson and Schwing 2003), physical conditions in the GOA, Bering Sea, and Sea of Okhotsk have remained in a state associated with the period after 1977, dominated by an unusually strong Aleutian Low. Bond *et al.* (2003) conducted a further analysis of winter North Pacific SST anomalies since 1950 and found the leading mode of SST to have a spatial pattern agreeing with the PDO, and explaining the regime shift in the 1970s (Fig. 1.8). The second spatial pattern – referred to as the Victoria mode – captures much of the SST variability between 1990 and 2002, with a distinct phase shift in 1998–99 (Fig. 1.8). The conclusion of this analysis is that abrupt climate shifts occur in the North Pacific, but they display more than one alternating spatial pattern (Figs. 1.8 and 1.9) and are too complex to be explained by a single climate index. At a minimum, we should evaluate the PDO and Victoria modes of long-term SST variability in the North Pacific as independent sources of regime shifts. They may have distinct mechanisms for their development, and different ecosystem impacts.

1.3 Long Time Series in the North Pacific

A limited number of locations in the North Pacific feature persistent and repeated sampling that allow multi-decadal time series of observations to be created. These are vital in providing a long-term context of recent conditions.

California Cooperative Oceanic Fisheries Investigations (CalCOFI)

The CalCOFI surveys of the CCS have been conducted since 1949, making it the longest and most complete multi-disciplinary ocean observational program in the world. The CalCOFI data base is vital for documenting decadal changes in the physics, chemistry and biology of the CCS. Bograd and Lynn (2003) identified abrupt changes in water property and circulation patterns around 1976 and 1998. For example, the upper water column became sharply more stratified after the 1976 regime shift, which reflected both an upper-ocean warming and a deepening of the thermocline.

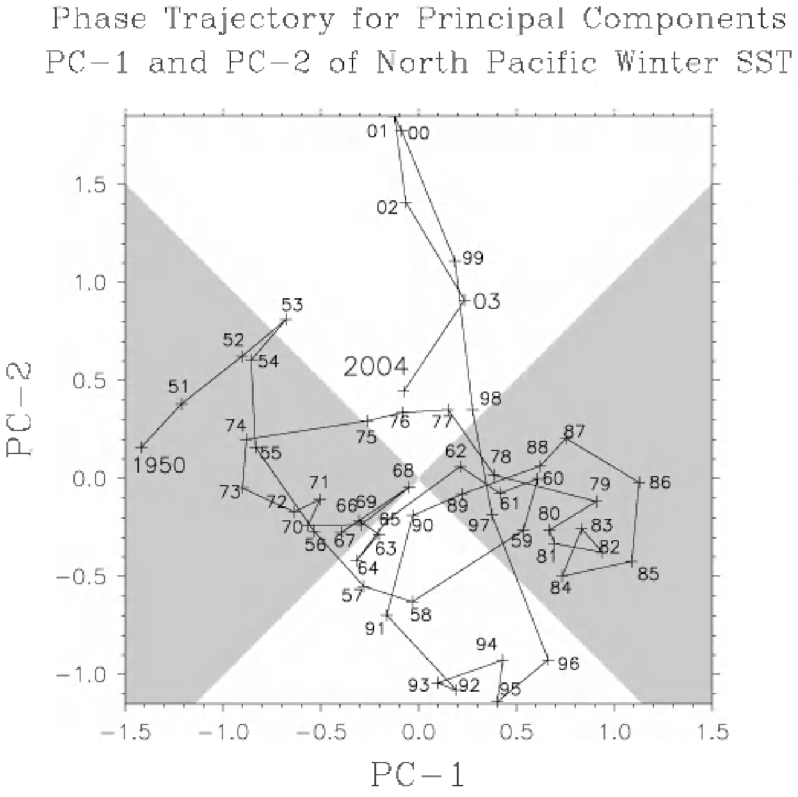


Fig. 1.9 Trajectory of the state of the North Pacific sea surface temperature anomaly (SSTA) in the phase space of the first two principal components, PC1 (abscissa) and PC2 (ordinate) from Figure 1.8. Labels showing years represent 5-year running means except at endpoints, which represent 3-year running means (from Bond *et al.* 2003). Previous to 1988, the major shifts in the spatial patterns of SST were captured by PC1 (of Figure 1.8), but have since been best represented by PC2 (of Figure 1.8).

Water mass properties are influenced by seasonal, interannual, and episodic circulation events. After 1989, the upper water column off southern California experienced an enhanced stratification, reflecting a greater warming of near-surface waters (Fig. 1.10). Stratification in 1999–2001 was anomalously weak in the core of the California Current, and the Southern California Bight's stratification weakened relative to the prior decade. The upper water column has also been cool and fresh relative to the long-term mean for the California Current. One explanation for this is a reduction in the transport of the Undercurrent beginning in 1998, resulting in more subarctic water in the Bight (Schwing *et al.* 2002b). These regime shifts have also been noted in ecosystem organization and productivity (Roemmich and McGowan 1995; McGowan *et al.* 2003; Lavaniegos and Ohman 2003; Rau *et al.* 2003).

Line-P

Line-P is a set of oceanographic stations extending westward from the mouth of Juan de Fuca Strait to Ocean Station Papa in the mid-GOA at 50°N, 145°W. Regular oceanographic sampling began in 1950 from Canadian Weatherships during their transits to and from Ocean Station Papa, and have been continued by Fisheries and Oceans Canada since the 1980s, following the termination of the Weathership program. Three cruises per year take temperature, salinity, nutrient and biological samples along this line, from surface to at least 1500 m depth. The data set provides a unique opportunity to examine changes in water properties between ocean surface and deep waters over 1400 km of ocean in the eastern GOA. It is the only such section in the entire Northeast Pacific Ocean north of California. High-quality, frequent samples extend back to 1968. Refer to Figures 1.6 and 1.7 for the variability along this line.

GAK Line

Long-term data on ocean hydrography are sparse in the northern GOA. Only the GAK1 site (the innermost station on the Seward Line), located near the mouth of Resurrection Bay at 60°N, 149°W and in the core of the Alaska Coastal Current (ACC) has good coverage, both interseasonally and long-term (1970 to the present). Water column temperature and salinity in the northern GOA respond to seasonal changes in heat flux, freshwater input and winds.

Substantial long-term variability in hydrography (both temperature and salinity) is present in the 30-year GAK1 record (Figs. 3 and 4, Royer, in press). Before the 1977 regime shift, temperatures were anomalously colder than normal at all depths (0–250 m) at GAK1 (Fig. 1.11). After 1977, alternating periods of warm and cold temperature anomalies occurred, with warm events most evident at intermediate depths (50–150 m) in 1977, the early and mid-1980s, 1987 and 1992. The largest warm event occurred in 1998, presumably a high-latitude manifestation of the strong 1997–98 El Niño. The warming for all of these events, except the 1998 event, appeared to occur simultaneously at all depths. The 1998 warming was preceded by surface warming in 1997. The lack of sloping isotherms with time suggests that the warm or cool conditions are advected into the region, rather than locally forced by winds, runoff, heating and cooling (Royer, in press). Sea surface temperatures were average or below average at GAK1 and along Line-P during 1999–2002. However, summer 2002 and winter 2003 temperatures were above normal at GAK1 and below average on Line-P (PICES, 2004). A small, but significant, amount of the variance in the upper layer temperature signal occurred at the 5-year period; more of the deeper water variance occurred at this period. Temperature at most depths was positively correlated with the PDO, which suggests that the PDO may be a useful index of GAK1 temperature throughout the water column, not just the SST (Royer, in press). Deep (150 m) water temperature anomalies at GAK1 reflect each of the ENSO events between 1977 and 2000. These responses to the El Niño are likely an alongshore (northward) displacement of the normal coastal temperature gradient. GAK1 temperatures at all depths were positively and significantly correlated with freshwater discharge 1–3 months earlier (Royer, in press).

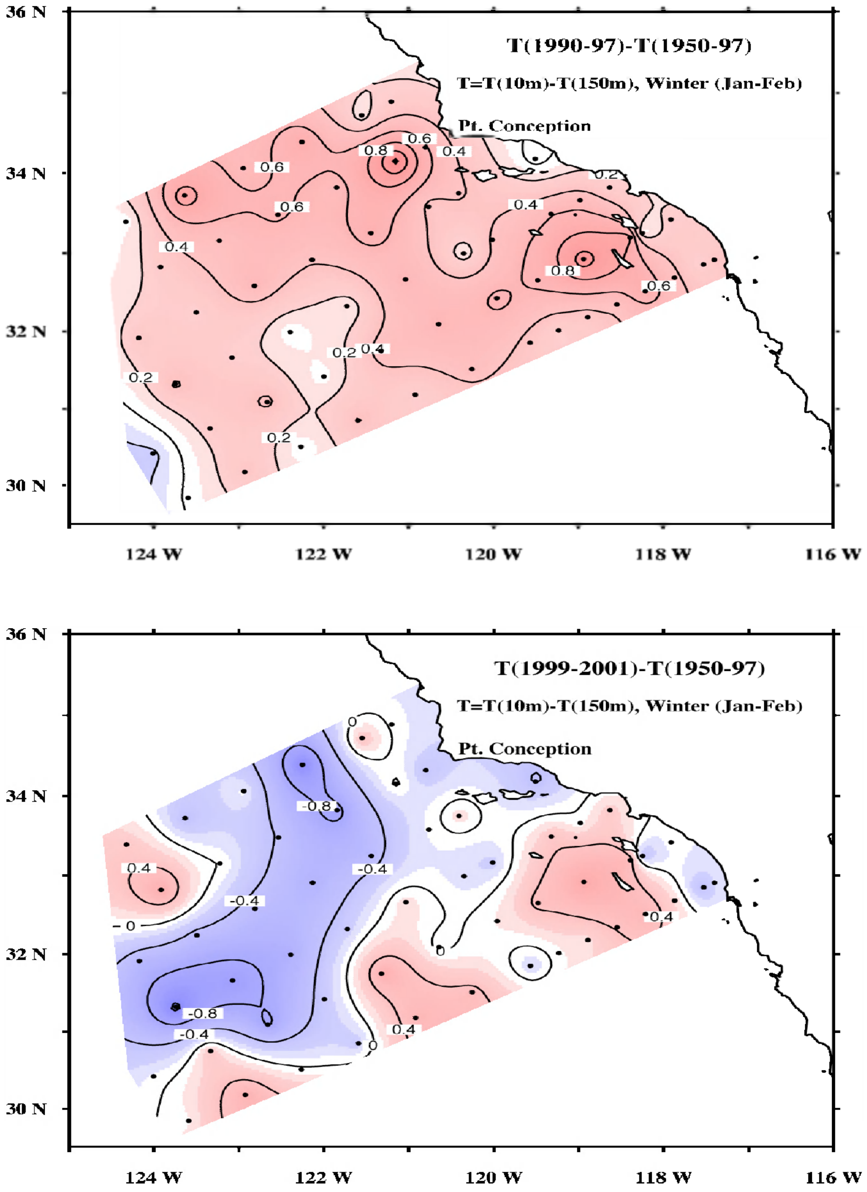


Fig. 1.10 Winter ocean stratification anomalies for the Southern Califorinia Bight region for 1990–97 (top) and 1999–2001 (bottom). Stratification is defined as the difference in temperature at 10 m and 150 m. Reference period is 1950–97. After 1989, the upper water column experienced enhanced stratification due, in part, to greater warming in the near-surface layers. Stratification in 1999–2001 was weak relative to the prior regime due to a cooler and fresher near-surface layer.

Prior to 1977, surface salinity at GAK1 was high (Fig. 1.11). This, coupled with lower surface water temperatures, suggests that the waters of the ACC, and perhaps a larger region of the North Pacific subarctic were different from those observed after 1977. After 1977, there were periods of alternating salty and fresh anomalies, with the most significant being more saline deepwater in 1985, and to a lesser extent in 1989–90 and 1995. As with temperature, salinity at 0–100 m depth was significantly negatively correlated with freshwater discharge one month earlier (Royer, in press). A trend towards a shallower mixed layer depth has been observed at Ocean Station Papa (Fig. 1.12), but not in the northern GOA at GAK1.

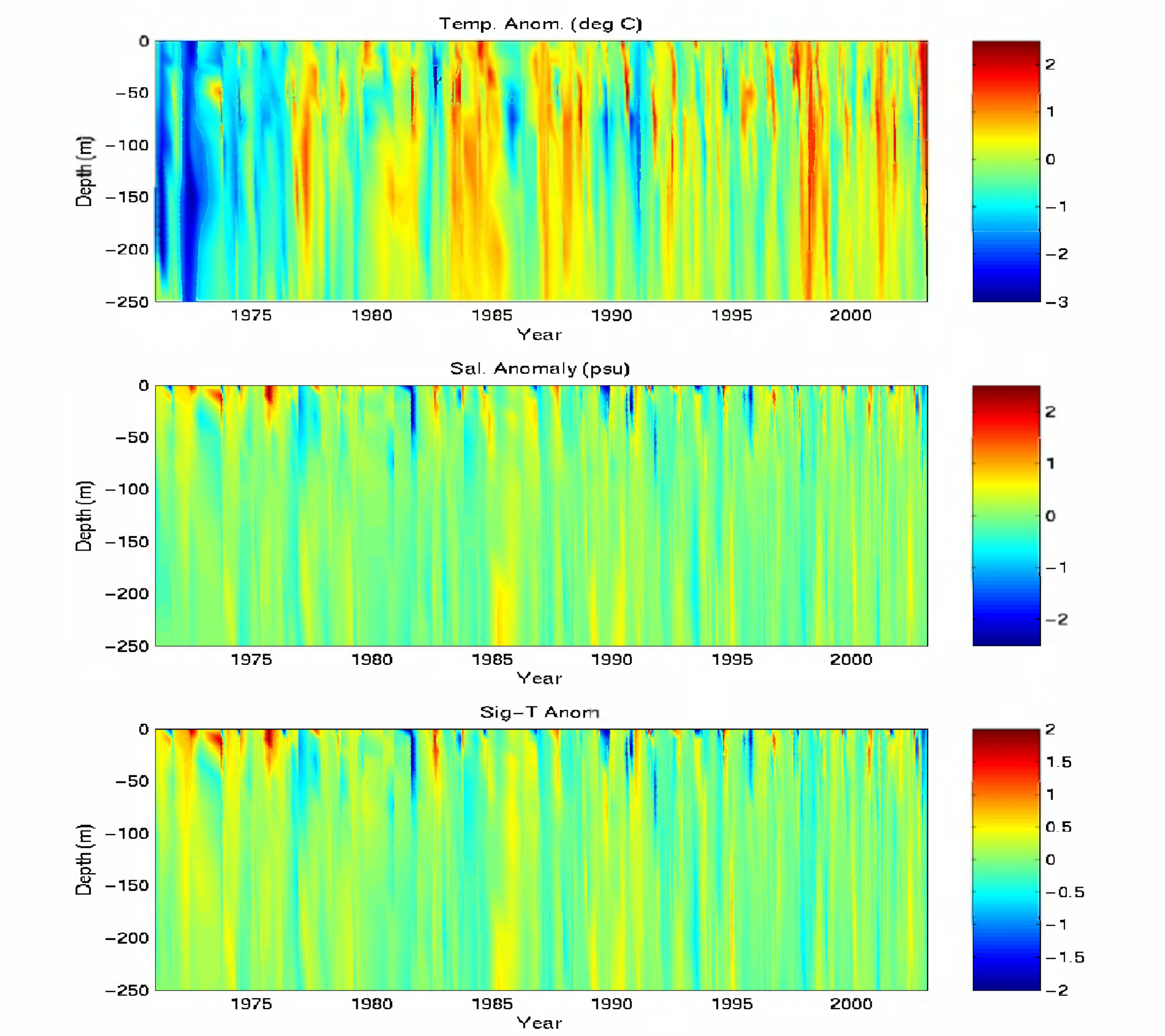


Fig. 1.11 Temperature, salinity, and density (sigma-T) anomalies *versus* time and depth at station GAK1. (Data were attained from http://www.ims.uaf.edu/gak1/). Seasonal cycles within the data were removed with a LOESS smoother. Interannual and decadal-scale changes in ocean conditions are typically observed throughout the water column at GAK1. The greatest changes in temperature and salinity occurred in 1977.

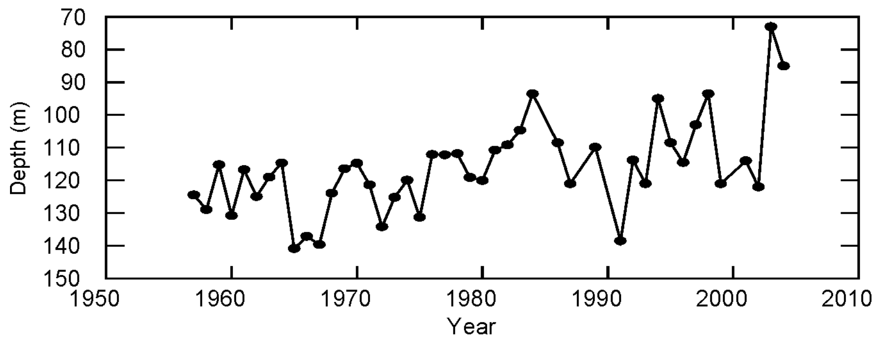


Fig. 1.12 Depth of the winter mixed layer at Ocean Station Papa (50°N, 145°W) in the Gulf of Alaska (from PICES 2004).

Paleoclimate reconstructions for the North Pacific

Several studies have used environmental proxies to reconstruct pre-instrumental values for the PDO index. One clear lesson from recent PDO reconstruction studies is that different proxy reconstructions yield different perspectives on past PDO behavior. For example, five different PDO reconstructions – three based on tree rings from different sites in North and South America, and two based on corals from different sites in the tropical Pacific – have generally low cross-correlations for the period 1840–1990 (see Gedalof *et al.* 2002). Gedalof *et al.* (2002) used principal components analysis to identify the common signal in these five different proxies, and developed a new PDO reconstruction for 1840–1990 that exhibited relatively large amplitude at periods close to 80 years, yet variable amplitude in periods of approximately 20 and 23 years. A key result from this analysis suggests that the strength of PDO variations was weak throughout much of the nineteenth century, yet relatively strong (comparable to its twentieth century prominence) in the period from approxiamtely 1600–1750.

Fluctuations in the biomass of the California sardine and northern anchovy off southern California have been estimated by scale deposition rates in sediments (Baumgartner *et al.* 1992). These paleorecords indicate these populations have varied on 50- to 100-year periods for the past 1700 years. The roughly 100-year oscillations of anchovy correspond with global climate cycles (Jiang *et al.* 2002), so they give a reasonable proxy of prehistoric regime shifts in the CCS.

A relatively new perspective on the warm season SST history of the Northeast Pacific has been offered by Strom *et al.*'s (2004) analysis of geoduck growth increments from a collection site in Juan de Fuca Strait. They demonstrate that annual growth rings in geoduck clam shells are well-correlated with observed annually averaged March–October SSTs in Juan de Fuca Strait over 1921–98, and over much of the North Pacific in a pattern quite similar to the PDO pattern. The geoduck-based SST reconstruction extends back to 1840, and suggests that the 1990s were the warmest decade during that time.

Finney *et al.* (2000) showed that the enrichment of ^{15}N in Alaska lakebed sediments is a proxy for the abundance of spawning sockeye salmon in lake systems. The 300-year ^{15}N record showed substantial interdecadal variability, which corresponded relatively well with tree-ring based GOA SST reconstructions for 1700–1850, but poorly from 1850–1900. These paleo-reconstructions suggest that the relationship between interdecadal changes in Pacific Ocean SSTs and Alaska sockeye salmon production have been variable since about 1700.

Finney *et al.* (2002) extended the lakebed ^{15}N records and found both interdecadal and centennial scale variations from 300 BC to the present. Specifically, the sediment records had relatively high ^{15}N concentrations from 300 BC to 100 BC, then very low ^{15}N from 100 BC to 600 AD, with near-modern era ^{15}N ranges of values from 1000 AD to the present. A comparison between this paleo-salmon record and the California sardine and anchovy reconstructions of Baumgartner *et al.* (1992) showed a relative lack of correspondence in variations over the past 2 millennia. This situation contrasts with the historical record that has a relatively good correspondence between warm periods in the Northeast Pacific and high abundances of Alaska sockeye salmon and California sardines.

1.4 Decadal Climate Variability in Ecological Regions of the North Pacific

When applicable, we collectively describe regions whose recent conditions have been similar. This may infer that these regions are dominated by similar physical processes, which may be a key in identifying regime shifts. On the other hand, it is recognized that the large ecosystems described here may have strong regional differences in physical condition, which is reflected in distinctly different responses to long-term climate variability (Parrish *et al.* 1983; Schwing and Mendelssohn 1997; Mendelssohn and Schwing 2002; Mendelssohn *et al.* 2003). Thus, regime shifts may be more evident, and have greater ecological impacts, in certain North Pacific ecosystems, or even within certain areas within these ecosystems.

Central North Pacific

The Transition Zone Chlorophyll Front (TZCF) which stretches zonally across the central North Pacific, separating subarctic and subtropical waters, is a biologically dynamic and productive region (Polovina *et al.* 2000, 2001, 2004). Cyclonic wind stress around the Aleutian Low creates a large region of open ocean upwelling (Ekman pumping) north of this zone, while North Pacific High winds lead to a downwelling-favorable region to the south. Southward Ekman surface transport results in the convergence of nutrient-rich subarctic water from the north, creating a distinct physical and biological front. The area north of about 40°N has been anomalously cool since 1998. This is probably related to a deeper Aleutian Low, with stronger cyclonic winds and greater Ekman pumping and surface layer mixing, and much stronger westerly winds in the vicinity of the North Pacific Current. The winter TZCF has been situated farther north than usual since 1998 (Bograd *et al.* 2004).

In contrast, the intensification of the North Pacific High and large-scale shifts in wind forcing in 1998, which contributed to the shift toward cooler conditions along the North American west coast, also led to a warming of the central North Pacific due to reduced mixing of the upper ocean combined with enhanced downward displacement of the thermocline. These have been identified as the main processes controlling mixed layer temperatures in the central North Pacific (Polovina *et al.* 1994, 1995; Miller *et al.* 1994; Parrish *et al.* 2000; Huang and Liu 2001).

California Current System

The state of the CCS region is examined here with a brief review of SST, SSH, and Pacific Fisheries Environmental Laboratory upwelling indices. The recent history of the CCS showed exceptionally warm SSTs, high SSHs, and anomalously weak upwelling (southward) winds in the southern half of the CCS from about 1992–98. The anomalously warm coastal zone conditions were especially evident during the strong tropical El Niño episodes of 1991–92 and 1997–98. A rapid shift to cooler-than-average SSTs in mid-1998 initiated a 4-year period of cooler-than-average SSTs, and lowered nearshore and raised offshore SSHs. From 1998 to the present, upwelling winds have been mostly above average for the region between 33°N and 42°N. Beginning in 2003, SSTs in the nearshore California Current have returned to levels typical of the 1980s and early 1990s, and the leading pattern of SSHs in the CCS region switched phases during the fall/winter period of 2002–03, and switched phases again in mid-2003 to the high onshore/low offshore SSH pattern. Because of the strong year-to-year variability in the CCS region, and the clear tendency for tropical ENSO events to influence conditions in the CCS, it is difficult to provide a near real-time separation of the interannual and decadal time-scale influences that are present.

For the entire CCS, a period of especially warm SSTs began in the early 1990s and ended in 1998, while a period of relatively cool surface temperatures that began in 1998 was interrupted, or may have ended, in 2002 (Fig. 1.13).

Upwelling winds were anomalously strong from the mid-1960s to mid-1970s from 33°–48°N, anomalously weak from the late 1970s to late 1980s from 42°–48°N, anomalously weak in the early to mid-1990s at 36°–38°N, and then mostly very strong in the period from 1998–2004 from 36°–42°N. In contrast, upwelling winds were weaker than average during the winters of 2003 and 2004 at 45°N and 48°N, indicating enhanced winter downwelling at those latitudes (Fig. 1.14).

Gulf of Alaska

Figure 1.15 shows maps of normal (or neutral) temperatures at the ocean surface and 100 m depth in summer and winter. The warmest waters in this region lie beyond the continental shelf west of Vancouver Island, and the coldest waters are typically southeast of the Aleutian Islands of Alaska, near the middle of the Alaska Gyre. In summer, the band of cooler water on the continental shelf adjacent to the west coast of Vancouver Island is part of the process of coastal upwelling, which brings deep cool water to the ocean surface nearshore when winds blow from the north or northwest. Such winds are typical in summer all along the Canadian west coast, as well as the U.S. coast to the south. Summers with stronger winds from the north will see cooler-than-normal surface, and even subsurface waters along the Canadian and U.S. west coasts.

Cool waters in the northwest GOA are found in the center of the Alaskan Gyre, near 52°N, 152°W, which lies inside the Aleutian Low. The cyclonic winter winds around the Low push ocean surface water away from mid-gyre and colder water upwells to take its place, lowering water temperatures even at depths of 100 m (Fig. 1.15). Winters with a stronger Aleutian Low will see even cooler temperatures in this region.

Anomalies of ocean temperature at 10 and 120 m below surface (Fig. 1.16) are based on measurements by a conductivity-temperature-depth (CTD) profiler on a research vessel, an autonomous Argo profiler, or by an expendable bathythermograph (XBT) deployed from ships. Near-surface (10-m depth) waters were cooler than normal in 2001 in the southeast Gulf, and somewhat warmer in the northeast. These anomalies weakened in summer 2002, and then reversed in summer 2003. Conditions in the northwest in 2002 are not clear, due to lack of observations. The warming of the southeast GOA supports the observations noted previously, that currents near the west coast carried more California Current waters at the ocean surface into Canadian waters in 2002 and early 2003.

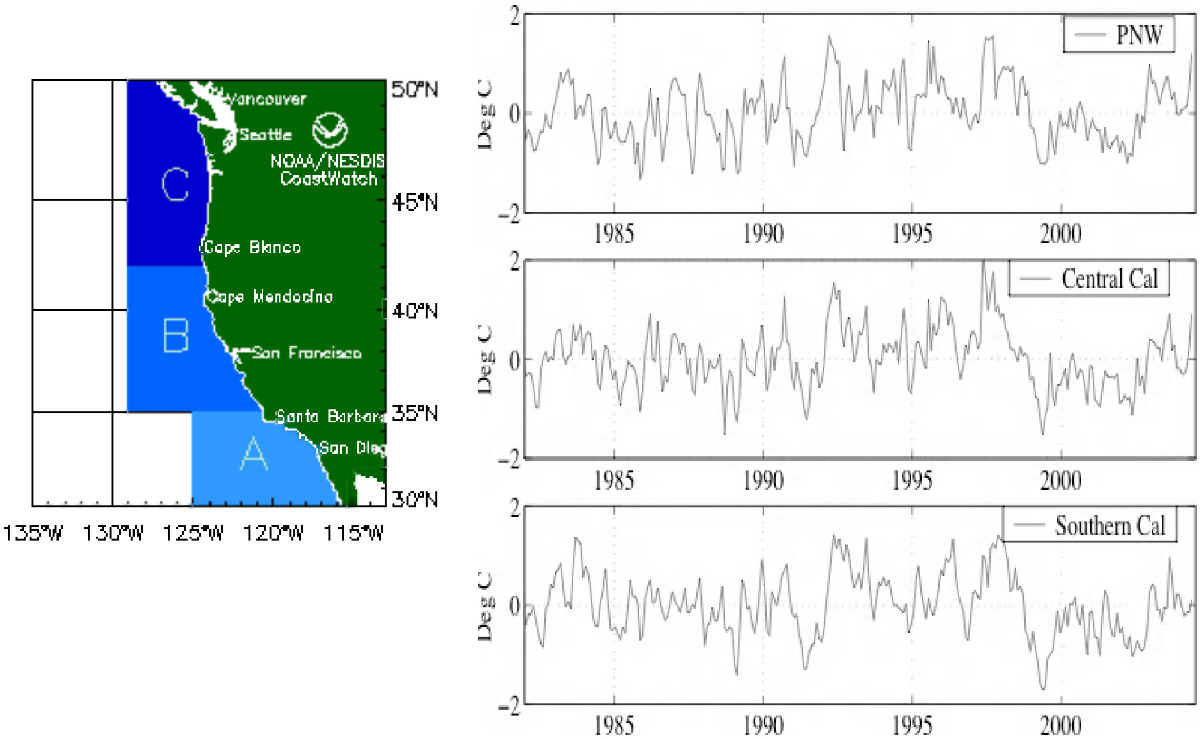


Fig. 1.13 Observed monthly sea surface temperature (SST) anomalies (right panel) for the three subregions of the California Current System (CCS) (left panel). Anomalies are in °C and are calculated with respect to 1982–2001 climatology. Data are from 1° × 1° resolution using optimum interpolation (OI) of SST (Reynolds and Smith 1994). A period of especially warm SSTs began in the early 1990s and ended in 1998. In 1998, a period of relatively cool surface temperatures began. The El Niño event of 2002–03 interrupted this cool period, and SSTs have remained warmer since 2002.

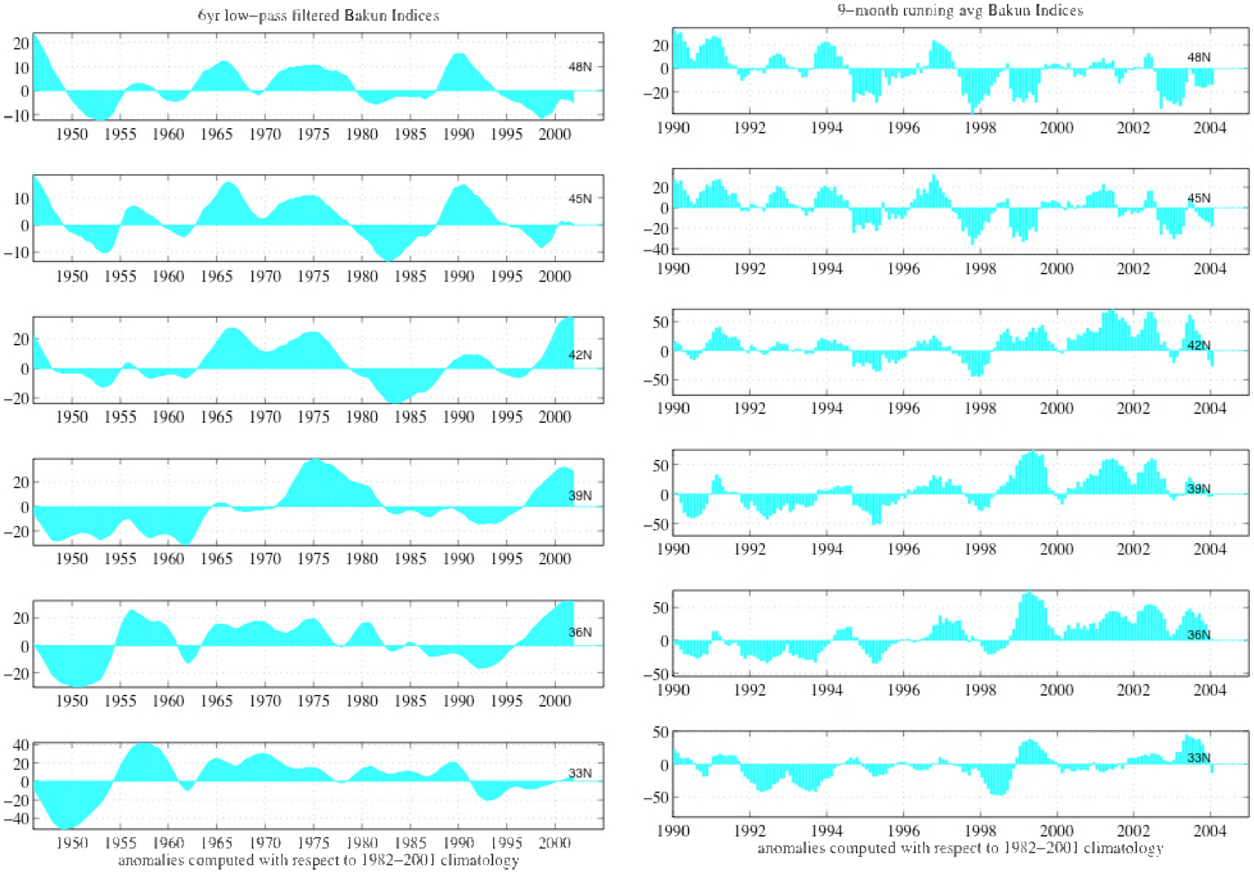


Fig. 1.14 Observed anomalous coastal upwelling indices from 48°N to 33°N. Left panel shows 6-year low-pass filtered monthly anomalies for 1946–2004, while the right panel shows the 9-month running mean values from 1990–2004. Positive anomalies are associated with southward wind anomalies. Reference period is 1982–2001. At all latitudes of the California Current, upwelling winds were strong from the mid-1960s to the mid-1970s. The 1977 regime shift corresponded to a shift of weak upwelling winds at the more northern latitudes (42°–48°N), but this shift was delayed at the more southern latitudes. At 36°–42°N latitudes upwelling winds have been very strong since 1998.

Temperatures at 120 m depth show significant cooling in the southeast GOA from summer 2001 to summer 2002, as noted along Line-P and off Oregon, earlier in this report. The cold anomaly weakened somewhat but was still present in the summer of 2003. The winter winds of 1999 to 2002 are suspected to have formed this cold anomaly near the middle of the Alaskan Gyre, and the anomaly slowly deepened as it drifted southeastward, reducing temperatures along its path. The waters from 100–150 m below surface are only weakly influenced by winter storm winds, so once a cold anomaly reaches this depth it may persist and spread out for several years. During the winters of 2002–03 and 2003–04, this deep mixing was much reduced. Currents at 10 m depth are more readily altered by changing wind patterns, and the ocean surface currents pattern of 2002 to early 2003 likely warmed the surface waters of the southeast GOA during this period.

The cold anomaly noted in the summer maps in Fig. 1.16 is still present through the following winter, the most recent season of observations available. This layer of water at 120 m depth (actually from about 75–175 m depth, depending on location) was the coldest ever observed to hit the continental shelf of Vancouver Island to Oregon in 2002, and it is not surprising it has persisted almost another 2 years, and through the weak El Niño of 2002–03.

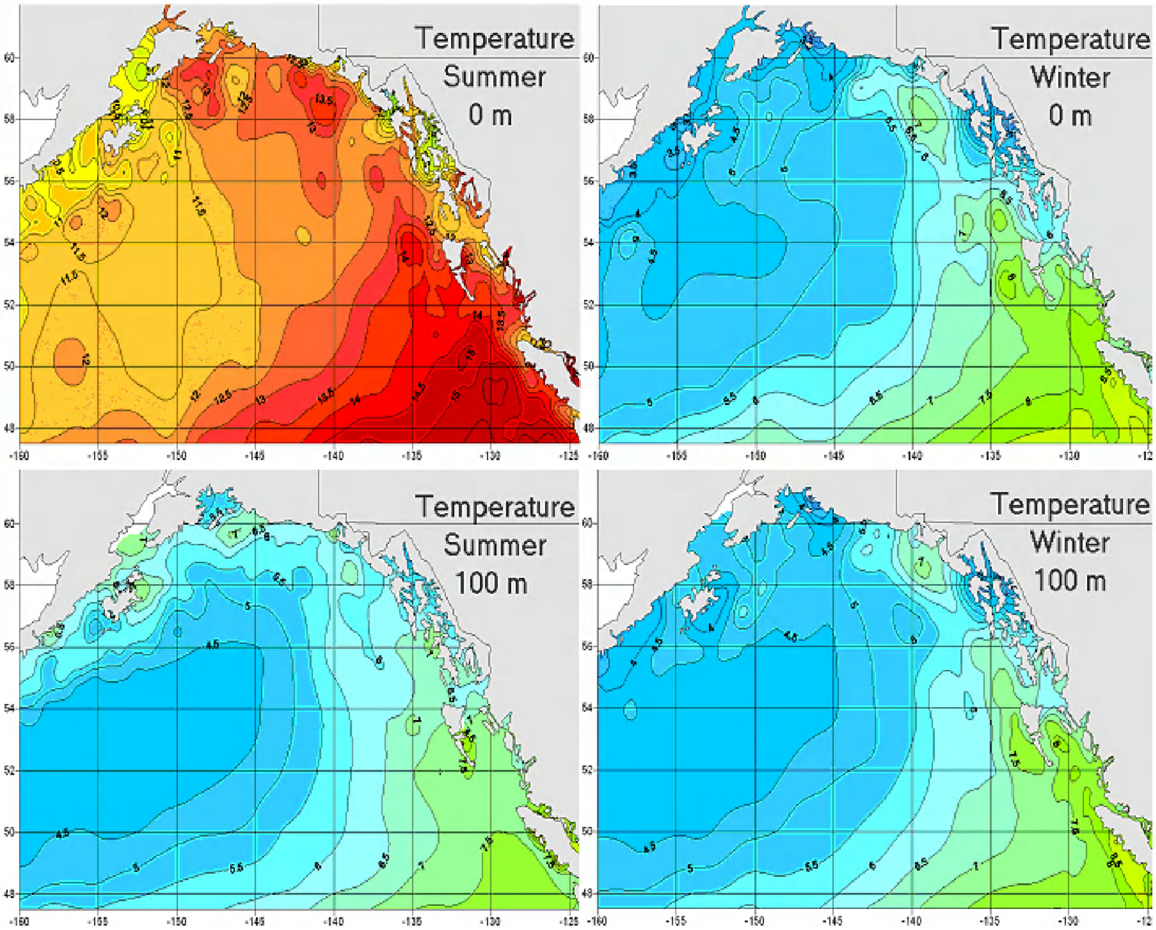
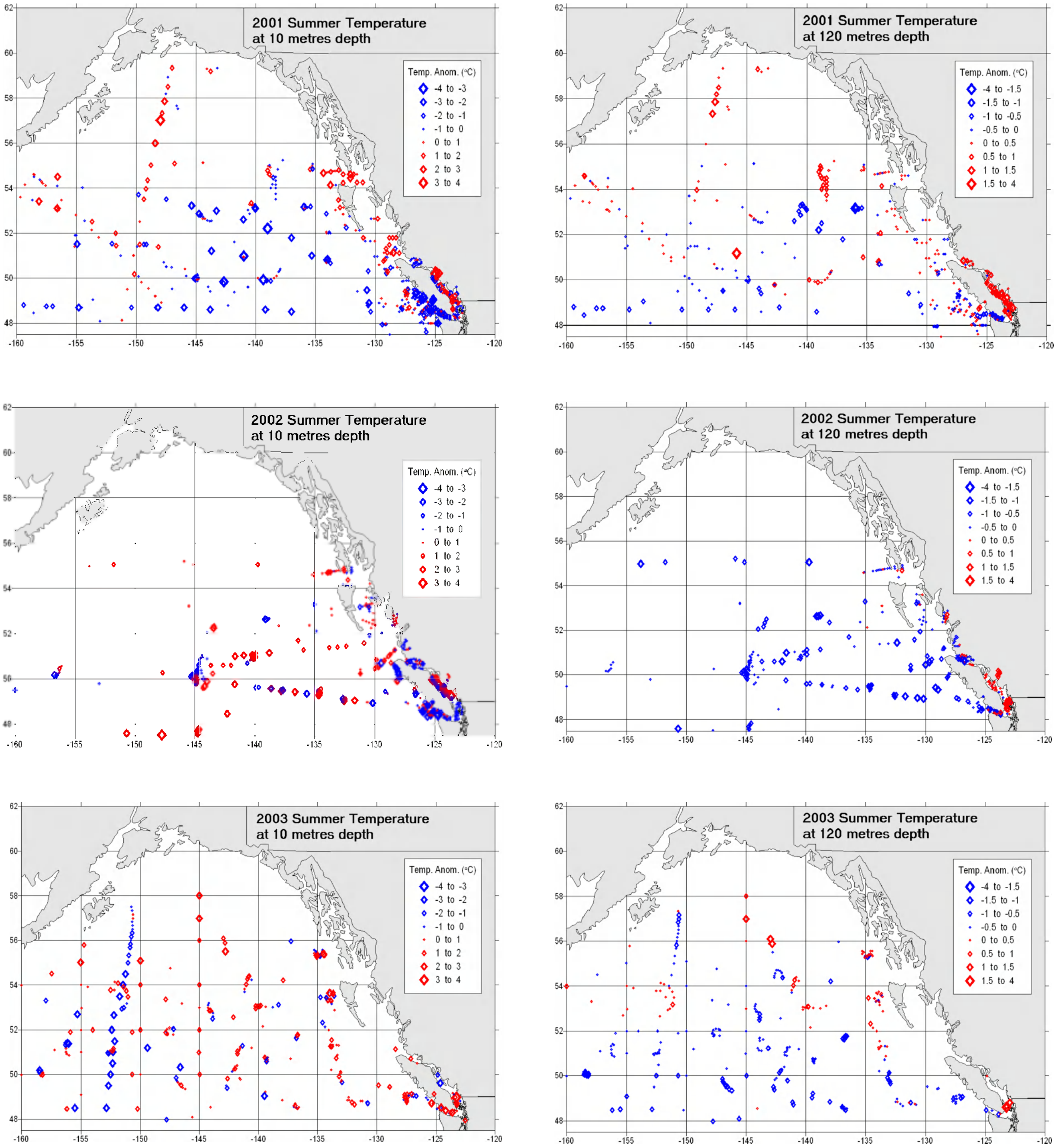


Fig. 1.15 Average temperatures (°C) at 0 and 100 m depth in years without El Niño or La Niña events. The warmest waters occur on the continental shelf off Vancouver Island (48°–50°N) and the Queen Charlotte Islands (52°–54°N). The coldest waters are typically southeast of the Aleutian Islands, near the center of the Alaskan Gyre.

Bering Sea and Aleutian Islands

Bering Sea climate is determined by the percentage of time that the cold, dry Arctic air mass to the north, or the moist, warm maritime air mass to the south are dominant in the region. Thus the physical and ecological properties of the Bering Sea are sensitive indicators for north–south shifts in climate properties (Hunt *et al.* 2002). The region was strongly influenced by the 1977 regime shift in the North Pacific, as indicated by a deepening and strengthening of the Aleutian Low, which resulted in a transition from generally cold to warm conditions. In the 1990s, there was an influence from the Arctic Oscillation (AO) which resulted in warmer springs and early ice retreat (Overland *et al.* 1999).

With the exception of 1999, the southeast Bering Sea has been especially warm over the last 5 years. The warm air temperature anomalies often encountered in spring are now extending earlier into winter. Sea ice is nearly non-existent south of 58°N, the region of interest for Bering Sea fisheries. Depth-averaged sea temperatures in summer, from a mooring at 70 m depth on the southeast shelf, were 1.5°C warmer in 2002 and 2003 than during the mid-1990s. What is particularly unusual about this recent period is that the warmer Bering Sea shows considerable year-to-year persistence in many properties compared to earlier periods, and appears less coupled to large-scale teleconnection patterns such as the PDO and AO. Bering Sea indicators should be watched closely over the next 5 years to confirm this shift.



2001 Summer Temperature at 10 metres depth

2001 Summer Temperature at 120 metres depth

2002 Summer Temperature at 10 metres depth

2002 Summer Temperature at 120 metres depth

2003 Summer Temperature at 10 metres depth

2003 Summer Temperature at 120 metres depth

Fig. 1.16 Temperature anomalies (°C) at 10 and 120 m depth in the summers of 2001 to 2003. The size of the diamond represents the magnitude of the warm (red) or cold (blue) anomaly, according to the inset scale on each map. The near-surface waters were cooler than normal in 2001 in the southeast region and warmer in the northeast region. These anomalies weakened in the summer of 2002, and then reversed in 2003. Temperatures at 120 m depth show significant cooling in the southeast Gulf of Alaska in 2001 and 2002, with a weakening of this anomaly in 2003.

The Aleutian Islands are influenced by the Aleutian Low pressure system, but because they are co-located, the local response is very sensitive to the details in the Low's position and magnitude. In particular, the climate of the western Aleutian Islands has a different character than the climate of the eastern part, with low correlations in surface air temperature (SAT) between the regions bounded by 170°W (Rodionov *et al.*, in press). SAT variations in the eastern Aleutians are more closely associated with regime-like changes in the PDO phase similar to that in the GOA and the southeast Bering Sea. The western Aleutians show more of a long-term linear trend toward colder winters and greater intraseasonal variability. While it is not always the case, cold periods in the western Aleutians are largely associated with an increase in cyclonic activity over the Bering Sea (lower Aleutian Low pressures) and with southward advection of cold Siberian air behind the cold fronts of passing cyclones. Thus 1998–2003 was a cold period, as the mean winter SLP averaged over the Bering Sea area was at its lowest since 1900. However, the winters in 1996 and 1997 were anomalously warm. In response to a decrease from a positive PDO phase in 1998, SAT in the eastern Aleutians decreased sharply. This cold period lasted only 3 years, 1998–2000, after which time temperatures returned to the values characteristic of the warm climate regime established since 1977.

Western North Pacific

EOF analysis of monthly-averaged air temperatures in the western North Pacific (25°–50°N; 130°–160°E) identifies two dominant spatial patterns (Fig. 1.17). The first pattern is represented by the first mode of the EOF1 (explaining 38.6% of the variance) and is a spatial pattern with no distinct east–west or north–south oscillation. However, the second mode of the EOF2 analysis (explaining 26.1% of the variance) has a distinct north–south spatial pattern. Both sets of spatial patterns are important throughout the Northwest Pacific Ocean. The first mode has a positive phase until 1955 when it switches to a negative phase, and in the late 1980s it switches back to an overall positive phase (Fig. 1.17). The first mode also exhibits a close relationship with the PDO index pre-1955, and again after the late 1980s (Fig. 1.18). The second mode has no decadal-scale pattern over time (Fig. 1.17), but since the late 1990s has been in a positive phase corresponding to a north–south spatial pattern observed in the western North Pacific, with a continued warming trend in southern regions and a cooling trend in northern regions.

1.5 Mechanisms

It is essential to identify the sources and mechanisms of regime shifts if we are to truly understand their evolution and predictability, and eventually forecast their future impacts. The exact mechanisms that control decadal variability in the North Pacific are not well understood. Miller and Schneider (2000) provide a comprehensive review of these mechanisms. One difficulty is that only about 37% of the winter interannual variance of the Aleutian Low is on time scales greater than 5 years (Overland *et al.* 1999), thus it is difficult to sort signal from noise in an analysis. Yet shifts like the 1976–77 PDO phase change and other climate modes are often associated with large re-organizations of regional ecosystems. The main forcing for the entire North Pacific is the seasonally varying difference in heating near the equator and the pole. As cold polar air flows south, it becomes unstable because of the rotating Earth, which creates major variations over a broad range of time and space scales. The atmospheric flow is considered generally chaotic, in that weather predictions based on similar, but slightly different initial states, will rapidly diverge.

At the simplest level, atmospheric variability can be modeled as a random process with energy at all time scales, so-called white noise. The ocean is an integrator of the atmospheric signal so that the many atmospheric storms contribute to deepening the oceanic mixed layer. The ocean also stores heat much more effectively than the atmosphere. This integration, or smoothing, of the high frequency signal, while not impacting the forcing by low frequencies, is referred to as red noise. A red noise process – where the ocean integrates atmospheric forcing into regime-like patterns of variability – can result in time series that randomly produce features similar to decadal trends or regime-like behavior in the North Pacific (Pierce 2001).

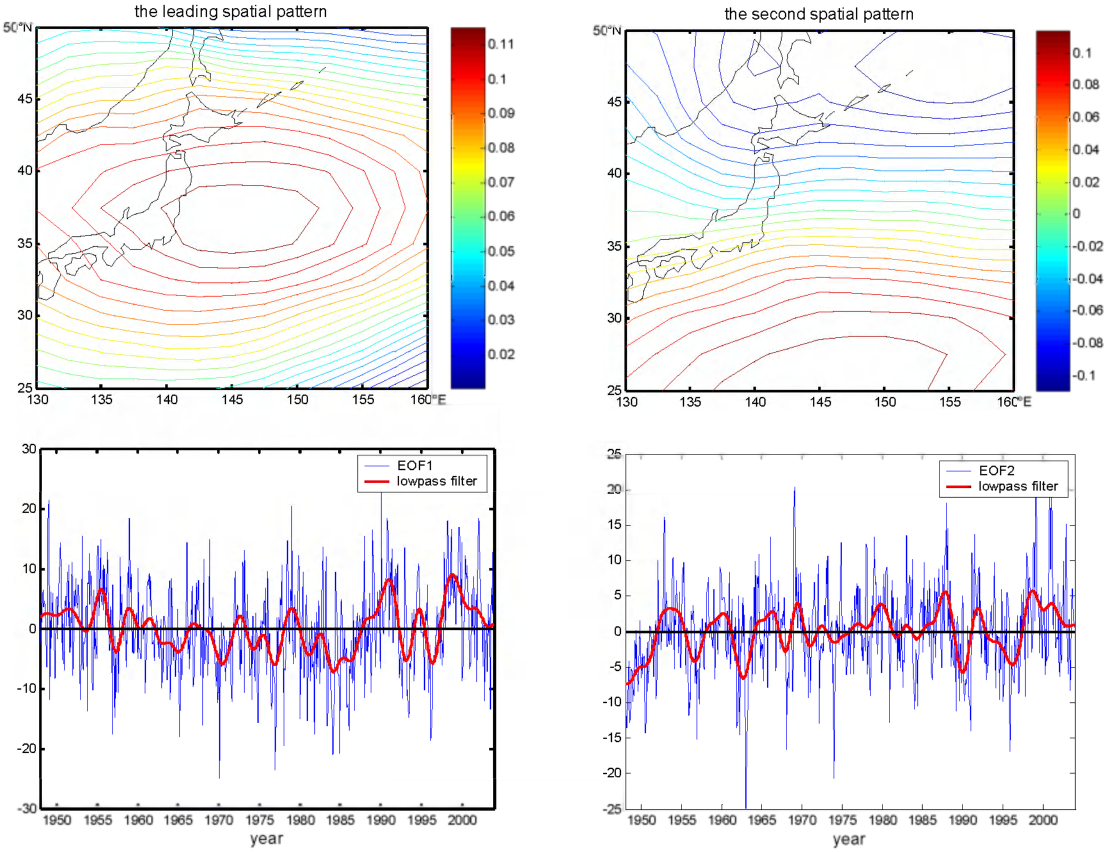


Fig. 1.17 First (left panels) and second (right panels) modes of the empirical orthogonal function (EOF) for air temperature data in the Northwest Pacific Ocean. Top panels reflect spatial pattern to EOF analyses, and bottom panels are the mean annual EOF coefficients (red lines denote Butterworth low-pass filter). Since the late 1990s, the second mode, EOF2, has been in a positive phase, corresponding to a north–south spatial pattern in the Northwest Pacific with a continued warming trend in southern regions and a cooling trend in northern regions. This mode has previously not exhibited a strong decadal-scale variability.

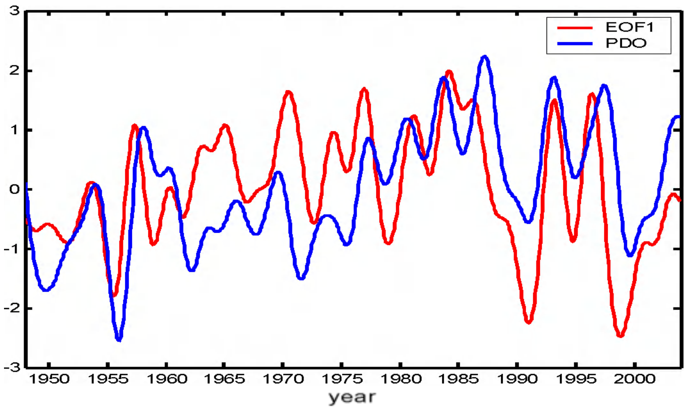


Fig. 1.18 Comparison of the first empirical orthogonal function (EOF1) (red line) for analysis of air temperatures of the Northwest Pacific Ocean to the Pacific Decadal Oscillation (PDO) index (blue line). Time series have been filtered with a Butterworth low-pass filter and normalized. The first mode also exhibits a close relationship with the PDO index pre-1955 and again after the late 1980s.

Even though a red noise model may explain North Pacific variability, it does not include the known complexity of the climate system. There are many processes on different time scales that affect the North Pacific. These include influences from the equator (ENSO), snow cover in Asia, changes in the Arctic, subsurface oceanographic temperature anomalies that advect around the Pacific basin with decadal time scales, and internal dynamics (*e.g.*, Rossby waves). An equally simple statistical model such as red noise is the "long-memory" model; this model is the equivalent of a combination of many red noise processes with different time scales (Percival *et al.* 2001). A long memory process – wherein the ocean maintains information from many past atmospheric events – also produces records very similar to the regime-like North Pacific variability.

North Pacific variability can also be modeled as a true oscillation with a decadal (PDO) time scale. A series of papers by Minobe (1997, 1999, 2000) has identified a 50- to 70-year climate oscillation in observational records that interacts with bidecadal variability to explain the observed regime shifts in the 1920s, 1940s, and 1970s, and projected a new shift roughly around 1999. Ware and Thomson (2000) have found that these oscillatory modes have occurred in the Northeast Pacific climate for at least the past 400 years. There is also observational and model evidence that internal ocean modes may set the time scale of regime shifts. Latif and Barnett (1994, 1996) and Barnett *et al.* (1999) have modeled a 20-year coupled atmosphere–ocean oscillation that may be the driving force for the PDO. This bidecadal oscillation has been identified in ocean observations (Schneider *et al.* 1999a, 1999b; Zhang and Liu 1999). A shortcoming of these methods is the assumption that the properties of the PDO and other climate time series are consistent over time, while the reality is that climate signals appear to be non-stationary (Percival *et al.* 2001; Gedalof *et al.* 2002; Schwing *et al.* 2003).

A recent study by Newman *et al.* (2003) demonstrates that the one-dimensional "re-emergence" mechanism – whereby deep wintertime mixed layers can yield substantial memory in mid-latitude SSTs from one winter-spring to the next – combined with random white noise and interannually energetic ENSO teleconnections, serves as a useful null hypothesis for the observed twentieth century behavior of the PDO. This explanation for the PDO suggests that the mechanisms giving rise to the PDO are intimately tied to the mechanisms causing ENSO variability. Furthermore, this model suggests that PDO predictability is limited to the combined predictability of ENSO and re-emergence physics. In this scenario, PDO predictability (and the ability to predict regime shifts) is limited to lead times of about 2 years.

Alternative explanations for the observed twentieth century variability in the North Pacific have focused on deterministic coupled ocean–atmosphere physics involving tropical-only, extratropical-only, and tropical-extratropical interactions; stochastic resonance, wherein random white noise forcing from the atmosphere, coupled with preferred modes of oceanographic variability, leads to enhanced oceanographic responses at preferred time scales; or externally forced excitation of ocean–atmosphere climate variations (solar forcing, lunar nodal tidal cycles, *etc.*). It is impossible, based simply on the limited record of physical oceanographic data, to say which model – red noise, long memory, or oscillation – is better. They all can explain the North Pacific variability over the century of observational records; it would require almost 300 years of data to choose one over the other (Percival *et al.* 2002).

What we learn from this review of mechanisms is that the regime shift concept – rapid shifts between regimes on decadal scales – is a reasonable conceptual model for the North Pacific. The nature of regimes is due to a combination of intrinsic variability of the atmosphere and ocean, and forcing influences from other geographical areas (teleconnections). Since the climate system is complex, occasionally chaotic, with untested mechanisms, and dominated by abrupt changes, prediction of the future state of the North Pacific is currently impractical. However, given the importance of regimes to ecological systems, four approaches are suggested. The first is the acceptance of the regime concept over a steady state view of ecosystems. The second is the development and maintenance of a comprehensive observational program to monitor and rapidly recognize state changes in ecosystems and the environment. The third is the development of operationally useful indices which characterize climate signals that impact fishery populations and ecosystems, and the support of research efforts to link climate indices to predictable parts of the climate system (*e.g.*, ENSO). The fourth is the use of integrated assessments. Here, various long-memory climate and ecosystem scenarios can be projected into the future to assess the vulnerabilities of different ecosystems, risk assessments can be undertaken, and management strategies can be developed accordingly.

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2. Coherent Regional Responses

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2.1 Introduction

The Pacific basin-wide changes in climate and ocean parameters are reported in Section 1. To describe specific regional responses to the basin-wide changes, we divided the North Pacific into five major regions (Fig. 2.1): the central North Pacific, which includes the transition zone and the Hawaiian Islands; the California Current System from California up to northern Vancouver Island; the Gulf of Alaska system from northern Vancouver Island to the start of the Aleutian Islands, including the central Gulf region; the Bering Sea and Aleutian Islands; the western North Pacific, which includes the Sea of Okhotsk, the Tsushima Current region, the Kuroshio/Oyashio Current region, the Yellow Sea and the East China Sea. Regional responses were detected in physical oceanographic parameters such as temperature and salinity, and in organisms at both lower trophic levels (phytoplankton, zooplankton, and invertebrates) and at higher trophic levels, including fishes and marine mammals. Detailed descriptions of the observed regional responses to the 1998 basin-wide shift are provided in Appendices 1–5.

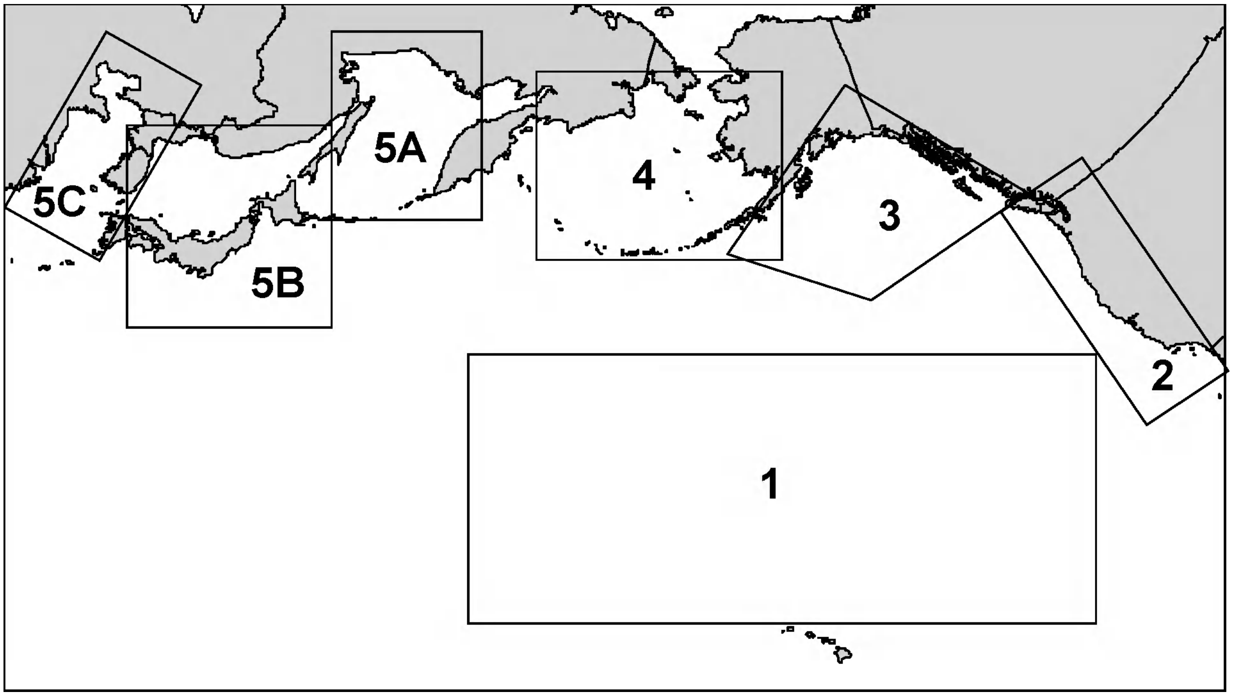

Fig. 2.1 Designation of the five regions of the North Pacific for which ecosystem responses are reported: (1) central North Pacific; (2) California Current System; (3) Gulf of Alaska; (4) Bering Sea and Aleutian Islands: (5) western North Pacific comprised of (A) Sea of Okhotsk, (B) Tsushima Current region and Kuroshio/Oyashio Current region and (C) Yellow Sea and East China Sea.

2.2 Central North Pacific (CNP)

The central North Pacific experienced an abrupt change, beginning in 1999, characterized by a rise in sea surface height (SSH), indicating an increase in the depth of the top of the thermocline. At the same time the eastern and northern boundaries of the North Pacific experienced a drop in SSH, indicating a shoaling of the depth of the top of the thermocline. In the central North Pacific, the SSH rise was accompanied by a northward shift of low surface chlorophyll water. At higher trophic levels, Hawaiian monk seal pup survival at northern atolls in the Northwest Hawaiian Islands dropped since 1999. Also, since 1999 the albacore fishing grounds for the U.S. troll fleet shifted eastward. By 2003, the high SSH anomaly in the central North Pacific had dissipated, suggesting it was a response to the 1999 La Niña rather than a decadal shift.

2.3 California Current System (CCS)

Conditions in the California Current System are subject to decade-scale regime behavior with an overlay of episodic warm El Niño and cold La Niña events that last a year or two. In the CCS, there have been strong ecosystem responses to the 1977 and 1989 regime shifts. The 1977 regime shift led to a protracted period of warm surface waters, with a deepening of the thermocline and the implication of lower productivity. However, available zooplankton time series suggest that salp biomass declined after 1977, while euphausiid biomass remained unchanged and copepod biomass actually increased. Following the 1977 regime shift, overall recruitment improved for species such as Pacific sardine, and other species experienced intermittent very strong year classes (Pacific hake and Pacific cod). After the 1989 regime shift, the warm surface waters intensified and became unproductive for many coastal species. In coastal waters, zooplankton shelf species were replaced by more southerly and oceanic species. Many fish species (Pacific salmon, Pacific hake, Pacific cod, and rockfish species) experienced almost a decade of poor recruitment. Southern migratory pelagics (Pacific sardines and Pacific hake) extended the northern limit of their distribution to northern British Columbia, and in some years, the Gulf of Alaska (GOA).

After an intense El Niño in 1998, the CCS experienced a very cold La Niña in 1999. Since 1999, sea surface temperatures (SSTs) have tended to return gradually toward warm conditions similar to those in the 1980s and early 1990s, but thermocline depths are now much shallower and nutrient levels are higher, generating higher primary and secondary production. Beginning in 1999, coastal waters saw a return of shelf zooplankton, and many coastal fish stocks experienced substantial improvements in year class success. Some stocks produced good year classes in 1999 (*e.g.*, Pacific hake), and recent returns of several salmon stocks have improved; Columbia River salmon runs have been extraordinary. In addition, the distribution of migratory pelagic fishes (Pacific sardine and Pacific hake) contracted to a more southerly distribution. There is growing evidence, based on a strong and diverse biological response, that a regime shift favoring coastal organisms occurred in 1998.

2.4 Gulf of Alaska (GOA)

Ecosystem responses to regime shifts in the GOA were strong after the 1977 shift, but weaker after the 1989 and 1998 shifts. Variation in the strength of responses to climate shifts may be due to the geographical location of the GOA in relation to the spatial pattern of climate variability in the North Pacific. Prior to 1989, climate forcing varied in an east–west pattern, and the GOA was exposed to extremes in this forcing. After 1989, climate forcing varied in a north–south pattern, with the GOA acting as a transition zone between the extremes in this forcing. The 1989 and 1998 regime shifts did not, therefore, result in strong signals in the GOA.

There were both physical and biological responses to all regime shifts in the GOA. However, the primary reorganization of the GOA ecosystem occurred after the 1977 shift. After 1977, the Aleutian Low intensified, resulting in a stronger Alaska current, warmer water temperatures, increased coastal rain and, therefore, increased water column stability. The optimal stability window hypothesis suggests that water column stability is the limiting factor for primary production in the GOA (Gargett 1997). A doubling of zooplankton biomass between the 1950s and 1960s, and in the 1980s, indicates that production was positively affected after the 1977 regime shift (Brodeur and Ware 1992). Recruitment and survival of salmon and demersal fish species also improved after 1977. Catches of Pacific salmon, recruitment of rockfish (Pacific ocean perch), and flatfish (arrowtooth flounder, halibut, and flathead sole) recruitment and biomass all increased. There are indications that shrimp and forage fish, such as capelin, were negatively affected by the 1977 shift, as survey catches declined dramatically in the early 1980s (Anderson 2003). The reduced availability of forage fish may have been related to the decline in marine mammal and seabird populations observed after the 1977 shift (Piatt and Anderson 1996).

After 1989, water temperatures were cooler and more variable in the coastal GOA, suggesting that production may have been lower and more variable. After 1989, British Columbia salmon catches and survival were low and herring declined in Queen Charlotte Islands (northern British Columbia). However, salmon catches in Alaska remained high. Groundfish biomass trends that began in the early 1980s continued, with increases in flatfish biomass. By the late 1980s, arrowtooth flounder, rather than walleye pollock, were dominant. Large groundfish biomass estimates resulted in negative recruit per spawning biomass anomalies of demersal fish.

There is some indication that the GOA ecosystem may have responded weakly to the 1998 regime shift. Increased storm intensity from 1999 to 2001 resulted in a deeper mixed layer depth in the central GOA, and coastal temperatures were average or slightly below average. After 1998, coho survival increased in British Columbia, shrimp catches increased in the northern GOA, and the 1999 year class of both walleye pollock and Pacific cod was strong in the northern GOA. Recruitment information from longer-lived species will be available in the near future, enabling scientists to determine if there were other responses to the 1998 climate shift.

It is apparent that many components of the GOA ecosystem respond to decadal-scale variability in climate and ocean dynamics. It is unknown if changes observed after the 1998 shift will persist in the GOA or how long the current conditions in the GOA will last. Predicting regime shifts will be difficult until the mechanisms that cause the shifts are understood. Monitoring indicator species is one method to improve our knowledge of the mechanisms that cause the shifts. Potential indicator species of regime shifts would include those that have a short life-span, are sensitive to changes, are key trophic groups, and/or are targeted by fisheries which produce data that are readily available. Examples of potential indicator species in the GOA that fit some of these criteria include sockeye and pink salmon, Pacific herring, juvenile fish abundance, ichthyoplankton, as well as zooplankton biomass and composition.

2.5 Bering Sea and Aleutian Islands

Bering Sea (BS)

There is no evidence of a shift in the Bering Sea system since 1977. The Bering Sea was subject to a change in the physical environment and an ecosystem response after 1977, a minor influence from shifts in Arctic atmospheric circulation in the early 1990s, and persistent warm conditions.

A major transformation, or regime shift, of the Bering Sea occurred in atmospheric conditions around 1977, changing from a predominantly cold Arctic climate to a warmer subarctic maritime climate as part of the Pacific Decadal Oscillation (PDO). This shift in physical forcing was accompanied by a major re-organization of the marine ecosystem on the Bering Sea shelf over the following decade. Fisheries surveys and model calculations show a shift in the importance of pollock to the ecosystem, from near 10% of the energy flow at mid-trophic levels in the 1950s–60s, to over 50% in the 1980s, although biological information for the earlier period is limited and often speculative. Weather data beginning in the 1910s, and proxy data (*e.g.*, tree rings) back to 1800, suggest that, except for a period in the 1930s, the Bering Sea was generally cool before 1977, with sufficient time for slow-growing, long-lived, cold-adapted species to adjust. Thus the last few decades appear to be a transition period for the Bering Sea ecosystem.

A specific Arctic influence on the Bering Sea began in the early 1990s, as a shift in polar vortex winds (the Arctic Oscillation – AO) reinforced the warm Bering Sea conditions, especially promoting an earlier timing of spring meltback of sea ice. Flatfish increased in the mid-1980s due to changes in larval advection, but the AO shift to weaker winds in the early 1990s reduced these favorable conditions for flatfish larval advection. Warm conditions tend to favor pelagic over benthic components of the ecosystem. Cold water species, *i.e.*, Greenland turbot, Arctic cod, snow crab and a cold water amphipod, are no longer found in abundance in the southeast Bering Sea, and the range of Pacific walrus is moving northward. While it is difficult to show direct causality, the timing of the reduction in marine mammals suggests some loss of their traditional Arctic habitat. Although ecological conditions appear to be mostly stable over the last decade, the warmest water column temperatures have occurred in 2001–03 on the southeast Bering Sea shelf, despite considerable year-to-year variability in the AO and PDO.

Overall climate change occurring in the Arctic, as indicated by warmer atmospheric and oceanic temperatures and loss of 15% of sea ice and tundra area over the previous two decades, is making the Bering Sea less sensitive to the intrinsic climate variability of the North Pacific. Indeed, when the waters off the west coast of the continental United States shifted to cooler conditions after 1998, the subarctic did not change (Victoria pattern), in contrast to three earlier PDO shifts in the twentieth century. Thus the Bering Sea will likely continue on its current warm trajectory, with biomes transitioning northward, allowing pollock a larger domain at the expense of cold- and ice-adapted species, rather than transitioning back to a cold regime.

Aleutian Islands (AI)

Climatic conditions vary between the east and west Aleutian Islands around 170°W: to the west there is a long-term cooling trend in winter, while to the east, conditions change with the PDO. This is also near the first major pass between the Pacific and Bering Seas for currents coming from the east. Biological conditions in the Aleutian Islands have changed since the 1980s, and it is too soon to discern if there was a change associated with the 1998 shift. Pollock and Atka mackerel do not appear to vary on a decadal scale. However, the biomass of pollock appears to be higher now than it was in the 1980s. Pacific ocean perch population dynamics vary on a decadal scale; for example, Pacific ocean perch survival changed at approximate times of regime shifts, 1977 and 1989. There is not enough information on the early life history of Pacific ocean perch to define a mechanism for the observed variations.

2.6 Western North Pacific (WNP)

Physical and biological data were summarized by three main regions: the Sea of Okhotsk; the Tsushima Current region and Kuroshio/Oyashio Current region; and the Yellow and East China Seas. The response to the 1989 regime shift was strong in all regions of the western North Pacific, from the East China Sea through to the Sea of Okhotsk, including the Kuroshio/Oyashio Current region. Winter air temperatures increased, which corresponded to warmer SSTs. These conditions have persisted to 2003 and appear to be connected to the east–west dipole pattern observed in basin-wide SST variability. A strong response to the 1998 regime shift was observed only in the Sea of Okhotsk, with an intensification of colder conditions and sea ice extent. This intensification corresponded to a persistent increase in Sea of Okhotsk zooplankton biomass in 1999, particularly in the spring, for large-sized plankton such as euphausiids, amphipods, copepods, and arrow worms. Changes in the epipelagic fish community were also evident, with Japanese sardine, previously a dominant species, replaced by herring, capelin and Japanese anchovy. Walleye pollock remained the most abundant species in the Sea of Ohkotsk, but the intensification of colder conditions in 1998 corresponded to a decrease in walleye pollock biomass. Consistent biological responses to the 1998 shift were not evident in the other western North Pacific regions. The biomass of warm water macro-algae in the Tsushima Current region increased when water temperatures increased in the late 1990s. Zooplankton biomass in the Kuroshio Current region has varied since 1978, but has remained at low levels. Conversely, zooplankton biomass in the eastern Yellow Sea has remained at high levels since the late 1990s. Phytoplankton and zooplankton biomass has declined in the Bohai Sea, the western Yellow Sea, and the East China Sea since the early 1980s. In both the Kuroshio and Tsushima Current areas, Japanese sardine began to decline in abundance around 1988. In contrast, Japanese anchovy, jack mackerel and Japanese common squid have increased in abundance since the mid-1980s. Most fish abundance and recruitment were normal in 1998, but recruitment of Japanese common squid and Pacific saury were extremely poor. Groundfish species in the Yellow Sea have declined in abundance from the 1960s to 1990s. Japanese common squid have increased and maintained high levels since the 1990s.

2.7 Coherence in Regional Responses to the 1998 Regime Shift

Although each region does not respond in the same manner to a regime shift, it is clear that regions do respond in some manner to most shifts. The 1998 regime shift had the greatest impact in the most southerly regions (*i.e.*, the central North Pacific and the California Current System) and had virtually no impact in the Bering Sea. It is important to note that the El Niño event in 2002–03 has produced a signal that may have confounded characterization of the new state. Table 2.1 provides a summary of the basin-wide climate–ocean indices (Section 1), and the physical and biological components of each region, which are reported in detail in Appendices 1–5. The table is intended to provide a single source of summary information of all of the indices and time series that were reviewed by the Study Group. For each data series, the overall state was characterized for regime periods to provide an indication of the nature of that climate, ocean or ecosystem component during previous regimes (1947–76; 1977–88; 1989–97). In a similar manner, each year subsequent to 1998 was also categorized to provide an indication of which components changed, when those components changed, and the impact of the 2002–03 El Niño event.

2.8 Climate Indicators for Detecting Regime Shifts

A number of indices and indicators are used operationally to quantify climate state and variability. These are derived principally from available long-term data and easy-to-monitor physical fields. Some of the indices relevant to identifying decadal climate variability are described in Section 1. For ecosystem variability, fishery-based and other biologically-based indicators should be used as well, although these are less developed. Because they are proven reasonable indicators of past regime shifts, the existing climate indices (*e.g.*, PDO, Victoria, Northern Oscillation Index) should continue to be tracked and used as indicators of changes in climate and North Pacific Ocean conditions. However, research should also continue on developing and testing the utility of new indicators.

Decadal climate variability in the North Pacific is not a two-state system represented by a single mode (*e.g.*, alternating cool/warm states), but is a result of more than one climate mode. It is not plausible to predict when the system will go back to the previous phase of a mode such as the PDO, because it may switch to a different mode. Furthermore, it is not possible to say when the next change will occur, but only to detect if a change has occurred in accordance to some criteria of a regime shift. The observational record is short relative to the time scale of regime shifts, so it is not certain if the modes observed this century are regular in timing and intensity. Furthermore, it is possible that additional modes of climate variability have existed in the past, prior to instrumented monitoring, but within the evolutionary scope of fish populations, and perhaps new patterns will become dominant as a result of future natural and anthropogenic climate change.

Existing indicators generally characterize basin-scale patterns. It is important to monitor physical changes at regional scales, and to use indices which represent fields or processes that directly affect fishery populations (*e.g.*, coastal upwelling, circulation, stratification) rather than a broad-scale index that may be integrating a number of different signals in different regions. On the other hand, while the historical sequence of regime shifts requires multiple indicators to fully explain basin-scale variability, it is more likely that a single indicator will consistently describe regional climate shifts.

Sea surface height and ocean color observed from satellites may be reliable regime indicators because they integrate many processes of ecological importance (thermal structure, circulation, primary production), and satellite technology makes these fields consistently and regularly available. Monitoring to develop and maintain indices that are more directly and intimately related to the productivity of a fishery population or ecosystem should be a high priority because these types of indices will be consistent in explaining biological variability – as opposed to the common indicators currently available which are merely proxies of the biological changes we seek to track. Finally, research should continue on identifying the mechanisms by which climate change leads to ecosystem response. Such efforts are critical if we are to efficiently recognize the signals that will produce the shifts in marine populations of importance to managers.

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Table 2.1 Summary table of basin-wide climate ocean indices and regional physical and biological parameters by regime period (1948–1976; 1977–1988; 1989–1997) and by year subsequent to 1998. For each item, the value or definition designated to the symbols ● and ○ (typically the extremes of the range of values or definitions) are indicated. In all cases, the symbol ◍ indicates moderate values, ⇗ indicates a period of increasing trend, ⇙ indicates a period of decreasing trend, ⇔ indicates no change in pattern or value and ⊗ indicates a period of variability in the parameter, *i.e.*, no apparent trend or persistent pattern.

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Climate Ocean Indices												
Pacific Decadal Oscillation (winter)	1950-2004	●	○	○	○	◍	◍	◍	◍	○	◍	●=negative value; ○=positive value
Victoria pattern (winter)	1950-2004	⊗	◍	●	◍	○	○	○	○	◍	◍	●=negative value; ○=positive value
Arctic Oscillation	1950-2001	◍	●	○	○	⊗	⊗	⊗				●=negative value; ○=positive value
Northern Oscillation Index	1950-2003	○	●	●	●	○	○	○	○	●	◍	●=negative value; ○=positive value
Multivariate ElNiño-LaNiña Southern Oscillation Index	1950-2003	○	●	●	●	○	●	◍	◍	●	◍	●=negative value; ○=positive value
Central North Pacific												
Physical Oceanography												
Sea surface height	1992-2004			●	●	○	○	○	○	●	●	●=low height; ○=high height
Lower Trophic Levels												
Transition Zone Chlorophyll Front latitude	1997-2004			●	●	○	○	○	○	●	●	●=southerly; ○=northlerly
Fishes												
Albacore tuna fishery distribution	1995-2003			●	●	○	○	○	○	○		●=oceanic waters; ○=coastal waters
Higher Trophic Levels												
Kure/Midway monk seals	1995-2002			○	○	◍	●	●	●	◍		●=low pup survival; ○=high survival
California Current System												
Physical Oceanography												
Sea surface temperature	1900-2004	●	○	○	○	●	●	●	○	○		●=cool; ○=warm

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Stratification intensity	1950-2003	●	↗	○	⊗	●	◍	◍	◍	◍		●=weak; ○=strong
Mixed layer depth	1949-2004	●	↙	○	⊗	●						●=shallow; ○=deep
Alongshore current strength	1949-2004	○	●	●	⊗	○	○	○	○	◍		●=weak; ○=strong
Upwelling strength	1946-2004		○	●	⊗	○	○	○	○	○		●=weak; ○=strong
Lower Trophic Levels												
Chlorophyll *a*	1978-1986 1997-2003			●	●	○	○	○	○	○		●=low concentration; ○=high
Salp biomass	1952-2003	○	●	●	●	↗	↗	↗	↗	↗		●=low; ○=high
Copepod biomass	1952-2003	◍	○	●	○	○	○	○	○	○		●=low; ○=high
Euphausiid biomass	1952-2003	⊗	⊗	⊗	●	◍	◍	◍	◍	◍		●=low; ○=high
Zooplankton composition – Core of the current	1952-2001	○	◍	●	●	◍	○	◍	◍	◍	◍	●=southern species; ◍=normal; ○=northern species
Zooplankton composition – Periphery zones	1969-2003	◍	◍	●	●	◍	○	◍	◍	◍	●	●=southern species; ◍=normal; ○=northern species
Invertebrates												
Squid catch	1981-2003			↗	●	○	○	○	◍	◍		●=low landings; ○=high
Crab catch	1981-2003			↗	●	◍	◍	◍	◍	○		●=low landings; ○=high
Shrimp – west coast of Vancouver Island	1972-2003		●	⊗	●	●	◍	○	○	●		●=low biomass; ○=high
Fishes												
Pelagics												
Coho salmon – British Columbia	1980-2003	○	○	↙	●	●	●	●	●	●		●=low abundance; ○=high
Columbia River salmon	1940-2004	⊗	○	●	●	○	○	○	○	○	○	● = low returns; ○ = high
Pacific herring	1950-2003	⊗	↙	●	●	●	●	◍	◍	◍		●=low biomass
Pacific sardine	1948-2003	absent	↗	↗	○	○	○	○	○	○		○=high biomass, recruitment
Pacific hake biomass	1948-2004	↗	○	↙	●	●	●	●	●	●	◍	●=low; ○=high
Pacific hake distribution	1948-2004	●	●	↗	○	↙	↙	↙	↙	↙	↙	●=southerly distribution; ↗=expanding; ↙=contracting; ○=northerly
Gadids												
British Columbia Pacific cod	1956-2003	○	○	●	●	◍	○	◍	◍	◍		●=poor recruitment; ○=good
Rockfish												
California juvenile rockfish survey	1983-2002		○	⊗	●	●	↗	↗	○			●=poor recruitment; ○=good

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Gulf of Alaska												
Physical Oceanography												
Gulf of Alaska sea surface temperature	1970-2002	●	⊗	⊗	○	◍	◍	◍	○			●=cool; ○=warm
Gulf of Alaska sea surface salinity	1970-2002	○	⊗	⊗	⊗	⊗	⊗	⊗	⊗			○=high
Northern British Columbia sea surface temperature	1948-2003	●	○	○	○	●	●	●	●	○		●=cool; ○=warm
Haida eddy occurrence	1993-2004			⊗	○	○	●	●	●	○	○	●=few eddies; ○=many
Gulf of Alaska mixed layer depth	1970-2002	⬄	⬄	⬄	⬄	⬄	⬄	⬄	⬄			⬄=no change in depth
Ocean Station Papa mixed layer depth	1957-2003	⊗	○	⊗	○	◍	◍	◍	○	○		○=shallow
Freshwater discharge	1930-2000	⬄	⬄	⬄	⬄	⬄	⬄					⬄=no change or trend
Lower Trophic Levels												
Nutrients	1998-2000				●	◍	○					●=low concentration; ○=high
Chlorophyll *a*	1998-2001				●	○	○	●				●=low concentration; ○=high
Gulf of Alaska zooplankton	1956-1962 1980-89	●	○									●=low biomass; ○=high
Ocean Station Papa zooplankton timing	1970-2001		●	○	○	◍	◍	◍				●=late; ○=early
Invertebrates												
Shrimp survey	1973-2002	○	⬃	●	●	●	◍	◍	◍			●=low CPUE; ○=high
Crab fishery	1980-2002		◍	○	●	◍	◍	○	○			●=low CPUE; ○=high
Fishes												
Pelagics												
Southeast Alaska herring	1980-2002		●	◍	○	○	○	○	○			●=low biomass; ○=high
Northern British Columbia herring	1951-2003	⊗	⊗	⊗	◍	◍	◍	◍	◍	◍		●=low biomass; ○=high
Eulachon	1973-2002	⊗	⊗	●	●	●	●	●	○			●=low survey CPUE; ○=high
Capelin	1973-2002	○	⬃	●	●	●	●	●	●			●=close to zero survey CPUE
Alaska sockeye salmon	1900-2001	●	○	○	◍	○	◍	◍				●=low catch; ○=high
Alaska pink salmon	1900-2001	●	○	○	○	○	○	○				●=low catch; ○=high
Alaska coho salmon	1900-2001	●	○	○	○	○	○	○				●=low catch; ○=high
Northern British Columbia coho salmon	1980-2004		⬃	⬃	◍	◍	○	○	○	○		●=low abundance; ○=high

	Length of time series	Regime 1948-1976	Regime 1977-1988	Regime 1989-1997	Year 1998	Year 1999	Year 2000	Year 2001	Year 2002	Year 2003	Year 2004	
Gadids												
Walleye pollock	1967-2003	⬀	⊗	⬃	●	●	●	●	●	●		●=low biomass; ○=high
		○	○	●	●	○	◍	●				●=poor recruitment; ○=good
		○	◍	●	◍	○	○	●				●=low R/S survival; ○=high
Gulf of Alaska Pacific cod	1977-2001		⬀	⬃	●	●	●	●				●=low biomass; ○=high
			○	○	○	○	○	●				●=poor recruitment; ○=good
			○	◍	◍	◍	◍	●				●=low R/S survival; ○=high
Northern British Columbia Pacific cod	1956-2001	○	○	●	●	●	●	●				●=poor recruitment; ○=good
Gulf of Alaska sablefish	1960-2001	⊗	⊗	⬃	●	●	●	◍				●=low biomass; ○=high
		○	○	●	●	●	●	●				●=poor recruitment; ○=good
		⊗	○	○	●	●						●=low R/S survival; ○=high
Northern British Columbia sablefish	1976-1999		○	●	●	○						●=low R/S survival; ○=high
Flatfish												
Flathead sole	1981-1998		⬀	⬀	○							●=low biomass; ○=high
			○	○	○							●=poor recruitment; ○=good
			○	●	○							●=low R/S survival; ○=high
Central Gulf of Alaska halibut	1974-2004	●	⬀	⬀	⬃	⬃	⬃	⬃	⬃	⬃		●=low biomass; ○=high
		●	○	○	◍	◍	◍	◍	◍	◍	◍	●=poor recruitment; ○=good
Southeast Alaska halibut	1974-2004	●	⬀	⬀	○	○	○	○	○	○		●=low biomass; ○=high
		●	○	○	○	○	○	○	○	○	○	●=poor recruitment; ○=good
British Columbia halibut	1974-2004	●	⬀	⬀	○	○	○	○	○	○		●=low biomass; ○=high
		●	○	○	○	○	○	○	○	○	○	●=poor recruitment; ○=good
Arrowtooth flounder	1960-1997	●	⬀	⬀								●=low biomass; ○=high
		⬀	○	○								●=poor recruitment; ○=good
		⬀	○	●								●=low R/S survival; ○=high
Rockfish												
Gulf of Alaska Pacific ocean perch	1960-1998	⬃	●	⬃	◍							●=low biomass; ○=high
		○	○	○	◍							●=poor recruitment; ○=good
		●	○	○								●=low R/S survival; ○=high
Queen Charlotte Sound Pacific ocean perch	1962-1993	●	○	●								●=poor recruitment; ○=good
Bering Sea and Aleutian Islands												
Physical Oceanography												
Surface air temperature at St. Paul Island	1917-2004	●	○	○	○	◍	○	○	○	○	○	●=cold; ○=warm

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Ice at 57°–58°N	1973-2003	○	⊗	⊗	●	●	⊗	none	●	none		●=less than 30%; ○=greater than 70%
Temperature (0–70 m) at M2	1995-2003			4°C	5°C	3°C	5°C	5°C	6°C	6°C		
Lower Trophic Levels												
Jellyfish	1982-2003		●	○	○	○	○	●	●	●		●=low biomass; ○=high
Invertebrates												
Benthos	1975-2000	○	◍	◍	○			◍				○=high survey CPUE
Eastern Bering Sea crab	1980-2002		⇙;⇗	⇙	◍	●	◍	◍	●			●=low total mature biomass; ○=high
Fishes												
Gadids												
Aleutian Islands walleye pollock	1977-2002		⇙	⇗	○	○	○	○	○			●=low biomass; ○=high
			⊗	⊗	◍	◍	◍	◍	◍			●=poor recruitment; ○=good
Eastern Bering Sea walleye pollock	1963-2002	●	○	○	○	○	○	○	○			●=low biomass; ○=high
		⊗	⊗	⊗	◍	◍	◍	●	●			●=poor recruitment; ○=good
		○	⇙	●	◍	◍	●	●	●			●=low R/S survival; ○=high
Eastern Bering Sea Pacific cod	1978-2002		⇗	⇙	◍	◍	○	●	◍			●=low biomass; ○=high
			⊗	⊗	◍	◍	◍	◍	◍			●=poor recruitment; ○=good
			⇙	◍	◍	◍	◍	◍	◍			●=low R/S survival; ○=high
Flatfish												
Eastern Bering Sea yellowfin sole	1960-1999	●	⇗	⇙								●=low biomass; ○=high
		⇗	⊗	●								●=poor recruitment; ○=good
		⇗	⇙	●								●=low R/S survival; ○=high
Bering Sea Greenland turbot	1973-2000		⇙	⇙	●	●	●					●=low biomass; ○=high
		⊗	⇙	●	●	●	●					●=poor recruitment; ○=good
			○	●	◍	◍	◍					●=low R/S survival; ○=high
Eastern Bering Sea arrowtooth flounder	1974-1999	⇗	⇗	○	○	○						●=low biomass; ○=high
		⊗	⇙	◍	◍	◍						●=poor recruitment; ○=good
		○	●	●	●	●						●=low R/S survival; ○=high
Eastern Bering Sea rock sole	1971-1998	⇗	⇗	⇗	○							●=low biomass; ○=high
		⇗	⇗	⇙	●							●=poor recruitment; ○=good
		◍	◍	●	●							●=low R/S survival; ○=high
Bering Sea flathead sole	1974-2001	⇗	⇗	⇙	○	○	○	○				●=low biomass; ○=high
		○	○	⇙	●	●	●	●				●=poor recruitment; ○=good
		○	○	●	●	●	●	●				●=low R/S survival; ○=high

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Rockfish												
Eastern Bering Sea and Aleutian Islands Pacific ocean perch	1960-1993	⇙ ● ●	⇗ ◍ ○	⇗ ◍ ●								●=low biomass; ○=high ●=poor recruitment; ○=good ●=low R/S survival; ○=high
Higher Trophic Levels												
Pribilof fur seals	1975-1998	○	⇙	●	●							●=low pup survival; ○=high
Western North Pacific												
Sea of Okhotsk												
Physical Oceanography												
Sea ice coverage	1930-2002	○	⇙	●	●	○	○	○	○			●=low extent; ○=high extent
Sea temperature at 50-200m	1996-2000			○	○	●	●					●=cold; ○=warm
Lower Trophic Levels												
Summer–fall zooplankton	1984; 1986; 1988; 1997-2002		○	●	●	○	○	○				●=low biomass; ○=high
Fishes												
Pelagics												
Herring	1985; 1986; 1988; 1998-2002		⊗		○	○	◍	◍	◍			●=lower proportion of epipelagic community; ○=higher proportion
Capelin	1985; 1986; 1988; 1998-2002		●		●	●	●	○	○			●=lower proportion of epipelagic community; ○=higher proportion
Gadids												
Walleye pollock	1984-1999		○	◍	●	●						●=low spawning biomass; ○=high
Tsushima Current Region												
Physical Oceanography												
Sea surface temperature off coastal Hokkaido	1965-2001	○	●	○	●	●	●	●				●=negative anomaly; ○=positive
Sea surface temperature off coastal Honshu	1965-2001	◍	●	○	○	○	○	○				●=negative anomaly; ○=positive
Sea surface temperature off coastal Korea	1968-2002	⊗	●	○	○	○	○	○	○			●=negative anomaly; ○=positive
Winter sea temperature at 50 m depth in western Sea of Japan	1965-2003	●	●	○	○	○	○	○	○	○		●=negative anomaly; ○=positive

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Lower Trophic												
Primary production off coastal Korea	1960-1990	○	●									●=negative anomaly; ○=positive
Zooplankton abundance off coastal Korea	1960-1990	○	●									●=negative anomaly; ○=positive
Invertebrates												
Common squid fishery	1973-2003	◍	●	⇗	●	○	○	○	○	○		●=low CPUE; ○=high
Fishes												
Pelagics												
Jack mackerel	1973-2002	◍ ●	⇗ ●	○ ⊗	○ ●	○ ●	○ ●	○ ●	○ ●			●=low biomass; ○=high ●=low R/S survival; ○=high
Chub mackerel	1973-2002	○ ○	○ ⇙	⇗ ◍	● ○	● ○	● ○	● ○	● ○			●=low biomass; ○=high ●=low R/S survival; ○=high
Spotted mackerel	1992-2002			◍ ⊗	○ ○	○ ●	○ ●	○ ●	○ ●			●=low biomass; ○=high ●=low R/S survival; ○=high
Japanese sardine	1988-2002			⇙ ●	● ○	● ●	● ◍	● ○	● ○			●=low biomass; ○=high ●=low R/S survival; ○=high
Anchovy	1988-2002			⇗ ⊗	○ ●	○ ●	◍ ◍	● ○	● ◍			●=low biomass; ○=high ●=low R/S survival; ○=high
Round herring	1991-2002			⇙ ⊗	◍ ◍	◍ ◍	● ◍	● ○	● ○			●=low biomass; ○=high ●=low R/S survival; ○=high
Higher Trophic Levels												
Hokkaido seabirds	1984-2001		●	○	○	○	○	○	○			●=sardine dominant diet; ○=anchovy
Kuroshio-Oyashio Current Region												
Physical Oceanography												
Spatial extent of Oyashio Current	1960-2003	●	○	○	◍	●	●	○	○	○		●=negative area anomaly; ○=positive area anomaly
Winter sea surface temperature in Kuroshio	1950-2002	●	⊗	○	○	○	◍	○				●=cool; ○=warm
Lower Trophic Levels												
Oyashio zooplankton	1972-1999	○	●	⊗	●	●						●=low biomass; ○=high
Fishes												
Pelagics												
Chub mackerel	1950-2001	○ ○	⇙ ◍	● ⊗	● ●	● ●	● ◍	● ●				●=low biomass; ○=high ●=low R/S survival; ○=high

	Length of time series	Regime			Year							
		1948-1976	1977-1988	1989-1997	1998	1999	2000	2001	2002	2003	2004	
Japanese sardine	1950-2001	⇗ ○	○ ◍	⇙ ●	● ◍	● ●	● ◍	● ●				●=low biomass; ○=high ●=low R/S survival; ○=high
Pacific saury	1980-2002		⇗	○	●	●	●	◍	●			●=low commercial CPUE; ○=high
Yellow Sea and East China Sea												
Physical Oceanography												
Sea surface temperature off Korean coast	1965-2002	●	⊗	⇗	○	○	○	◍	◍			●=cool; ○=warm
Air temperature at Quingdao	1950-2003	●	◍	○	○	○	○	○	○			●=cool; ○=warm
Bohai Sea nutrient concentrations	1959; 1982; 1992	◍ ◍ ○	◍ ◍ ○	◍ ● ●								●=low nitrogen; ○=high ●=low phosphate; ○=high ●=low silicate; ○=high
Lower Trophic Levels												
Bohai Sea phytoplankton	1982; 1992; 1998		○	◍	●							●=low primary productivity; ○=high
Bohai Sea zooplankton	1959; 1982; 1992; 1998	◍	◍	●	○							●=low biomass; ○=high
Yellow Sea zooplankton	1978-2001		●	○	○	○	○	○				●=low biomass; ○=high
Fishes												
Pelagics												
Yellow sea anchovy	1954-2001	●	⇗	⇗	○	○	○	◍				●=low biomass; ○=high
Pacific herring	1968-1976	◍	●	●	●							●=very low biomass, no fishery
Demersal Fishes	1960-2002	○	⇙	●	●	●	●	●	●			●=low proportion in fish community; ○=high

3. Implications for the Management of Marine Resources

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3.1 Introduction

There has been much discussion recently on the need for ecosystem assessment and ecosystem-based fisheries management (ESA 1998; FRCC 1998; NMFS 1999; Brodziak and Link 2002; FAO 2003; Garcia *et al.* 2003). Often these two terms have been used interchangeably. However, they do reflect different approaches. Ecosystem assessment is relatively well defined and includes monitoring climate–ocean indices and indicator species to detect ecosystem changes, *i.e.*, assessing the state of the environment. It is important to note that fisheries agencies currently do not manage ecosystems, rather they manage the human impacts on ecosystems. As such, ecosystem-based fisheries management reflects the incorporation of knowledge of the state of the ecosystem (*i.e.*, the ecosystem assessment) into single species assessments when making management decisions. This approach has recently been referred to as Ecosystem Approaches to Fisheries (FAO 2003; Browman and Stergiou 2004). It is an approach that explicitly accounts for ecosystem processes when formulating management actions which may still encompass traditional management tools, such as total allowable catch, but which will likely be different quantitatively as a result of taking account of more factors (Sissenwine and Murawski 2004). Ecosystem-based fisheries management provides a framework for managing marine resources that can consider climate regimes and regime shift impacts on marine ecosystems.

Agencies charged with fisheries management should develop policies immediately which will explicitly specify decision rules and subsequent actions to be taken in response to preliminary indications that a regime shift has occurred. These decision rules need to be included in long-range policies and plans. Management actions should consider the life history of the species of interest, and can encompass varying response times, depending on the species' lifespan and rate of production. The provision of stock assessment advice needs to indicate explicitly the likely consequences of alternate harvest strategies to stock viability, under various recruitment assumptions.

3.2 Response Time of Biota to Regime Shifts

Marine organisms have evolved life history strategies to cope with variability in their environment. These life history strategies range from short-lived, highly variable stock dynamics, which respond immediately to changes in their environment, to extremely long-lived species whose population dynamics are mainly stable (King and McFarlane 2003).

Short-lived species have a shorter generation time which helps to maximize their intrinsic rate of population growth, despite typically having relatively low fecundity. Longevity allows a species to persist through prolonged periods of poor productivity (Leaman and Beamish 1984; McFarlane and Beamish 1986). Long-lived species are typically highly fecund, which allows them to take immediate advantage of changes to more productive regimes, through increased year class success. It is important to note that the intrinsic rate of population growth in long-lived species is lower than in short-lived species, so improved year class success translates into delayed increases in population productivity.

3.3 Response Time of Management to Regime Shifts

Since most fisheries are conducted on mature fish, the age of recruitment to the fishery typically corresponds to the age of maturity. It is possible to use the age of maturity as an indication of how long fisheries managers have to respond to a shift in productivity. For example, Pacific cod matures and recruits to the fishery at age 2+. A shift in productivity, reflected in year class success, would have impacts on the available biomass within 3 years, *i.e.*, this is when a strong year class will appear as a large increase in biomass for the fishery. Conversely, a large year class in a rockfish species would not appear as an increase in biomass to the fishery for 8–10 years (depending on the species). The response time of management actions to regime shifts may be lagged by a correspondence to the age of recruitment of the species of interest.

3.4 Provision of Stock Assessment Advice

Fisheries agencies need to direct fisheries scientists to provide harvest recommendations that reflect a range of risk (low to high) to the stock under different assumptions of productivity or recruitment (*e.g.*, low, medium and high year class success). Different levels of productivity appear to be decadal in nature, corresponding to different regimes, with changes in productivity corresponding to regime shifts (Beamish and Bouillon 1993; Francis and Hare 1994; McFarlane *et al.* 2000; Hare and Mantua 2000; Hollowed *et al.* 2001). Stock assessment scientists should also provide managers with an indication of the most probable productivity level for that particular regime. Managers can make decisions on harvest levels using ancillary information (ecosystem assessments, climate–ocean indices, indicator species) to select the most likely productivity assumption. It is important to note that scientific advice will remain only one of the myriad of factors that managers use to make decisions. Managers will need to consider economic, political and social factors when selecting the appropriate level of risk to the stock that they are willing to accept, and select harvest rates accordingly.

Polovina (2004) reviewed numerous studies that investigate optimum harvest rates for fisheries that are impacted by regime shifts. In some studies, a constant harvest rate strategy generally performed well (Walters and Parma 1996; DiNardo and Wetherall 1999). Polovina (2004) suggested that a constant harvest rate strategy, when applicable, should employ a rate well below traditional benchmarks. However, the preferred strategy is a regime-specific harvest rate (Spencer 1997; Peterman *et al.* 2000; MacCall 2002). For example, a population simulation model of Pacific sardine (*Sardinops sagax*), using a regime-specific harvest rate strategy, produced higher average annual yields and lower variability in spawning biomass than a constant harvest rate strategy (MacCall 2002; Polovina 2004). Improved results could still be achieved even if the switch in harvest rates was delayed some years after the regime shift. However, it should be noted that the simulation assumed regime periods of a known duration, which is not applicable for the current state of knowledge.

In the case of short-lived species that exhibit highly autocorrelated recruitment responses to climate shifts, stock assessment scientists have a high probability of detecting the processes or indices that influence production. Assessment scientists should be directed to incorporate these processes into their assessment advice. When providing advice to managers, stock projections can be conducted, using best estimates of 5- to 10-year climate regimes, to directly incorporate environmental forcing. It should be noted that preservation of spawning stock biomass at levels consistent with maximum sustainable yield (MSY) for a productive period will probably be impossible when the stock shifts to a less productive regime. Minimum stock size thresholds may be the best protection for species with this type of life history strategy. Imposing this type of stock protection will likely result in prolonged periods of no directed harvest during unfavorable regimes.

In the case of long-lived species, the response of the spawning stock biomass to regime shifts will be slower or lagged by the age of recruitment to the regime shift year. For these species, annual recruitment is only a fraction of the spawning stock biomass, and longevity ensures a relatively long reproductive cycle, enabling populations to endure prolonged periods of unfavorable environmental conditions. Maintaining an appropriate age-structure in spawning stock biomass should be a paramount management goal for long-lived, late-maturing species.

In all cases, it is important to maintain a critical spawning biomass. This is a level which ensures that the population is able to withstand long periods of poor environmental conditions. It does imply that exploitation levels may be severely reduced, or in some cases, that no fishing could occur during prolonged periods of poor recruitment.

3.5 Decision Rules

Agencies need to develop policies which explicitly specify decision rules and subsequent actions to be taken in response to preliminary indications that a regime shift has occurred. These decision rules need to be included in long-range policies and plans. Stock assessment advice should provide an indication of the likely consequences of alternate harvest strategies, under various recruitment assumptions, to stock viability. Decision rules must reflect the need to always maintain a critical spawning biomass and a robust age composition. The most appropriate approach to managing fisheries, given regime shift impacts, is to apply regime-specific harvest rates. These harvest rates should be part of the decision rule framework, and should be associated with timeframes for management response triggered when there are indications that a regime shift has occurred. As discussed above, the response time (*i.e.*, changes in harvest rates) can be lagged to correspond to the species-specific biological rates (*i.e.*, age of recruitment) and still enable higher average annual yields and lower variability in spawning biomass. If the regime shift corresponds to an increase in productivity, then delaying the change in harvest rate (from low to high) would allow the population to rapidly increase, resulting in increased recruits under the spawner-recruit relationship of the more productive regime (Polovina 2004). If the regime shift corresponds to a decrease in productivity, then delaying the change in harvest rate (from high to low) and the fishing down of the population will not reduce recruitment under the spawner-recruit relationship of a less productive regime (Polovina 2004). The caveat for delaying a switch from high to low harvest rates in less productive regimes is that aggressive harvest rates could result in a population level that is at, or near, the critical spawning biomass, which could translate into a prolonged period of no fishing. To address this, managers could also consider a provisional step-wise approach to changing harvest rates with regime shifts until the productivity level of a new regime has been verified.

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Appendix 1: Recent Ecosystem Changes in the Central North Pacific

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Summary

The central North Pacific experienced an abrupt change beginning in 1999, characterized by a rise in sea surface height (SSH), indicating an increase in the depth of the top of the thermocline. At the same time, the eastern and northern boundaries of the North Pacific experienced a drop in SSH, indicating a shoaling of the depth of the top of the thermocline. In the central North Pacific, the SSH rise was accompanied by a northward shift of low surface chlorophyll water. At higher trophic levels, Hawaiian monk seal pup survival at northern atolls in the Northwestern Hawaiian Islands has dropped since 1999. Also, since 1999 the albacore fishing grounds for the U.S. troll fleet has shifted eastward. By 2003, the high SSH in the central North Pacific dissipated, suggesting it was a response to the 1999 La Niña rather than a decadal shift.

A1.1 Introduction

In this section we will examine changes in the central North Pacific ecosystem primarily since 1999, based on a range of data, including satellite altimetry and satellite ocean color, Northwestern Hawaiian Islands monk seal pup survival, and spatial distribution of the troll fishing grounds for albacore. However, it should be noted as background that earlier changes have been documented. Physical and biological changes have been described in the central North Pacific over the period 1960 to the early 1990s. The winter and spring mixed layer depth in the central Transition Zone and northern Subtropical Gyre was 30–80% greater during 1977–88 than during 1960–76, based on vertical temperature records (Polovina *et al.* 1995). A simulation model indicated that the deeper mixed layer would bring deep nutrients into the euphotic zone and increase phytoplanton biomass in this region (Polovina *et al.* 1995). Since the late 1980s, coincident with the 1989 regime shift noticed elsewhere in the North Pacific, there has been a drop in productivity, perhaps a return to pre-1977 levels, of a number of marine ecosystem components of the Northwestern Hawaiian Islands, including spiny lobster, sea birds, and monk seals (Polovina *et al.* 1994; Polovina and Haight 1999).

A1.2 Physical Oceanography

Sea surface height

Time series of empirical orthogonal functions (EOFs) derived from sea surface height (SSH) estimated with satellite altimetry provide indicators which describe temporal and spatial changes in geostrophic transport and the ocean vertical structure, especially changes in the depth of the top of thermocline, which may have important ecosystem implications. In order to capture important regional dynamics in SSH changes, we partition the North Pacific into four regions and compute the first SSH EOF for each region (Figs. A1.1a–d; Polovina and Howell, in press). In the equatorial regions, the first SSH EOF captures 36% of the monthly SSH variation, with a spatial dipole pattern where the eastern and western Pacific vary in an opposite manner (Fig. A1.1a). During the strong 1997–98 El Niño, the SSH in the western Pacific dropped by as much as 28 cm and in the eastern North Pacific rose by 28 cm (Fig. A1.1a). This indicator shows the 2002–03 El Niño had a much weaker impact on equatorial SSH than the 1997–98 event (Fig. A1.1a). This SSH EOF is basically an El Niño indicator, but because it is based on SSH rather than SST or atmospheric pressure, it better describes changes in vertical structure and geostrophic transport than the more traditional indices.

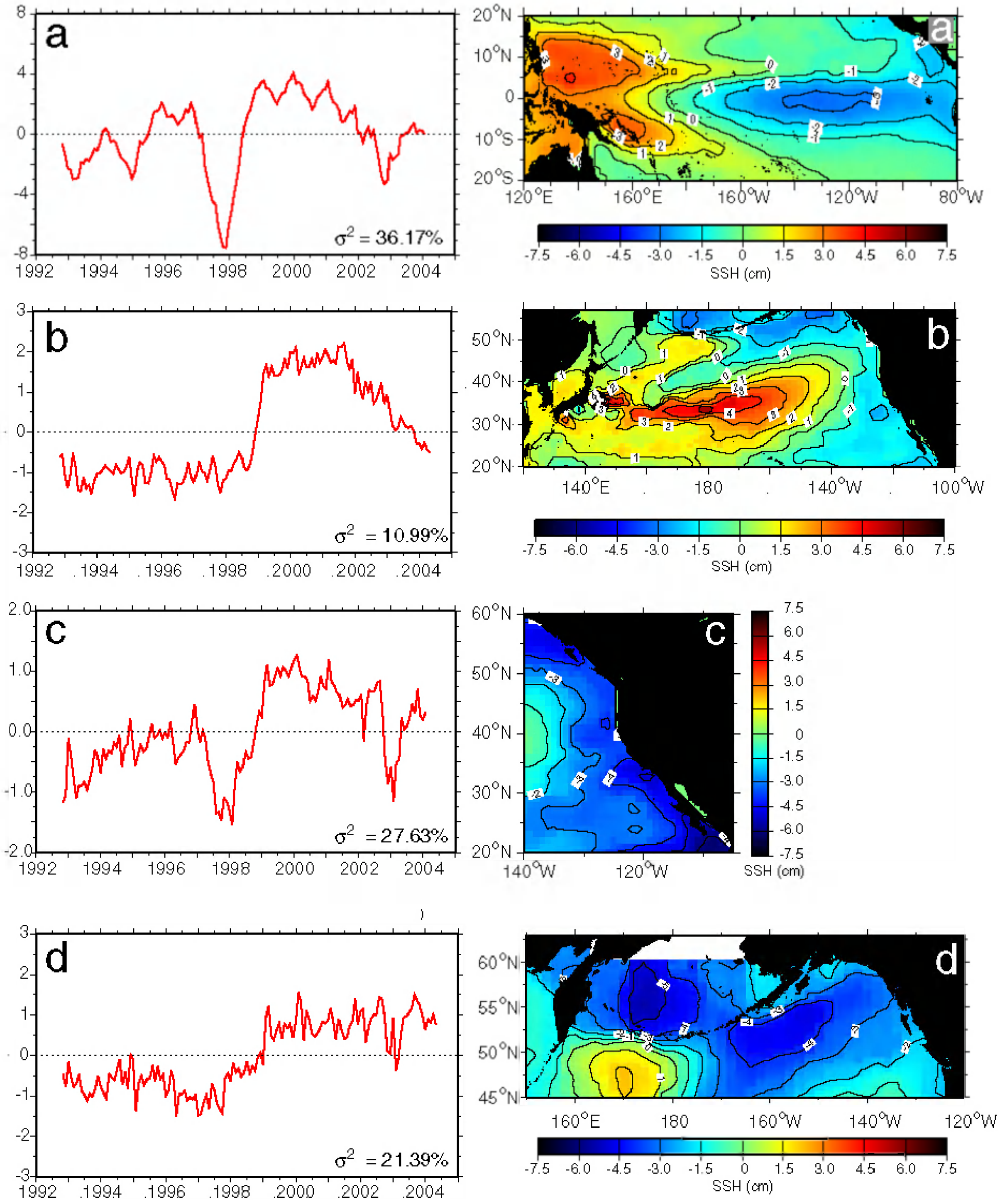

Fig. A1.1 The first empirical orthogonal function (EOF) modes of sea surface height (SSH) for (a) the equatorial Pacific, (b) the central North Pacific, (c) the eastern Pacific, and (d) the Alaskan Gyre. The weighting functions are presented as time series in the left panels and the corresponding spatial patterns are in the right panels, with the annotation on the time series representing the variance explained for the mode of each region.

The next regional indicator is the first SSH EOF from the mid-latitude region, defined as 20°–45°N latitude, and it captures 11% of the monthly SSH variation. This indicator identifies an abrupt change in SSH which occurred in 1999, characterized by SSH rising in the central North Pacific (Fig. A1.1b). This increase in SSH represents an increase in heat content, stratification, and depth of the top of the thermocline. The change persisted for several years, but by 2004, conditions returned back to baseline levels, thus probably reflecting the impact of the strong 1999 La Niña rather than a regime shift (Fig. A1.1b).

The third regional indicator is the first SSH EOF from the eastern North Pacific, 20°–60°N latitude, and explains 28% of the monthly SSH variation. This indicator shows a sharp and more persistent drop in SSH in 1999, interrupted by the relatively strong mid-latitude 2002–03 El Niño (Fig. A1.1c). The drop in SSH indicates a shoaling of the top of the thermocline.

The fourth regional indicator is the first SSH EOF for the Gulf of Alaska and Bering Sea, north of 45°N latitude, and explains 20% of the monthly SSH variation. This indicator finds that a drop in SSH developed more gradually than in the eastern North Pacific, beginning in 1999, and persists through 2004 with minimal impact from the 2002–03 El Niño (Fig. A1.1d).

These four regional EOFs distill over a decade of SSH data in the North Pacific to identify some major spatial and temporal patterns of ocean dynamics in the North Pacific. In particular, the mid-latitudes experienced an abrupt warming and deeper thermocline from 1999 through 2002 and now, in early 2004, conditions appear to be reversing. However, in the eastern and northern North Pacific a drop is SSH was experienced in 1999 which persists through the present, although conditions may be returning to baseline levels in the eastern North Pacific. Furthermore, these regional indicators show that while the 2002–03 El Niño was weak in the equatorial region, it was relatively strong in the eastern North Pacific.

A1.3 Lower Trophic Levels

Surface chlorophyll

Satellite imagery of surface chlorophyll *a* in the North Pacific shows two distinct regions: a region of relatively low surface chlorophyll representing the warm, vertically stratified subtropical gyre, and to the north, a region of relatively high surface chlorophyll representing the Transition Zone and subarctic gyre. The boundary between these two regions is termed the Transition Zone Chlorophyll Front (TZCF) and is an important migration and forage habitat for large pelagic species (Polovina *et al.* 2001; Fig. A1.2a). Contouring the 0.2 mg m^{-3} surface chlorophyll *a* level from SeaWiFS ocean color satellite imagery provides an excellent indicator of the position of the TZCF (Polovina *et al.* 2001). Satellite ocean color data have shown that the position of TZCF migrates seasonally north and south about 1,000 km. In the summer, as the central North Pacific warms and becomes more stratified, the TZCF typically shifts northward to the 40°–45°N latitude region, while in the winter, as storm tracks shift southward and vertically mix the central North Pacific, the TZCF moves southward to about 28°–32°N latitude (Polovina *et al.* 2001). However, there is considerable interannual variability in the winter position of the TZCF. In years when SSH in the central North Pacific was anomalously high, indicating anomalously warm and vertically stratified conditions (1999–2002, Fig. A1.1b), the winter position of the TZCF between 150°–180°W longitude is shifted northward (Fig. A1.2b). The winter position of the TZCF gives one measure of the northern boundary of the subtropical gyre, so that tracking this feature over time provides an indicator of large-scale atmosphere and ocean changes. The winter position of the TZCF also has regional impacts. In years when the TZCF is shifted southward (1997, 1998, 2003), it impinges on the northern atolls of the Northwestern Hawaiian Islands, while in other years its winter position lies hundreds of kilometers north of these atolls (Fig. A1.2b). The monthly time series of surface chlorophyll for the region around the northern atolls shows high values in 1997, 1998, and 2003, as a result of a southward-shifted TZCF

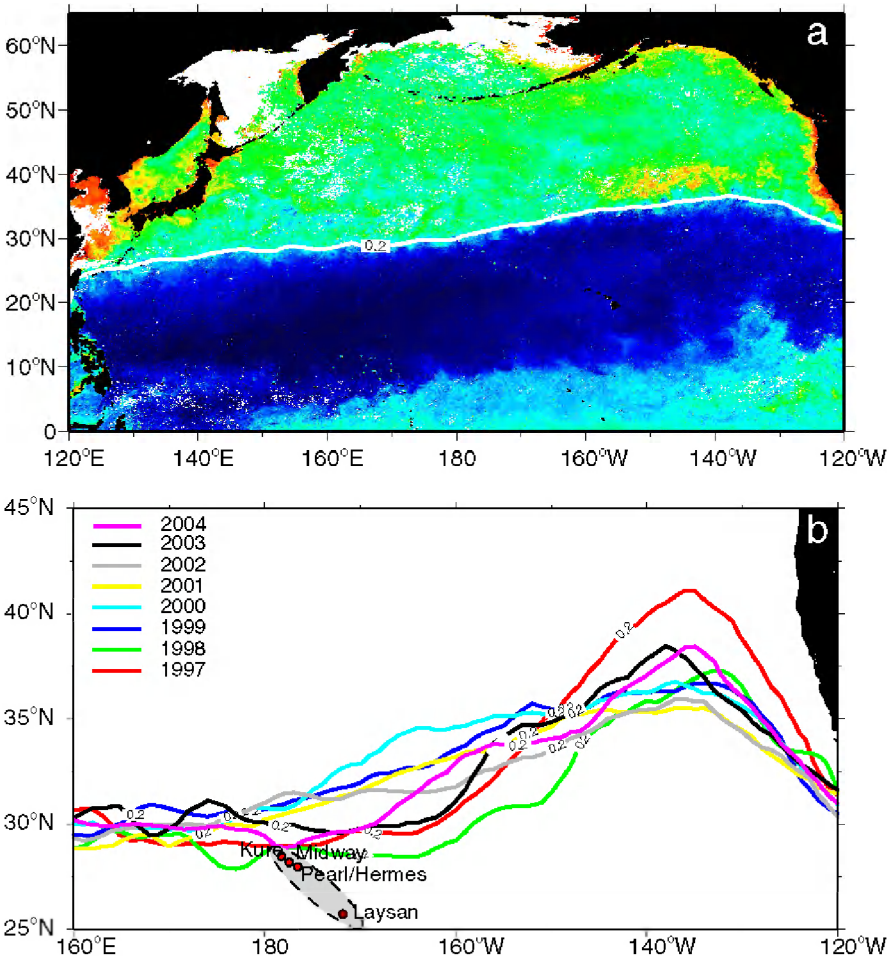

Fig. A1.2 (a) February 2002 SeaWiFS surface chlorophyll. (b) The 0.2 Transition Zone Chlorophyll Front for January and February plotted by year for the central North Pacific.

(Fig. A1.3a). In winters when the TZCF impinges on the northern atolls, the monk seal habitat is characterized by higher chlorophyll, vertically mixed cooler water, and a convergent front which appears to support a variety of large pelagics including squids, tunas, and turtles. However, in winters when the TZCF is well north of the atolls, their habitat consists of strong, vertically stratified, low chlorophyll warm water and no productive front. These different oceanographic conditions may have higher trophic level impacts. For example, Hawaiian monk seal survival rates for pups born on Pearl and Hermes Atoll, and Midway Atoll, appear to respond to these different oceanographic conditions. During 1999–2002 when the TZCF is north of the atolls, indicated by low chlorophyll values, pup survival declined, with some time lag, and since 2003 when the TZCF shifted southward, an increase in survival is suggested (Fig. A1.3). Preliminary evidence suggests that in winters when the TZCF impinges on the northern atolls, the monk seals at these atolls are fatter and likely have higher survival rates than in winters when the TZCF is shifted north of the atolls (Antonelis *et al.* 2003).

A1.4 Invertebrates

A preliminary stock assessment for spiny lobster (*Panulirus marginatus*) in the Northwestern Hawaiian Islands, based on the Mulitfan CL model, has found that recruitment dropped in the late 1980s, and remained at lower levels through to the present (G. Dinardo, PIFSC pers. comm.). This finding is consistent with earlier evidence of a drop in ecosystem productivity in the Northwestern Hawaiian Islands since 1989 (Polovina *et al.* 1994; Polovina and Haight 1999).

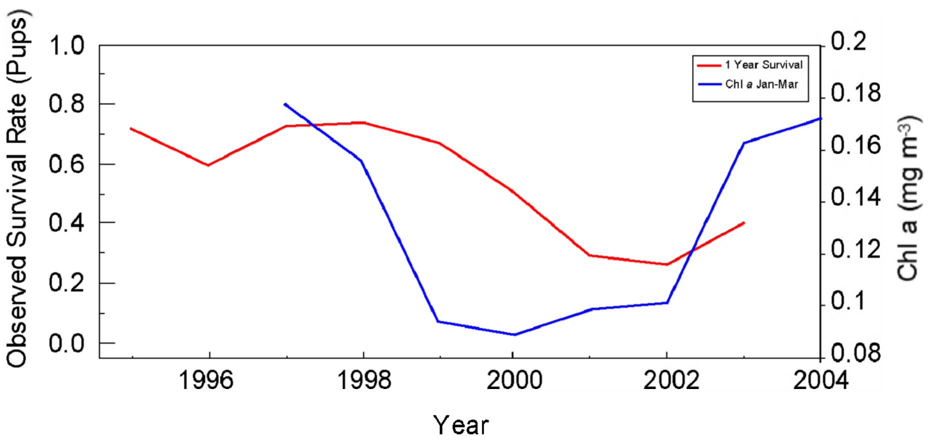

Fig. A1.3 January–March average SeaWiFS chlorophyll *a* values, 1997–2003, in a box 179.5°E–174.5°W, 28°–30°N around Midway and Kure Atolls (blue). Survival rates to 1 year for Hawaiian monk seal pups at Pearl and Hermes, Kure, and Midway Atolls (red). Monk seal survival data for 2003 are preliminary.

A1.5 Fishes

Albacore tuna (*Thunnus abalunga*)

Juvenile albacore tuna migrate across the North Pacific Transition Zone (Laurs and Lynn 1991). The U.S. troll fishery, based in California, has a season roughly spanning the months April to October. The troll fleet begins in the central North Pacific in April and moves eastward, following the albacore during their eastward migration. In some years a productive fishing ground develops in the region between 140°–150°W longitude and 35°–45°N latitude which persists through August, while in other years the fleet quickly moves across the Transition Zone to fishing grounds along the coast of North America. A plot of the monthly percent catch of albacore in the troll fishery east of 140°W shows that in the years 1995–97, a relatively small percentage of the total annual albacore catch was taken east of 140°W (Fig. A1.4). However, since 1999 this pattern has changed with over 50% of the albacore landed east of 140°W, beginning in July (Fig. A1.4). The shift in the fishing ground from the central Pacific to eastern North Pacific may be a response of the albacore to the more productive oceanographic conditions in the eastern North Pacific since 1999 that persisted through 2003. Not only is the shift in the albacore fishing ground an indication of oceanographic changes, the earlier arrival of an abundant population of albacore in the eastern North Pacific may have ecosystem impacts on the albacore prey population.

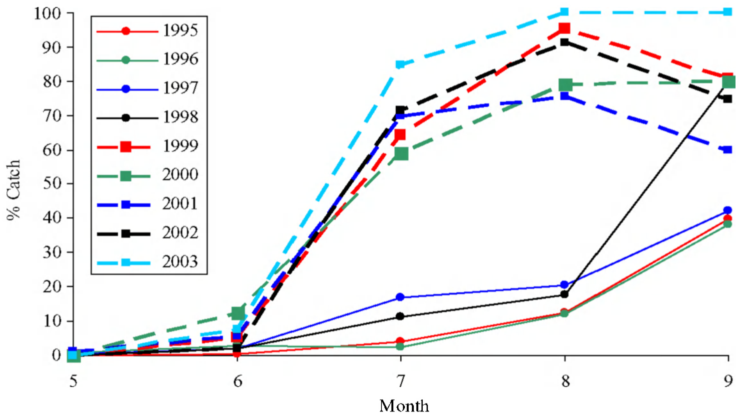

Fig. A1.4 The monthly percent of annual albacore tuna landings caught east of 140°W longitude for the U.S. troll fishery.

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Appendix 2: Recent Ecosystem Changes in the California Current System

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Summary

The California Current System (CCS) extends from British Columbia, Canada, to northern Baja California, Mexico. It is a well-studied area and benefits from a comparatively long history of physical and biological observations. Conditions in the CCS are subject to decade-scale regime behavior, with an overlay of episodic warm El Niño and cold La Niña events that last a year or two.

In the CCS, there have been strong ecosystem responses to the 1977 and 1989 regime shifts. The 1977 regime shift led to a protracted period of warm surface waters, with a deepening of the thermocline and the implication of lower productivity. However, available zooplankton time series suggest that salp biomass declined after 1977, while euphausiid biomass remained unchanged, and copepod biomass actually increased. Following the 1977 regime shift, overall recruitment improved for species such as Pacific sardine, and other species experienced intermittent very strong year classes (Pacific hake and Pacific cod). After the 1989 regime shift, the warm surface waters intensified and became unproductive for many coastal species. In coastal waters, zooplankton shelf species were replaced by more southerly and oceanic species. Many fish species (Pacific salmon, Pacific hake, Pacific cod, rockfish species) experienced almost a decade of poor recruitment. Southern migratory pelagics (Pacific sardines and Pacific hake) extended the northern limit of their distribution to northern British Columbia, and in some years, to the Gulf of Alaska.

After an intense El Niño in 1998, the CCS experienced a very cold La Niña in 1999. Since 1999, sea surface temperatures have tended to return gradually toward warm conditions similar to those in the 1980s and early 1990s, but thermocline depths are now much shallower and nutrient levels are higher, generating higher primary and secondary production. Beginning in 1999, coastal waters saw a return of shelf zooplankton, and many coastal fish stocks experienced substantial improvements in year class success. Some stocks produced good year classes in 1999 (e.g., *Pacific hake), and recent returns of several salmon stocks have improved; Columbia River salmon runs have been extraordinary. In addition, the distribution of migratory pelagics (Pacific sardine and Pacific hake) contracted to a more southerly distribution. There is growing evidence, based on a strong and diverse biological response, that a regime shift favoring coastal organisms occurred in 1998.*

A2.1 Introduction

The California Current System (CCS) extends along the west coast of North America from British Columbia, Canada, to northern Baja California, Mexico. Although this is one of the most thoroughly studied portions of the world's ocean, its properties and dynamics are still not well understood. During the decade of the 1990s, patterns of low frequency (periodicity greater than 10 years) and large-scale (extent greater than 1000 km) fluctuations in the ocean and atmosphere that appear to have a strong influence on biological productivity of the system, were identified. The CCS exhibits these regimes and regime shifts especially strongly.

A2.2 Physical Oceanography

The oceanography of the CCS has been relatively well studied, principally because of the long history of the California Cooperative Oceanic Fisheries Investigations (CalCOFI) field survey program (Bograd *et al.* 2003) and a long sampling record off Oregon (Smith *et al.* 2001). The interaction of large-scale circulation of the North Pacific with regional and local forces and factors of the coastal continental boundary controls the circulation and water mass properties of the CCS. The surface flow, the California Current, is the southward-flowing, eastern segment of the clockwise North Pacific Gyre, receiving cool, low-salinity, nutrient-rich water from the North Pacific Current off Oregon, Washington, and southern British Columbia (about 45°–50°N). It terminates off Baja California where it feeds the offshore-flowing component of the Gyre.

Most of the large-scale southward flow occurs in the upper 200 m of the ocean. The California Undercurrent is a warm, high-salinity, low-oxygen poleward flow that lies along the continental slope centered at about 250–300 m depth. Hickey (1979, 1998) and Huyer (1983) provide detailed reviews of the CCS circulation and physical state.

The CCS features a strong annual signal that is predominantly a result of seasonal shifts in large-scale atmospheric forcing. In spring, winds from the northwest establish persistent strong coastal upwelling, which continues into the fall (Fig. A2.1). As a result, an equatorward coastal jet develops in spring, which moves offshore and develops meanders (Strub and James 2000). The greatest seasonal eddy kinetic energy, and most complex physical environment in terms of fronts and eddies, occurs in late summer and fall. The California Undercurrent shoals in late fall – at the time that upwelling-favorable winds slacken or become predominantly northward – and appears as a surface current, called the Inshore Countercurrent, or Davidson Current, in winter (Lynn and Simpson 1987). However, nearshore poleward flows can be found locally off central California most of the year (Yoklavich *et al.* 1997; Steger *et al.* 2000).

While the general transport of the CCS is southward, local variability in the flow is strongly influenced by coastal processes. These include coastal topography and submarine bathymetry, local heterogeneity in wind forcing, and local freshwater inputs. The most notable, and well studied, interruption in the generally southward flow is the Southern California Bight which features a predominant clockwise circulation and a distinct coastal countercurrent. On a more local scale, headlands and capes determine sites of strong upwelling and upwelling filaments (Kelly 1985; Brink and Cowles 1991; Rosenfeld *et al.* 1994).

The seasonal cycle is superimposed on significant interannual and longer variability. One of the most important sources of interannual variability is the El Niño–La Niña forcing that originates in the equatorial Pacific (Enfield and Allen 1980; Chelton *et al.* 1982; Strub and James 2002). The earliest recognition of their extratropical impacts was identified in the CCS following the 1957–58 El Niño event (Sette and Isaacs 1960). However, the signal of individual El Niños in the CCS varies (Schwing *et al.* 2002; Mendelssohn *et al.* 2003). Some events have a strong subsurface signal indicative of an equatorial origin that is transmitted via coastal ocean waves. Others are predominantly a near-surface signal, suggesting that these El Niños affect the CCS primarily via atmospheric teleconnections and alterations of the CCS by local atmospheric forcing. These patterns of spatial separation could affect populations differently, depending on their preferred habitat.

The upper ocean response to climate forcing in the CCS is also partitioned laterally and vertically (Fig. A2.2). Based on its physical character, the CCS can be separated into three distinct regions, which correspond to biogeographic provinces separated by Cape Mendocino and Point Conception (Parrish *et al.* 1983). These regions feature distinctly differing climatologies. The long-term climate shifts also are reflected differently in these regions, presumably because the dominant physics of each region interacts with large-scale climate signals (Schwing *et al.* 1998). For example, the central CCS region, which is dominated by coastal upwelling, has shown a tendency for increased spring–summer upwelling over the past 50 years that is not evident to the

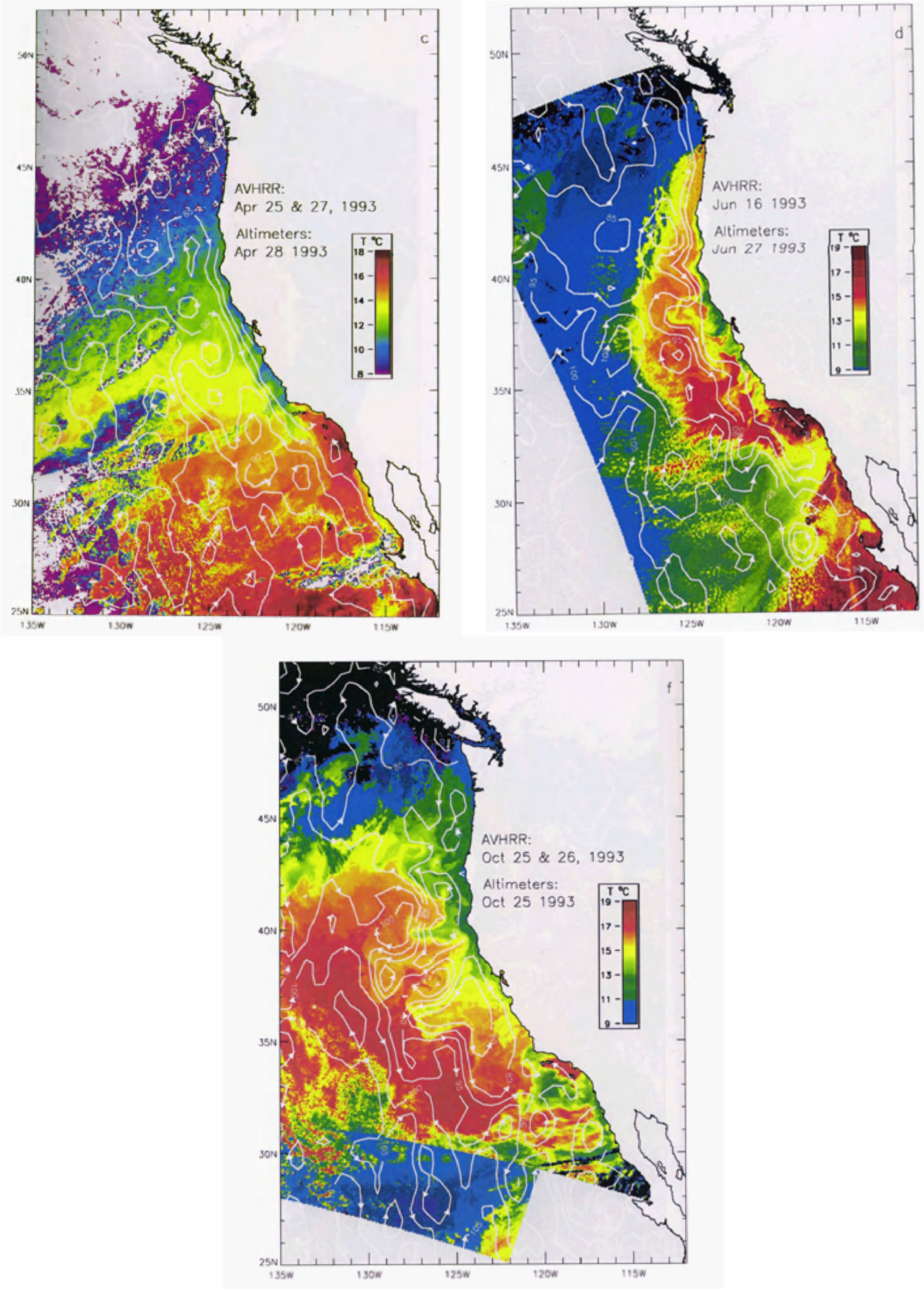

Fig. A2.1 Snapshots of altimeter sea surface height fields (contours) and Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) (color) representing California Current System (CCS) spring, summer and fall conditions (from Strub and James 2000).

north or south (Schwing and Mendelssohn 1997). Ocean temperatures to the north, and within the thermocline, began warming several years prior to the often-cited 1976 regime shift (Fig. A2.2).

The CCS has displayed a long-term warming tendency throughout its extent (Roemmich and McGowan 1995; Mendelssohn *et al.* 2003). In addition, long-term increases in stratification and a deepening of the thermocline in the coastal CCS over the past 50 years (Palacios *et al.* 2004) imply that nutrient input to the photic layer and overall productivity has declined over time (Roemmich and McGowan 1995). The magnitude and timing of the seasonal cycle of upper ocean temperature, thermocline strength and depth vary as well (Mendelssohn *et al.* 2004; Palacios *et al.* 2004), potentially affecting the ambient conditions for seasonal upwelling and the timing of biological cycles.

Decadal-scale sea surface temperature (SST) variations in the CCS are strongly coupled with basin- to global-scale atmospheric fields, rather than to local wind forcing (Parrish *et al.* 2000). Interannual, decadal and longer-term fluctuations in the CCS are approximately synchronous with other eastern boundary current systems, demonstrating that global processes interacting with local dynamics are responsible for much of the long-term variability in the CCS – including regime shifts. For example, the CCS and Humboldt Current regions, with similar dynamics (*e.g.*, strong coastal upwelling zones), display corresponding long-term wind and SST trends, indicating that global climate variability contributes to geographically distinct regime shift responses (Mendelssohn and Schwing 2002).

The spatially distinct responses to regime shifts and long-term climate change are likely to lead to different impacts on marine populations, depending on the CCS regions and depths they exploit. For organisms that inhabit different regions at different life stages (larval *versus* adult), or during key life strategies (migration, reproduction), this may provide a clue about which of these biological aspects are most sensitive to climate variability.

A2.3 Lower Trophic Levels

Phytoplankton and pigment concentration

For various reasons, there is less information available about possible phytoplankton regime shifts in the CCS. Part of the problem is difficulty of sampling – phytoplankton populations can bloom very rapidly and locally in the CCS, so data series must be very densely spaced to avoid the aliasing of high frequency variability. In more slowly varying offshore populations, Venrick *et al.* (1987) showed a strong upward trend in Central Gyre chlorophyll concentration from 1964–85, with the strongest change near 1975. Within the CCS, the best hope for time series is from sequential satellite mapping of ocean color. Two non-overlapping time series are now available:

1. CZCS (Coastal Zone Color Scanner) 1978–86, and
2. SeaWiFS (Sea-viewing Wide Field-of-view Sensor) 1997–present.

Neither period captures the hypothesized 1977 and 1989–90 regime shifts, and the two data sets are not fully intercomparable. However, the recent 1998–99 period was resolved extremely well. Average pigment concentration 0–100 km from the coast increased after 1998 throughout the CCS (Fig. A2.3), and the margin of the zone of high pigment concentration also moved farther offshore (Thomas *et al.* 2001).

Information about changes in phytoplankton species composition within the CCS is potentially available for some taxa (mostly larger species with hard cell walls). A long time series of phytoplankton cell counts has been collected from the Scripps Pier, but has not been fully analyzed and interpreted. Varved sediment columns from anoxic basins in, and near, the CCS provide a potentially very long time record, but must be interpreted with care due to selective and time-cumulative dissolution of microfossils. Sancetta (1995) reports records from the Gulf of California, and McQuoid and Hobson (2001) from Saanich Inlet, British Columbia.

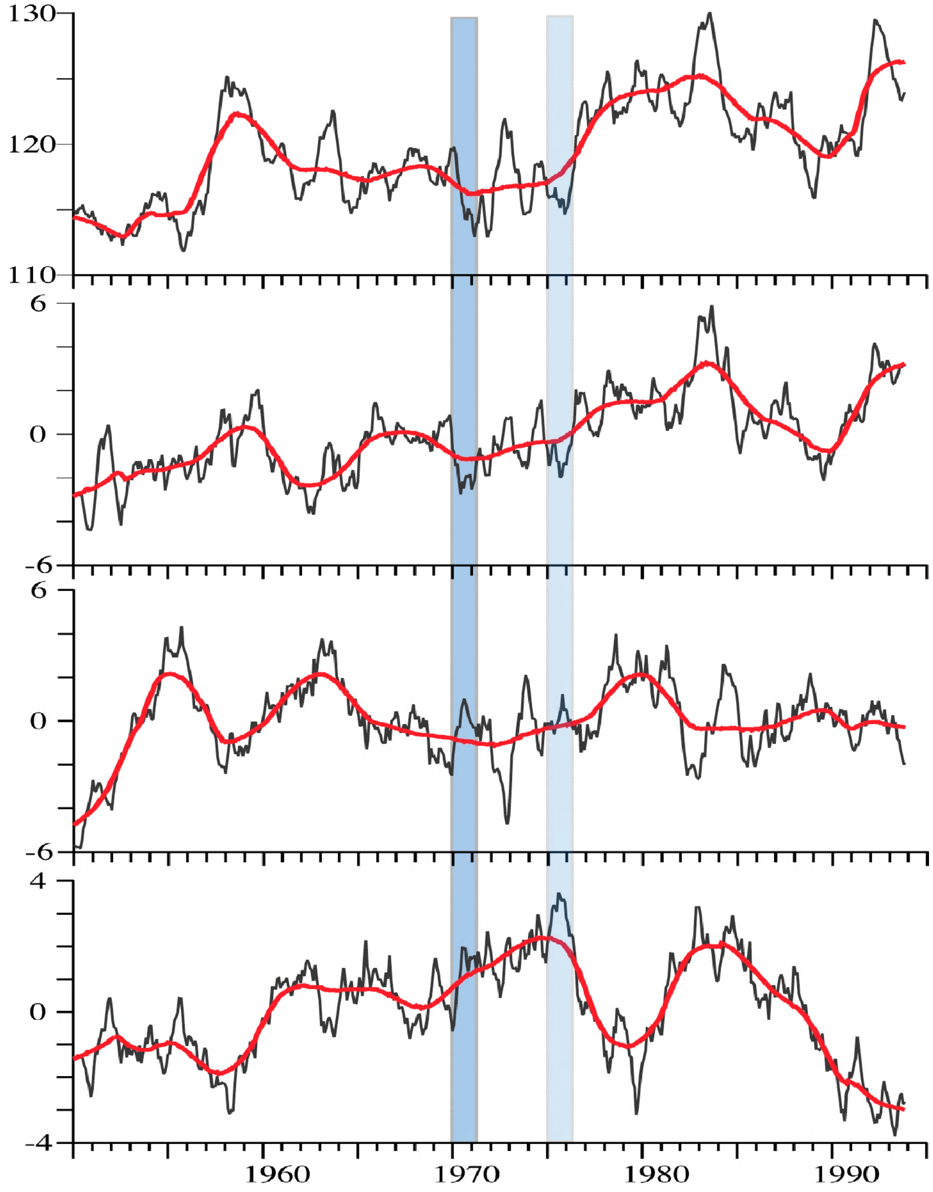

Fig. A2.2 Time series of common trends (top to bottom) of California Current System (CCS) ocean temperature, based on 110 time series. The first trend is the system tendency for warming, with El Niño–Southern Oscillation (ENSO) and regime shifts superimposed. The second trend is a cross-shore mode, with coastal locations having a stronger impact from ENSO and decadal events. The third trend is an alongshore mode, showing ENSO events with a greater northern extent. The fourth trend is a depth mode, showing trends in stratification. Blue vertical bars highlight 1970 and 1976 to contrast differences in the 1970s regime shift in different geographical domains of the CCS (adapted from Mendelssohn *et al.* 2003).

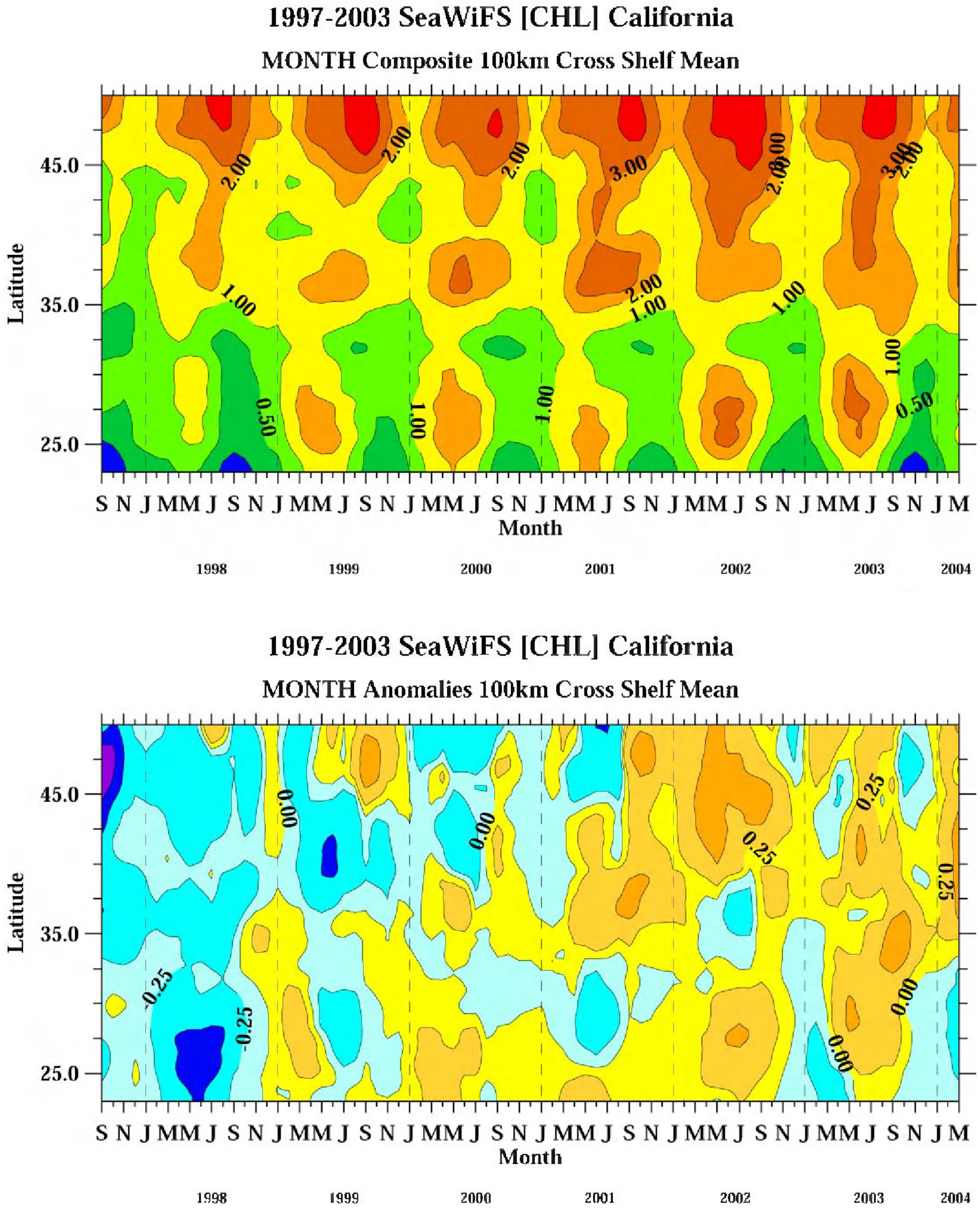

Fig. A2.3 SeaWiFS latitude *vs.* monthly records of average chlorophyll concentration (top panel) and anomalies from the average seasonal cycle (bottom panel) during and after the 1998–99 interval. Chlorophyll estimates are averaged within each month and across the 0–100 km zone extending seaward from the coast. After 1998, zones of low pigment concentration became briefer and narrower; zones of high pigment concentration became more prolonged and extensive (updated and extended from Thomas *et al.* 2001; courtesy, A. Thomas).

Zooplankton

Long-term (>20 years) records of zooplankton biomass and community composition in the CCS are available from central–southern California (CalCOFI 1950–present), southern Vancouver Island (1979–present), and central Oregon (1969–73, 1983, and 1996–2001). Collectively, they provide strong evidence that zooplankton variability at decadal time scales is:

- intense (order of magnitude typical range);
- coherent in form over the full width of the CCS and over alongshore distances >400 km;
- sometimes abrupt, with major transitions between high and low abundance matching within ±1 year the "regime shift" dates identified from climate and fisheries indices;
- coherent in the *timing* of transitions, perhaps extending the full alongshore length of the CCS, and poleward into the Alaska Current system.

Data from the CalCOFI region are summarized in Figures A2.4 and A2.5, and from British Columbia and Oregon in Figure A2.6. In all three regions, the zooplankton time series show large and persistent deviations from local average annual cycles. Runs of higher-than-average or lower-than-average abundance typically persist for 5–10 years or longer (*vs.* the 1- to 2-year duration of individual ENSO events).

For the CalCOFI region, the earliest analyses (Fig. A2.4) were by Bernal (1979, 1981), Bernal and McGowan (1981), Chelton *et al.* (1982), and Roessler and Chelton (1987). These covered data from 1951–82, and were mostly confined to zooplankton biomass. (Roessler and Chelton (1987) added a brief discussion of 1958 anomalies in alongshore species distributions.) In each of the four alongshore sub-regions extending from San Francisco Bay to southern Baja California, zooplankton biomass from 1950–57 was very high, and from 1958–62, very low. From 1962–82, biomass was initially high but became anomalously low part way through the 1970s (earlier off southern Baja California; later off central California). Higher biomass was significantly correlated with various indices of stronger equatorward flow in the California Current (low coastal sea level, cross-shore dynamic height gradient, low temperature, low salinity). However, much of the total variance (especially in the physical data) was associated with the start of the 1958 El Niño event.

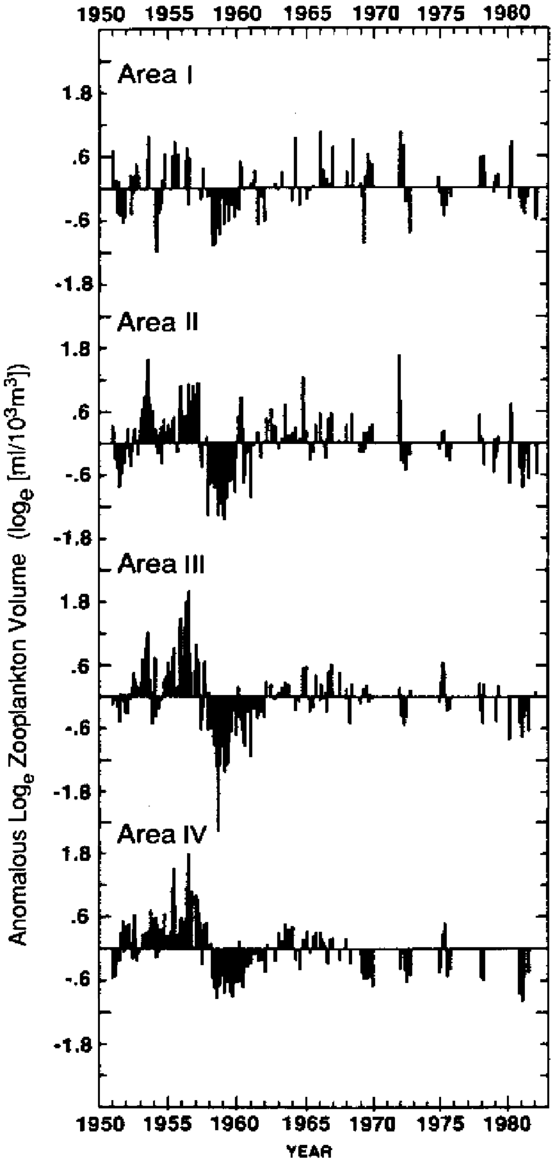

Fig. A2.4 1951–82 time series of zooplankton biomass anomalies in four regions of the CCS. Regions are arranged from north to south: (I) San Francisco to Point Conception, (II) Point Conception to San Diego, (III) Baja California (San Diego to Puenta Eugenia), (IV) Baja California Sur (Puenta Eugenia to Isla Magdalena). Note the strong alongshore covariance over an alongshore distance of nearly 1500 km (from Roessler and Chelton 1987).

Subsequent CalCOFI sampling and analyses have been restricted to the alongshore zone between Point Conception and San Diego (30°–35°N). Results are summarized in Figure A2.5. Roemmich and McGowan (1995) and McGowan *et al.* (2003) showed that a prolonged downward trend in total zooplankton biomass began in the mid-1970s (perhaps in 1976) and continued through to 1998. This decline affected the full width of the California Current (Fig. A2.5) but was more strongly correlated with sea surface warming and an increase in vertical stratification, rather than with either upwelling intensity or transport variability. However, taxonomically-resolved time series for the CalCOFI region (side bars in Fig. A2.5) have been produced for pelagic tunicates (Lavaniegos and Ohman 2003), copepods (Rebstock 2001, 2002, 2003) and euphausiids (Brinton and Townsend 2003), and these time series indicate that the overall decline in total zooplankton biomass was driven by long-term declines in the biomass of pelagic tunicates. Lavaniegos and Ohman (2003) documented a major decline in abundance of some (but not all) salp species after the mid-1970s, and a subsequent increase in abundance since 1999. Rebstock (2001, 2002, 2003) found that the copepod dominance hierarchy was stable (nearly always dominated by *Calanus pacificus* and *Metridia pacifica*). Strong El Niño conditions during the late 1950s and early 1980s affected copepod abundance (Rebstock 2002). The 1977 regime shift resulted in an increase in abundance of calanoid copepods, and the 1989 regime shift corresponded to a decrease in copepod abundance around 1990 (Rebstock 2002). Subsequent observations support an additional large increase in copepod abundance in 1998–99. Large changes in euphausiid community composition have been observed, with subtropical species increasing in dominance since the late 1970s, but from 1999 to at least 2002, there has been a return to dominance of subarctic euphausiid species (Brinton and Townsend 2003). Unlike pelagic tunicates and calanoid copepods, there does not appear to be any significant changes in euphausiid abundance across regime periods (Brinton and Townsend 2003).

Data from the British Columbia and Oregon continental margins (Fig. A2.6, plus far right sidebar in Figure A2.5) show very strong spatial and temporal covariance within groups of ecologically similar species. The most striking result was a partial to near-complete replacement, during the 1990s, of the resident continental shelf copepod community (dominated by *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*) by species "normally" abundant off central and southern California (*Clausocalanus* spp., *Paracalanus parvus*, and *Ctenocalanus vanus*). This trend abruptly reversed during the 1997–99 El Niño–La Niña, and since 1999 the zooplankton community has resembled the average for the 1970s–80s.

A2.4 Invertebrates

Significant changes in species composition have been observed when large-scale ecosystem re-organizations have occurred. Globally, Caddy and Rodhouse (1998) noted that as groundfish stocks have declined, they appear to have been replaced by increases in cephalopod populations. In the coastal Gulf of Alaska, a switch from a crustacean- to a groundfish-dominated system was observed, following the regime shift of the late 1970s (Anderson and Piatt 1999). In the Northwest Atlantic, there was a significant change in species composition following the collapse of the northern cod stock, but in contrast to that in the Gulf of Alaska, the shift in the Northwest Atlantic was from a groundfish- to a crustacean-dominated system.

In California, the top three most valuable fisheries (as landed value) have recently been market squid (*Loligo opalescens*), sea urchin (*Strongylocentrotus fransicanus*) and Pacific Ocean shrimp (*Pandalus jordanii*) (Rogers-Bennett 2002). Dungeness crab (*Cancer magister*) has long been a commercially important invertebrate in Washington and Oregon. Landings of market squid, Dungeness crab, and Pacific Ocean shrimp in California, Oregon and Washington since 1981 show marked declines in 1983 and 1998, corresponding to the strong El Niño events of those years; they also illustrate the increasing trend in landings over time for squid as the fishery developed (Fig. A2.6).

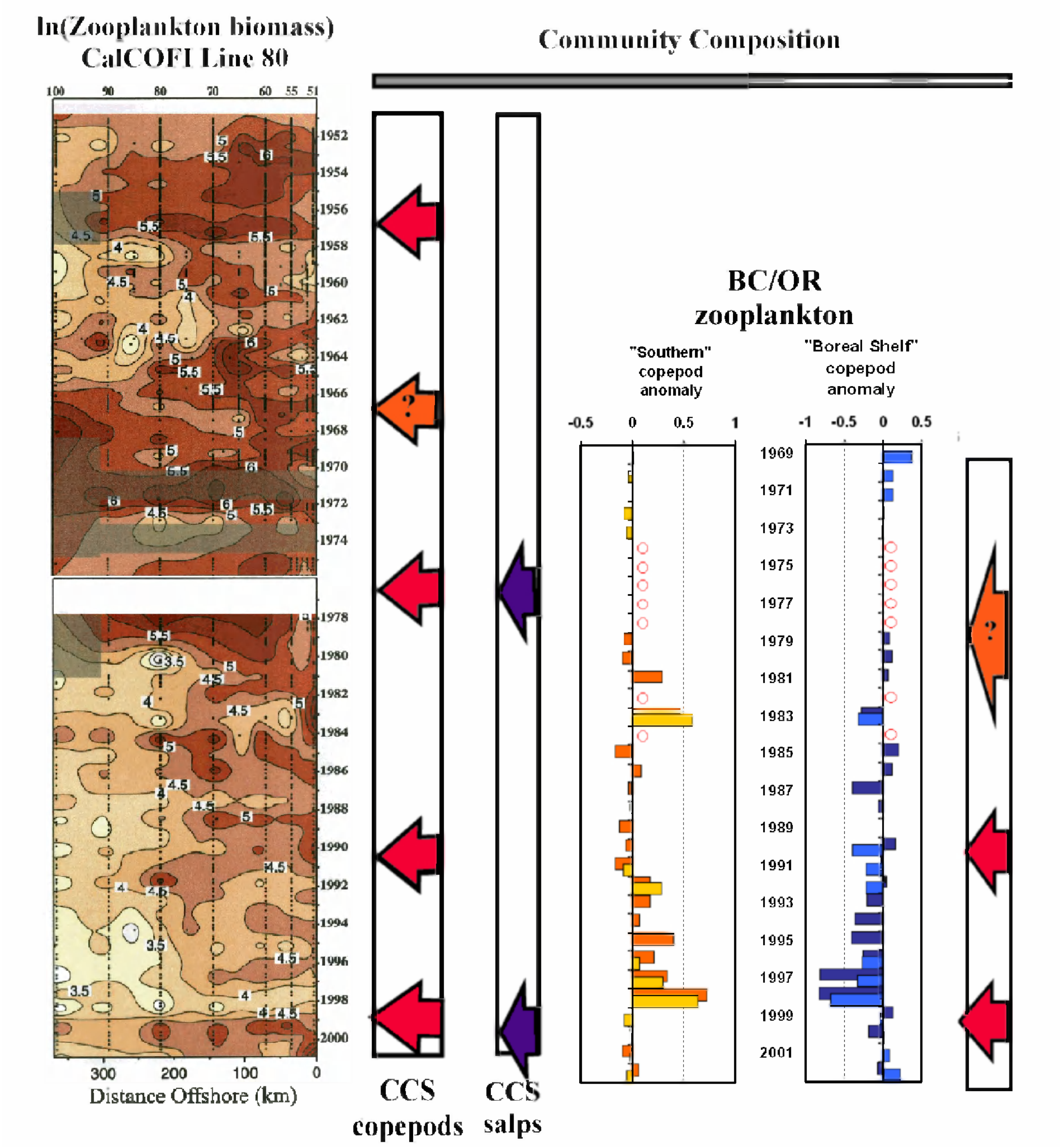

Fig. A2.5 Zooplankton biomass and community variability in the California Current System (CCS), 1952 to present. Contour plot in left panel shows cross-shore time series of zooplankton biomass for CalCOFI Line 80 (near Point Conception). Right hand side bars show timing match with transitions (indicated by arrows) in CalCOFI, British Columbia, and Oregon zooplankton species abundance/community composition. Data from multiple sources: CCS copepods from Rebstock (2001, 2002, 2003; red) and updated data (Ohman, pers. comm.), CCS salps from Lavaniegos and Ohman (2003), British Columbia/Oregon zooplankton from Mackas *et al.* (2004). Arrows with a question mark denote transitions that are uncertain, either due to changes in sampling protocol (CCS copepods) or lack of data (British Columbia/Oregon zooplankton) (from Mackas 2004).

The recent decline in landings of squid (dominated by California) and the increases in landings of Dungeness crab (dominated by Washington and Oregon) suggest a possible change in the fisheries since 2001. It should be noted that these crab populations appear to cycle in abundance, with peaks and troughs every 8–10 years (Otto and Jamieson 2001). Landings of shrimp (dominated by Washington and Oregon) have been increasing since the 1998 El Niño and the return of cool water in 1999. This recovery of ocean shrimp populations in the CCS is corroborated by fishery-independent shrimp surveys conducted off southern Vancouver Island at the northern end of the California Current (Fig. A2.7). The population biomass estimated from these surveys was highest in the mid-1970s prior to the 1977 regime shift, with a local maximum in 2002 after increasing since 2000, consistent with an expectation that this shrimp species does better with cooler conditions. Note there was a decrease in the population biomass off Vancouver Island (Fig. A2.7) and in Washington–Oregon landings (Fig. A2.6) in 2003, coinciding with warmer conditions of a mild ENSO event in late 2002.

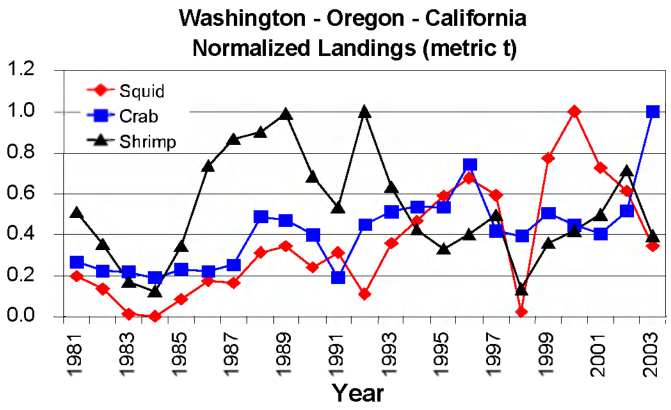

Fig. A2.6 Washington/Oregon/California landings of market squid (*Loligo opalescens*), Dungeness crab (*Cancer magister*) and Pacific Ocean shrimp (*Pandalus jordanii*). Values have been normalized to the maximum value in the data series for each species. Data are from the Pacific Fisheries Information Network (PacFIN) database maintained by the Pacific States Marine Fisheries Commission (www.psmfc.org).

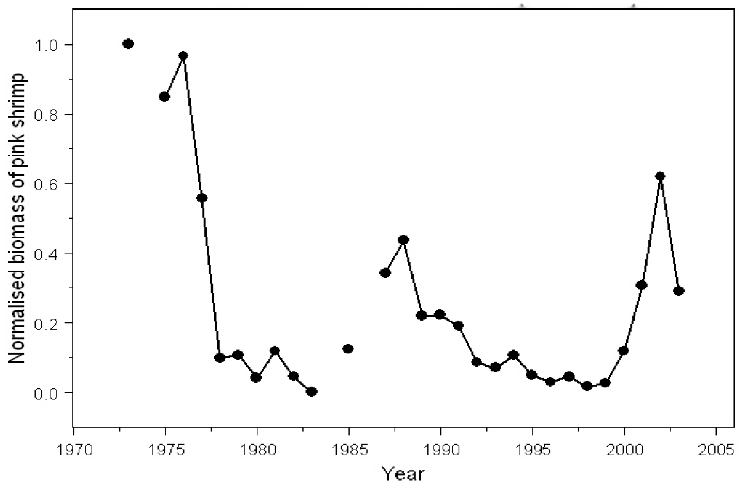

Fig. A2.7 Fishery-independent survey estimates of population biomass of *Pandalus jordanii* (Pacific Ocean shrimp or smooth pink shrimp) for the southern continental shelf of Vancouver Island, British Columbia, at the northern end of the California Current system. Values have been normalized to the maximum value in the data series.

A2.5 Fishes

Pelagics

Coho salmon (*Oncorhynchus kisutch*)

Coho salmon are one of seven species of the genus *Oncorhynchus* native to North America and are distributed from the Bering Sea as far south as the Sacramento River system in California (see Sandercock (1991) for a review). Coho salmon are anadromous, migrating to the marine environment in the spring as smolts, and returning to freshwater in the fall and early winter of their third year to spawn and die. Fry emerge from the gravel in the following spring and usually reside in freshwater for a year before migrating to sea as smolts. Almost all coho spend 18 months at sea before returning to freshwater and therefore have a 3-year life cycle. Jacks (precocious males), which spend only 6 months in the ocean, are found in some populations. Adult coho usually weigh from 2–5 kg (45–70 cm in length) and only rarely exceed 9 kg. Coho favor smaller streams and are widely dispersed within the northern portion of the California Current ecosystem. The Fraser River is the largest river in British Columbia, and the interior Fraser (*i.e.*, upstream of the Fraser canyon) constitutes most of the drainage basin. Interior Fraser coho occupy a significant proportion (~25%) of the range of coho salmon within Canada. Estimates of coho abundance for this region indicate a substantial decline in abundance from the early 1980s to the present (Fig. A2.8, from Simpson *et al.* 2004). It is believed that reduced survival in the marine environment has been the main determinant of recent reduced population abundance. Overfishing, changing marine conditions, and habitat perturbations all contributed to declines (Bradford and Irvine 2000; Bradford 1999). Excessive fishing resulted when harvest rates were not reduced quickly enough in response to climate-driven declines in marine productivity. In addition, coho declines were often related to the intensity of human disturbance in freshwater, whereby extensive urbanization has impacted available spawning habitats through stream destruction or watershed impacts from upstream logging operations. Comparable declines in coho marine survival have been noted in the Strait of Georgia, Puget Sound and in the Oregon coho production index (Beamish *et al.* 2001a). All three indices suggest a long-term decline in coho survival, beginning in the mid-1970s. However, recent improvement in the Oregon coho production index implies that conditions have changed since 1999 (Fig. A2.9). Beamish *et al.* (1999, 2001a) suggest that the reduction in survival is related to a number of changes in the oceanic environment, particularly the Aleutian Low Pressure Index (ALPI) which may have reduced the available food supply of coho smolts, leading to increased overwinter mortality. In addition, in the Strait of Georgia there may have been increased competition for food with Pacific herring during the first year in the ocean, again impacting coho survival (Beamish *et al.* 2001b).

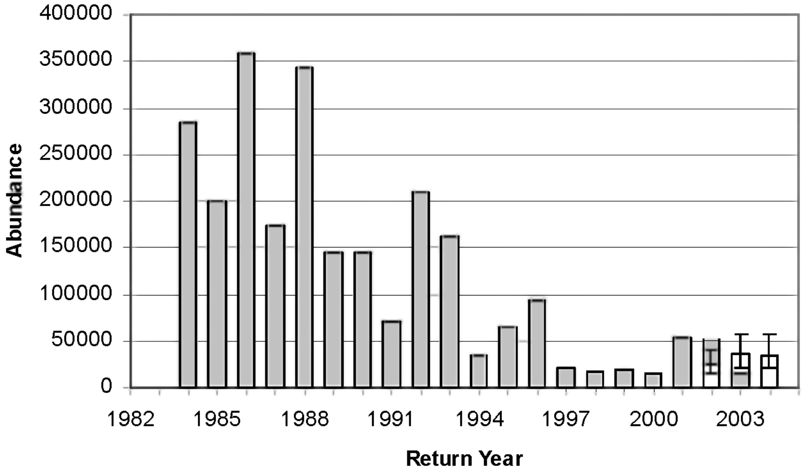

Fig. A2.8 Estimated abundance of Thompson River, British Columbia, watershed coho from 1984 to 2003. The forecasts for 2002–04 are shown as clear bars with associated 50% confidence intervals.

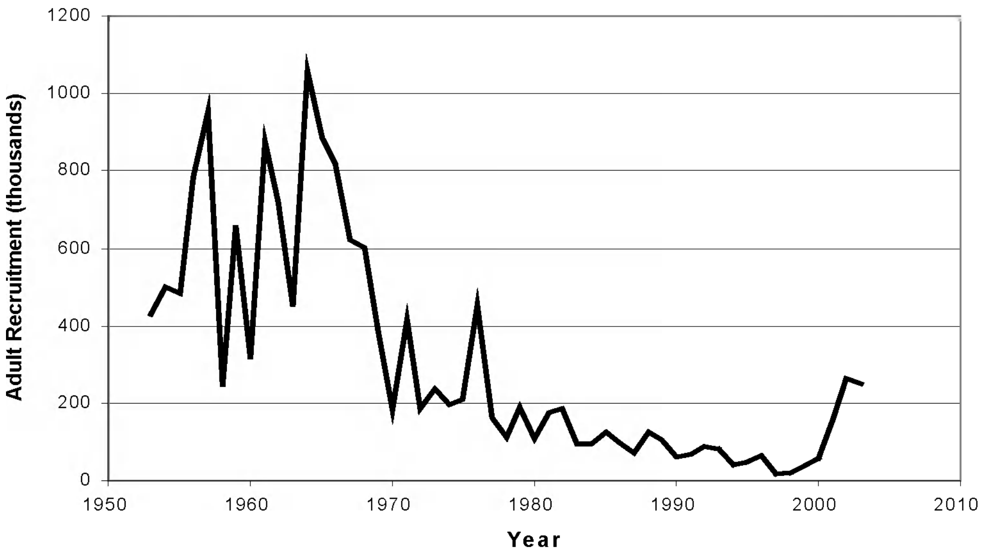

Fig. A2.9 Adult recruitment estimates for Oregon Production Index coho salmon. Data were provided by the Oregon Department of Fisheries and Wildlife, Oregon Production Index Technical Team.

Columbia River salmon (*Oncorhynchus* spp.)

The Columbia River experienced very low returns for many salmon species or stocks during the 1990s, while relatively high values were recorded for spring and fall chinook (*O. tshawytscha*), coho, sockeye (*O. nerka*), and summer steelhead (*O. mykiss*) in the mid-1980s and again in 1999, 2000, and 2001 (Fig. A2.10). Data for 2002 and 2003 (not shown) include continued high returns for spring, summer, and fall chinook, and summer steelhead. Spring chinook returns for 2004 were about 190,000 fish, well above the 10-year average and comparable to returns typically observed in the 1980s. From 1940 to the mid-1990s, there was an inverse relationship between Alaskan catches of sockeye and pink salmon (*O. gorbuscha*) and Columbia River spring chinook returns (Fig. A2.11). Since the late 1990s, values have been high for both groups.

Pacific herring *(Clupea pallasi)*

Pacific herring are distributed around the perimeter of the North Pacific, from the Yellow Sea in Asia, to southern California (Haegele and Schweigert 1985). They are intertidal spring spawners throughout the range, laying adhesive eggs on any available algal substrates, and so depend on suitable inshore habitat at the beginning of their life cycle. The eggs hatch into free-floating larvae within 2–3 weeks, depending on ambient water temperature. Juveniles spend their first summer in inshore waters feeding on copepods, then migrate offshore to join immature and adult stocks during the fall of their first year or late spring of their second summer. In general, herring migrate back to their spawning areas for the first time at age 3 in the south and age 4 in the north. Herring in the eastern Pacific normally live to ages less than 10 years, although fish as old as age 15 have been taken historically in some areas.

The California Current ecosystem supports a substantial number of herring stocks. Numerous minor herring stocks exist between San Diego and Vancouver Island, including Puget Sound. The major stocks in this ecosystem are found in San Francisco Bay, on the west coast of Vancouver Island (WCVI), and within the Strait of Georgia. Herring abundance within the San Francisco Bay area has fluctuated dramatically from very high levels, exceeding 100,000 tons in the early 1980s, to less than 20,000 tons in recent years (Watters, pers. comm.; Fig. A2.12). No clear explanations for the decline are evident but negative impacts of the strong 1982–83 El Niño on herring growth and survival have been noted (Spratt 1987). Within the northern part of this current system, a number of small stocks occur within Puget Sound, and these have remained at relatively stable levels, with the exception of Cherry Point, which has declined dramatically since the early 1980s when it was impacted by a significant roe fishery. Despite fishery closures, the stock has not recovered. The other two major herring stocks at the northern edge of this ecosystem spawn on the WCVI and in the Strait of Georgia (Schweigert 2001). After being decimated by a reduction fishery in the late 1960s, both stocks recovered to high levels of abundance in the early 1970s, approaching 200,000 tons combined (Fig. A2.12). Abundance declined markedly in both areas in the mid-1980s, approaching 50,000 tons, and then increased again. The Strait of Georgia stock has increased almost exponentially, reaching a historical high of over 150,000 tons in recent years, while the WCVI stock increased to about 50,000 tons in the late 1980s, and has subsequently declined to about 20,000 tons in recent years. Factors affecting the survival and productivity of these stocks are only partially understood. Herring on the WCVI are impacted by hake on the offshore feeding grounds and have shown lower recruitment in years of higher SSTs when it is expected that more hake migrate farther north to feed on immature herring (Ware and McFarlane 1986). However, herring in the Strait of Georgia continue to show good survival rates, and it is suggested that the reduced growth rate of hake has mitigated herring predation by hake in this area (McFarlane *et al.* 2001).

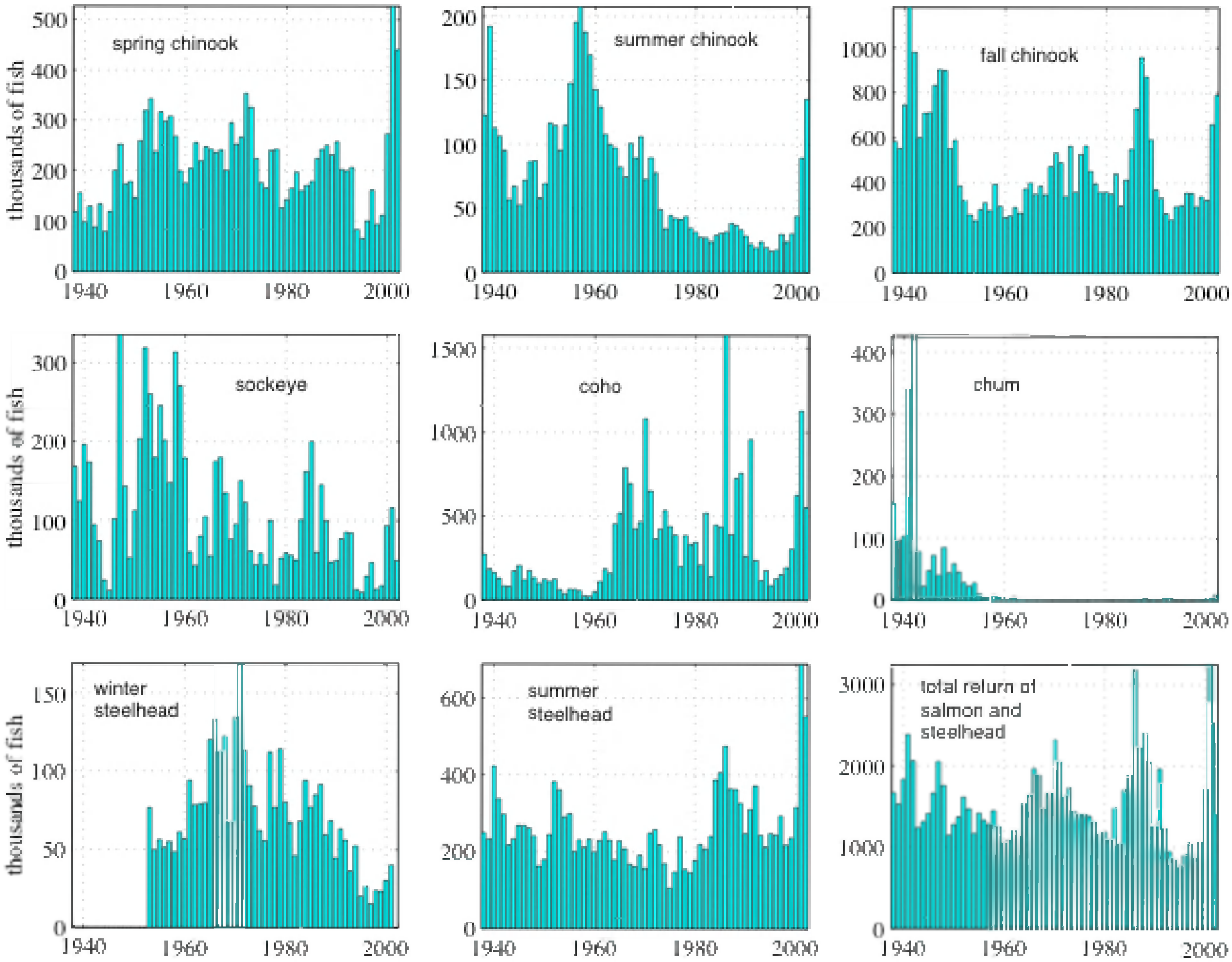

Fig. A2.10 Minimum estimates for annual adult salmon returns to the Columbia River mouth (lower river catch + counts at Bonneville Dam). Data provided by the Oregon Department of Fish and Wildlife and the Northwest Power Council.

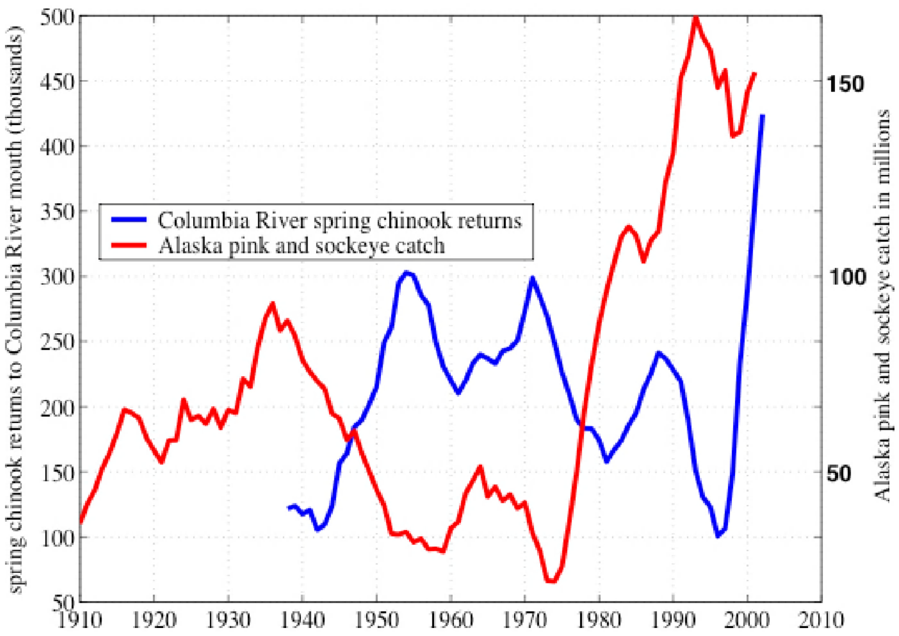

Fig. A2.11 Comparison of observed Alaska sockeye and pink salmon catches *vs.* Columbia River spring chinook returns (5-year running averages).

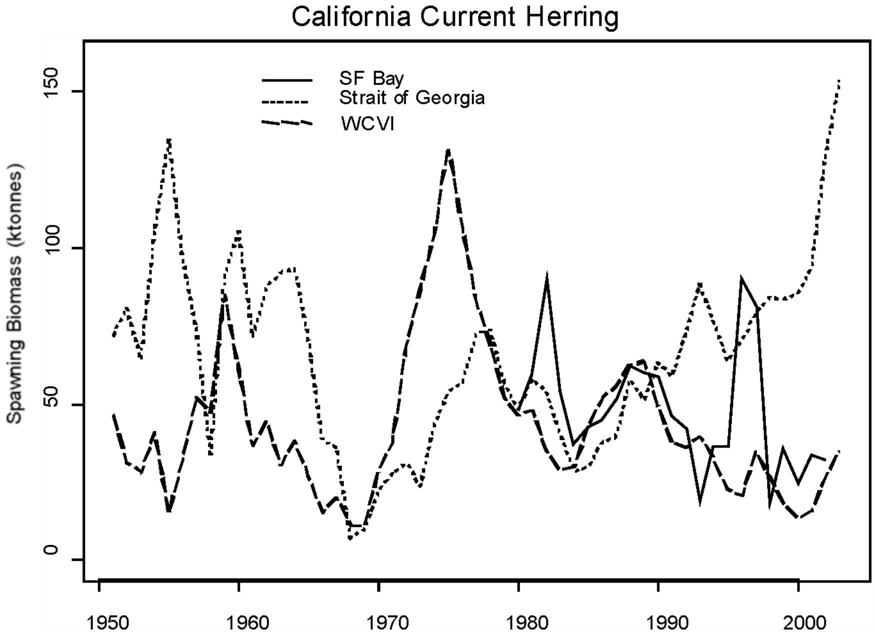

Fig. A2.12 Abundance trends for three stocks of Pacific herring: San Francisco Bay (SF Bay), Strait of Georgia, and the west coast Vancouver Island (WCVI).

A number of authors have also noted an inverse relationship between herring survival and SST in the northern California Current ecosystem (Ware 1991; Schweigert 1993; Zebdi and Collie 1995; Williams and Quinn II 2000). It appears that this effect occurs primarily in the outer coastal areas and is associated with increased predation, possibly in conjunction with negative impacts on the food supply. Environmental impacts on herring in the more southerly stocks appear to be associated with major El Niño events which affect the food supply, adversely impacting growth rate, and ultimately the survival of herring in San Francisco Bay (Spratt 1987).

Pacific sardine (*Sardinops sagax*)

During the twentieth century, Pacific sardine abundance fluctuated from a high of 3 million tons *ca*. 1930, to undetectably low levels in the 1960s and 70s, and back to 1 million tons at the end of the century (Murphy 1966; MacCall 1979; Conser *et al*. 2002). Patterns of sardine scales preserved in laminated anaerobic sediments, representing nearly 2000 years of history, indicate that California's sardines have always been subject to very large fluctuations in abundance (Baumgartner *et al*. 1992). The recent increase in sardine abundance appears to have been associated with post-1976 environmental conditions. Jacobson and MacCall (1995) describe the relationship between sardine recruitment, parental abundance and multi-year average SSTs measured at the Scripps Institution of Oceanography Pier (Fig. A2.13). At an average temperature of 16.5°C (typical of the 1945–1975 period), the sardine stock has almost no surplus production and cannot sustain a fishery. At a temperature of 17.3°C (typical of pre-1945 and post-1975 years), sustainable yield can potentially exceed 1 million tons annually, provided the parental abundance is at a biomass of about 2 million tons, a level that has not yet been achieved in the recent recovery. Except for a brief cooling period in 1999, Scripps Pier temperature continued to be warm through 2003 (Fig. A2.13).

Pacific sardine are a migratory species. When the northern sardine stock is large and ocean conditions are favorable, sardines migrate to British Columbia waters in the summer to feed. In 1947, the fishery on these summer migrants collapsed due to the complete absence of sardines in Canadian waters. After a 45-year absence from Canadian waters, sardines reappeared throughout the continental shelf waters off the WCVI in 1992. Research surveys indicated that their distribution from 1992–96 was limited to the southern part of Vancouver Island. In 1997, their distribution expanded northward and by 1998, sardines inhabited the waters throughout Hecate Strait (northern coast of British Columbia), located east of the Queen Charlotte Islands, and up to Dixon Entrance (southeast Alaska). Spawning was reported off the WCVI in 1997 and 1998. In 1999, following the El Niño, research surveys indicated that sardine distribution in Canadian waters contracted southward. By 2003, sardines did not appear in Canadian waters until late July and were confined to coastal inlets along Vancouver Island. The 2003 survey off Vancouver Island found virtually no sardines in the offshore waters, except in the south, and some concentrations at the mouth of the inlets.

Gadids

Pacific cod (*Gadus macrocephalus*)

Pacific cod are distributed throughout the coastal North Pacific, from Santa Monica, California, up through the Bering Sea and to the Sea of Japan. Growth is rapid within the first year, with Pacific cod reaching lengths of approximately 30 cm. Maximum recorded sizes exceed 100 cm, and estimated maximum age is 11 years (Westrheim 1996). Pacific cod recruit to the fishery at age 2 and a length of approximately 40 cm, and are fully mature at age 3, corresponding to approximately 50 cm (Westrheim 1996).

In British Columbia, there are four stocks defined for management purposes: Strait of Georgia, WCVI, Queen Charlotte Sound, and Hecate Strait. Though there are currently no genetic analyses to verify stock delineation, tagging studies indicate that there is very little movement of Pacific cod between these four areas (Westrheim 1996). The WCVI and the Hecate Strait stocks have historically supported commercial fisheries, and are the two stocks for which stock assessment information is available. Assessments on both stocks indicated a dramatic decline in biomass in the 1990s, from historic high levels of abundance in the 1980s (Sinclair 2000; Sinclair *et al.* 2001; Starr *et al.* 2002). These declines were attributed to nine poor consecutive year classes, beginning in 1990 (DFO 1999). The WCVI stock is part of the CCS. A delay-difference assessment model (Starr *et al.* 2002), which incorporates Pacific cod bycatch rates in a shrimp trawl survey, provides estimates of the number of recruits, which has remained at low levels since 1990 (Fig. A2.14).

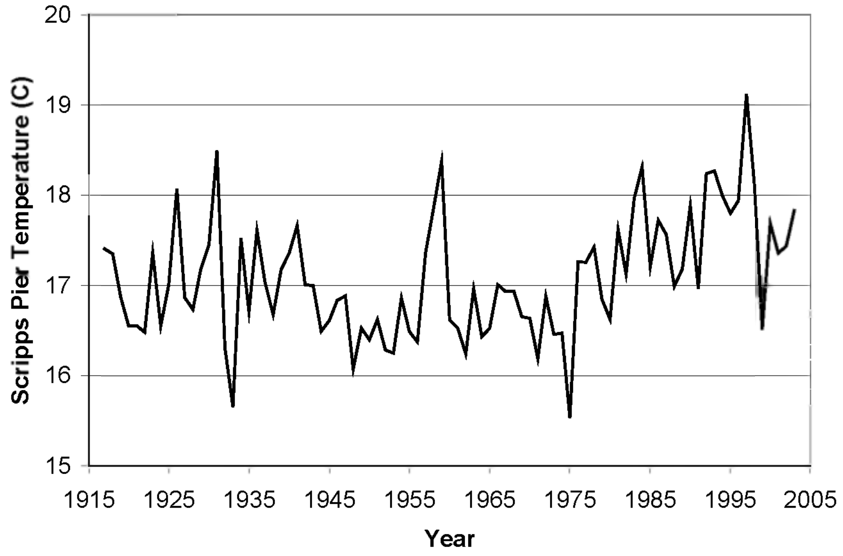

Fig. A2.13 Annual average sea surface temperatures (SSTs) measured at Scripps Pier, La Jolla, California.

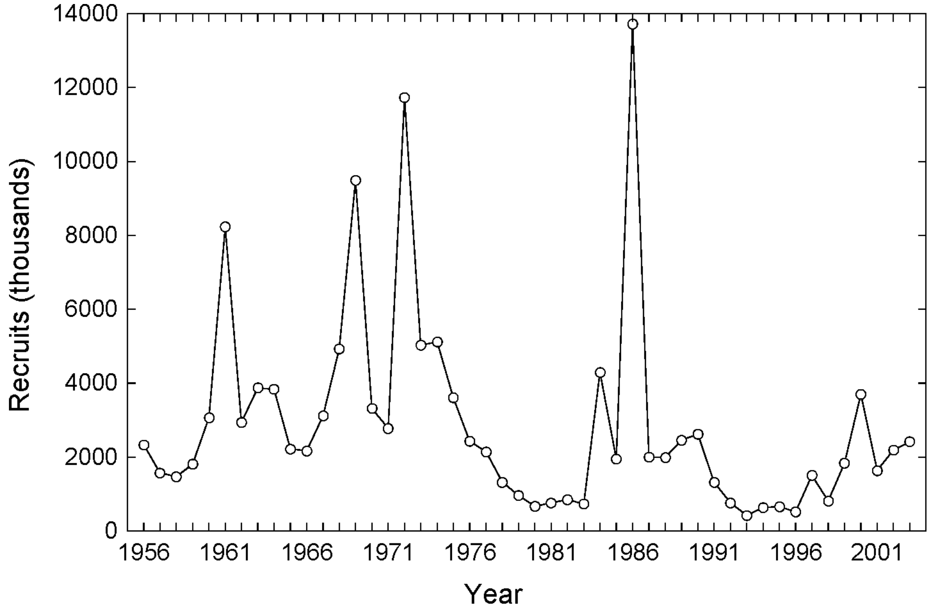

Fig. A2.14 Number of recruits (1000s of fish) of the west coast of Vancouver Island (WCVI) Pacific cod stock estimated by a delay-difference model (from Starr *et al.* 2002).

Pacific hake (*Merluccius productus*)

Pacific hake range throughout the CCS, from Baja California to the Gulf of Alaska. Their distribution and abundance are closely linked to oceanographic conditions in the Northeast Pacific. The biomass, which is typically over 1 million tons, supports large domestic fisheries in both Canada and the United States.

Unusual juvenile and adult distribution patterns have been seen in the Pacific hake population since 1990. Juvenile distribution expanded northward from 1994–99. This was evident in the increased numbers of juveniles (ages 2 and 3) present in the Canadian fishery catches. In addition, an acoustic survey in 1998 off the Queen Charlotte Islands (northern British Columbia) observed numerous age-1 juveniles (1997 year class). During the 1990s, a greater proportion of the total mature population migrated into Canadian waters, and in some years were present in the Gulf of Alaska. Equally dramatic was the contraction of Pacific hake distribution in 2000 and 2001, with a low occurrence of Pacific hake off Canada. Information from a 2003 survey indicates a return to distribution patterns observed in the 1980s, with the northern limit of Pacific hake distribution at northern Vancouver Island (central British Columbia).

During the 1970s and 1980s, strong year classes in Pacific hake occurred every 3–4 years (1973, 1977, 1980, 1984, 1987, 1988). From 1989–98, there was only one strong year class of Pacific hake. Reflecting this, acoustic estimates of Pacific hake biomass declined steadily from the early 1990s, with the lowest observed biomass occurring in 2001 (738 thousand tons). In contrast, the 2003 biomass estimate (1.8 million tons) increased 120% over the 2001 survey estimate. The strong 1999 year class appeared as age-2 fish in the 2001 survey, and entered the mature population as age-4 fish in 2003. This isolated large year class is principally responsible for the increase in biomass estimated for 2003, and abundance is projected to decline over the next few years (Helser *et al.* 2004). This is the first above-average year class since the late 1980s.

Rockfish

Juvenile rockfish (*Sebastes* spp.)

The abundance of juvenile rockfish has been monitored off the central California coast since 1983. In May and June of each year, the National Marine Fisheries Service Santa Cruz Laboratory conducts a month-long midwater trawl survey at standard stations (Ralston and Howard 1995), and annual abundance indices are derived by a delta-GLM (generalized linear model) approach using main effects of year, location and calendar date (Stefansson 1996). About ten species of rockfish are regularly encountered, three of which are not significantly exploited. The fish are sampled at an average age of about 100 days, near the end of their pelagic stage, and immediately prior to settlement. It is assumed that the principal life history events determining recruitment strength have been experienced by that age. Stock assessments of exploited species have confirmed that these juvenile abundances are well correlated with estimated recruitment strength. Because conventional fishery stock assessments are unable to estimate recruitment strength until a cohort is several years old and has entered the fishery, this juvenile rockfish survey provides information on recent recruitment patterns that would not otherwise be available for many years.

The poor recruitment experienced by many eastern Pacific groundfish species during the 1990s is shown clearly by the coherent decline of all ten rockfish species in the survey (Fig. A2.15). Catch rates of juvenile rockfish declined 1000-fold from 1988–98, a period of warming ocean temperatures. The pattern was shared by every species in the survey, including unexploited species. Several species were not encountered at all by the survey from 1996–98, and those zero values of catch rate cannot be plotted on the log scale of Figure A2.15. Abundance of juvenile rockfish did not recover immediately with the shift to cooler ocean temperatures in 1999 and 2000, although recent stock assessments show that some groundfish species, such as bocaccio (*S. paucispinis*) and lingcod (*Ophiodon elongatus*), produced unusually strong recruitment in 1999 (MacCall 2003; Jagielo *et al.* 2004). Abundance of juvenile rockfish increased somewhat in 2001, and in 2002–04, has returned to levels similar to those seen in the 1980s. Survey results in the El Niño year of 2003 were lower than adjacent years, which is consistent with observations from previous El Niño years.

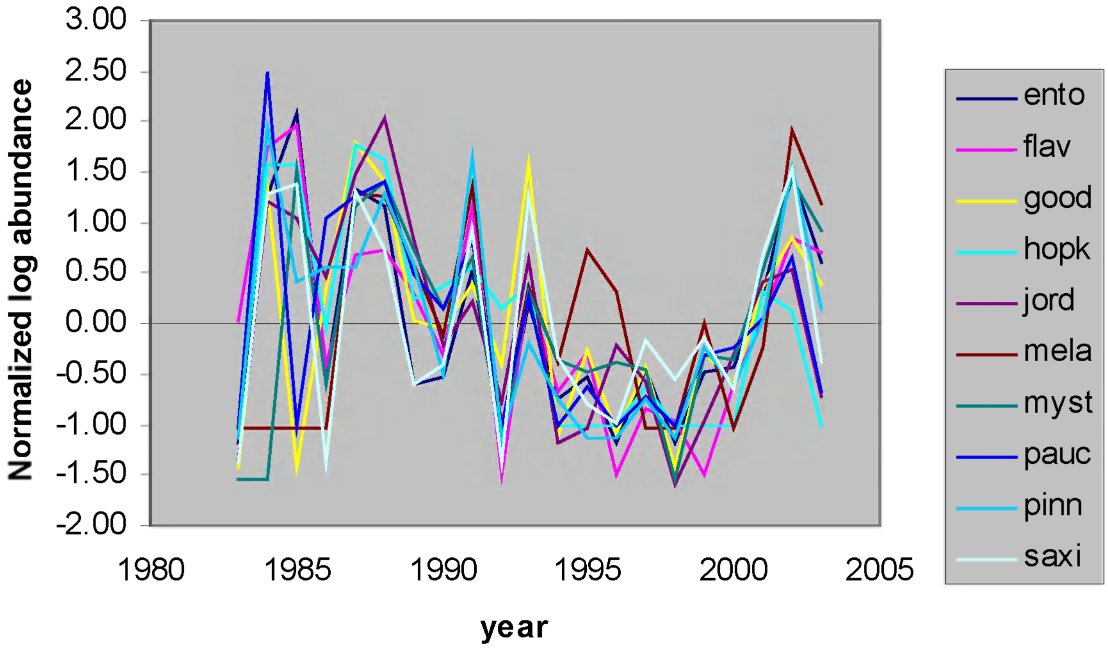

Fig. A2.15 Fluctuations in abundance of juvenile rockfish off central California, as measured by catch rates in midwater trawls. Preliminary results for the 2004 survey appear similar to 2002.

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Appendix 3: Recent Ecosystem Changes in the Gulf of Alaska

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Summary

Evidence suggests that there were climate regime shifts in 1977, 1989, and 1998 in the North Pacific. Ecosystem responses to these shifts in the Gulf of Alaska (GOA) were strong after the 1977 shift, but weaker after the 1989 and 1998 shifts. Variation in the strength of responses to climate shifts may be due to the geographical location of the GOA in relation to the spatial pattern of climate variability in the North Pacific. Prior to 1989, climate forcing varied in an east–west pattern, and the GOA was exposed to extremes in this forcing. After 1989, climate forcing varied in a north–south pattern, with the GOA acting as a transition zone between the extremes in this forcing. The 1989 and 1998 regime shifts did not, therefore, result in strong signals in the GOA.

There were both physical and biological responses to all regime shifts in the GOA. However, the primary re-organization of the GOA ecosystem occurred after the 1977 shift. After 1977, the Aleutian Low intensified, resulting in a stronger Alaska Current, warmer water temperatures, increased coastal rain, and, therefore, increased water column stability. The optimal stability window hypothesis suggests that water column stability is the limiting factor for primary production in the GOA (Gargett 1997). A doubling of zooplankton biomass between the 1950s–60s and in the 1980s indicates that production was positively affected after the 1977 regime shift (Brodeur and Ware 1992). Recruitment and survival of salmon and demersal fish species also improved after 1977. Catches of Pacific salmon, recruitment of rockfish (Pacific ocean perch), and flatfish (arrowtooth flounder, halibut, and flathead sole) recruitment and biomass all increased. There are indications that shrimp and forage fish, such as capelin, were negatively affected by the 1977 shift, as survey catches declined dramatically in the early 1980s (Anderson 2003). Availability of forage fish may have been related to the decline in marine mammal and seabird populations observed after the 1977 shift (Piatt and Anderson 1996).

After 1989, water temperatures were cooler and more variable in the coastal GOA, suggesting that production may have been lower and more variable. After 1989, British Columbia (B.C.) salmon catches and survival were low and Queen Charlotte Island (northern B.C.) herring declined. Salmon catches in Alaska, however, remained high. Groundfish biomass trends which began in the early 1980s continued, with increases in flatfish biomass. By the late 1980s, arrowtooth flounder, rather than walleye pollock, were dominant. Large groundfish biomass estimates resulted in negative recruit per spawning biomass anomalies of demersal fish.

There is some indication that the GOA ecosystem may have weakly responded to the 1998 regime shift. Increased storm intensity from 1999 to 2001 resulted in a deeper mixed layer depth in the central GOA, and coastal temperatures were average or slightly below average. After 1998, coho survival increased in southern B.C., shrimp catches increased in the northern GOA, and the 1999 year class of both walleye pollock and Pacific cod was strong in the northern GOA. Recruitment information from longer-lived species will be available in the near future, enabling scientists to determine if there were other responses to the 1998 climate shift.

It is apparent that many components of the GOA ecosystem respond to decadal-scale variability in climate and ocean dynamics. It is unknown if changes observed after the 1998 shift will persist in the GOA and how long the current conditions in the GOA will last. Predicting regime shifts will be difficult until the mechanisms that cause the shifts are understood (Minobe 2000). Monitoring indicator species is one method to improve our knowledge of the mechanisms that cause the shifts. Potential indicator species of regime shifts would include those which have a short life-span, are sensitive to changes, are key trophic groups, and/or are targeted by fisheries which produce data that are readily available. Examples of potential indicator species in the GOA that fit some of these criteria include sockeye and pink salmon, juvenile fish abundance, ichthyoplankton, as well as zooplankton biomass and composition.

A3.1 Introduction

In this section we examine biological changes in the Gulf of Alaska (GOA) system, which is here defined to include coastal waters of northern British Columbia (B.C.), southeast Alaska, central Alaska and the central GOA. Atmospheric processes that influence the central GOA, particularly seawater temperatures as measured along Line-P, are reported in Section 1 (Subsections 1.2 and 1.3). Also reported in Section 1 are recent oceanographic changes in the Alaskan Coastal Current, the Alaska Current and Alaskan Stream, the central and northern GOA and northern B.C. Though data are limited, some recent nutrient and chlorophyll *a* concentration data were available and presented in this section. We provide zooplankton biomass data for the Alaskan Shelf and in the Alaskan Gyre. Survey catch per unit effort (CPUE) of pandalid shrimp is given. Where available, data are presented for catch, CPUE, recruitment, biomass, recruit per spawning biomass, and/or growth for pelagic fishes (Pacific herring, capelin, and eulachon), gadids (walleye pollock and Pacific cod), sablefish, flatfish (arrowtooth flounder, flathead sole, and Pacific halibut), and rockfish (Pacific ocean perch and yellowtail rockfish). In stocks that are abundant, the relationship between recruits and spawners may not be linear, *i.e.*, density-dependent factors may limit recruitment. Under these circumstances, the pattern of recruits per spawner will appear as an inverse of the spawning biomass because annual rates of production have leveled off. For this reason, we present both recruitment and recruits per spawner. Marine mammal and seabird information is also included.

A3.2 Physical Oceanography

Long-term hydrographic conditions in the GOA are based primarily on sampling at the GAK1 station near the mouth of Resurrection Bay, along Line-P extending west from the mouth of Juan de Fuca Strait, and at British Columbia coastal lighthouses. These are detailed in Section 1 (Decadal-scale Climate Events).

Water column temperature and salinity in the northern GOA respond to seasonal changes in heat flux, freshwater input and winds, but substantial long-term variability is evident over the past several decades. A significant amount of temperature variance is at the 5-year period. Before 1977, the upper water column was anomalously cool and near-surface waters were anomalously saline. Conditions after 1977 alternated between warm fresh and cold saline waters. The largest warm event occurred in association with the strong 1997–98 El Niño. These anomalies are advected into the region, rather than locally forced by winds, runoff, heating and cooling (Royer, in press). Sea surface temperatures (SSTs) were average or below average at GAK1, and along Line-P during 1999–2002. However, summer 2002 and winter 2003 temperatures were above normal at GAK1 and below average on Line-P (PICES 2004). Temperature at most depths is positively correlated with the Pacific Decadal Oscillation (PDO). A shallowing mixed layer depth trend has been observed at Ocean Station Papa, Line-P, but not in the northern GOA.

Coastal temperatures also shifted to colder water after 1998, but this regime was interrupted by a warming in 2003, possibly a response to the 2002–03 El Niño. It is, so far, uncertain if this shift to warmer waters has continued into 2004. Coastal salinities do not reveal an El Niño impact, nor a 1998 regime shift, but do reveal a multi-decadal decline in salinity at Langara Island, (northern

Queen Charlotte Islands). The impact of this trend on nearby southeast Alaskan waters is not known.

A3.3 Lower Trophic Levels

Despite the long-recognized high fish productivity of the northern GOA shelf, there have been few studies of the nutrient concentrations, chlorophyll (phytoplankton biomass), and primary production which support this high fish production. Production in both the oceanic and neritic regions is highly seasonal, with very low production during winter and moderate to high production during the summer. Light levels and the mixed layer depth are limiting factors of phytoplankton blooms in the winter and spring. There is an increase in phytoplankton production in the spring; the bloom is not large in oceanic regions, but it is in neritic regions. In coastal regions, the spring bloom of phytoplankton depletes surface waters of essential nutrients (primarily nitrate), therefore, spring bloom conditions are short-lived. Mixed layer depth, light levels and nutrients may vary interannually, thereby affecting production.

Nutrients

Interannual variability in nutrient concentration in the coastal GOA can be large (Childers *et al.*, in press). This is illustrated with data from GAK1 (core of the Alaska Coastal Current (ACC)) and GAK4 (located at mid-shelf) for 1998–2000 (Figs. A3.1 and A3.2). In the northern GOA, March stratification was stronger in 1998 and 2000 than in 1999, with a well mixed, saltier and cooler upper 100 m. Integrated over the entire water column, nitrate was lowest in 1998 and highest in 2000 (almost double that of 1998) at both GAK1 and GAK4. This "initial" March condition is important because it sets an upper limit on total nitrate availability for the spring bloom, since there is little (or no) replenishment of shelf nutrients in the spring, or until late fall–winter. The higher concentration of nutrients in 2000 resulted in larger phytoplankton blooms for that year (Figs. A3.1 and A3.2). Nutrient concentrations at the surface (0–10 m depth) became completely depleted in each of the 3 years, but the timing and duration of the period of depletion varied interannually and spatially (across the shelf). At GAK1, surface nutrients were depleted by July 1998 and August 1999. However, in 2000, a year with the highest beginning nutrient levels, nutrients were depleted by April, and remained depleted through October. At GAK4, there was less interannual variability in the timing of nitrate depletion, and surface nutrient depletion was apparent in July–August. Nitrate depletion and the phytoplankton bloom occur first on the inner shelf, within the ACC and later on the middle and outer shelf. This is likely due to the early water column stabilization on the inner shelf provided by the fresher water of the ACC. At Ocean Station Papa, winter nutrient levels were low during most of the 1990s, but have increased in recent years.

Phytoplankton

Chlorophyll *a* concentrations are indicative of phytoplankton biomass, and vary seasonally and interannually (Childers *et al.*, in press). For example, March chlorophyll concentrations at GAK1 were low in 1999 relative to 1998 and 2000. However, May chlorophyll concentrations were highest in 1999 relative to 1998 and 2000 (Childers *et al.*, in press, Fig. A3.3). The analysis by Childers *et al.* (in press) at GAK1 and an Empirical Orthoganal Function (EOF) analysis of SeaWiFS data for the entire GOA (Brickley and Thomas 2004) indicate that, overall, 1998 had the lowest concentrations of chlorophyll (Fig. A3.4). Also, the chlorophyll maximum was strongest in 1999 and 2000, and somewhat weaker in 2001 (Childers *et al.*, in press; Brickley and Thomas 2004). Perhaps this "interannual" difference was a reflection of a seasonal difference in which the conditions in 1999 were such that the spring bloom was delayed substantially early in spring, but later was manifested as an abnormally intense spring bloom in May. Unfortunately, we have so little data that defining "normal" is difficult, especially when one also considers the spatially patchy distributions.

The community composition of phytoplankton may also vary interannually. For example, phytoplankton at Ocean Station Papa shifted from an autotrophic flagellate-dominated community to one consisting of over 50% coccolithophores in 2000, which were also observed in SeaWiFS data.

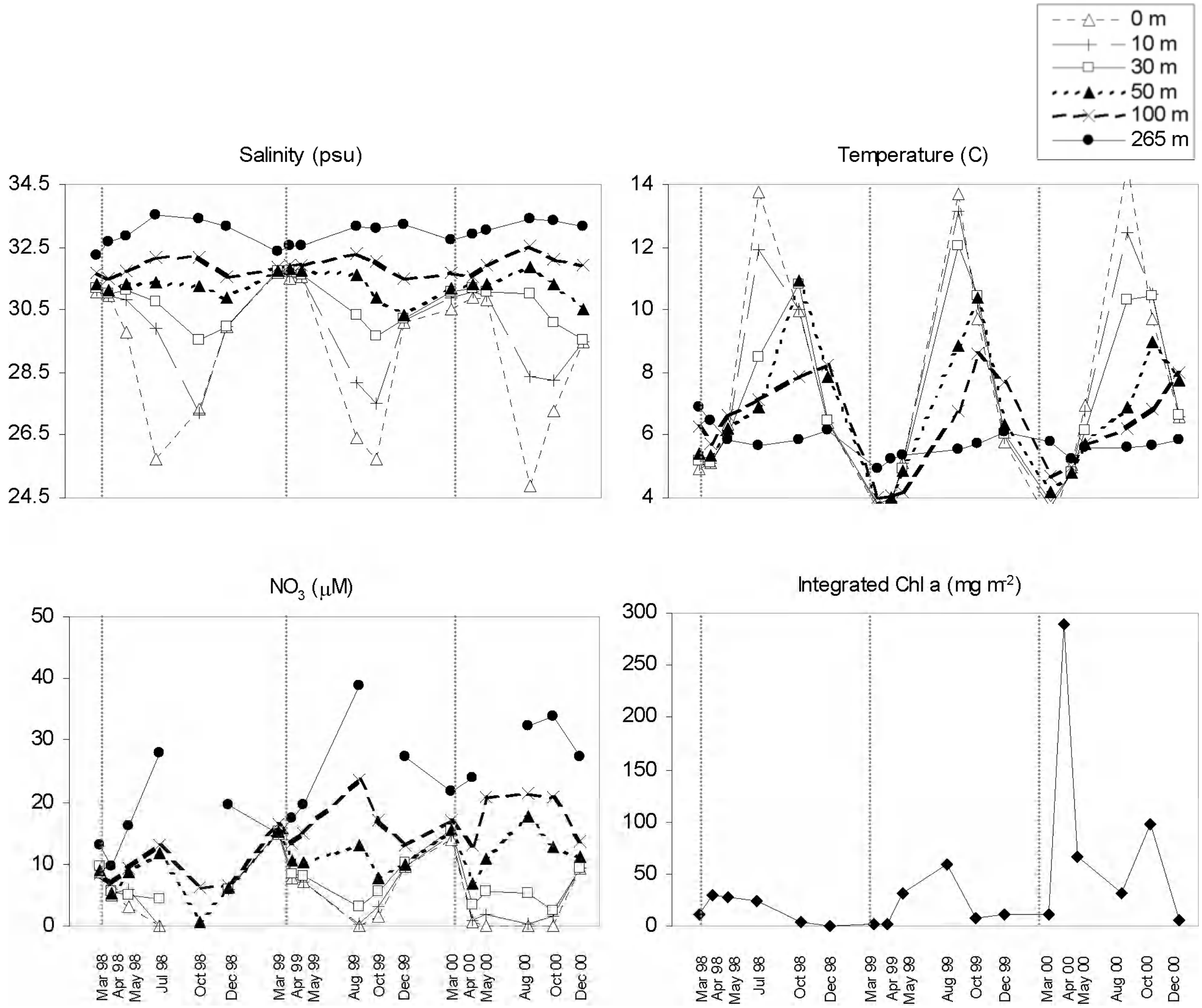


Fig. A3.1 Time series (1998–2000) of salinity, temperature, nitrate, and integrated chlorophyll *a* concentration (0–50 m depth) at GAK1. Dashed vertical lines indicate March data (figure 11 from Childers *et al.* in press).

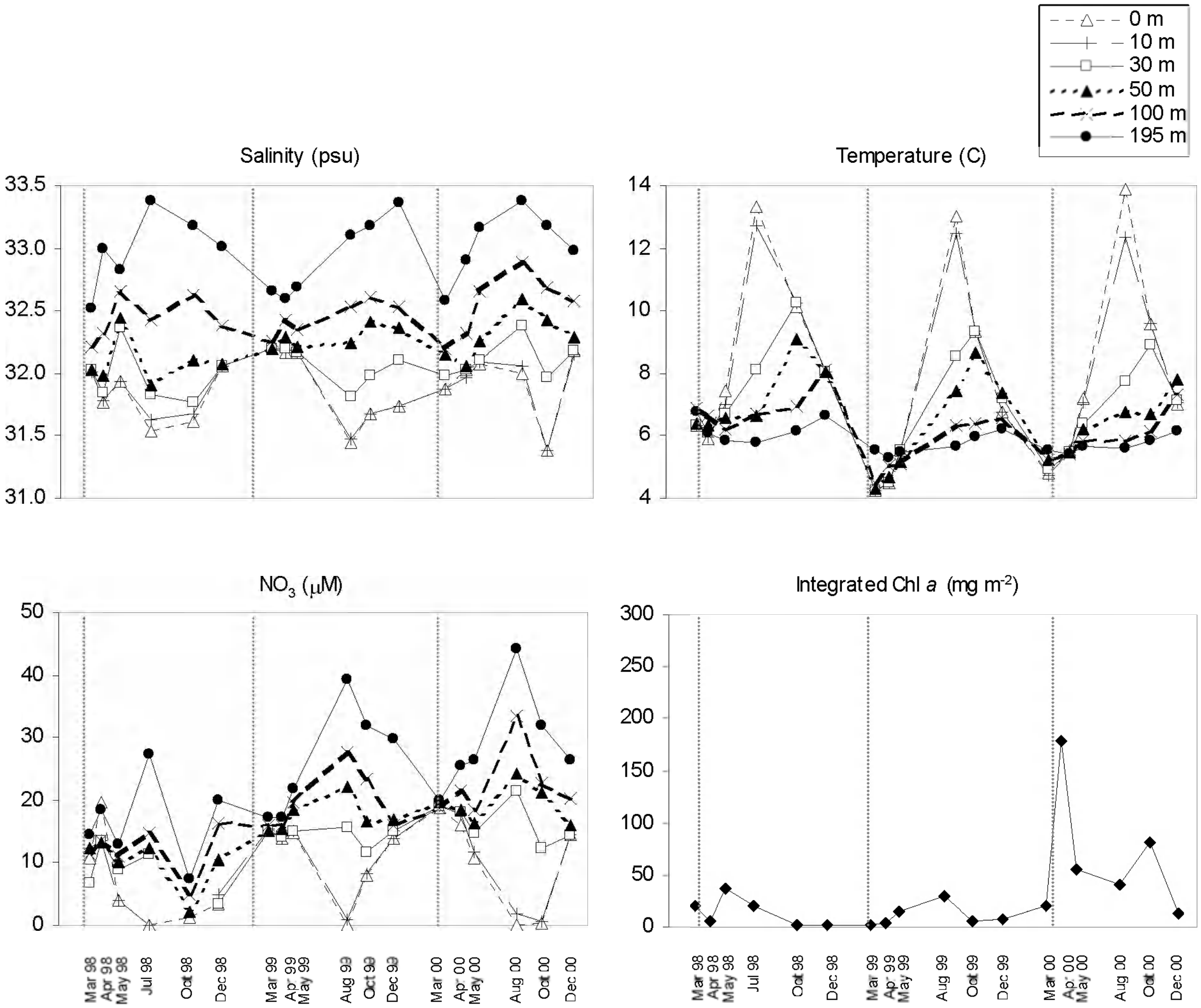


Fig. A3.2 Time series (1998–2000) of salinity, temperature, nitrate, and integrated chlorophyll *a* concentration (0–50 m depth) at GAK4. Dashed vertical lines indicate March data (figure 11 from Childers *et al.* in press).

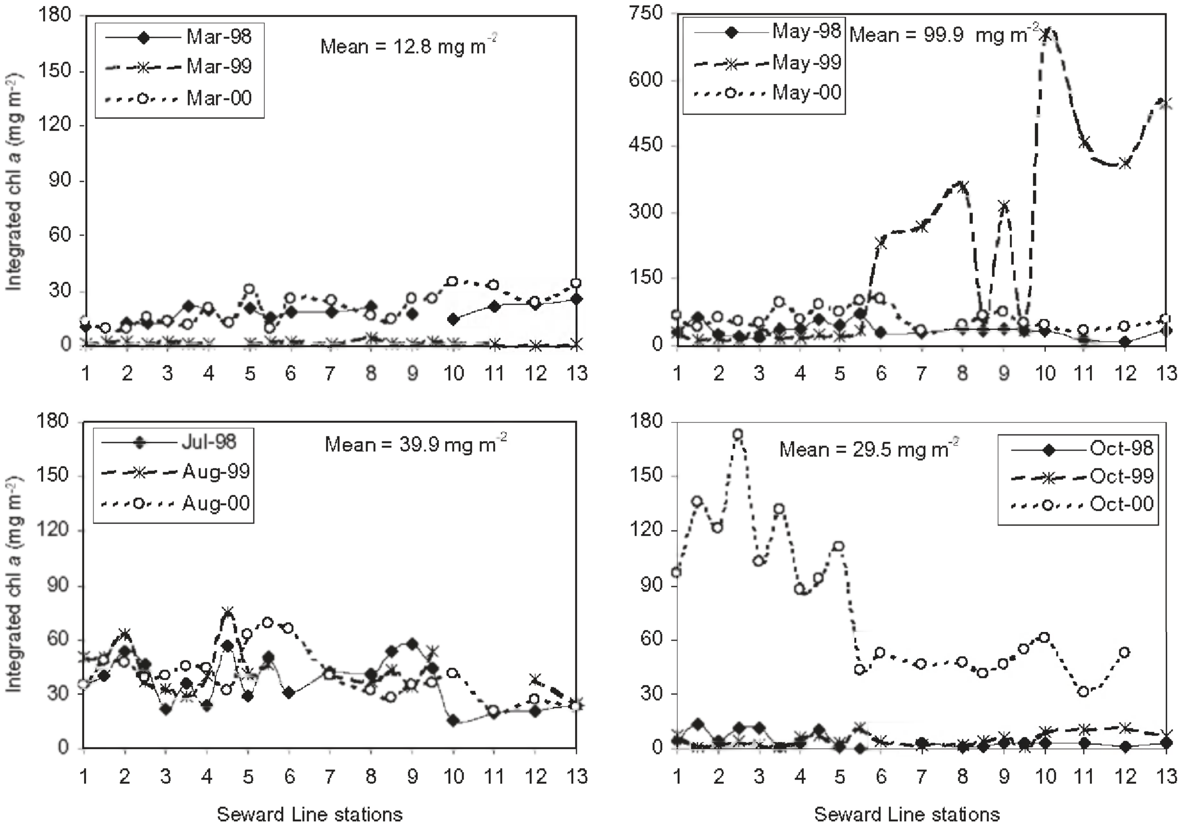


Fig. A3.3 Vertically integrated chlorophyll concentrations (mg m^{-2}) across the Gulf of Alaska shelf in March, May, July–August, and October of 1998–2000. Note the change in *y* scale for May (figure 3 from Childers *et al.* in press).

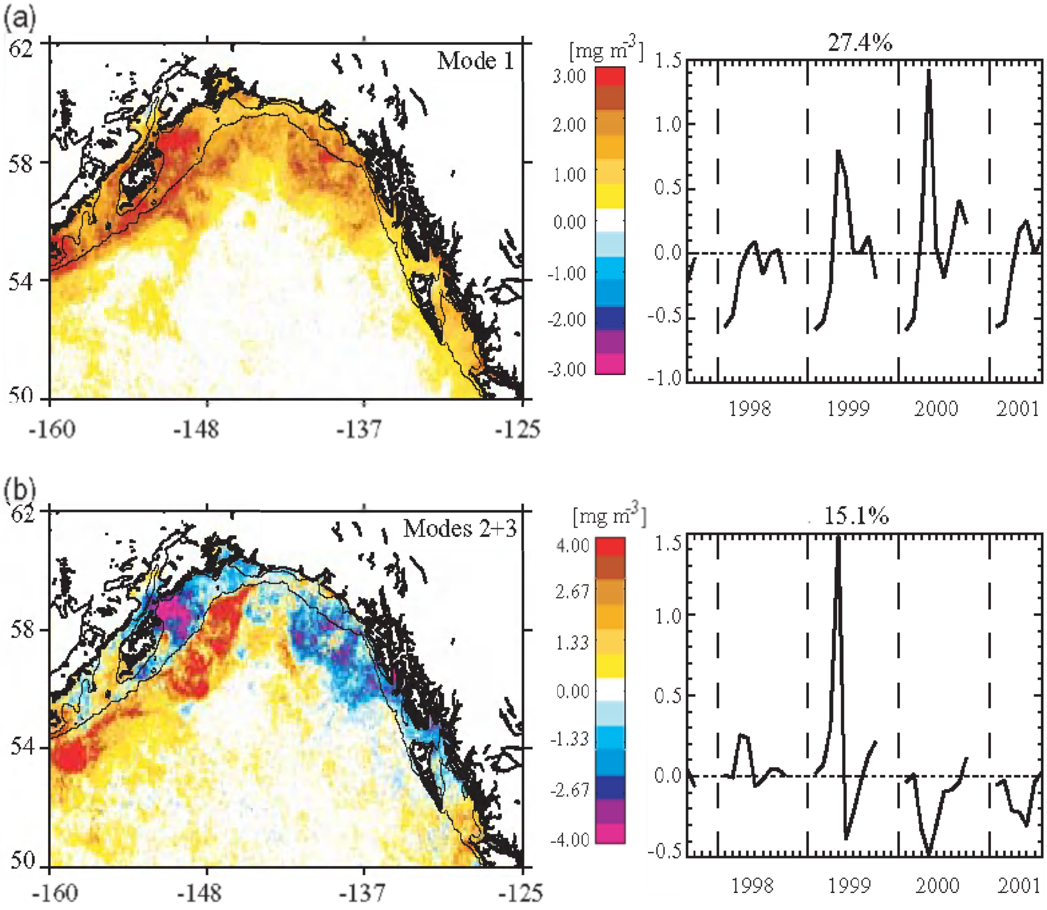


Fig. A3.4 Empirical orthogonal function (EOF) decomposition of the monthly image time series (excluding winter, November–January) showing (a) the dominant mode (27.4% of variance) and its associated time series, and (b) the summed second and third most dominant modes (15.1% of variance) and their associated time series. The temporal mean is removed from each pixel and masking is applied to exclude pixels from the heads of major bays, fjords, and river outlets (white regions inshore of the shelfbreak in mode 1) (figure from Brickley and Thomas 2004).

Zooplankton

Zooplankton time series data are sparse for the GOA. There is some evidence which suggests that the magnitude and timing of blooms respond to interannual and decadal-scale variability. A doubling of zooplankton biomass was observed in the subarctic Pacific between 1956–62 and 1980–89 (Brodeur and Ware 1992). Also, data from a continuous plankton recorder suggest that mesozooplankton biomass increased during 2000–02 (Fig. A3.5; PICES 2004). Observations at Ocean Station Papa indicate that zooplankton population development timing has changed on a decadal scale: development was late in the 1970s, early in the 1990s, and average from 1999–2001 (Mackas *et al.* 1998; PICES 2004). In southern B.C. waters, the community composition of zooplankton also appears to vary on a decadal scale and may be related to changes in the ocean and climate conditions (Mackas *et al.* 2001). From 1990–98, the zooplankton assemblage was comprised of species from areas to the south (California Current) (Mackas *et al.* 2001). Changes in primary and secondary production, as well as community composition, may influence the survival of larval, juvenile, and forage fish.

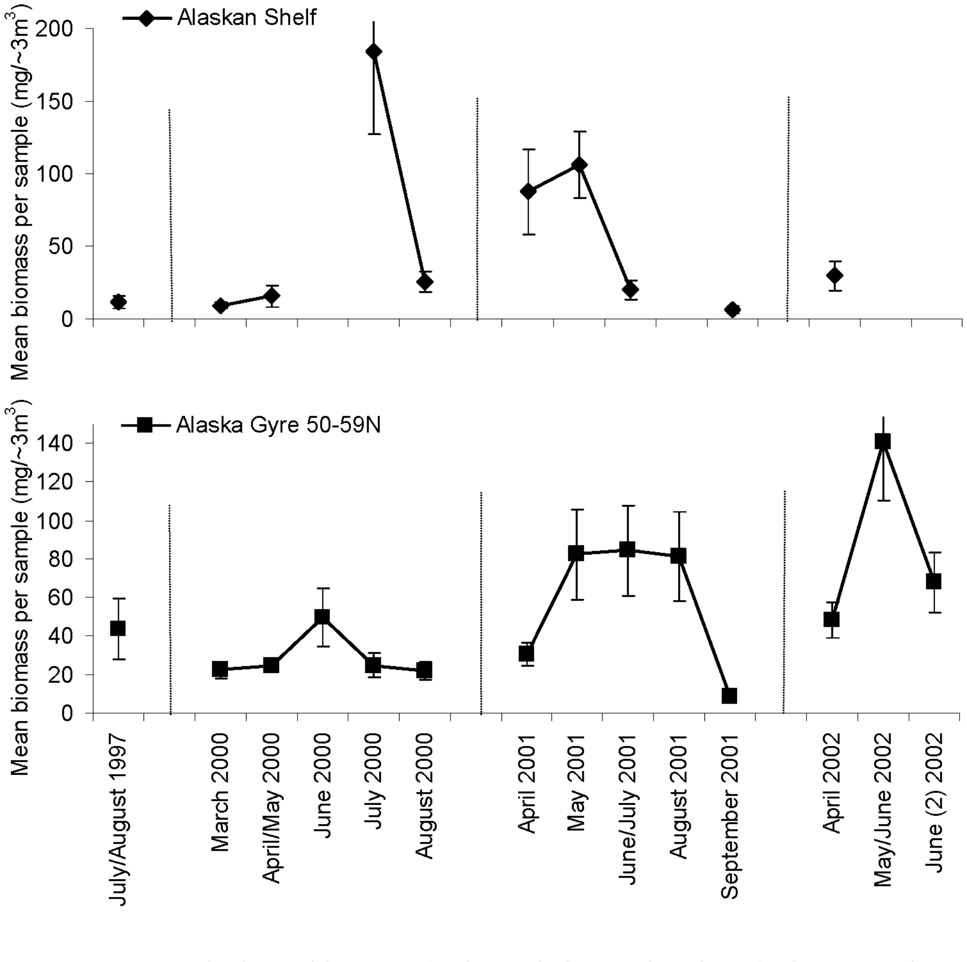


Fig. A3.5 Mean mesozooplankton biomass (estimated from abundance) from continuous plankton recorder transects sampled in 1997 and between March 2000 and summer 2002 (Sonia Batten, Sir Alastair Hardy Foundation for Ocean Science, pers. comm.). Error bars are one standard error (from PICES 2004).

A3.4 Invertebrates

Shrimp

Abundance of pandalid shrimp, as sampled in small mesh surveys in the GOA, appears to vary on a decadal scale (Anderson 2003). Abundance decreased after the mid-1970s, and increased after 1998 (Fig. A3.6). Average catch per tow for all pandalids combined increased to over 75 kg km^{-1} in 2001, and was 38.5 kg km^{-1} in 2002. Relative pandalid shrimp abundance at this level last occurred in survey results nearly 20 years ago, in the early 1980s. The most significant recovery, among pandalid species, has occurred with *Pandalus goniurus*. This species had become almost functionally extinct in GOA shallow nearshore locations where, formerly, it was locally abundant during the 1970s, but in 2002, CPUE was the highest on record since 1984. The CPUE for all shrimp species approaches the abundance of the early 1980s for the survey series. Therefore, recent survey results support the notion that pandalid shrimp, as a group, are showing signs of regaining importance in the community structure of the GOA. Recent increases in shrimp populations are directly linked to colder conditions as indicated by the PDO (http://tao.atmos.washington.edu/pdo) since 1998. Sustained high population abundance of pandalid shrimp, as a group, would require a continued shift to colder ocean conditions (Anderson 2000). Along with favorable oceanographic conditions to allow strong recruitment of shrimp, there will also need to be declines in predation pressure. These principle factors are important in determining future pandalid population trends and possibly trends in other species abundance, as well (Anderson 2003).

Crabs

Hecate Strait, British Columbia, is at the southern end of the Alaska downwelling system (Ware and McFarlane 1989) and the GOA, and has the largest B.C. population of Dungeness crab (*Cancer magister*). In contrast to the Dungeness crab populations in the California Current System, this B.C. population does not appear to have 8- to 10-year cycles in abundance, but depends on sporadic recruitment events such as occurred in the early 1990s (Fig. A3.7). Landings per unit of effort (t vessel-day^{-1}) declined to a minimum in 1998, coincident with the warm conditions of the large El Niño Southern Oscillation event, but have been increasing with the cooler conditions since 2000. This fishery has no catch quota limits, but is managed using a combination of size, sex (males only), and season restrictions. The unit of effort used here (vessel days) does not account for potential increases in fishing power which may have occurred due to the rise in the number of traps per vessel.

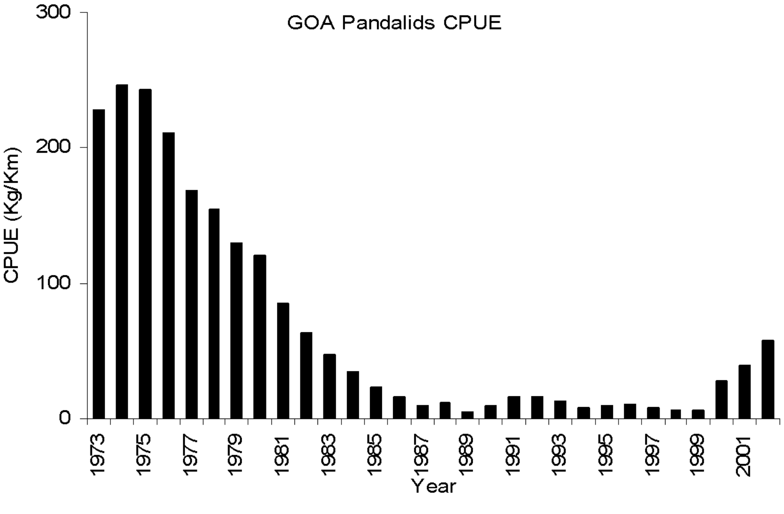


Fig. A3.6 Three-year average catch per unit effort (CPUE) (kg km^{-1} trawled) of pandalid shrimp in the Gulf of Alaska (GOA) small mesh survey, 1973–2002 (Anderson 2003).

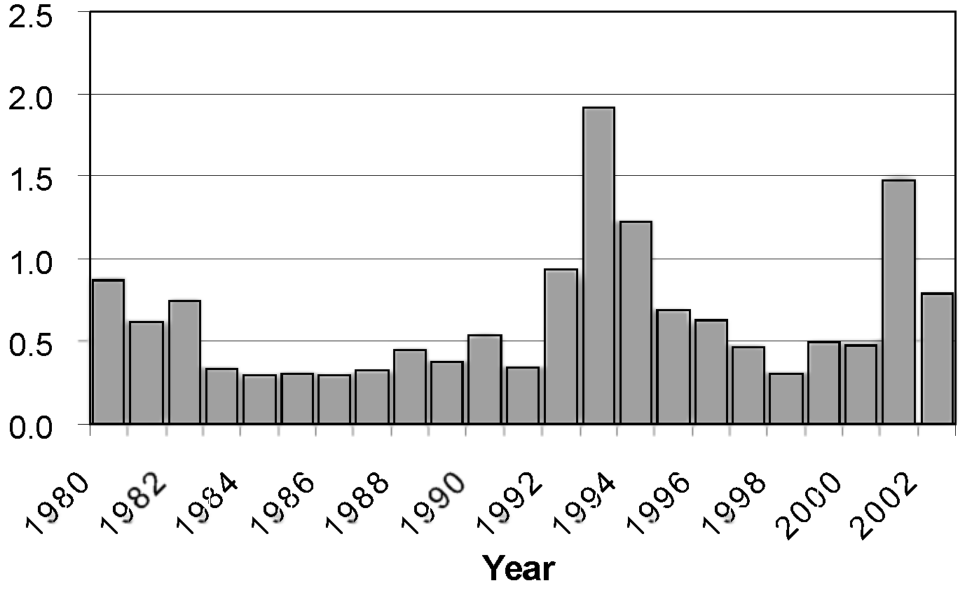


Fig. A3.7 Hecate Strait, British Columbia, landings per unit of effort (t vessel day^{-1}) of Dungeness crab (*Cancer magister*) from 1980–2003.

A3.5 Fishes

Pelagics

Pacific herring *(Clupea pallasi)*

Pacific herring are distributed generally around the perimeter of the North Pacific, from the Yellow Sea in Asia, to southern California in North America (Haegele and Schweigert 1985). Since herring are intertidal spawners, they are dependent on suitable inshore habitat for at least a part of their life cycle. Pacific herring are spring spawners throughout the range, laying adhesive eggs on available substrata and hatching free-floating larvae within 2–3 weeks, depending on ambient water temperature. Juveniles spend their first summer in inshore waters feeding on copepods, then migrate offshore to join immature and adult stocks during the fall of their first year or late spring of their second summer, at which time they become more dependent on euphausiids. In general, herring migrate back to their spawning areas for the first time at age 3 in the south and age 4, or older, in the north. Herring in the eastern Pacific normally live to ages less than 10 although fish up to age 15, or more, have been taken historically in some areas.

The Alaska Gyre ecosystem supports a number of herring stocks. In the GOA, herring range from the Aleutians to Prince William Sound, with the latter area supporting the largest stock. In southeast Alaska, several stocks are fished on a routine basis, with the most important stocks occurring at Sitka. In British Columbia, there are three major northern migratory stocks (Prince Rupert, Queen Charlotte Islands, and the Central Coast), all of similar relative abundance. The major stock in the GOA occurs in Prince William Sound, with an estimated spawning biomass approaching 170,000 tonnes in the late 1980s (Johnson 2002). The fishery has been conducted with purse seines, drift gillnets, or trawls for fall food and bait. The spring fishery for roe consists of both seine and drift gillnet gear sectors, as well as a wild and pound spawn-on-kelp fishery. As in British Columbia, an extensive reduction fishery occurred throughout southeast Alaska from the 1930s through the mid-1960s when stocks collapsed. The fishery was closed and re-opened as the current roe fishery in 1971.

Since 1974, the fishery catch has averaged 6,000 tonnes annually, with numerous closures since 1994 (Johnson 2002). Survival of young-of-the-year herring is determined by the amount of energy they store before their first winter (Foy and Paul 1999). There is also evidence of high levels of viral hemorrhagic septicemia, *Ichthyofonus hoferi*, in some years, which has been suggested as the limiting factor in the slow recovery of this stock (Marty *et al.* 1998).

Within southeast Alaska, the major herring stock spawns at Sitka, with abundance fluctuating between 25,000 and 50,000 tonnes, roughly half the entire abundance in southeast Alaska (Fig. A3.8). Other significant runs occur at Kah Shakes, Craig, and W. Behm Canal. Overall, total abundance in the area has remained relatively stable since 1980, with an increasing trend since 1994. The largest fishery occurs at Sitka, using purse seines.

In B.C., abundance of the three major herring stocks has fluctuated since 1980, with no clear trends in Prince Rupert or the Central Coast (Fig. A3.8; Schweigert 2001). The population in the Queen Charlotte Islands increased to a recent high level in the early 1980s, and has subsequently declined to a near-historic low level with no evidence of recent rebuilding despite the absence of all but the spawn-on-kelp fishery. Overall, combined abundance of these stocks has averaged about 87,000 tonnes since 1951, but has declined from over 100,000 tonnes in the early 1980s to about 60,000 tonnes in recent years.

It has been noted by Williams and Quinn II (2000b), Zebdi and Collie (1995), and others that herring populations in the GOA are closely linked to environmental fluctuations, particularly SST. Herring stocks in southeast Alaska and B.C. were found to respond in opposite directions to temperature inputs although the mechanisms involved remain unclear.

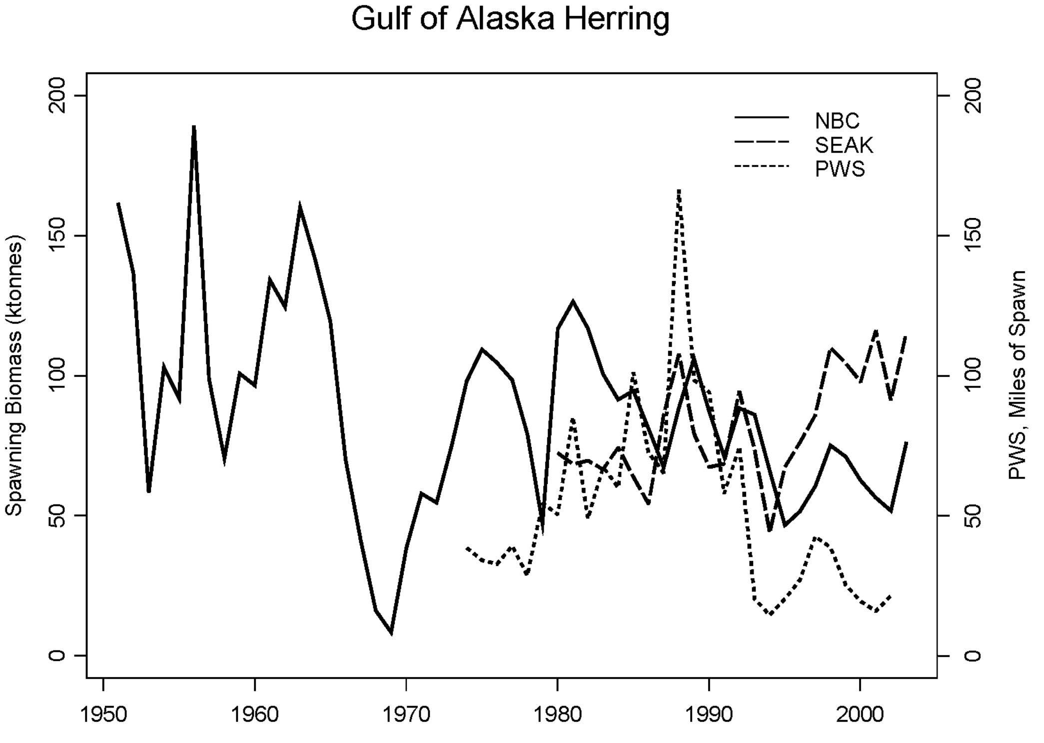


Fig. A3.8 Estimated combined annual herring spawning biomass at major spawning areas in northern British Columbia (1951–2002), southeast Alaska (1980–2002), and Prince William Sound (1974–2001).

Capelin (*Mallotus villosus*)

Capelin are distributed along the coastlines of southern British Columbia to Alaska (Nelson 2003), in cool slope waters (Hollowed *et al.*, in review). Capelin spawn in spring in intertidal areas at the age of 3–4 (11–17 cm) and most die after spawning (Pahlke 1985). Fast-growing capelin mature earlier than slow-growing capelin. Capelin catches in the Alaska Department of Fish and Game (ADF&G) small mesh survey in the northern GOA decreased in the 1980s (Fig. A3.9; Piatt and Anderson 1996; Anderson and Piatt 1999). Capelin have remained at relatively low levels of less than 0.1 kg km^{-1}, well below their historic peak abundance of 16.8 kg km^{-1} in 1980 (Anderson 2003). The decline in capelin abundance has been attributed to an increase in water temperature (Piatt and Anderson 1996; Anderson *et al.* 1997). Capelin are also captured incidentally in the National Marine Fisheries Service (NMFS) Resource Assessment and Conservation Engineering (RACE) bottom trawl survey of the shelf, which may provide an index of abundance (Fig. A3.9). Catches were high in the central and eastern GOA in 1996. However, this survey is not designed to assess capelin, and increases in abundance were influenced by a very few and unusually large catches (Brown 2003).

Eulachon (*Thaleichthys pacificus*)

Eulachon are distributed from northern California to the Bering Sea. They are anadromous fish that spawn in coastal rivers. Eulachon spawn primarily at the age of 3 and most do not survive after spawning. Very little is known about eulachon, but observer and fishery data suggest that their abundance decreased in the 1980s (Fritz *et al.* 1993). Average eulachon catch in the north GOA ADF&G small mesh survey was 1.9 and 6.7 kg km^{-1} during the 2001 and 2002 surveys, respectively (Fig. A3.9). This is the highest level observed for eulachon in the last 30 years. Recent ocean conditions have been optimal for juvenile survival. A major recruitment event of juvenile eulachon was evident in the size frequency data collected in 2002. A strong size mode at around 8 cm fork length was evident in many sampling locations (Jackson 2003). This size mode of eulachon in small-mesh trawl survey catches is seldom observed. High catches were also recorded in the NMFS RACE bottom trawl survey in 2001, although this survey was not designed to sample these fish (Fig. A3.9).

Salmonidae

Pacific salmon rear in the GOA and central Bering Sea and are managed in four regions of Alaska: southeast Alaska, central (Prince William Sound, Cook Inlet, and Bristol Bay), AYK (Arctic, Yukon, Kuskokwim), and westward (Kodiak, Chignik, and Alaska Peninsula). Salmon distribution throughout the GOA and Bering Sea varies by species and stocks, some of which migrate between the two areas (K.W. Myers, University of Washington, pers. comm.). Pink, sockeye, and coho salmon generally spend the majority of their ocean lives in offshore pelagic waters, bounded by brief periods of migration through coastal areas as juveniles and returning adults.

Pink salmon (*Oncorhynchus gorbuscha*) are distributed from California to Russia and Korea. They have a 2-year life cycle that genetically separates odd and even year pink salmon. Pink salmon spawn between June and October in intertidal zones or in streams, within a few miles of the coast. Eggs hatch in winter or spring, and fry migrate from streams to the ocean. Sockeye salmon (*Oncorhynchus nerka*) are distributed from California to the Bering Sea and Japan. They spawn in late summer to fall, depending on temperature, in streams and tributaries. Eggs hatch in the spring, and fry migrate downstream to lakes where they spend 1 to 3 years before migrating to sea. Sockeye spend 1 to 4 years at sea before returning to their natal streams to spawn and die. Coho salmon (*Oncorhynchus kisutch*) is one of seven species of the genus Oncorhynchus native to North America. Coho salmon are anadromous, migrating to the marine environment in the spring as smolts and returning to freshwater in the fall and early winter of their third year to spawn and die. Fry emerge from the gravel in the following spring and usually reside in freshwater for a year before migrating to sea as smolts. Almost all coho spend 18 months at sea before returning to freshwater and therefore, have a 3-year life cycle. Jacks (precocious males), which spend only 6 months in the ocean, are found in some populations. Adult coho usually weigh from 2–5 kg (45–70 cm in length) and only rarely exceed 9 kg. Coho favor smaller streams and are widely dispersed throughout the GOA ecosystem.

Catches of salmon are used as an index of salmon abundance because estimates of total runs are difficult to attain. Generally, Alaskan salmon stocks have been stable and at high levels of abundance for the last 20 years (Fig. A3.10; Eggers 2003). Asian stocks have shown similar trends, while Pacific Northwest and British Columbia stocks have been at lower levels. During the last decade, there have been some weak runs observed, particularly in certain areas of western Alaska, due to weak recruitment events. Notable examples include Yukon River fall chum, Yukon River summer chum, Yukon River chinook, and Kvichak River sockeye salmon. Observed weak year class strengths, however, have not been observed for most other Alaskan salmon stocks. Abundance of sockeye salmon in all areas increased from the mid-1970s to the 1980s (Fig. A3.10). Since then the increased abundance has been stable and at high levels. Pink salmon catches have generally been high in all regions in the last decade, and appeared to begin increasing in the late 1970s (Fig. A3.10). Marine survival of Prince William Sound hatchery pink salmon appeared to increase after 1977, but does not appear to have shifted after the 1989 or the 1998 regime shifts (Fig. A3.11). Coho catches have been moderate to high in all regions. Coho fisheries in central and western Alaska are not fully developed due to the late run and lack of processor interest. The coho catch in AYK from 1998 to 2002 has been lower than in the previous decade, but still above catches in the 1960s and 1970s (Fig. A3.10). In northern B.C., the Skeena and Nass River systems support some of the

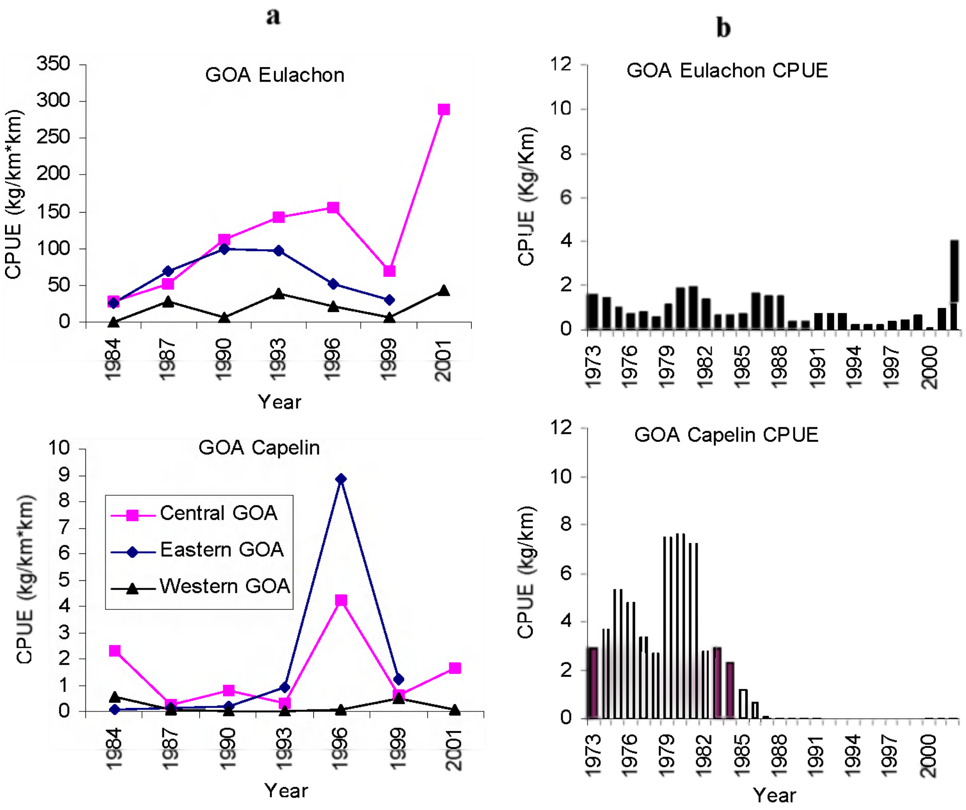


Fig. A3.9 (a) Biomass index values of eulachon and capelin as captured incidentally in the National Marine Fisheries Service (NMFS) Resource Assessment and Conservation Engineering (RACE) bottom trawl survey of the shelf (Brown 2003) and (b) 3-year average catch per unit effort (CPUE) (kg km^{-1} trawled) of eulachon and capelin in the Gulf of Alaska (GOA) small mesh survey 1973–2002 (Anderson 2003).

largest coho runs in this ecosystem. Indices of coho abundance for this region indicate a moderate decline in abundance from the early 1980s to the mid-1990s (Fig. A3.12), but a dramatic increase in abundance in recent years (J. Sawada, unpub. data). It is believed that reduced survival in the marine environment has been the main determinant of the coho population decline, which has recently ameliorated. Overfishing, changing marine conditions, and habitat perturbations all contributed to coho declines (Bradford and Irvine 2000). Excessive fishing resulted when harvest rates were not reduced quickly enough in response to climate-driven declines in marine productivity. Bradford (1999) also notes that coho survival was highly correlated among geographically adjacent stocks, suggesting that local environmental conditions have a greater influence on coho production than global conditions. However, factors determining larger-scale coho survival are unclear, although Beamish *et al.* (1999) suggest there are evident climatic links.

General trends in salmon production have been attributed to PDO-scale variability (Hare and Francis 1995), ocean temperature (Downton and Miller 1998), and regional-scale SSTs (Mueter *et al.* 2002). A period of high Alaskan salmon production, from the mid-1970s to the late 1990s, has been attributed to changes in ocean and atmospheric conditions which increased survival, as well as enhanced hatchery releases (Beamish and Bouillon 1993; Coronado and Hilborn 1998; Mantua *et al.* 1997). The increased production was accompanied by a decrease in average salmon weight at maturity, from 1975–93, which has been attributed to density dependence (Fig. A3.10; Bigler *et al.* 1996; Ishida *et al.* 1993), SST (Pyper and Peterman 1999; Hinch *et al.* 1995; Ishida *et al.* 1995), and sea surface salinity (Morita *et al.* 2001).

Catch by species data were provided by Doug Eggers (ADF&G). A full report (Eggers 2003) of run forecasts and a review of the 2002 season is available at http://www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmhome.htm#forecasts.

Gadids and groundfish

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock are semi-pelagic and distributed throughout temperate and subarctic waters of the North Pacific (Wolotira *et al.* 1993). They represent the second most abundant groundfish in the GOA and are exploited in the western/central GOA. Major spawning concentrations occur in Shelikof Strait and near the Shumagin Islands (Kendall *et al.* 1996; DiCosimo and Kimball 2001). Fifty percent of females mature at age 5, or at about 43 cm length. Juvenile pollock are pelagic zooplanktivores and are prey to many fish (Carlson 1995). As pollock age, they become increasingly demersal, piscivorous, and potentially cannibalistic.

Pollock biomass increased from 1969, peaked in 1982, and has since decreased through to 2001 (Fig. A3.13). There was a significant linear decrease in survival (median recruit per spawning biomass anomalies) from 1969–2001. Survival was significantly higher prior to the 1977 regime shift than after the shift (Fig. A3.13). Pollock recruitment is variable, with strong year classes occurring every 4 to 6 years (Dorn *et al.* 2003). Rather than responding to decadal-scale variability, a higher incidence of strong year classes is associated with El Niño north conditions (Hollowed *et al.* 2001).

Density-dependent processes may, in part, determine growth, or length-at-age, of pollock in the GOA. Age 4 pollock tend to weigh less and are shorter when there is a strong year class, such as the 1988, 1994, and 1999 year classes (Dorn *et al.* 2003). Pollock lengths at older ages, such as ages 7 and 10, increased from the early 1980s to the present (Fig. A3.13). This increase in length-at-age coincided with a decrease in total biomass of pollock in the GOA, suggesting density-dependent growth. The growth time series does not include estimates prior to the 1977 regime shift, and pollock growth did not appear to respond to the 1989 or 1998 regime shifts. It is, therefore, unclear if the changes in pollock growth in the GOA were responses to decadal-scale climate variations.

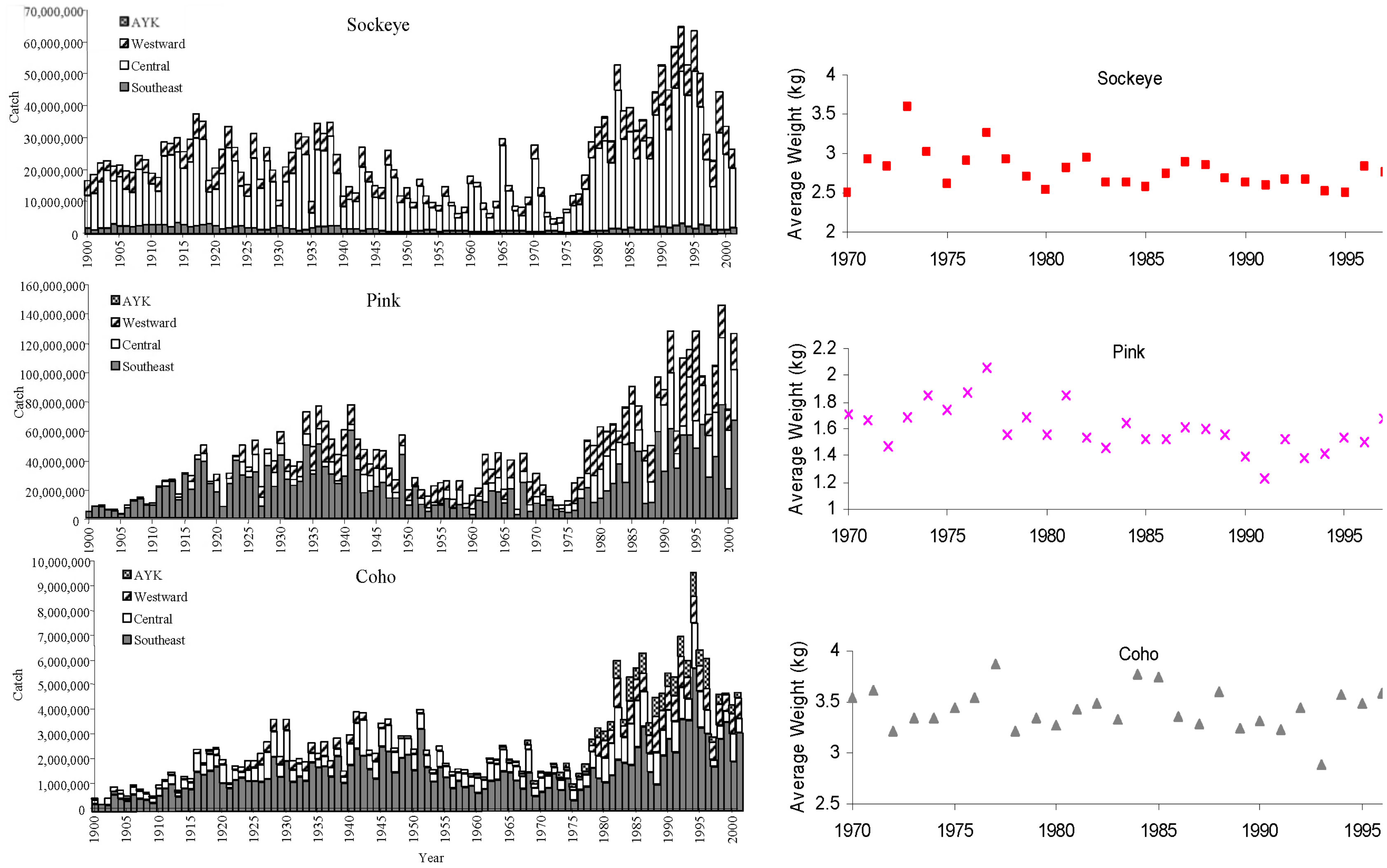


Fig. A3.10 Historical catch and average weight (kg) of sockeye, pink, and coho salmon by area in Alaska. Weight data were obtained from the Alaska Department of Fish and Game website (http://www.cf.adfg.state.ak.us/geninfo/finfish/salmon/catchval/history/1970–2001s.htm). Left hand panels are catch; right hand panels are average weights.

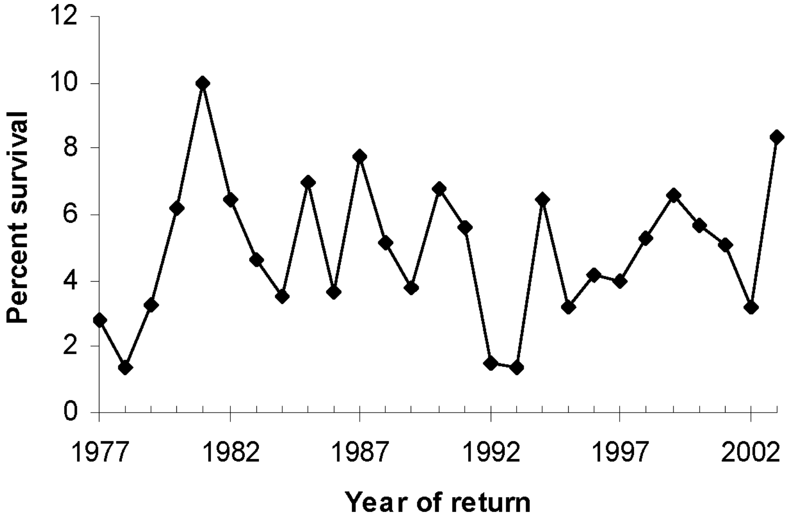


Fig. A3.11 Marine survival of Prince William Sound hatchery pink salmon by year of return, 1977–2003.

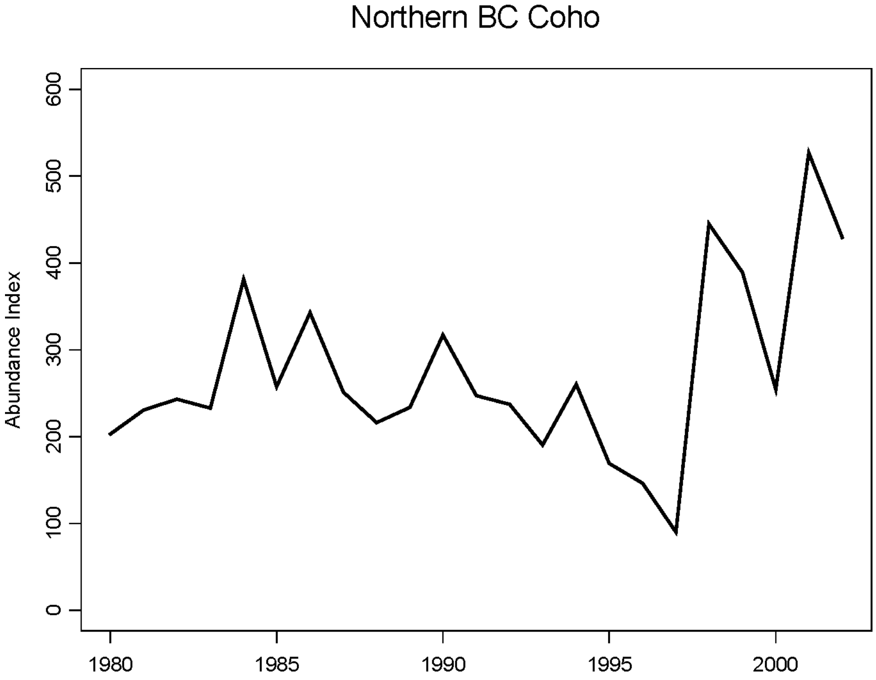


Fig. A3.12 Index of coho salmon abundance in northern B.C., 1980–2002.

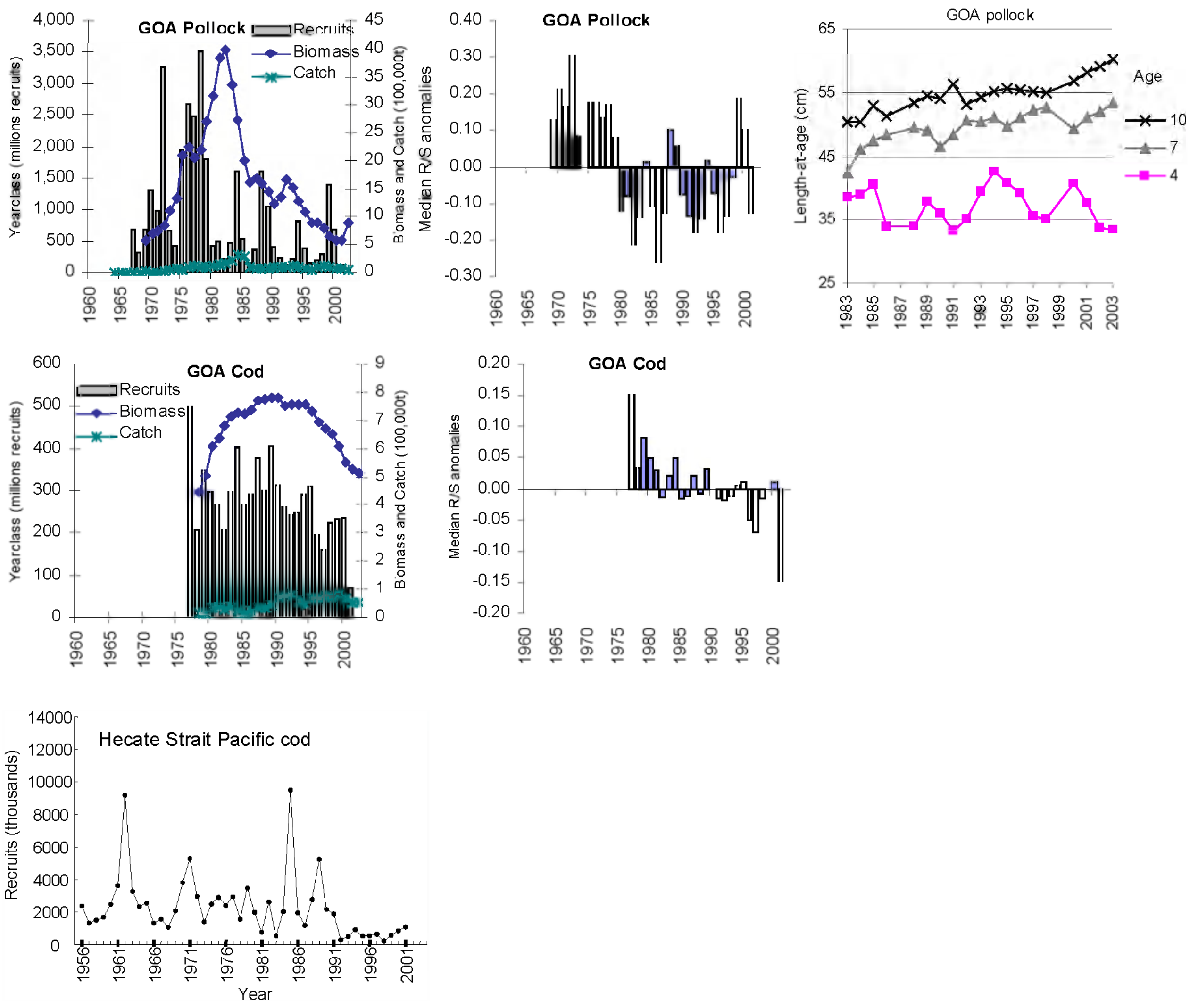


Fig. A3.13 Gulf of Alaska (GOA) gadid (walleye pollock and Pacific cod) recruits (millions of fish), biomass and catch (100,000 tonnes) in the left panels and median recruit per spawning biomass anomalies (middle panels). The pollock length-at-age data (right panel) was taken from the echointegration trawl survey conducted annually in Shelikof Strait, Gulf of Alaska. Hecate Strait Pacific cod stock recruits (1000s of fish) were estimated by a catch-at-length model (adapted from Sinclair *et al.* 2001).

Pacific cod (*Gadus macrocephalus*)

Pacific cod can be found at all depths up to 500 m on the upper slope and continental shelf of the North Pacific, from California to Norton Sound (Bakkala 1984). Pacific cod are demersal fish that spend the winter and spring in deep waters, and migrate to shallower waters in the summer. Fifty percent of females mature at about 6.7 years of age or 67 cm (Thompson and Dorn 2003). Spawning occurs in late winter in relatively small areas near the bottom. Eggs sink to the bottom and are adhesive (Hirschberger and Smith 1983), and after hatching, larvae occur in the upper 45 m of the water column. Larvae migrate to deeper water as they grow. Growth is rapid within the first year, with Pacific cod reaching lengths of approximately 30 cm. Juvenile Pacific cod consume invertebrates, and become omnivorous as they get larger. Cod move over large areas, resulting in genetically indistinct stocks in the GOA, Aleutian Islands, and Bering Sea (Shimada and Kimura 1994; Grant *et al.* 1987).

The biomass of Pacific cod increased during 1978–90, remained high in the early 1990s, and then decreased to 2001 (Fig. A3.13). There has been a decreasing trend in recruitment since 1990 as well. Median recruit per spawning biomass anomalies indicate that survival linearly decreased significantly from 1977 to 2001. Pacific cod survival appears to vary on the same temporal scale as that of pollock in the GOA. Median recruit per spawning biomass anomalies of GOA Pacific cod and pollock follow similar trends, suggesting that both species are responding to similar large-scale processes. As with pollock, cod have a higher incidence of strong year classes and are associated with El Niño northern conditions (Hollowed *et al.* 2001).

In British Columbia, there are four stocks defined for management purposes: Strait of Georgia, west coast of Vancouver Island, Queen Charlotte Sound and Hecate Strait (adjacent to the GOA). Though there are currently no genetic analyses to verify stock delineation, tagging studies indicate that there is very little movement of Pacific cod between these four areas (Westrheim 1996). The west coast of Vancouver Island and the Hecate Strait stocks have historically supported commercial fisheries and are the two stocks for which stock assessment information is available. Assessments on both stocks indicated a dramatic decline in biomass (tonnes) in the 1990s from historic high levels in the 1980s (Sinclair 2000; Sinclair *et al.* 2001; Starr *et al.* 2002). These declines contributed to nine poor consecutive year classes, beginning in 1990 (DFO 1999). Recruitment estimates are produced by a delay-difference stock production analysis which incorporates research survey data (Sinclair *et al.* 2001; Fig. A3.13).

Recruitment in the Hecate Strait stock has been linked to sea level height, a proxy variable for relative water movement through Hecate Strait (Tyler and Crawford 1991). In the 1990s, this environmental variable suggested that oceanic conditions were unfavorable for recruitment. However, since 1999, this variable has indicated that Pacific cod recruitment may be improving (Sinclair *et al.* 2001).

Sablefish (*Anoplopoma fimbria*)

Sablefish are distributed from northern Mexico to the GOA, Aleutian Islands, Bering Sea, and to the coasts of Siberia, Kamchatka, and northern Japan (Wolotira *et al.* 1993). They are found at depths greater than 200 m along the edge of the continental slope, shelf gullies, and deep fjords (Sigler *et al.* 2003). Tagging studies suggest that there are two populations: a northern population that is distributed from Alaska to northern B.C., and a southern population that extends from southern B.C. to California (McDevitt 1990; Saunders *et al.* 1996; Kimura *et al.* 1998). The two populations mix in waters off southern B.C. and northern Washington (Sigler *et al.* 2003). Sablefish spawn in the winter at the edge of the continental slope in depths between 300–500 m (McFarlane and Beamish 1983; McFarlane and Nagata 1988). The northern population spawns approximately one month later than the southern population (Sigler *et al.* 2001). Larval fish hatch at about 300–400 m depth, then descend to 1000 m within 18 days after spawning. Within a few days of their descent, larval sablefish begin to ascend and feed on copepod larvae. Juvenile sablefish inhabit shallow inshore shelf waters (< 200 m), and by ages 2–5, move to deeper offshore slope waters.

Recruitment strength appears to be determined at the larval stage (McFarlane and Beamish 1992). Growth of sablefish is rapid in the first few years, then slows appreciably in this long-lived species (Sigler *et al.* 2001; Kimura *et al.* 1998). Males tend to undergo a reduction in growth rate earlier than females. The majority of fish in the fishery are between the ages of 4 and 35, but the oldest sablefish aged to date is 113 years (Beamish and McFarlane 2000).

In Alaska, sablefish are assessed in the combined area of the GOA and Bering Sea with an age-structured model that incorporates both fishery and survey catch data (Sigler *et al.* 2003). Sablefish biomass peaked in 1968 and 1985, and was at a minimum in 1963, 1980, and 1997 (Fig. A3.14). Recruitment and survival have been variable but may be related to winter environmental conditions. Strong recruitment tends to occur when there is a northerly current drift or above-average SSTs (Sigler *et al.* 2001). Strong year classes occurred in 1960, 1977, and 1984, which coincided with strong year classes of other groundfish in Alaska (Hollowed and Wooster 1992). Recent strong year classes include 1995, 1997, and 1998 (Sigler *et al.* 2003).

In Canadian waters, sablefish are caught commercially by trap, longline and trawl fishing gear. Over the last two decades, the commercial catch has ranged from 2,000 tonnes to 5,400 tonnes, and has averaged approximately 4,500 tonnes (Haist *et al.* 2004). The stock is characterized by periods of strong and weak year class success (King *et al.* 2000). Periods with above-average year classes are characterized by intense Aleutian Lows, above-average frequency of south-westerly winds, relatively weak winter downwelling, strong summer upwelling, and above-average abundances of subarctic and boreal copepods (King *et al.* 2001). From 1977–88, the sablefish population had eight strong year classes, and four below-average year classes (King *et al.* 2000). From 1989–98, there were only two above-average year classes. There is an indication that year class success has improved since 1998 (King *et al.* 2001; Haist *et al.* 2004).

Productivity of the Canadian sablefish stock reflects the trends in recruitment. Estimates of surplus production (Haist *et al.* 2004) exhibit a distinct decadal-scale pattern (Fig. A3.14). From 1980–93, estimates of sablefish productivity are above average. From 1994–2002, these estimates are greatly reduced to average and below-average values. In 2003, the estimate of productivity increases dramatically. Sablefish recruit to the fishery at ages 4 and 5, so the changes in productivity described above correspond to the dynamics of the 1977–89; 1990–98 and the 1999 year classes, respectively.

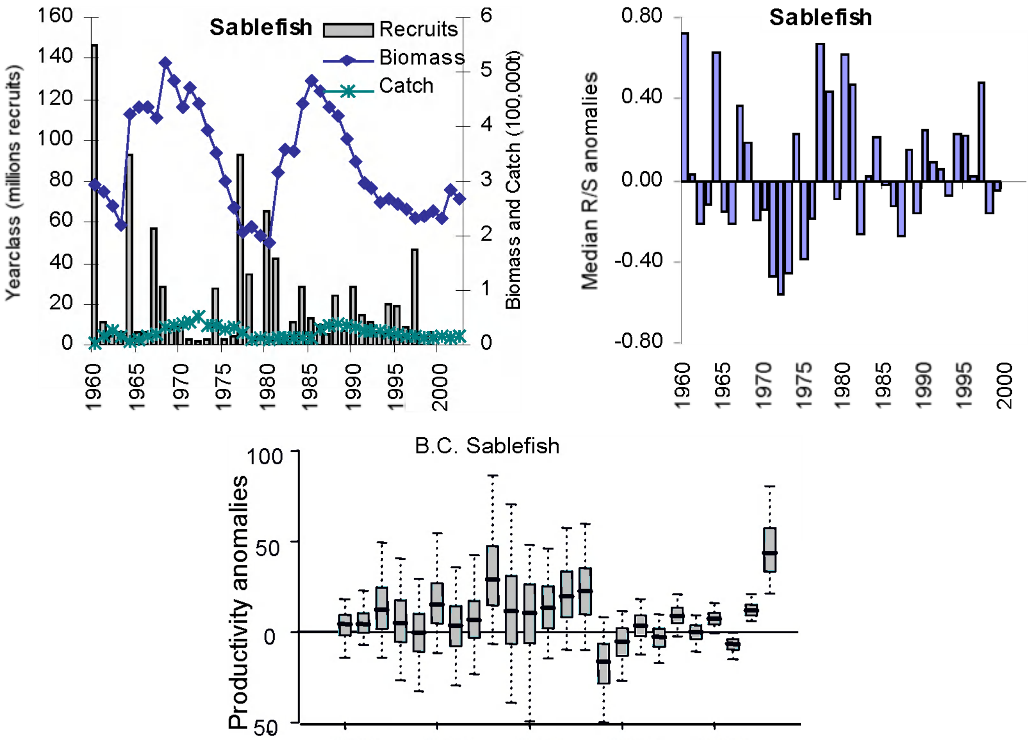


Fig. A3.14 Gulf of Alaska sablefish recruits (millions of fish), biomass and catch (100,000 tonnes), and median recruit per spawner biomass anomalies (top two graphs). Productivity anomalies of the Canadian sablefish stock (bottom graph) estimated by a biomass dynamics model by year (from Haist *et al.* 2004). Productivity approximates relative year class success lagged by 4 years (age of recruitment). The median is denoted by the thick horizontal lines, the interquartile range is denoted by the shaded boxes, and the 5th and 95th quantiles are denoted by the whiskers.

Flatfish

Arrowtooth flounder (*Atheresthes stomias*)

Arrowtooth flounder are distributed from California to the Bering Sea, and can be found on the continental shelf at the ages of 1 to 4, after which they are found at depths of 100–200 m in shelf and slope waters (Allen and Smith 1988; Martin and Clausen 1995). They are the most abundant groundfish in the GOA. Spawning occurs offshore between September and March, and 50% of females are mature at the age of 5 (Zimmermann 1997; Wilderbuer and Sample 2003), or 47 cm in length (Zimmermann 1997). Juveniles initially consume zooplankton and, as they grow, begin to consume shrimp and small fishes (Wilderbuer and Sample 2003). After arrowtooth flounder exceed 30 cm in length, they are primarily piscivorous, with their main prey consisting of walleye pollock (Wilderbuer and Sample 2003).

Arrowtooth flounder biomass and recruitment were relatively stable during 1961–71, after which they increased to record high levels in 1997 (Fig. A3.15). Median recruit per spawning biomass anomalies, an index of survival, were negative during 1961–69, and strongly positive from 1970–79 (Fig. A3.15). Change point analyses indicate that there was a significant step-change to higher survival after 1968, a significant linear decrease in survival during 1968–97, and minor, but significant, step-changes in 1979 and 1989. This suggests that arrowtooth flounder survival responds to decadal-scale variability. Recruitment success has been linked to improved transport to nurseries in El Niño years (Bailey and Picquelle 2002). Arrowtooth flounder length-at-ages 3–7 did not appear to change between the 1980s and the 1990s, although sample size in the 1990s was small (Fig. A3.15; Turnock *et al.* 2003).

Flathead sole (*Hippoglossoides elassodon*)

Flathead sole and Bering flounder (*Hippoglossoides robustus*) are similar and managed as a single stock (Wolotira *et al.* 1993). Flathead sole are distributed from northern California to Alaska. Adults are benthic, and overwinter near the continental shelf margin and migrate onto the outer shelf in spring. Age and size at maturity are unknown, but spawning occurs in spring near the continental margin (Walters and Wilderbuer 1997). Eggs are pelagic and larvae are planktonic, occupying shallow waters where they consume zooplankton. Flathead sole recruit to the fishery at age 3. Adult flathead sole consume primarily benthic invertebrates.

The time series of flathead sole in the GOA is short, beginning in 1981. Therefore, it is difficult to determine if flathead sole respond to decadal-scale climate variability. Their biomass increased from 1984–96, and has declined in recent years (Fig. A3.15). Median recruit per spawning biomass anomalies, indicative of survival, were higher prior to 1988 than in following years, however, the difference was insignificant (Fig. A3.15). Strong recruitment of flathead sole in the Bering Sea may be linked to wind direction that advects larvae to nearshore nursery areas during spring (Wilderbuer *et al.* 2002). However, it is unknown if a similar mechanism is responsible for flathead sole recruitment variability in the GOA.

Pacific halibut (*Hippoglossus stenolepis*)

Pacific halibut are distributed in coastal waters from California to the northern Bering Sea to Hokkaido, Japan. Halibut spawn off the continental shelf in December through February. They attain sizes of 96 cm at 50% maturity, corresponding to ages 10–12 (Clark *et al.* 1999). Eggs and larvae are pelagic for approximately 6 months, after which the juvenile halibut, at approximately 35 mm length, settle in shallow waters for 5 to 7 years. Halibut are highly migratory for up to 10 years of age, after which time they are less migratory. The maximum recorded age for a halibut is 55 (IPHC 1998). Female halibut grow faster than male halibut (beginning around age 6) and attain much larger sizes. The largest recorded size for a female is 2.67 m, while males rarely exceed 1.5 m. Recruitment to the fishery begins around age 6, with full recruitment occurring around age 8–10 for females and somewhat later for males. Stock assessment of Pacific halibut is based on an age- and sex-structured model, with length-specific gear selectivity for commercial and survey data, and fit-to-age compositions for both commercial and survey catches (Clark and Hare 2004).

The population dynamics of Pacific halibut appears to respond to decadal-scale climate variability. Halibut biomass in the GOA generally increased after the 1977 regime shift through to the 1990s (Fig. A3.15). In the central GOA (from southeast Alaska to the southwest end of Kodiak Island), halibut biomass peaked in 1994, and has since decreased to a biomass similar to that in 1989. Halibut biomass in southeast Alaska has continued to increase to the present, whereas halibut biomass in B.C. leveled off in 1999. Recruitment appears to have responded to the 1977 regime shift, since it also increased after 1977 in all areas of the GOA (Clark *et al.* 1999). Halibut length-at-age (growth) decreased significantly in the central GOA and decreased slightly in B.C. during this time (Fig. A3.15; Clark *et al.* 1999). The decrease in halibut growth may be density dependent, rather than due to the environment. Both intra- and inter-specific competition may be important since both halibut and other flatfish (arrowtooth flounder and flathead sole) increased in abundance during the same approximate time period (Clark *et al.* 1999).

Rockfish

Pacific ocean perch (*Sebastes alutus*)

Pacific ocean perch occupy depths from 40–650 m on the outer continental shelf and upper slope, from southern California to the GOA and Bering Sea (Allen and Smith 1988). Fifty percent of females are mature by the age of 7 years, or at approximately 29 cm in length. Pacific ocean perch are viviparous; they spawn in the fall and females release larvae in the spring (Love *et al.* 2002). Larvae are found in surface waters and juveniles settle in nearshore rocky habitats, then progressively move to deeper waters on the shelf. They are long-lived fish that are fully recruited at age 8 and can live as long as 98 years (Heifetz *et al.* 2002). Pacific ocean perch begin recruiting to the fishery at age 7 and are fully recruited to the fishery by age 16. They consume primarily zooplankton throughout their life cycle but also consume myctophids in increasing proportions as they grow larger (Yang 2003).

Pacific ocean perch catches in the GOA declined in the late 1960s to the early 1980s, apparently due to overfishing, and began to increase after 1996 (Fig. A3.16; Hanselman *et al.* 2003). Current stock assessments indicate that biomass decreased to the late 1970s, after which it increased through to the 1990s (Fig. A3.16). Survival of Pacific ocean perch appears to vary on a decadal scale and may be related to changes which occurred during regime shifts. Median recruit per spawning biomass anomalies, indicative of survival, were negative prior to the 1977 regime shift, positive in the 1980s after the 1977 shift, and negative in the 1990s after the 1989 shift (Fig. A3.16). High autocorrelation between catch and recruitment time series also suggests that rockfish in the GOA respond to long-term influences (Hollowed *et al.* 2001). Pacific ocean perch growth, however, does not appear to have changed during the time period of 1984–96; there was a decrease in length-at-age in 1999 relative to other years (Fig. A3.16).

Pacific ocean perch is the most important rockfish species by landed value in catch for British Columbia rockfish fisheries. In Canadian waters, the primary fisheries for Pacific ocean perch occur in three gullies in Queen Charlotte Sound: Goose Island Gully, Mitchell's Gully and Moresby Gully. Other smaller fisheries occur off the west coasts of Vancouver Island and Queen Charlotte Islands. Based on parasite analyses, these five fishery areas are considered to be discrete stocks (Leaman and Kabata 1987). Stock assessments indicate that population dynamics are similar between these stocks (Richards and Olsen 1996; Schnute *et al.* 2001). A catch-at-age model for the Goose Island Gully stock (Schnute *et al.* 2001) indicates a decline in biomass from 1994 through to 2000. This decline has been attributed to relatively low productivity (Fig. A3.16) for year classes since the late 1980s (Schnute *et al.* 2001). If a new regime in 1998 results in improved recruitment for Pacific ocean perch, the resulting age 7 fish will not begin to appear in the fishery until 2005.

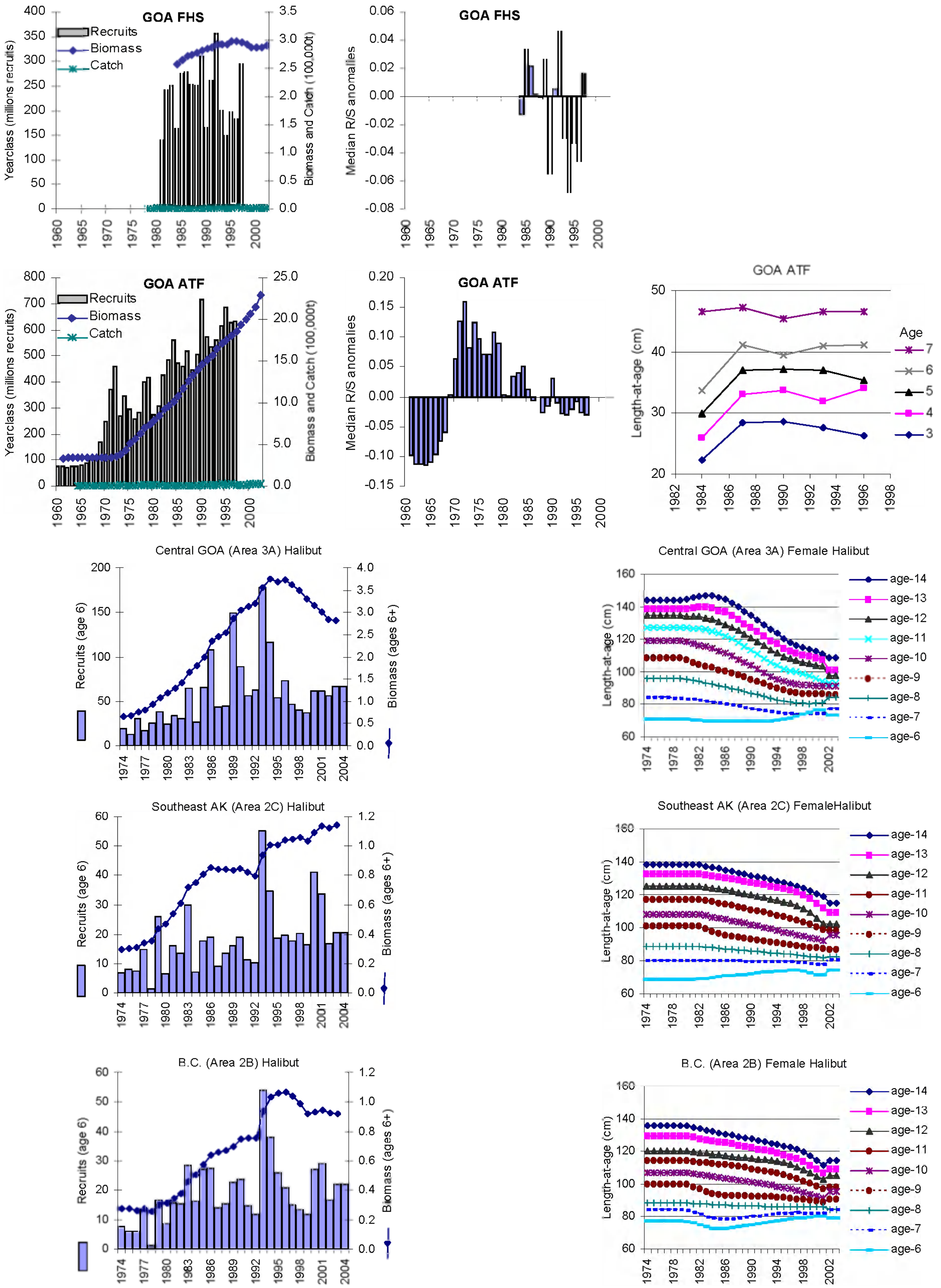


Fig. A3.15 Gulf of Alaska (GOA) flatfish: flathead sole (FHS), arrowtooth flounder (ATF), and Pacific halibut. Left panels: recruits (millions of fish), biomass and catch (100,000 tonnes), middle panels: median recruit per spawner biomass anomalies, right panels: length-at-age (cm). ATF mean length-at-age (cm) is for females sampled in the triennial surveys from 1984–96. Halibut length-at-age data are from the International Pacific Halibut Commission survey samples of females.

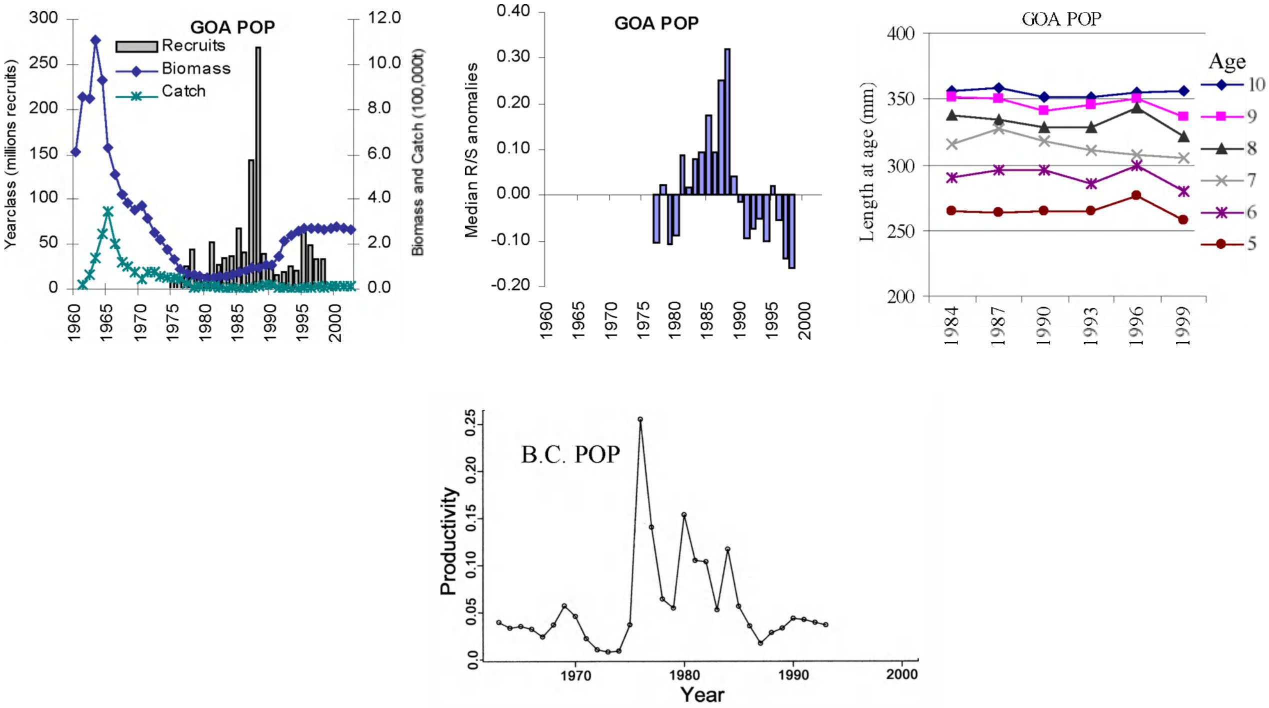


Fig. A3.16 Gulf of Alaska Pacific ocean perch (GOA POP). Left panel: recruits (millions of fish), biomass and catch (100,000 tonnes); middle panels: median recruit per spawner biomass anomalies and productivity; right panel: survey length-at-age (cm) (top three graphs). Goose Island Gully, B.C. Pacific ocean perch productivity was estimated from a catch-at-age model by year class (Schnute *et al.* 2001). Productivity approximates relative year class success lagged by approximately 8 years (age of recruitment).

Yellowtail rockfish (*Sebastes flavidus*)

Yellowtail rockfish are found throughout the Northeast Pacific Ocean, from southern California through to Admiralty Island, Alaska. The center of abundance is from Oregon to British Columbia. Commercial concentrations are fished from about 100–200 m depth (Lai *et al.* 2003). Yellowtail rockfish attain a maximum size of 70 cm. The oldest recorded age is 64 years. Generally, the size at 50% maturity for females is 37–45 cm (6–11 years old) and for males is 34–41 cm (5–9 years). Yellowtail rockfish begin recruiting to the fishery at age 4 (Lai *et al.* 2003).

In B.C., yellowtail rockfish comprise two stocks: (1) the southern boundary stock, which is off the west coast of Vancouver Island and is considered to be an extension of the northern Washington stock (California Current System), and (2) the coastal stock, which ranges from northwestern Vancouver Island to Alaska (Gulf of Alaska system). Data for the coastal stock are limited, but the population dynamics are considered to be similar to those observed for the southern boundary stock (Fisheries and Oceans Canada 1999). Poor recruitment in the early 1990s resulted in a severe decline in yellowtail biomass in the mid-1990s. This trend has continued through 2002.

A3.6 Higher Trophic Levels

Marine birds

Seabirds are distributed throughout the North Pacific and include albatrosses, shearwaters, petrels, cormorants, gulls, murres, murrelets, auklets, puffins, and sea ducks. The diet of seabirds varies spatially, temporally, and among species, but includes zooplankton, squid, and forage fish, such as juvenile Pacific herring, smelt, sandlance, walleye pollock, salmon, rockfish, and flatfish.

Populations of many marine birds in Prince William Sound declined between the early 1970s and the early 1990s (Piatt and Anderson 1996; Lance *et al.* 2001). This decline has been attributed to a shift in climate which affected the availability of forage fish to marine birds (Piatt and Anderson 1996; Agler *et al.* 1999). For example, in Prince William Sound, sandlance comprised the majority of seabird diets in the 1970s, whereas gadids were the main prey item in the late 1980s (Kuletz *et al.* 1997). No discernable shifts have been observed in marine bird populations after the regime shifts of 1989 or 1998. However, marine birds are long-lived and population-level responses may lag behind regime shifts. In general, throughout 2001 surface plankton feeding populations (fulmars and petrels) have been stable or increasing, diving piscivorous cormorants appear to have declined, Kittlitz' murrelets are declining throughout the GOA (Kuletz *et al.* 2003), and trends of other marine bird populations vary among areas and species (Dragoo *et al.* 2003). In the northern GOA, marine bird populations are generally declining, while those in southeast Alaska appear to be stable or increasing (Fitzgerald *et al.* 2003).

There is a trend toward earlier breeding times throughout the North Pacific (Dragoo *et al.* 2003). The trend in breeding time could be due to climate changes and timing of spring plankton blooms (Root *et al.* 2003; Dragoo *et al.* 2003). In 2001, marine bird hatch timing was average or early in most areas, except for Storm-petrels in southeast Alaska (Dragoo *et al.* 2003). Also in 2001, the reproductive success of most plankton feeders was generally average to below average, whereas the reproductive success of surface-feeding piscivores (kittiwakes) and diving piscivores (cormorants, murres, murrelets, rhinoceros auklets, and puffins) was average to above average (Dragoo *et al.* 2003).

Marine mammals

Steller sea lions (*Eumetopias jubatus*)

Steller sea lions are distributed from California to Alaska and Japan (Loughlin *et al.* 1984). There are two distinct populations: the endangered western stock (from east of Prince William Sound to Russia and Japan) and the threatened eastern stock (from southeast Alaska to California) (Sinclair 2003). The population assessment for Steller sea lions included a number of techniques in the past and is currently accomplished by aerial surveys of non-pups and on-land pup counts (Sinclair 2003).

The western stock declined by about 70% from 1960–89 (Loughlin *et al.* 1992). Since then, the western stock has declined about 3.9% per year, from 1991–2001 (Strick *et al.* 1997; Sease *et al.* 1999; Sease and Loughlin 1999; Sease and Gudmundson 2002). An increase of 5.5% over a large geographic area (eastern GOA to the central Aleutian Islands) was observed in the population in 2002. The western stock population size in 2002, however, is still smaller than it was in 1998 (Sinclair 2003).

Overall, the eastern stock abundance is stable or increasing slowly, although in central and southern California numbers have declined by up to 10% per year (NMFS 1995; Calkins *et al.* 1999; Ferrero *et al.* 2000; Angliss and Lodge 2002). The population in southeast Alaska increased by an average of 5.9% per year from 1979–97 (Sinclair 2003). Within the last decade, the abundance of Steller sea lions in southeast Alaska and British Columbia have increased annually by 2–6% (Sease *et al.* 2001).

Harbor seals (*Phoca vitulina*)

Harbor seals are distributed from California to the GOA, Bering Sea and Aleutian Islands. They are generally non-migratory, and feed in marine, estuarine, and freshwater (Scheffer and Slipp 1944). Currently the number of stocks in Alaska is a matter of huge debate, however, most scientists believe the previous number (three) is without merit. Recent genetic data and analyses are presently undergoing independent review. The overall harbor seal population in the GOA is much lower than it was in the 1970s and 1980s, but shows some signs of improvement. The number of harbor seals in southeast Alaska is at least steady, if not still increasing (D. Withrow, National Marine Mammal Laboratory, pers. comm.).

A3.7 Coherence in Gulf of Alaska Fish

Patterns of variation in recruitment and survival of marine and anadromous fishes show synchronicity among stocks, ranging from regional to broad geographical scales. Synchronous strong year classes occur in numerous groundfish populations from California to the Bering Sea (Hollowed and Wooster 1992), with fewer strong year classes in the GOA and Bering Sea than off the United States west coast (Hollowed and Wooster 1995). Strong year classes tend to occur more frequently, and recruitment tends to be larger during the positive phase of the PDO when the Aleutian Low is more intense, and SSTs are above average along the coast (Hollowed and Wooster 1995; Hare and Mantua 2000). Recruitment is moderately to strongly correlated among herring populations within the GOA, while herring in the Bering Sea are distinct from other Northeast Pacific populations (Williams and Quinn II 2000a). Similar to groundfish, recruitment of most herring populations in the GOA and Bering Sea, with the exception of B.C. herring, is enhanced during periods with warm coastal air and SSTs (Williams and Quinn II 2000b). Catches of most salmon species in Alaska tend to show synchronous long-term variations and have generally been high during the recent warm phase of the PDO (Hare and Francis 1995). In contrast, catches along the United States west coast have been low during the same period (Hare *et al.* 1999). Survival rates among different salmon stocks in the GOA and Bering Sea display synchrony at regional spatial scales on the order of hundreds of kilometers, but are mainly independent at larger spatial scales (Peterman *et al.* 1998; Pyper *et al.* 2001; Pyper *et al.* 2002). Survival rates of salmon stocks in Alaska are enhanced when coastal SSTs are warm, while survival rates of B.C. and Washington stocks tend to be reduced during warm periods (Mueter *et al.* 2002).

Cluster analysis and ordination techniques indicate that recruitment patterns of fish stocks in the GOA did not cluster into very cohesive groups (Table A3.1 and Fig. A3.17a), and were characterized by a more continuous distribution in ordination space (not shown). However, recruitment of Pacific ocean perch, thornyhead, and sockeye salmon was well correlated (average correlation: $\rho = 0.61$), while recruitment of halibut, chum salmon, herring and pollock was moderately correlated ($\rho = 0.23$). Clustering of survival rate series for GOA stocks resulted in at least two cohesive groups of species (Table A3.1 and Fig. A3.17b). The first group included three slope species (Pacific ocean perch, northern rockfish, and shortspine thornyhead) whose survival was relatively strongly correlated ($\rho = 0.51$). Another relatively cohesive group was comprised of the two gadids (Pacific cod and pollock), two flatfish species (Pacific halibut and arrowtooth flounder), and two salmon species (pink and chum salmon). The average correlation among survival rates of these species was 0.38, and their survival rates were uncorrelated or negatively correlated with those of the first group. In particular, arrowtooth flounder survival was negatively correlated with survival of all three species in the first group.

There is evidence for strong positive covariation among certain groups of stocks within the GOA. Most notably, survival rates of pollock and cod were strongly correlated within the GOA. If survival rates (residuals from stock-recruitment models) are indicative of environmental influences, strong covariation in survival is likely to reflect common environmental forcing. Hence a common forcing mechanism appears to drive the survival of cod and pollock within the GOA. Recruitment and survival rates for a number of species in the GOA were positively correlated with gadid recruitment and survival, suggesting common environmental forcing across these species.

A3.8 Combined Standardized Indices of Recruitment and Survival Rate

This section provides indices of overall recruitment and survival rate (adjusted for spawner abundance) across the major commercial groundfish species and across major pelagic stocks in the GOA. Time series of recruitment and spawning biomass for demersal fish stocks were obtained from 2002 North Pacific Fishery Management Council (NPFMC) Stock Assessment and Fishery Evaluation (SAFE) reports (2002a and 2002b). Recruitment and spawner abundances for salmon stocks, grouped by region, are based on Peterman *et al.* (1998), Pyper *et al.* (2001, 2002), and Mueter *et al.* (2002). Herring recruitment series are from Williams and Quinn II (2000b). Survival rate (SR) indices for each stock were computed as residuals from a Ricker spawner-recruit model. A Ricker model with first-order autocorrelated errors was fit to each spawner-recruit series using a generalized least-squares regression of log (recruits-per-spawner) on spawner abundance. Each time series of recruitment or SR indices was standardized to have a mean of 0 and a standard deviation of 1 (hence giving equal weight to each stock in the combined index). Recruitment or SR series were lined up by year class (ocean-entry year for salmon), resulting in matrices of recruitment (or SR indices) by year, with missing values at the beginning and end of many series. A combined standardized index of recruitment (CSI_R) and survival (CSI_{SR}) was then computed, following Boyd and Murray (2001). Briefly, all pairwise correlations between time series in a given data matrix (*e.g.*, recruitment series for all demersal stocks in the GOA) are computed based on those years with data for all stocks. The resulting correlation matrix is used to estimate annual means of standardized recruitment across all stocks. This approach allows estimation of annual average indices even for years that have missing data for some (or most) stocks. However, indices based on data for only a few stocks are highly uncertain. Uncertainty in the annual estimated means decreases if the component series are highly correlated (Boyd and Murray 2001).

Table A3.1 Stocks and stock groups used in analysis by species and region (GOA = Gulf of Alaska; PWS = Prince William Sound), range of year classes and number of years (NR) for which recruitment data were available and number of years (NSR) with both spawner (or spawning biomass) and recruitment data.

Scientific name	Common name	Region	Year classes	NR	NSR
Atheresthes stomias	arrowtooth flounder (ATF)	GOA	1958-1996	39	36
Hippoglossoides elassodon	flathead sole (FHS)	GOA	1981-1996	16	13
Hippoglossus stenolepis	Pacific halibut	GOA	1950-1995	46	46
Theragra chalcogramma	walleye pollock	GOA	1967-2000	34	32
Gadus macrocephalus	Pacific cod	GOA	1975-1999	25	22
Sebastes alutus	Pacific ocean perch (POP)	GOA	1959-1998	40	38
Sebastes polyspinis	northern rockfish (NRF)	GOA	1975-1994	20	18
Sebastolobus sp	Thornyheads	GOA	1962-1996	35	30
Oncorhynchus nerka	sockeye salmon	western GOA	1952-1995	44	44
Oncorhynchus nerka	sockeye salmon	central GOA	1972-1993	22	22
Oncorhynchus keta	Chum salmon	central GOA	1973-1993	21	21
Oncorhynchus gorbuscha	pink salmon	western GOA	1963-1996	34	34
Oncorhynchus gorbuscha	pink salmon	Kodiak	1963-1997	35	35
Oncorhynchus keta	Chum salmon	western GOA	1963-1993	31	31
Oncorhynchus gorbuscha	pink salmon	central GOA	1972-1997	26	26
Oncorhynchus keta	Chum salmon	PWS	1967-1994	28	28
Clupea pallasi	Pacific herring	GOA	1972-1993	22	0

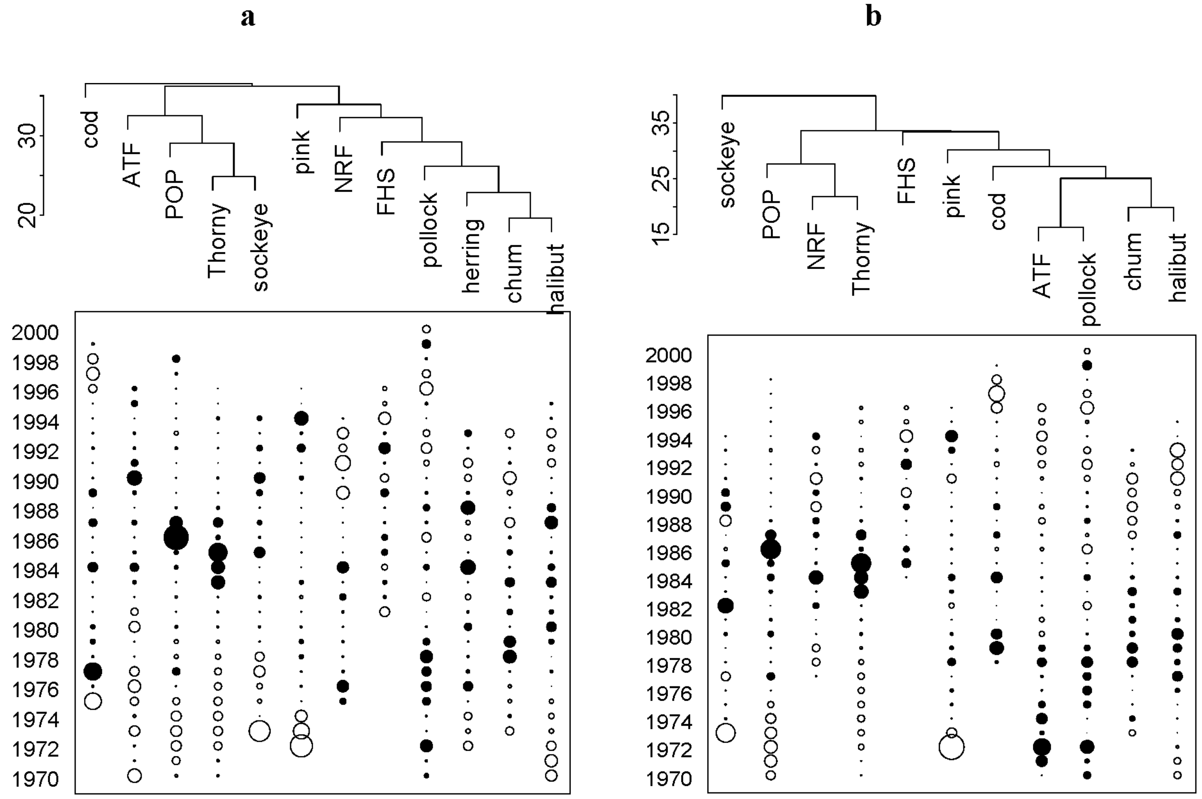
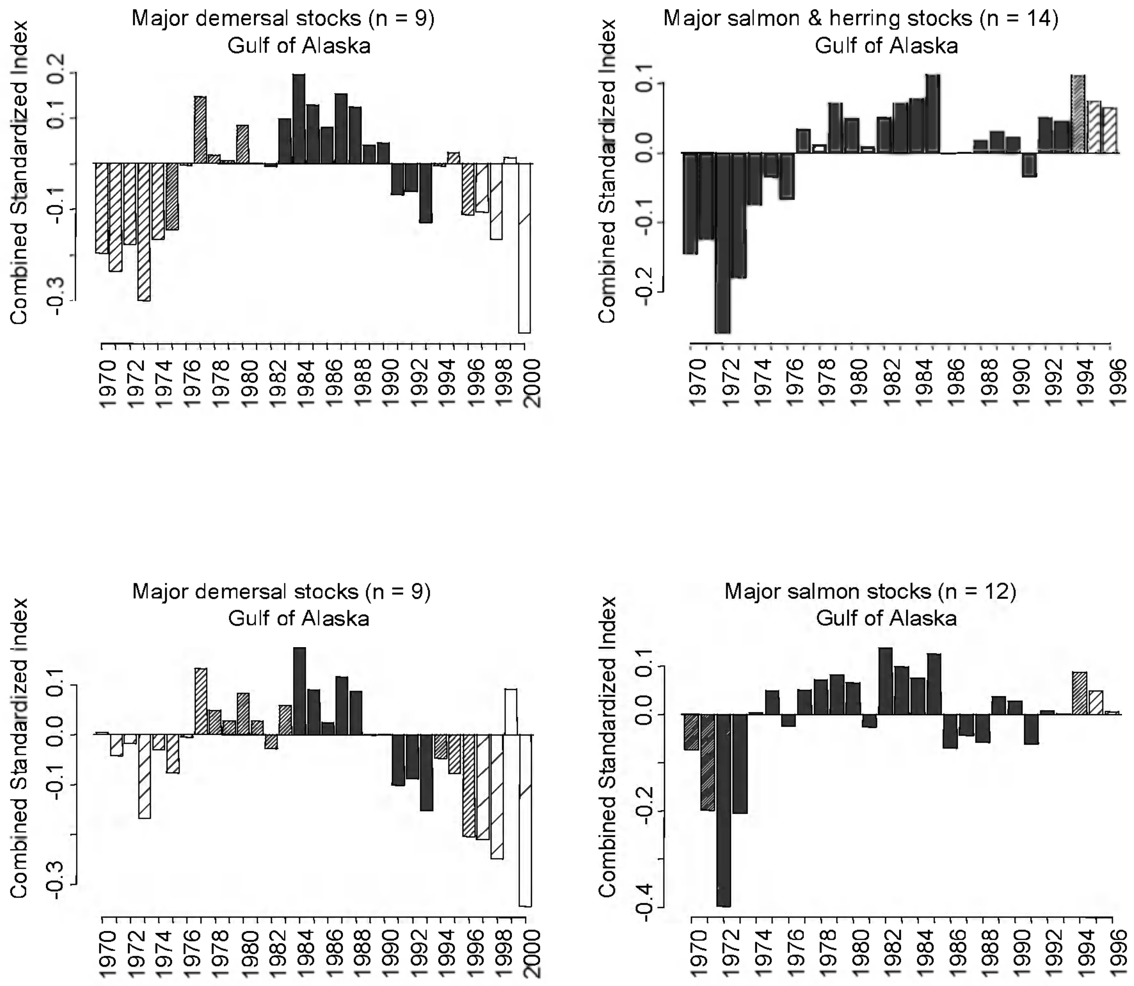


Fig. A3.17 Dendogram of Gulf of Alaska stocks based on hierarchical cluster analysis (average linkage clustering) of pairwise Manhatten distances among standardized (a) recruitment and (b) survival series, and standardized series of positive (filled circles) and negative (open circle) (a) recruitment and (b) survival anomalies for each species, 1970–2000. For species codes see Table A3.1.

The CSI_R suggests that recruitment of demersal species in the GOA have above-average recruitments from 1977–89, and below-average recruitments in the early 1970s and most of the 1990s (Fig. A3.17). These changes correspond to the regime shifts of 1977 and 1989–90. The CSI_R for pelagic stocks reflects a strong increase in recruitment around the 1977 ocean-entry year but no apparent change after 1989.

The CSI_SR is more variable but shows similar patterns (Fig. A3.18). A marked increase in survival is apparent in GOA groundfish and pelagic fishes in 1976 or 1977. Survival of demersal stocks was relatively low in the 1990s in the GOA, with the exception of 1999. However, the CSI is based on few stocks in the late 1990s.



Major demersal stocks (n = 9)
Gulf of Alaska

Major salmon & herring stocks (n = 14)
Gulf of Alaska

Major demersal stocks (n = 9)
Gulf of Alaska

Major salmon stocks (n = 12)
Gulf of Alaska

Fig. A3.18 Combined standardized index of recruitment (top two graphs) and survival rates (bottom two graphs; residuals from Ricker spawner-recruit model) across demersal (graphs on left) and pelagic (graphs on right) stocks or stock groups in the Gulf of Alaska. Solid bars represent years with data for all stocks. Lighter shading corresponds to years with more missing stocks. Series were truncated in 1970 and only years with data for at least two stocks were included (figure adapted from Mueter 2003).

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Appendix 4: Recent Ecosystem Changes in the Bering Sea and Aleutian Islands

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Summary

Bering Sea

The Bering Sea was subject to a change in the physical environment and an ecosystem response after 1977, a minor influence from shifts in Arctic atmospheric circulation in the early 1990s, and persistent warm conditions.

A major transformation, or regime shift, of the Bering Sea occurred in atmospheric conditions around 1977, changing from a predominantly cold Arctic climate to a warmer subarctic maritime climate as part of the Pacific Decadal Oscillation (PDO). This shift in physical forcing was accompanied by a major re-organization of the marine ecosystem on the Bering Sea shelf over the following decade. Fisheries surveys and model calculations show a shift in the importance of pollock to the ecosystem, to over 50% of the energy flow at mid-trophic levels in the 1980s from near 10% in the 1950s and 1960s (Trites et al. *1999), although biological information for the earlier period is limited and often speculative. Weather data, beginning in the 1910s, and proxy data (*e.g.*, tree rings) back to 1800 suggest that, except for a period in the 1930s, the Bering Sea was generally cool before 1977, with sufficient time for slow growing, long-lived, cold-adapted species to adjust. Thus the last few decades appear to be a transition period for the Bering Sea ecosystem.*

A comprehensive report (NAS 1996) attributes the ecosystem re-organization toward pollock to the combination of fishing and the 1976 regime shift. The report states that fishing of large whales increased the availability of planktonic prey, fishing on herring reduced competition, and fishing on flatfish reduced predation. The modeling study of Trites et al. *(1999) noted that the 400% increase in pollock biomass could not be explained solely by trophic interaction from these removals, and favored environmental shifts as an explanation. The model showed that, once established, pollock could become a major factor in structuring the ecosystem. While the physical shift after 1976 was abrupt and pollock biomass increased rapidly, the ecosystem adjustment probably took a prolonged period, as relative biomass shifted within the ecosystem. Biodiversity measures (richness and evenness) of groundfish, excluding pollock, decreased throughout the 1980s, and were stable in the 1990s (Hoff 2003). Jellyfish, which share a common trophic level with juvenile pollock and herring, may have played a role in the ecosystem adjustment as their biomass increased exponentially, beginning in the early 1980s, but have crashed recently in 2001–03.*

A specific Arctic influence on the Bering Sea began in the early 1990s, as a shift in polar vortex winds (the Arctic Oscillation – AO) reinforced the warm Bering Sea conditions, especially promoting an earlier timing of spring meltback of sea ice. Flatfish increased in the mid-1980s due to changes in larval advection (Wilderbuer et al. *2002), but the AO shift to weaker winds reduced these favorable conditions (Overland* et al. *1999).*

Warm conditions tend to favor pelagic over benthic components of the ecosystem (Hunt et al. *2002; Palmer 2003). Cold water species,* i.e.*, Greenland turbot, Arctic cod, snow crab and a cold water* *amphipod, are no longer found in abundance in the southeast Bering Sea, and the range of Pacific walrus is moving northward. While it is difficult to show direct causality, the timing of the reduction in marine mammals suggests some loss of their traditional Arctic habitat. Although ecological conditions appear mostly stable over the last decade, the warmest water column temperatures have occurred in 2001–03 on the southeast Bering Sea shelf, despite considerable year-to-year variability in the AO and PDO.*

We hypothesize that the overall climate change occurring in the Arctic, as indicated by warmer atmospheric and oceanic temperatures and loss of 15% of sea ice and tundra area over the previous two decades, is making the Bering Sea less sensitive to the intrinsic climate variability of the North Pacific. Indeed, when the waters off the west coast of the continental United States shifted to cooler conditions after 1998, the subarctic did not change (Victoria pattern), in contrast to three earlier PDO shifts in the twentieth century. Thus we project that the Bering Sea will more likely continue on its current warm trajectory, with biomes transitioning northward, allowing pollock a larger domain at the expense of cold- and ice-adapted species (Fig. A4.1), rather than transitioning back to a cold regime. Bering Sea indicators (climate and fisheries data) should be watched closely over the next 5 years to confirm or reject this hypothesis.

Aleutian Islands

Climatic conditions vary between the east and west Aleutian Islands around 170°W: to the west there is a long-term cooling trend in winter, while to the east, conditions change with the PDO. This is also near the first major pass between the Pacific and the Bering Sea for currents coming from the east. Biological conditions in the Aleutian Islands have changed since the 1980s, and it is too soon to discern if there was a change associated with the 1998 shift. Pollock and Atka mackerel do not appear to vary on a decadal-scale, however, the biomass of pollock appears to be higher than it was in the 1980s. Pacific ocean perch population dynamics vary on a decadal-scale. For example, Pacific ocean perch survival changed at approximate times of regime shifts, 1975 and 1989. There is not enough information on the early life history of Pacific ocean perch to define a mechanism for the observed variations.

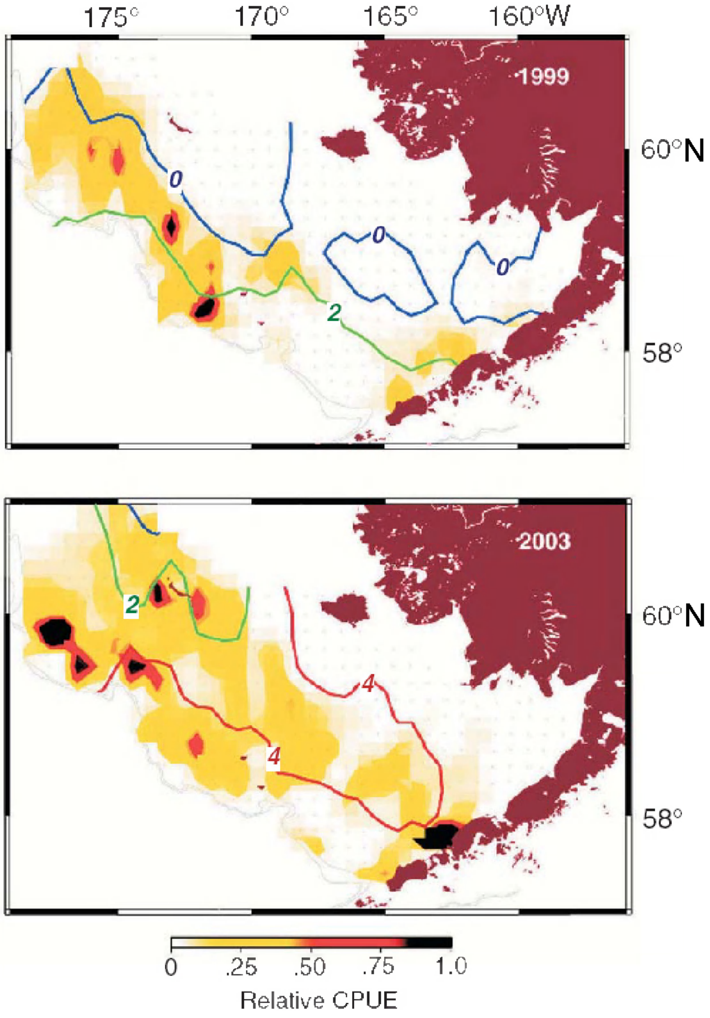

Fig. A4.1 Bottom temperatures and walleye pollock catch per unit effort (tons/hectare) observed during the 1999 and 2003 National Marine Fisheries Service bottom trawl survey (after Ianelli *In* SAFE Report 2003). Recent years have been mostly warm with pollock extending over the shelf; 1999, a cold year, is the major exception.

A4.1 Introduction

In this Section we report on recent changes in the Bering Sea and Aleutian Islands ecosystems. Data on air and seawater temperatures were available for interpretation for the Bering Sea, and oceanic flow for the Aleutian Islands. We report on nutrient levels, phytoplankton composition and zooplankton productivity for the Bering Sea. Information on Bering Sea invertebrates, such as jellyfish and crabs, is provided. We present catch data for Bristol Bay sockeye salmon, and where available, recruitment and biomass estimates and growth data for the semi-pelagic Atka mackerel, gadids (walleye pollock and Pacific cod), flatfish (yellowfin sole, Greenland turbot, arrowtooth flounder, flathead sole, and rock sole), and the rockfish, Pacific ocean perch. Where available, these data are presented separately for each ecosystem, however, some fish stocks are assessed as a single unit for these two combined systems. Also available are data on fur seals in the Pribolf Islands.

A4.2 Bering Sea Environmental Variables and Physical Oceanography

There is an extended climate record for the Bering Sea shelf based on air temperature from St. Paul Island (Fig. A4.2, left panel) and from sea-ice observations. Monthly temperature anomalies, beginning in 1950, are shown relative to a 1961–90 base period. The primary pattern is a sharp transition, following 1976, from cold (blue) anomalies (-6°) for February–September, followed by warm anomalies (+4°) from January through April. After 1995, spring comes early (warm April) although this is anticipated in earlier years: 1989, 1990, 1993. Starting in 2000, warm anomalies extend from February through November. Ice concentration (percent areal coverage) is shown for a 1° rectangle (57°–58°N). The 1976 shift is clearly seen (Fig. A4.2, right panel); the second dramatic reduction is the almost complete lack of sea ice at this latitude after 2000. Nine years of depth-averaged water temperatures from a mooring located at a depth of 70 m in the southeast Bering Sea (M2) show temperatures warmer by approximately 1.5°C for summers of 1998 and 2001–03 compared to earlier in the record (Fig. A4. 3).

A4.3 Bering Sea Lower Trophic Levels

The total production of phytoplankton is difficult to estimate because of its variability in time and space. Observations of nutrients over the previous two decades show that a steady amount is available for production, and a steady drawdown by phytoplankton for the years following the 1976 regime shift. What has appeared to change is the timing and species composition due to the variability of the ice edge. With greater ice extents, the bloom occurred in early spring, associated with ocean stratification due to ice melt. More commonly since the 1980s, is that the blooms are not tied spatially to the location of the ice, and production begins in May from stratification due to solar insolation. In the last decade, there have been only 3 years (1995, 1997 and 1999) over the southeastern shelf that have had ice associated blooms. Particularly since 2000, the ice extent has been relatively minimal, resulting in later spring phytoplankton blooms.

In addition to the typical phytoplankton bloom, since 1997, the Bering Sea has had a series of large coccolithophorid blooms. The role these blooms play in the food web is not well understood, but they have occurred in all but two of eight summers and are thought to be associated with low nutrient levels.

It is hypothesized that during early ice edge blooms there is a miss-match with the developing zooplankton, so primary production sinks to the benthic community, while later blooms favor retention in the pelagic system (Hunt and Stabeno 2002). The inverse relation of the growth of pollock and yellow fin sole suggests an inverse relation between benthic and pelagic productivity on a yearly basis (Palmer 2003). In the southeastern Bering Sea, physics and plankton production interact to determine prey levels for larval walleye pollock. Some zooplankton are predators, however, and these have the potential to influence the recruitment of commercially harvested species by preying on the larvae or other early life history stages (*e.g.*, euphausiids, amphipods, and jellyfish preying on the larvae and juveniles of pollock).

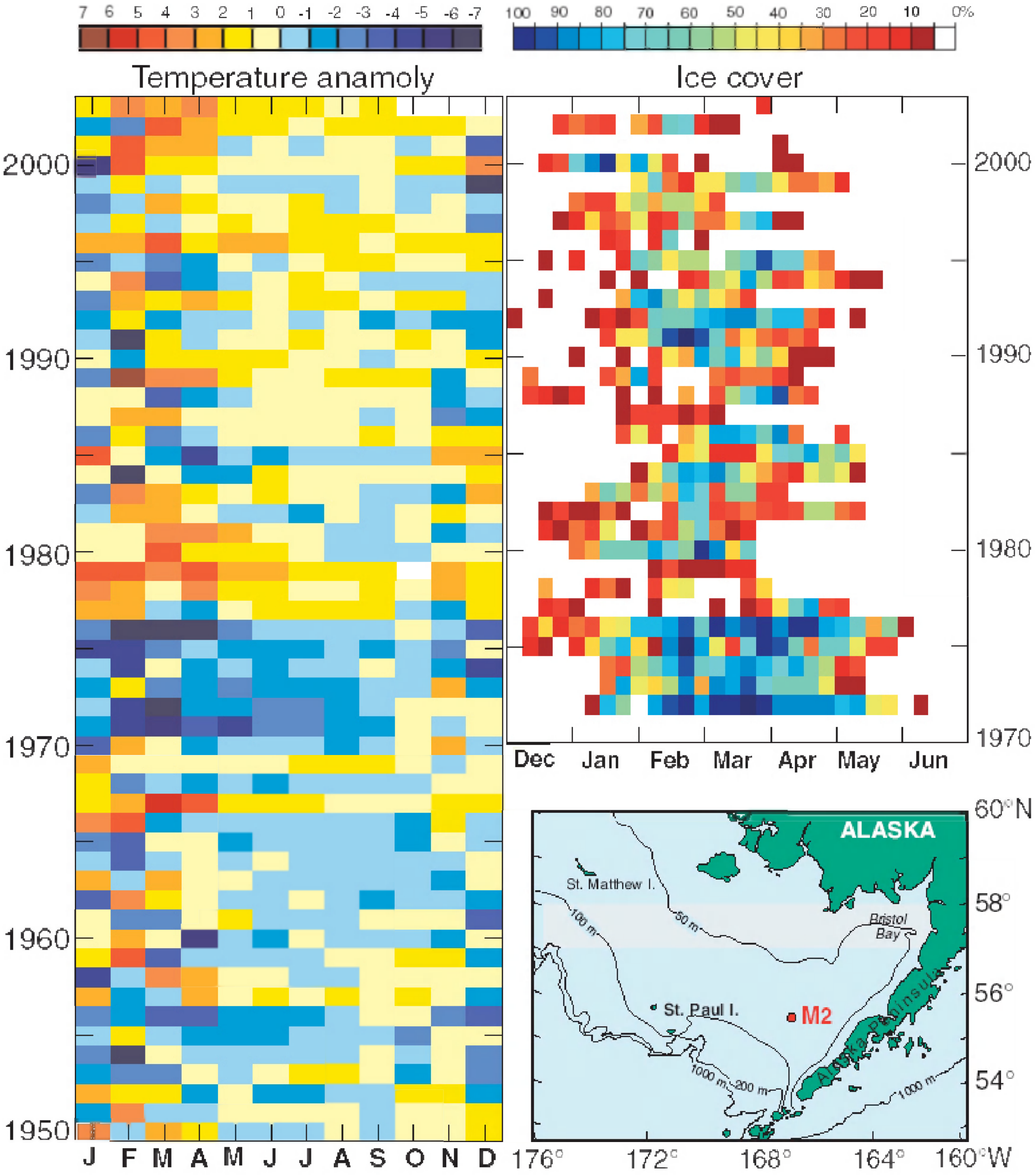

Fig. A4.2 Left panel: Monthly air temperature anomalies at St. Paul Island as a function of month and year. Note the shift to warmer temperatures both after 1976, and for 2001–03. Top right panel: Concentration (% cover) of sea ice over the southeastern Bering Sea between latitudes 57°N and 58°N. Note the near absence of sea ice at this latitude since 2001. Lower right panel: Location chart.

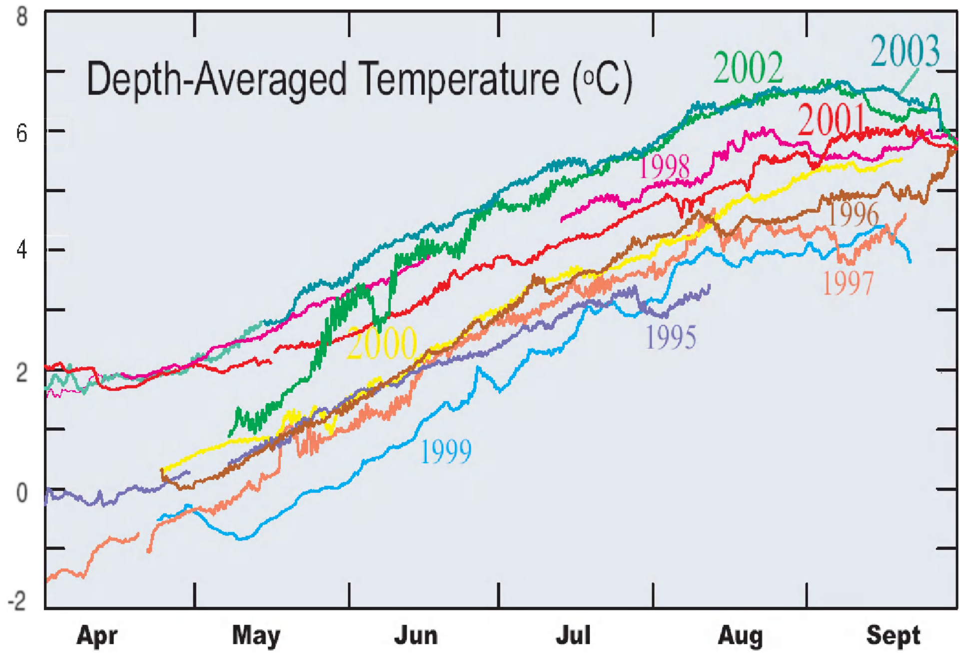

Fig. A4.3 The evolution of depth-averaged sea temperatures from an oceanography mooring at site M2 (56.8°N, 164°W) for spring and summer in different years. From 2001–03, there were consistently warm temperatures compared to 9 years of record. See Figure A4.2 for location map.

Based on limited sampling of zooplankton from 1954–99 from the Japanese training vessel *Oshoru Maru*, there has been no apparent long-term trend in zooplankton biomass on the Bering Sea shelf (Sugimoto and Tadokoro 1997; Napp *et al.* 2002). Research evidence does suggest, however, that spring biomass of shelf copepods is several times higher in warm years (Coyle and Pinchuk 2002). Temperature also appears to be a more important factor for zooplankton variability than phytoplankton availability.

A4.4 Bering Sea Invertebrates

Jellyfish

The increase in abundance of jellyfish (Fig. A4.4) that began in the 1980s, caught as bycatch in the annual Bering Sea trawl survey (Brodeur *et al.* 1999), did not continue in 2001–03. The 2001–03 levels were close to those seen in the 1980s.

Benthic invertebrates

The catch per unit effort (CPUE) of invertebrates (Fig. A4.5) in selected bottom trawl surveys for the 1980s–90s (Conners *et al.* 2002) shows a decrease from 1975–77 values. While this decline is made up of a decrease in crabs, presumably due to fishing, and an increase in other species, one cannot say that there is an overall increase in benthic invertebrate productivity in recent decades.

Crabs

Crabs in the Bering Sea share similar life histories. After mating, female crabs carry eggs for approximately 1 year before they hatch, generally in April. Juveniles are pelagic for approximately 2–3 months before settling to their preferred benthic habitat. Juveniles molt several times each year, whereas adults molt once annually or sometimes less frequently.

A trawl survey is conducted annually in the eastern Bering Sea to determine the distribution and abundance of crab and groundfish. Precision of crab abundance indices is low because crabs have a patchy distribution, females often prefer rocky, untrawlable areas, and small crabs are not well represented in the samples. Crab abundance is generally low (Fig. A4.6), and of the seven crab fisheries, two are open, five are closed, and four are considered overfished. Rebuilding plans have been developed, or are under development, for the overfished stocks. Total biomass of seven crab groups was high in 1980 and 1990, but has since decreased and remained low to 2002. The trends in crab biomass have been attributed to fishing pressure, competition, predation (predators, such as Pacific cod (*Gadus macrocephalus*), pollock (*Theragra chalcogramma*), and arrowtooth flounder (*Atheresthes stomias*), increased in the 1980s), and environmental variables (Loher *et al.* 1998).

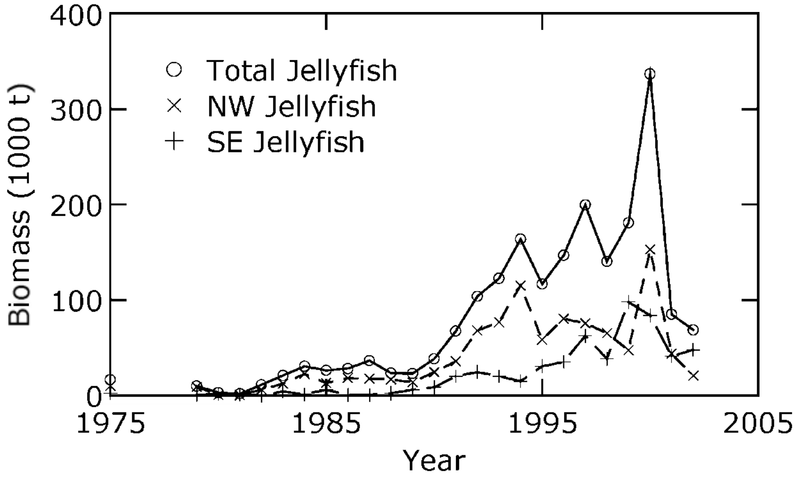

Fig. A4.4 Index of large medusae biomass during the National Marine Fisheries Service (NMFS) bottom trawl survey in the Bering Sea.

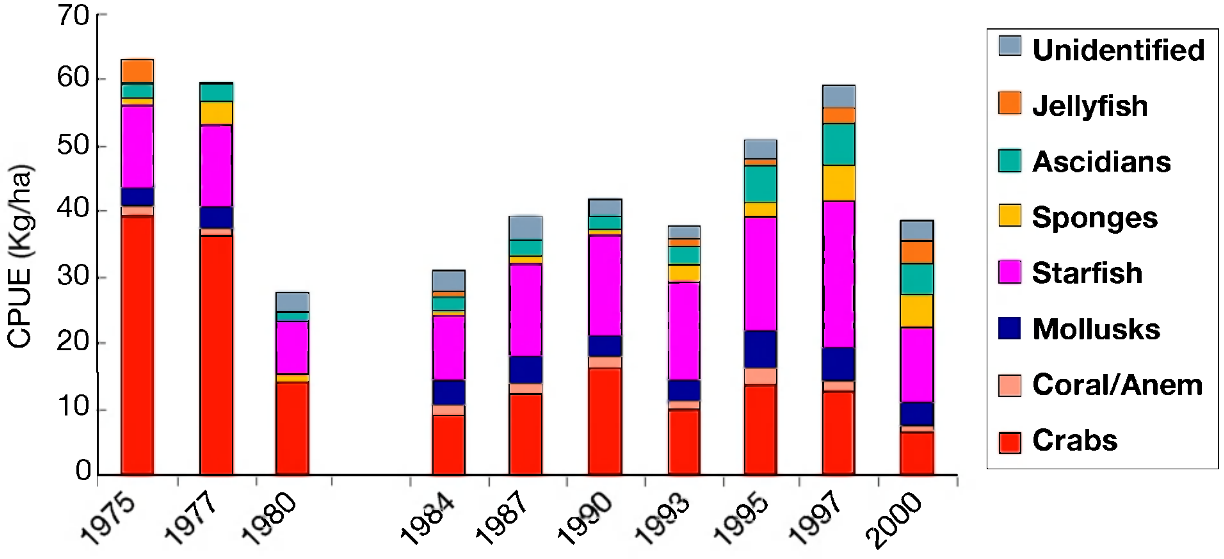

Fig. A4.5 Composition of invertebrate catch in selected bottom trawl surveys.

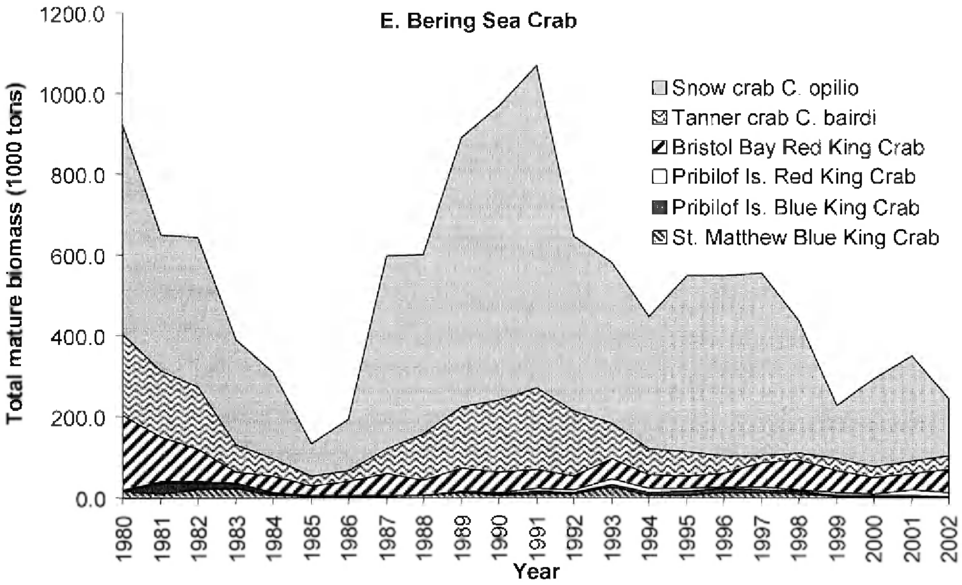

Fig. A4.6 Total mature biomass of eastern Bering Sea crab populations.

Red king crab (*Paralithodes camtschaticus*)

Red king crabs are distributed widely in the Bering Sea/Aleutian Islands and the Gulf of Alaska, and occupy shelf waters up to 250 m depth. Fifty percent of crabs mature at 120 mm (males) and 90 mm (females).

Bristol Bay red king crabs move to shallow water to spawn from January to June. Females carry eggs for 11 months, eggs hatch in April, and larvae are pelagic for 2 to 3 months before settling to shallow, high relief habitat, and gradually migrating to deeper water.

The mature biomass of Bristol Bay red king crab was highest in 1980, then declined, and has remained relatively low since 1983 (Fig. A4.6) (Stevens *et al.* 2002). The total mature biomass of crabs has remained above 50% of the maximum sustainable yield (MSY) biomass and, therefore, the stock is not considered overfished. The abundance of both legal and pre-recruit males increased considerably in 2002, whereas the number of mature females decreased slightly (Stevens *et al.* 2002).

Mature biomass of Pribilof Island red king crab (Fig. A4.6) was well below 50% MSY in the 1980s (Stevens *et al.* 2002). Since 1991, the mature biomass has been higher than the 50% MSY, with peaks in 1993 and 2001, and is not considered overfished. No change in abundance of large male crabs was observed, and estimates of both pre-recruit males and mature females are too imprecise to detect trends. The fishery for Pribilof Island red king crab is closed because there is no apparent recruitment to the population, and due to concerns of unacceptable levels of incidental catch of blue king crab (Stevens *et al.* 2002).

Blue king crab (*Paralithodes platypus*)

Blue king crab populations occupy areas around the Pribilof Islands, St. Matthew Island, and St. Lawrence Island, as well as other areas in the North Pacific, from southeast Alaska to Japan. Fifty percent maturity occurs when males reach 108 mm and females reach 96 mm. Females have a biennial ovarian cycle, eggs are retained for 14 months before they hatch, and larvae are pelagic for 3–4 months.

Blue king crab in the Pribilof Islands area are considered overfished since the reproductive population estimate (Fig. A4.6) fell below the 50% MSY in 2002 (Stevens *et al.* 2002). The abundance of legal and pre-recruit males and mature females decreased in 2002. Little or no recruitment is apparent in the population, which has been at low levels since the early 1980s (Stevens *et al.* 2002).

Blue king crab in the area of St. Matthew Island are also considered overfished (Stevens *et al.* 2002). The population has declined steeply since 1998 (Fig. A4.6). Both legal and pre-recruit male abundance decreased. Indices of female crab abundance are affected by their preference for inshore, rocky, and untrawlable habitat (Stevens *et al.* 2002).

Tanner crab (*Chionoecetes bairdi*)

Tanner crabs occupy shelf waters from Oregon to Kamchatka, including the eastern Bering Sea. Fifty percent of crabs mature when they are 110–115 mm (males) and 80–110 mm (females) (Tyler and Kruse 1997). Females carry eggs for about 1 year after they have been fertilized, and eggs hatch in the spring. Larvae are pelagic for the summer before settling to their preferred benthic habitat.

The eastern Bering Sea tanner crab population (Fig. A4.6) was high in the early 1980s and from 1988–92 (Stevens *et al.* 2002). The population has been low since then, and currently continues to decrease due to low recruitment. The mature biomass is below 50% MSY, therefore the stock is considered overfished, and the fishery has been closed since 1996 (Stevens *et al.* 2002).

Snow crab (*Chionoecetes opilio*)

The mature biomass of eastern Bering Sea snow crab (Fig. A4.6) was moderate to high in the early 1980s and from 1987–97 (Stevens *et al.* 2002). Recently, the biomass has declined and is currently below 50% MSY, and is considered overfished. The abundance of mature females has declined and there has been a lack of recruitment to the female reproductive stock, substantiated by the increasing prevalence of old shelled crab. Small male and female crabs are also decreasing in abundance (Stevens *et al.* 2002).

Hair crab (*Erimacrus isenbeckii*)

The population of hair crabs in all districts has been declining for several years, and the fishery has been closed since 2000 (Stevens *et al.* 2002). Recruitment trends are unclear due to poor representation of small crabs in survey tows.

A4.5 Bering Sea Fishes

Pelagics

Sockeye salmon (*Oncorhynchus nerka*)

Sockeye salmon are distributed throughout the North Pacific, from California to the Bering and Chukchi Seas to northern Hokkaido. Bristol Bay, in the southeast Bering Sea, is a major spawning area of sockeye salmon. Spawning occurs in late summer and fall in stream gravel. Eggs hatch after 5–8 months, and fry swim downstream to lakes where they spend one or more years growing before migrating to the ocean. Sockeye salmon spend 1–4 years in the ocean before returning to their natal stream to spawn.

Catch and escapement of Bristol Bay sockeye salmon are correlated and the sum provides a reasonable index of salmon abundance. Abundance of sockeye salmon in all areas increased from the mid-1970s to the 1980s (Fig. A4.7). Since then, the increased abundance has been stable and at high levels. Recruitment for most Bristol Bay sockeye salmon stocks, other than Kvichak, has been moderate to strong in the last decade. Abundance was lower after 1996, however, the levels of recruitment observed for weak stocks during the recent period are not unprecedented. Similar levels of returns per spawner were observed for Bristol Bay sockeye during the 1960s to early 1970s. Beginning with the 1973 brood year (>1979 return year) of Bristol Bay sockeye salmon, the number of returning adults produced from each spawner showed a dramatic increase across most stocks (Fair 2003). However, poor returns in 1996–98 suggested a return to a level of productivity similar to the pre-1978 period. Fish from the 1996–98 return years reared in the ocean when temperatures were above average, whereas cooler than average ocean temperatures characterized the pre-1978 period. Recent ocean temperatures and returns to Bristol Bay in 1999 and 2000 suggest that returns in 2003 may be more characteristic of the 1978–95 period (Fair 2003).

Gadids

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock are semi-pelagic species and distributed throughout temperate and subarctic waters of the North Pacific (Wolotira *et al.* 1993). They represent the dominant biomass of groundfish in the eastern Bering Sea. There are three stocks in the Bering Sea, the most abundant of which is the eastern Bering Sea stock (Ianelli *et al.* 2003a,b). This stock is found on the shelf from Unimak Pass to the United States–Russia Convention line. Pollock overwinter along the outer shelf and migrate to shallow waters to spawn in early spring in large concentrations north of Unimak Pass (Witherell 2000; Ianelli *et al.* 2003a). Walleye pollock in the Aleutian Islands region spawn in February to April (Barbeaux *et al.* 2003). When the cold pool is reduced or absent from the shelf, as it was in 2000–03, pollock distribution expands further onto the shelf (Ianelli *et al.* 2003a). Fifty percent of females mature at age 4, or at about 40 cm length. Juvenile pollock are pelagic zooplanktivores and are prey to many fish (Carlson 1995). As pollock age, they become increasingly demersal and piscivorous, and can be cannibalistic.

Recruit per spawning biomass anomalies, an indicator of survival, were generally positive from 1964–82, and negative from 1983–2002 (Fig. A4.8). Non-parametric Kruskal and Wallis tests and change-point analyses indicate that pollock survival did not respond to identified regime shifts (for example, 1977, 1989, or 1997–98), but did show some bi-decadal variation, with a linearly decreasing trend from 1964–2002. Average recruit per spawner anomalies were significantly higher prior to 1977 than after 1998. The major increase in biomass of walleye pollock is illustrated in Figure A4.9, following strong recruitment in the late 1970s. Except for 1991–92, biomass has been rather stable at about 4 million tonnes.

Increased survival has been linked to warmer temperatures (Quinn and Niebauer 1995; Hunt *et al.* 2002; Hunt and Stabeno 2002). The "Oscillating Control Hypothesis" proposes that during warm regimes, the ice retreats early and warmer waters lead to increased zooplankton production resulting in increased recruitment and survival of pollock (Hunt *et al.* 2002). Furthermore, after several warm years and high recruitment, piscivorous fish abundance would increase and exert top-down control on forage fish, including juvenile pollock. Negative average survival anomalies after 1998 and continued high relative pollock biomass may provide evidence of this top-down control (Fig. A4.8).

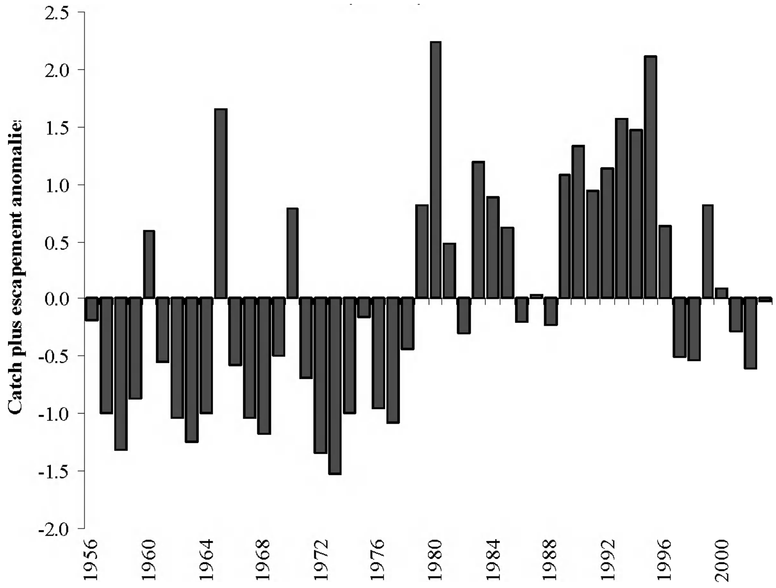

Fig. A4.7 Bristol Bay sockeye salmon catch plus escapement anomalies.

There is an apparent 10-year periodic trend in pollock lengths at ages 7 and 8 years that is inversely related to abundance (Fig. A4.8), indicating that density-dependent processes may be important (Ianelli *et al.* 2003a). Lengths-at-ages 7 and 8 years decreased slightly during 1983–89, and increased in the early 1990s. The length at ages 4, 5, and 6 generally remained stable from 1982–96. The 1992 year class (dashed line in Figure A4.8), which had anomalously high recruitment, exhibited anomalously lower mean-lengths-at-age compared to adjacent ages from 1996–2000.

Pacific cod (*Gadus macrocephalus*)

Pacific cod can be found at all depths up to 500 m on the upper slope and continental shelf of the North Pacific, from California to Norton Sound (Bakkala 1984). Pacific cod are demersal fish which spend the winter and spring in deep waters, and migrate to shallower waters in the summer. Spawning occurs in late winter, and 50% of females mature at about 6.7 years of age or 67 cm (Thompson and Dorn 2003). Eggs sink to the bottom where they are adhesive. Juvenile Pacific cod consume invertebrates, and become piscivorous as they get larger.

Pacific cod biomass peaked during 1985–88, and declined continually to 2001 (Fig. A4.8), with an upward trend in 2002 (Thompson and Dorn 2003). Median recruit per spawning biomass anomalies of Pacific cod, an index of survival, were generally positive from 1977–82, negative or neutral from 1983–95, and positive from 1996–2002 (Fig. A4.8). There was an insignificant step-change in Pacific cod survival after 1982, and there were no shifts associated with the 1989, or 1997/98 regime shifts. The shift in survival in 1982 was associated with an increase in biomass but it is unknown if this is in response to the 1977 regime shift. Interestingly, Pacific cod and walleye pollock have similar trends in survival, suggesting they are influenced by similar large-scale processes.

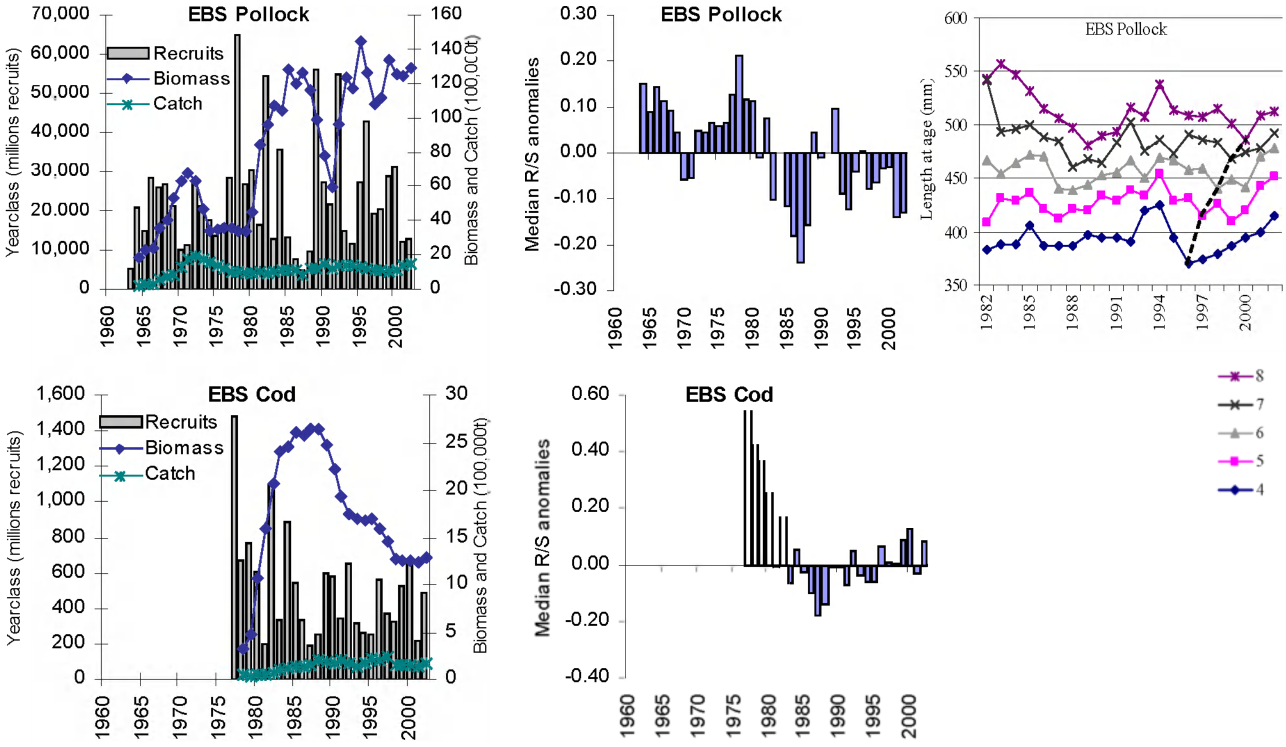

Fig. A4.8 Eastern Bering Sea (EBS) gadid (walleye pollock and Pacific cod) abundance estimates. Left panels: recruits (millions of fish), catch and biomass (100,000 t); middle panels: median recruit per spawning biomass anomalies; right panel: length-at-age.

Flatfish

Yellowfin sole (*Limanda aspera*)

Yellowfin sole are found in the North Pacific from British Columbia to the Chukchi Sea (Hart 1973). They are one of the most abundant flatfish in the Bering Sea and represent the largest flatfish fishery in U.S. waters (Wilderbuer and Nichol 2003). Overwintering occurs near the shelf-slope break, and summer feeding and spawning occur in shallow nearshore waters (Wilderbuer *et al.* 1992). Fifty percent of females mature at the age of 10.5 years, or 29 cm length (Nichol 1994). The pelagic eggs, larvae, and juveniles are found in shallow areas. Benthic invertebrates comprise the diet of yellowfin sole (Livingston 1993).

Yellowfin sole had an increase in spawning biomass following the 1976 regime shift, a stable population from 1985–95, and a decrease similar to other flatfish after this time. Median recruit per spawning biomass anomalies, an index of survival, were positive from 1964–81 and negative from 1982–98 (Fig. A4.9). Change-point analyses indicate that there has been a significant linear decrease in survival from 1964 to 1998 due to the relatively high biomass, and a lower level of recruitment after 1982 relative to previous years. With the exception of the 1987, 1988, and 1991 year classes, recruitment has been below average since 1983, resulting in a decline in the population (Fig. A4.9), although biomass is still high relative to the 1960s (Wilderbuer and Nichol 2003). The structure of recruitment and biomass until the previous decade for yellowfin sole is different from other flatfishes discussed below.

The lengths of 4- to 14-year-old yellowfin sole varied little from 1987–2002 (Fig. A4.9; Wilderbuer and Nichol 2003). One of the largest differences in weight-at-age was between a cold year (1999) and a warm year (2001), which may indicate temperature-related metabolic differences rather than a difference in the population growth (Wilderbuer and Nichol 2003). Growth differences have been attributed to interspecific competition rather than environmental variables (Williams 2003).

Greenland turbot (*Reinhardtius hippoglossoides*)

Greenland turbot can be found from southern California to Alaska, but primarily in the eastern Bering Sea and Aleutian Islands (Hubbs and Wilimovsky 1964). These demersal or semi-pelagic fish occupy slope waters and migrate to shallower waters in the spring. They spawn in winter on the slope, larvae are planktonic for 2–3 months, and juveniles, up to the age of 4, are found on the continental shelf (Bulatov 1983). Fifty percent of females mature at the age of 9 years, or 60 cm in length. Greenland turbot flourished in the cold years of 1971–76, but declined steadily, since the regime shift, to a level of 15% (up to 1999) of its peak biomass values. There appears to be long-term variability in the population of Greenland turbot biomass, recruitment, and survival (Fig. A4.9). Recruitment has followed a trend similar to the biomass. Median recruit per spawning biomass anomalies, an index of survival, were positive from 1972–79, and generally negative after 1979, with the exception of 6 years (Fig. A4.9). The cause of the decreased recruitment may be due to predation by other groundfish, which increased in abundance in the 1980s, or due to differences in ocean conditions owing to the 1977 regime shift (Ianelli *et al.* 2003b).

Arrowtooth flounder (*Atheresthes stomias*)

Arrowtooth flounder are distributed from California to the Bering Sea, and can be found on the continental shelf at the ages of 1 to 4, after which they are found at depths of 100–200 m in shelf and slope waters (Allen and Smith 1988; Martin and Clausen 1995). Spawning may occur between September and March, and 50% of females off the coast of Washington are mature at the age of 5, or 42 cm in length (Zimmermann 1997; Wilderbuer and Sample 2003). Larvae are planktonic for 2–3 months, and juveniles occupy shallow waters where they initially consume zooplankton and, as they grow, begin to consume benthic invertebrates (Wilderbuer and Sample 2003). After arrowtooth flounder exceed 30 cm in length, they are primarily piscivorous, with their main prey consisting of walleye pollock (Wilderbuer and Sample 2003).

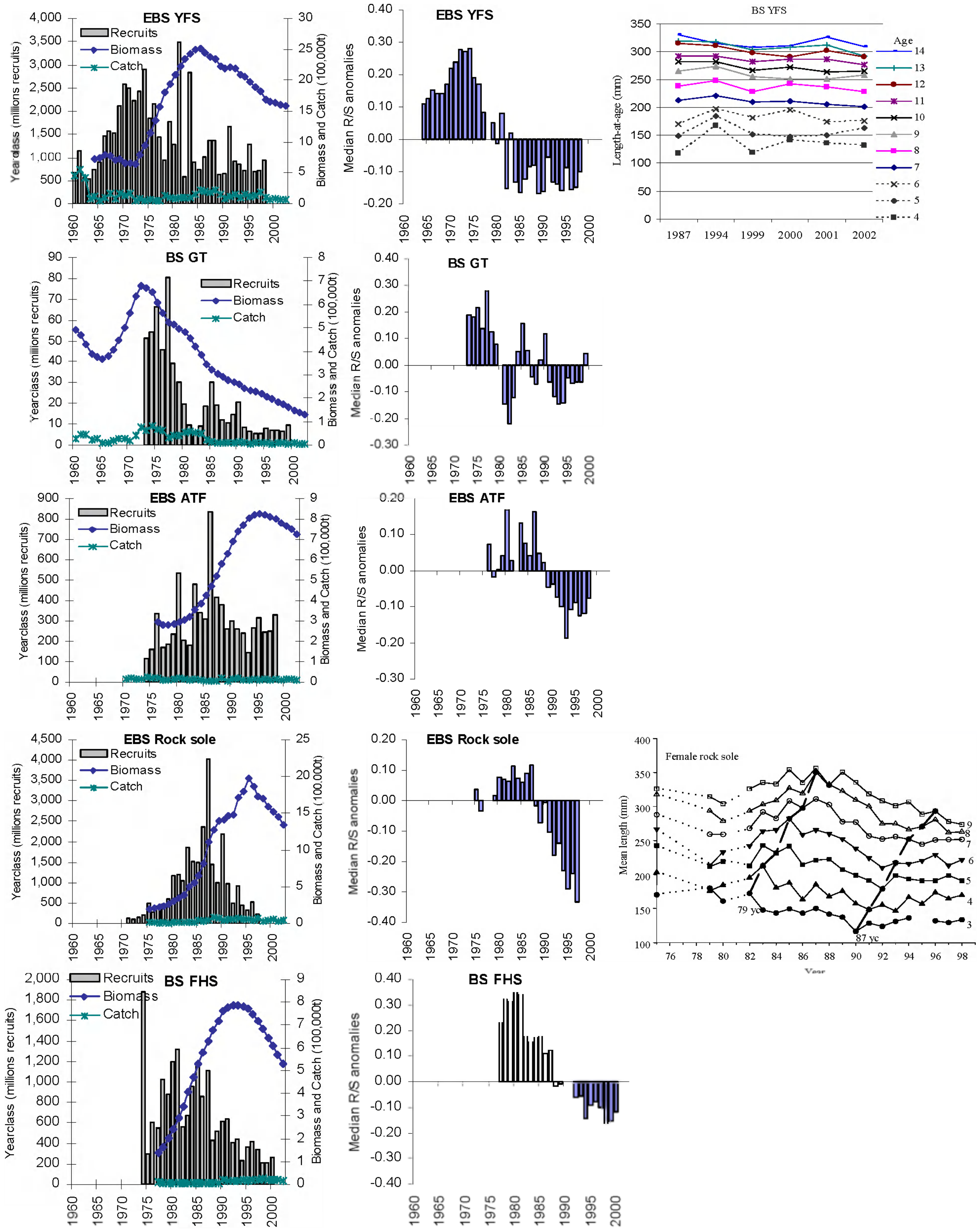

Fig. A4.9 Bering Sea (BS) flatfish abundance estimates. Left panels: recruits (millions of fish) and biomass (100,000 tonnes); middle panels: median recruit per spawning biomass anomalies; right panels: length-at-age. Yellowfin sole length-at-age graph was adapted from Wilderbuer and Nichol (2003). Rock sole length-at-age graph was adapted from Walters and Wilderbuer (2000). YFS = yellowfin sole; GT = Greenland turbot; ATF = arrowtooth flounder; FHS = flathead sole.

The biomass of arrowtooth flounder increased from 1978–95, after which there was a downturn from 1996–98 (Fig. A4.9). Abundance increased from 1983–95 due to five strong year classes: 1980, 1983, and 1986–88 (Wilderbuer and Sample 2003). The survival of arrowtooth flounder appears to vary on a decadal scale. Median recruit per spawning biomass anomalies, an index of survival, were positive from 1976–88, and negative from 1989–98 (Fig. A4.9). Survival decreased significantly after the 1989 regime shift. Recruitment strength may be linked to wind direction during spring (Wilderbuer *et al.* 2002). Years of consecutive strong recruitment for arrowtooth flounder, as well as for other winter-spawning flatfish (rock sole and flathead sole) in the 1980s, correspond to years when wind-driven advection of larvae to favorable inshore nursery grounds in Bristol Bay prevailed. The springtime pattern of winds changed to an offshore direction during the 1990s, which coincided with below-average recruitment (Wilderbuer *et al.* 2002).

Flathead sole (*Hippoglossus elassodon*)

Flathead sole and Bering flounder (*Hippoglossoides robustus*) are similar and managed as a single stock (Wolotira *et al.* 1993). Flathead sole are distributed from northern California to Alaska. Adults overwinter near the continental shelf margin and migrate onto the outer shelf in spring. Age and size at maturity are unknown, but spawning occurs in spring, near the continental margin (Walters and Wilderbuer 1997). Eggs are pelagic and larvae occupy shallow waters where they consume zooplankton. Adult flathead sole eat primarily benthic invertebrates.

The biomass of flathead sole had a similar trend as arrowtooth flounder; it increased from 1977–93, and decreased until 2000 (Fig. A4.9). Survival of flathead sole appears to vary on a decadal scale. Median recruit per spawning biomass anomalies were strongly positive from 1977–87, after which they were negative (Fig. A4.9). There was a significant decreasing linear trend in survival from 1977–2000. Strong recruitment of this and other winter-spawning flatfish species (arrowtooth flounder and rock sole) may be linked to wind direction that advects larvae to nearshore nursery areas during spring (Wilderbuer *et al.* 2002).

Rock sole (*Lepidopsetta polyxstra* and *L. bilineata*)

Two species of rock sole are distributed from California to the Bering Sea in the North Pacific and managed as a single stock (Wolotira *et al.* 1993). These are winter-spawning demersal fish that overwinter at the edge of the continental shelf and migrate to separate summer feeding grounds on the shelf. At the age of 7, 50% of female northern rock sole are mature (Stark and Somerton 2002). Eggs sink to the bottom where they are adhesive and, after hatching, larvae are planktonic for 2–3 months. Juveniles inhabit shallow waters where they consume zooplankton initially, and as they grow, consume benthic invertebrates (Wilderbuer and Walters 2003).

The biomass of rock sole followed a pattern similar to that of arrowtooth flounder and flathead sole (Fig. A4.9). Rock sole biomass increased from 1975–95, and then decreased in 1996 and 1997. Median recruit per spawning anomalies (index of survival) were significantly higher (positive) during 1975–87 than during 1988–97 (Fig. A4.9). There was a step-change in survival after 1987, indicating that rock sole survival varies on a decadal scale. Strong recruitment of this and other winter-spawning flatfish species (arrowtooth flounder and flathead sole) may be linked to wind direction that advects larvae to nearshore nursery areas during spring (Wilderbuer *et al.* 2002).

In the 1980s, length-at-age of both male and female rock sole decreased (Fig. A4.9). This was accompanied by an increased stock size, decreased weight-at-age for both male and female fish, and a westward expansion in their distribution (Walters and Wilderbuer 2000). The decrease in length- and weight-at-age may be due to density-dependent competition for food (Walters and Wilderbuer 2000; Williams 2003). Yellowfin sole and Alaska plaice comprise a large proportion of the groundfish biomass and consume similar prey as that of rock sole (Walters and Wilderbuer 2000; Lang *et al.* 1995). Competition among these fish species, or within the increasing stock size of rock sole, may have resulted in food limitation and the reduced size-at-age of rock sole (Walters and Wilderbuer 2000).

A4.6 Bering Sea Higher Trophic Levels

Much has been discussed elsewhere about the possible causes for marine mammal declines. For this report we note the coincidence of the declines to the 1976 regime shift and a more stable population at lower levels from the late 1980s through the 1990s, *e.g.*, for Pribilof fur seals (Fig. A4.10). The 2002 values are below the 1990s level. Pacific walrus, which were often found near the ice edge well south of St. Lawrence Island, are now found more frequently in the vicinity of the Island. These animals, which were certainly adapted to Arctic conditions over the previous century, may now be less adapted to current ice, temperature and ecological conditions.

A4.7 Coherence in Bering Sea Fish Responses

Based on time series of recruitment with different periods of overlap, cluster analysis and ordination techniques indicate Bering Sea stocks clustered into four well separated groups (Table A4.1 and Fig. A4.11a). Walleye pollock and Pacific cod shared a similar pattern of recruitment and had the highest observed correlation among all pairwise correlations (Spearman's rank correlation: $\rho = 0.77$). Flathead sole, arrowtooth flounder, and rock sole formed a second group with strong positive covariation (average pairwise rank correlation: $\rho = 0.66$). A third group consisted of Greenland turbot, yellowfin sole, and Alaska plaice, whose recruitment had a rank correlation of 0.41 on average. Finally, the pelagic stocks (sockeye salmon, Pacific herring, and chum salmon) comprised a fourth, less cohesive group with an average rank correlation of 0.02. Recruitment was typically uncorrelated, or negatively correlated, among stocks in the different groups.

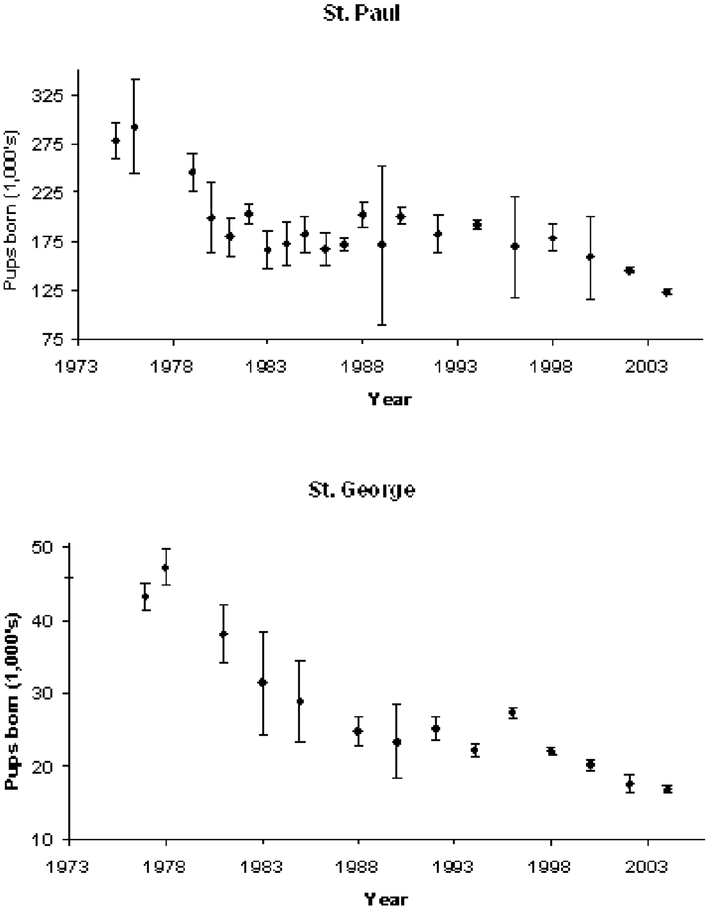

Fig. A4.10 Fur seal pup counts on the two Pribilof Islands.

Table A4.1 Stocks and stock groups used in analysis by species and region (BS = Bering Sea), range of year classes and number of years (NR) for which recruitment data were available and number of years (NSR) with both spawner (or spawning biomass) and recruitment data.

Scientific name	Common name	Region	Year classes	NR	NSR
Atheresthes stomias	arrowtooth flounder (ATF)	BS	1973-1999	27	24
Hippoglossoides elassodon	flathead sole (FHS)	BS	1975-1999	25	23
Reinhardtius hippoglossoides	Greenland turbot (GT)	BS	1970-1999	30	30
Limanda aspera	yellowfin sole (YFS)	BS	1959-1997	39	34
Lepidopsetta sp	rock sole (RS)	BS	1971-1998	28	24
Pleuronectes quadrituberculatus	Alaska plaice	BS	1970-1998	29	28
Theragra chalcogramma	walleye pollock	BS	1962-2000	39	37
Gadus macrocephalus	Pacific cod	BS	1975-1999	25	22
Oncorhynchus nerka	sockeye salmon	BS	1958-1995	38	38
Oncorhynchus keta	Chum salmon	BS	1979-1993	15	15
Clupea pallasi	Pacific herring	BS	1972-1992	21	0

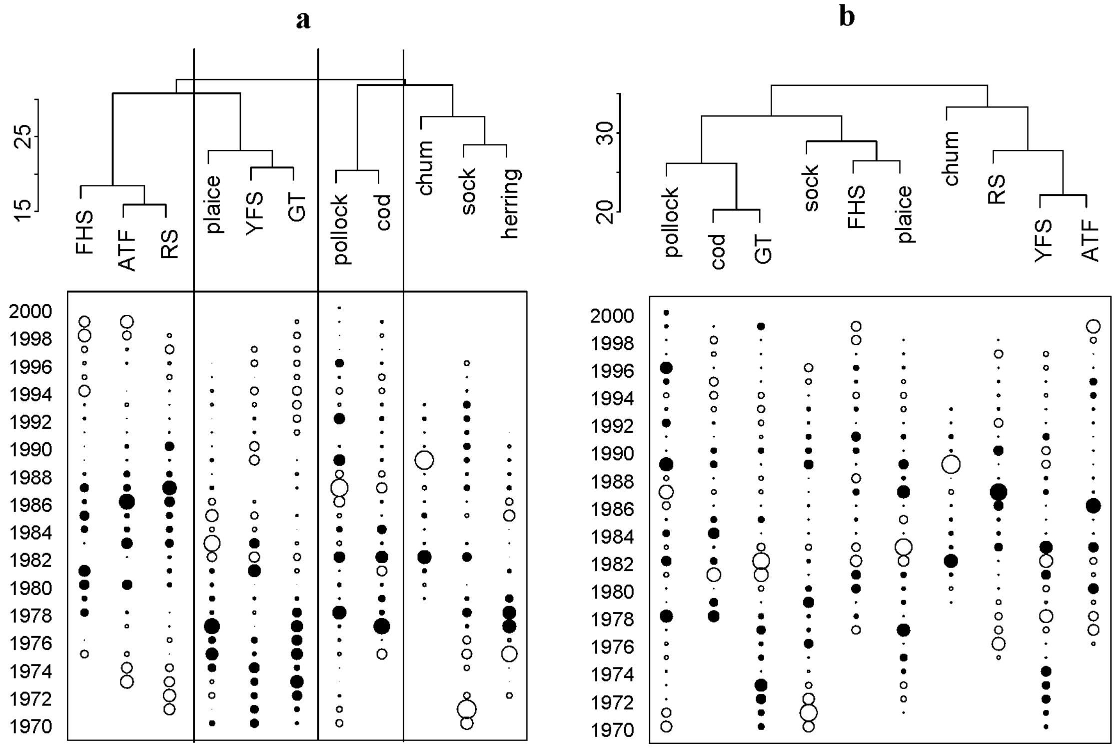

Fig. A4.11 Dendogram of Bering Sea stocks based on hierarchical cluster analysis (average linkage clustering) of pairwise Manhatten distances among standardized (a) recruitment and (b) survival series, and standardized series of positive (filled circles) and negative (open circles) (a) recruitment and (b) survival anomalies for each species, 1970–2000. For species codes see Table A4.1.

A cluster analysis of survival rate series resulted in three less well defined groups (Fig. A4.11b) that differed from those based on recruitment (Fig. A4.11a). Walleye pollock and Pacific cod formed a relatively cohesive group with Greenland turbot, due to a strong correlation between cod and pollock survival ($\rho = 0.61$), as well as a positive correlation between the survival of turbot and cod ($\rho = 0.37$). A second group consisted of arrowtooth flounder, yellowfin sole, and rock sole, whose survival rates had an average correlation of 0.37, while flathead sole, Alaska plaice, and sockeye salmon comprised a third, moderately correlated group ($\rho = 0.32$). Survival rates of species in the first group were negatively correlated with those in the second group. In particular, there was a strong negative correlation between yellowfin sole survival on the one hand, and survival rates of pollock and cod on the other hand ($\rho = -0.64$ and $\rho = -0.61$, respectively).

There is evidence for strong positive covariation among certain groups of stocks within the Bering Sea. Most notably, survival rates of pollock and cod were strongly correlated. If survival rates (residuals from stock-recruitment models) are indicative of environmental influences, strong covariation in survival is likely to reflect common environmental forcing. Hence a common forcing mechanism appears to drive the survival of cod and pollock. In contrast to widespread positive covariation, there were few cases where recruitment or survival rates showed strong negative correlations. A notable exception is the strong negative correlation between survival of yellowfin sole and survival of Pacific cod and walleye pollock, which may suggest that environmental forcing in the Bering Sea has opposite effects on the survival of yellowfin sole and gadids.

A4.8 Combined Standardized Indices of Bering Fish Recruitment and Survival Rate

This section provides indices of overall recruitment and survival rate (adjusted for spawner abundance) across the major commercial groundfish species, and across major pelagic stocks in the Bering Sea (Fig. A4.12). Time series of recruitment and spawning biomass for demersal fish stocks were obtained from North Pacific Fishery Management Council (NPFMC) Stock Assessment and Fishery Evaluation (SAFE) reports (2002a and 2002b). Recruitment and spawner abundances for salmon stocks, grouped by region, are based on Peterman *et al.* (1998), Pyper *et al.* (2001, 2002), and Mueter *et al.* (2002). Herring recruitment series are from Williams and Quinn II (2000). Survival rate (SR) indices for each stock were computed as residuals from a Ricker spawner-recruit model. A Ricker model with first-order autocorrelated errors was fit to each spawner-recruit series using a generalized least-squares regression of log (recruits-per-spawner) on spawner abundance. Each time series of recruitment or SR indices was standardized to have a mean of 0 and a standard deviation of 1 (hence giving equal weight to each stock in the combined index). Recruitment or SR series were lined up by year class (ocean-entry year for salmon), resulting in matrices of recruitment (or SR indices) by year with missing values at the beginning and end of many series. A combined standardized index of recruitment (CSI_R) and survival (CSI_{SR}) was then computed following Boyd and Murray (2001). Briefly, all pairwise correlations between time series in a given data matrix (*e.g.*, recruitment series for all demersal stocks in the Bering Sea) are computed based on those years with data for all stocks. The resulting correlation matrix is used to estimate annual means of standardized recruitment across all stocks. This approach allows estimation of annual average indices even for years that have missing data for some (or most) stocks. However, indices based on data for only a few stocks are highly uncertain. Uncertainty in the annual estimated means decreases if the component series are highly correlated (Boyd and Murray 2001).

The CSI_R suggests that recruitment of demersal species in the Bering Sea was above average from 1977–89 and below average in the early 1970s and most of the 1990s. These changes correspond to the regime shifts of 1977 and 1989–90. The CSI_R for pelagic stocks reflects a strong increase in recruitment around the 1977 ocean-entry year, but no apparent change after 1989.

The CSI_{SR} is more variable but shows similar patterns. A marked increase in survival is apparent in Bristol Bay sockeye in 1976 or 1977. However, in Bering Sea groundfish stocks, no similar increase in survival is apparent in the late 1970s, suggesting that the observed increase in recruitment was due to increases in spawner abundance rather than improved survival of recruits. Survival of demersal stocks in the Bering Sea was relatively low in the 1990s, with the exception of the year 2000. However, the CSI is based on few stocks in the late 1990s.

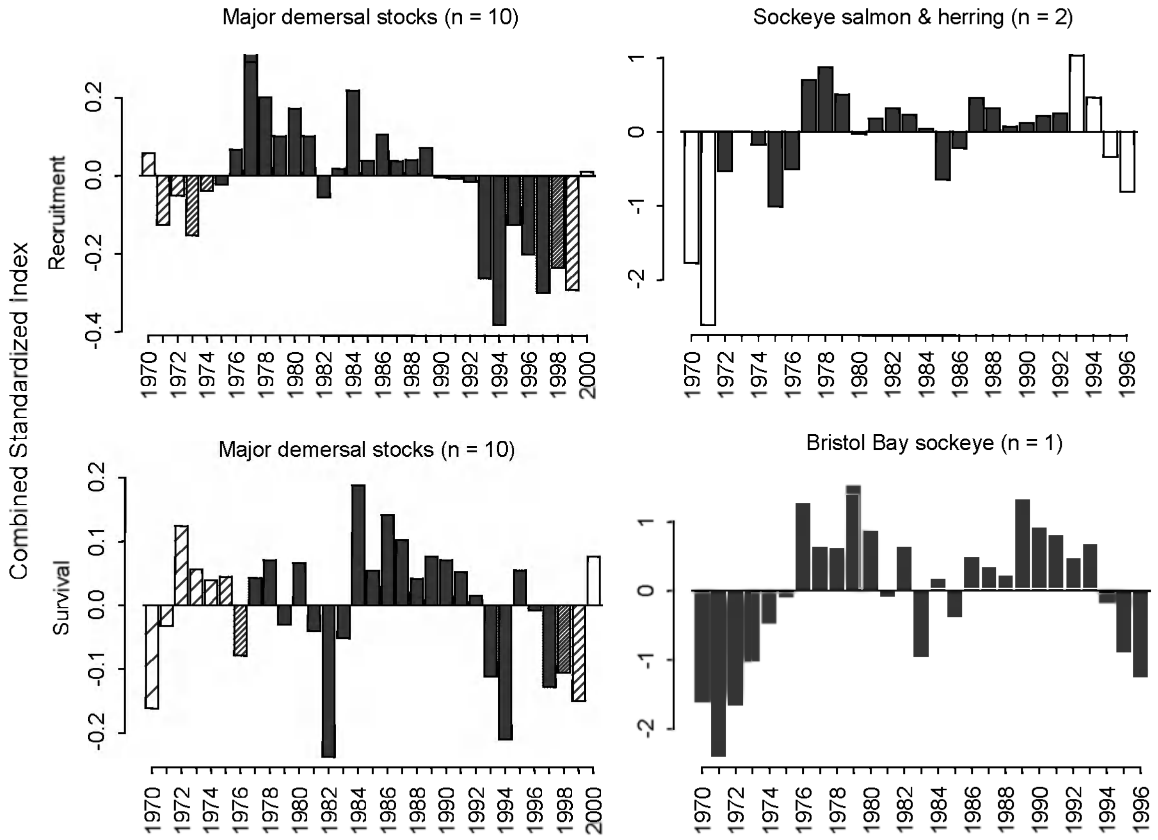

Fig. A4.12 Combined standardized index of (top panels) recruitment and (bottom panels) survival rates (residuals from Ricker spawner-recruit model) across demersal and pelagic stocks in the Bering Sea. Solid bars represent years with data for all stocks or stock groups. Lighter shading corresponds to years with more missing stocks. Series were truncated in 1970 and only years with data for at least two stocks were included, except for a single stock group (Bristol Bay sockeye) in the lower right panel.

A4.9 Aleutian Islands

Physical oceanography

The Aleutian Arc stretches approximately 3000 km from the tip of the Alaskan Peninsula to the Kamchatka Peninsula. The passes east of 170°W are shallow (sill depth <100 m) and narrow (<20 km). West of Samalga Pass (170°), deeper (>400 m) passes, such as Amukta Pass and Amchitka Pass, occur. West beyond the date line, the deepest passes (Near Strait and Kamchatka Strait) can be found. In addition to variation in depth, the north–south width the Aleutian Arc narrows from east to west, with the greatest north–south extent (>80 km) occurring east of Samalga Pass. Samalga Pass also appears to be a boundary between water properties, temperature, and types of zooplankton, whales, and fish stocks. These passes form a porous boundary between the North Pacific and the Bering Sea. As the currents interact with the topography of the Aleutian Arc, there is an exchange of water between the North Pacific Ocean and Bering Sea. The Alaskan Coastal Current flows through the shallow eastern passes (Samalga and eastward), while the Alaskan Stream is the source of the northward flow in the passes between Samalga and Near Strait. Only at Kamchatka Strait is there a net southward flow. Strong mixing occurs in all of the passes, but particularly in passes of depth <200 m. This introduces nutrients into the euphotic zone, thus supporting high productivity. The northward flow through the passes provides water to the Bering Sea, which is an important source of nutrients, heat and salt for the Bering Sea ecosystem (Favorite 1974; Stabeno *et al.* 1999). The magnitude of flow varies depending upon the size of the passes, with greatest northward transport occurring in Near Strait, Amchitka Pass and Amukta Pass. There is very little historical oceanographic information on this region. Recent studies show that climate signals from the Pacific, especially changes in the Alaska Stream, can influence the Bering Sea as well as have a local response. Slight shifts in the position of the Aleutian Low sea level pressure system can have large local impacts. To the east of 170°W, climate follows the PDO, while to the west there is a long-term trend toward colder conditions in winter.

Fishes

Gadids

Trends in Aleutain Islands pollock are difficult to discern due to uncertainty in biomass estimates in the 1980s and recruitment estimates prior to 1990 (Barbeaux *et al*. 2003). The biomass of Aleutian Islands pollock increased during 1990–95 (Fig. A4.13). Strong year classes of Aleutian Islands walleye pollock occurred in 1989 (also a strong year class in eastern Bering Sea pollock) and 1993 (not a strong year class in the eastern Bering Sea). Although, decadal-scale patterns in recruitment are difficult to discern, recruitment of Aleutian Islands pollock is significantly correlated with that of Aleutian Island Atka mackerel (Barbeaux *et al*. 2003). This suggests that both species are affected by the same large-scale processes.

Hexagrammids

Atka mackerel are distributed from southeast Alaska to the eastern Bering Sea and Aleutian Islands, and to the east coast of the Kamchatka Peninsula (Wolotira *et al*. 1993). These semi-pelagic schooling fish are the most abundant groundfish in the Aleutian Islands. They are distributed over the continental shelf, and migrate to shallower waters to spawn over the summer and fall (McDermott and Lowe 1997). Fifty percent of female Atka mackerel reach maturity by the age of 3.6 years, or 33–38 cm (McDermott and Lowe 1997). Females deposit eggs in nests which the males guard until hatching (Zolotov 1993). Larvae are planktonic, and juveniles recruit by the age of 2. Atka mackerel consume zooplankton, but fish also comprise a small percentage of their diet.

Atka mackerel biomass and recruitment is highly variable (Fig. A4.13). The top four year classes of Atka mackerel occurred in 1977, 1988, 1992, and 1998 (Lowe *et al*. 2003). Atka mackerel survival, as measured by recruit per spawning biomass anomalies, does not appear to vary on a decadal scale. Survival was anomalously high in 1977 and 1988, two years that are recognized as the end/beginning of a new climate regime in the Bering Sea and Aleutian Islands. Survival indices within those climate regimes, however, were not consistently positive or negative. Atka mackerel length- and weight-at-age have been found to vary among regions in the GOA and Aleutian Islands (Kimura and Ronholt 1988). Kimura and Ronholt (1988) found that the weight- and length-at-age of Atka mackerel did not vary among years. No discernable difference in length-at-age among years has been detected in recent data (S. Lowe, Alaska Fisheries Science Center, pers. comm.).

Rockfishes

Pacific ocean perch are distributed on the outer continental shelf and upper slope, from southern California to the Bering Sea (Allen and Smith 1988). Fifty percent of females are mature by the age of 7 years, or at 29 cm in length. Pacific ocean perch are viviparous; they spawn in the fall and females release larvae in the spring (Love *et al.* 2002). Larvae are found in surface waters; juveniles settle in nearshore rocky habitats then move to progressively deeper waters on the shelf. Pacific ocean perch are long-lived fish that are fully recruited at age 8, and can live as long as 98 years (Heifetz *et al*. 2002). They consume primarily zooplankton throughout their life cycle but also consume myctophids in increasing proportions as they grow larger (Yang 2003).

Pacific ocean perch biomass decreased from the 1960s to the mid-1970s, and increased from 1978–93, possibly due to catch rates (Fig. A4.13). Recruitment and survival of Pacific ocean perch appear to vary on decadal time scales. Median recruit per spawning biomass anomalies (index of survival) were negative during 1960–74 (except in 1961 and 1962), positive during 1975–88, and negative again during 1989–93 (Fig. A4.13). Recruitment followed the same temporal pattern as survival. Mechanisms for this decadal-scale variability in recruitment and survival have not been identified. Survey data from 1986–2002 indicate that there is no apparent trend in the mean lengths-at-age of Aleutian Islands Pacific ocean perch (Fig. A4.13). Also, little difference was found in Pacific ocean perch growth curves among years within a single area (Spencer and Ianelli 2003), but some differences in growth parameters exist between areas (D. Hanselman, Auke Bay Laboratory, NMFS, pers. comm.).

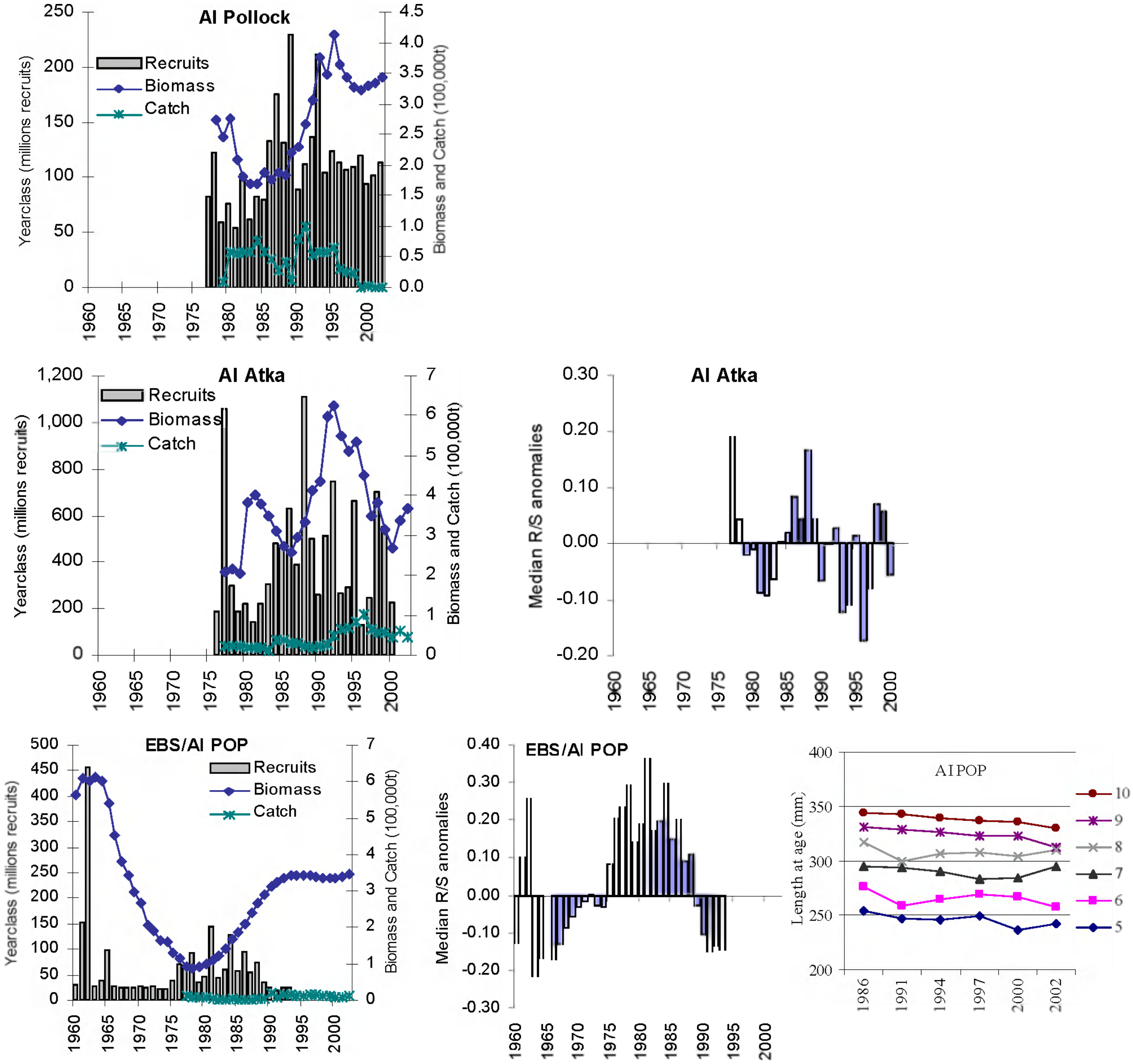

Fig. A4.13 (Top) Aleutian Islands (AI) pollock recruits, biomass and catch, and (middle) Atka mackerel abundance estimates; left panel: recruits, biomass and catch. Right panel: median recruit per spawning biomass anomalies. (Bottom) Eastern Bering Sea/Aleutian Islands (EBS/AI) Pacific ocean perch; same as other plots, with addition of length-at-age.

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Appendix 5: Recent Ecosystem Changes in the Western North Pacific

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Summary

Physical and biological data were summarized for three main regions: Sea of Okhotsk, Tsushima Current and Kuroshio/Oyashio Current regions, and the Yellow and East China Seas. The response to the 1989 regime shift was strong for all regions of the western North Pacific, from the East China Sea through to the Sea of Okhotsk, including the Kuroshio/Oyashio Current region. Winter air temperatures increased, which corresponded to warmer sea surface temperatures (SSTs). These conditions have persisted to 2003 and appear to be connected to the east–west dipole pattern observed in basin-wide SST variability. A strong response to the 1998 regime shift was observed only in the Sea of Okhotsk, with an intensification of colder conditions and sea ice extent. This intensification corresponded to a persistent increase in Sea of Okhotsk zooplankton biomass in 1999, particularly in the spring, for large-sized plankton such as euphausiids, amphipods, copepods and saggitas. Changes in the epipelagic fish community were also evident, with Japanese sardine, previously a dominant species, being replaced by herring, capelin and Japanese anchovy. Walleye pollock remained the most abundant species in the Sea of Ohkotsk, but the intensification of colder conditions in 1998 corresponded to a decrease in walleye pollock biomass. Consistent biological responses to the 1998 shift were not evident in the other regions. The biomass of warmwater macro-algae in the Tsushima Current region increased when water temperatures increased in the late 1990s. Zooplankton biomass in the Kuroshio Current region has varied since 1978, but has remained at low levels. Conversely, zooplankton biomass in the eastern Yellow Sea has remained at high levels since the late 1990s. Phytoplankton and zooplankton biomass has declined in the Bohai Sea, the western Yellow Sea, and the East China Sea since the early 1980s. In both the Kuroshio and Tsushima Current areas, Japanese sardine began to decline in abundance around 1988. In contrast, Japanese anchovy, jack mackerel and Japanese common squid increased in abundance after 1988. Most fish abundance and recruitment were normal in 1998, but recruitment of Japanese common squid and Pacific saury were extremely poor. Groundfish species in the Yellow Sea have declined in abundance from the 1960s to the 1990s. Japanese common squid have increased and maintained high levels since 1990s.

A5.1 Introduction

As a review of recent climate and ecosystem changes that have occurred in the western North Pacific, we present a brief report on changes in atmospheric processes, physical oceanography, lower trophic levels, and fishes in three regions: the Sea of Okhotsk; the Tsushima Current and the Kuroshio/Oyashio Current region; and the Yellow and East China Seas.

A5.2 Sea of Okhotsk

Atmospheric influences

As reported by Shuntov *et al.* (2002, 2003), the last part of the twentieth century can be characterized as a relatively cold period over the Far East. Cyclic changes in atmospheric processes and ice conditions in the far eastern seas indicate a pronounced increasing trend in cold atmospheric circulation and in ice conditions in the Sea of Okhotsk (Fig. A5.1; Glebova 2002).

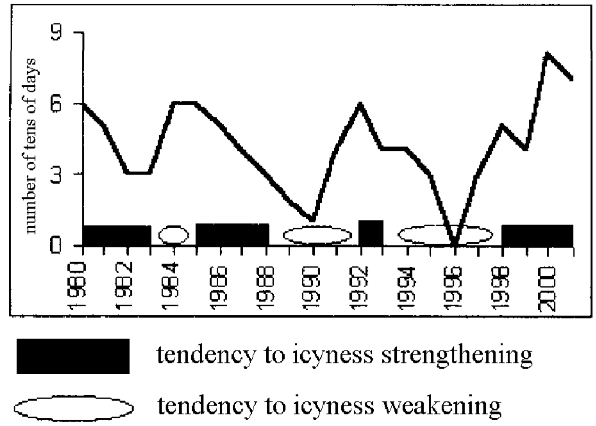

Fig. A5.1 Interannual variability of the recurrence of "cold" atmospheric circulation synoptic types (line) and nature of ice conditions in the Sea of Okhotsk (bars and ovals) (Glebova 2002).

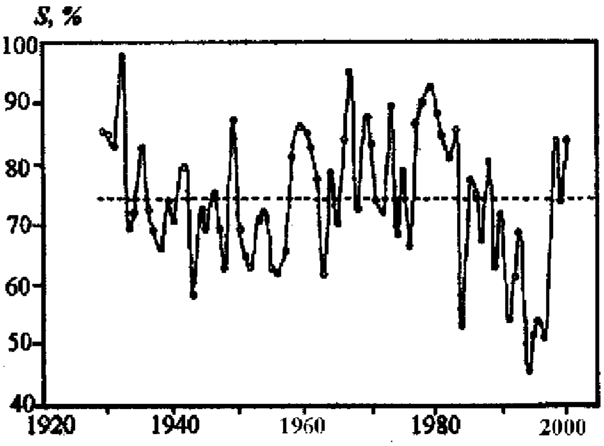

Fig. A5.2 Ice conditions for the Okhotsk Sea in March as measured by the proportion of the total area of the Sea of Okhotsk (S, %) covered by ice. The dashed line is the long-term mean (Ustinova *et al.* 2002).

Physical oceanography

The increase in the occurrence of cold atmospheric conditions in 1997 decreased water temperature (Table A5.1), improved ice conditions (Fig. A5.2; Ustinova *et al.* 2002), and impacted areas of subsurface cold seawater distribution with temperature less than 1°C in the cold intermediate layer (Khen *et al.* 2002). For example, the long-term mean area of subsurface cold waters in spring, with temperature less than 1°C in the cold intermediate layer, averages 379,000 km^2. In 1997, it amounted to 285,000 km^2 but in 1999, it was 565,000 km^2, and in 2002, it was 582,000 km^2. The corresponding summer long-term mean area is 172,000 km^2, and from 1997–2002, the area increased from 91,000 km^2 (in 1997) to 228,000 km^2 (in 1999), and to 274,000 km^2 (in 2002).

It should be noted that such obvious trends in water temperature dynamics and water circulation were not observed in adjacent Kurile waters. Moreover, in some cold years typical for the Sea of Okhotsk, positive anomalies of water temperature were observed near the Kurile Islands (Samko and Novikov 2002).

Lower trophic levels

A time series (1984–2002) of zooplankton abundance indicates a decrease in biomass from the mid-1980s till the mid-1990s, with insignificant interannual fluctuations. In 1997–98, zooplankton abundance was at a minimum but in 1999, it returned to high levels (Table A5.2; Shuntov *et al.* 1998; Shuntov *et al.* 2002) which was typical for the 1980s when both fish productivity and total catch were very high in the Sea of Okhotsk. The considerable decrease in nekton biomass, coupled with the increase in large zooplankton biomass (Table A5.2), suggests that fishes and squids are underexploiting plankton resources (Shuntov 2001; Dulepova 2002).

Table A5.1 Average water temperature in the 50–200 m layer for the two areas of the Sea of Okhotsk (Ustinova *et al.* 2002).

Area	1996	1997	1998	1999	2000
Western Kamchatka shelf (April)	0.40	1.13	0.01	–0.25	–0.28
North-western part (May-June)	–0.45	–0.12	–0.72	–0.94	–0.98

Table A5.2 Dynamics of average biomass of zooplankton (mg m^{-3}) in the northern Sea of Okhotsk in 1984, 1986, 1988 and 1997–2002.

Fraction	**1984**	**1986**	**1988**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Spring period									
Small fraction	n.d.*	n.d.	n.d.	108	35	38	41	26	18
Medium fraction	n.d.	n.d.	n.d.	73	11	55	49	24	45
Large fraction including:	n.d.	n.d.	n.d.	545	373	1561	1510	1136	1150
Euphausiids				144	145	731	670	326	459
Amphipods				8	13	9	10	12	17
Copepods				135	124	466	541	417	444
Chaetognaths				258	91	313	269	370	222
Total	**n.d.**	**n.d.**	**n.d.**	**726**	**419**	**1654**	**1600**	**1186**	**1213**
Summer-fall period									
Small fraction	341	295	267	190	119	142	105	88	n.d.
Medium fraction	218	296	394	155	125	220	195	251	n.d.
Large fraction including:	1036	1417	1671	460	567	835	831	557	n.d.
Euphausiids	375	700	544	131	125	314	417	206	n.d.
Amphipods	90	75	57	33	51	99	50	29	n.d.
Copepods	270	508	703	214	185	238	170	201	n.d.
Chaetognaths	301	134	367	78	186	184	194	121	n.d.
Total	**1595**	**2008**	**2332**	**805**	**811**	**1197**	**1131**	**896**	n.d.

* n.d. indicates no data available.

Fishes

Walleye pollock (*Theragra chalcogramma*) and Japanese sardine (*Sardinops melanostictus*) dominated the epipelagic fish community from the late 1970s to the mid-1990s. Since the late 1990s, the biomass of both these species has drastically decreased, and fishes such as herring (*Clupea harengus*), capelin (*Mallotus villosus*), and Japanese anchovy (*Engraulis japonicus*) have increased in abundance. Despite dramatic declines (Fig. A5.3), walleye pollock remain the most abundant epipelagic fish in the Sea of Okhotsk (Table A5.3; Shuntov *et al.* 1993; Dulepova 2002; Shuntov *et al.* 2003). Total fish biomass remains below levels of the 1970s to the 1990s.

There has been a significant decrease of the biomass of all major demersal fish species, excluding sculpins (cod, large and small flatfishes, and skates) in the Sea of Okhotsk. The total demersal fishes biomass declined by 50% between 1997 and 2000 (Shuntov *et al.* 2003). Biomass of benthic invertebrates also decreased (to approximately one third), due mainly to the decline in crabs, shrimps, and gastropods. However, groups such as sea urchins and squids have slightly increased in abundance.

A5.3 Tsushima Current Region and Kuroshio /Oyashio Current Region

Atmospheric influences

Empirical orthogonal function (EOF) analyses of seasonal air temperature time series from meteorological stations distributed around the Tsushima Current region for winter and spring (Fig. A5.4) indicated that in winter, a persistent shift to warmer conditions was evident in the late 1980s, and air temperature has remained at a high level. There were no shifts in average winter air temperatures around 1976 and 1998. In spring, however, a longer-term warming trend (with perhaps some evidence of a step-like character) appears, with 1998 as the first year of the most recent warmer stanza.

Table A5.3 Composition (%) of the epipelagic fish community in the northern Sea of Okhotsk in spring of 1985, 1986, 1988 and 1998–2002, and total fish biomass (millions of tonnes).

Species	1985	1986	1988	1998	1999	2000	2001	2002
Pollock	83.9	89.5	93.8	78.5	78.1	86.6	84.1	81.2
Herring	14.8	10.0	5.3	17.3	14.8	10.9	10.4	10.7
Capelin	0.9	0.2	0.1	0.4	0.8	0.6	1.8	1.8
Deep sea smelt	<0.1	<0.1	<0.1	1.5	3.5	0.6	1.1	3.5
Cyclopteriids	<0.1	<0.1	<0.1	3.0	0.1	0.1	0.1	0.2
Sakhalin plaice	<0.1	<0.1	<0.1	0.3	1.3	0.4	0.5	0.3
Other fishes	0.3	0.4	0.8	1.7	1.4	0.8	2.0	2.4
Total fish biomass	8.9	8.5	9.4	7.8	6.5	5.5	5.4	5.2

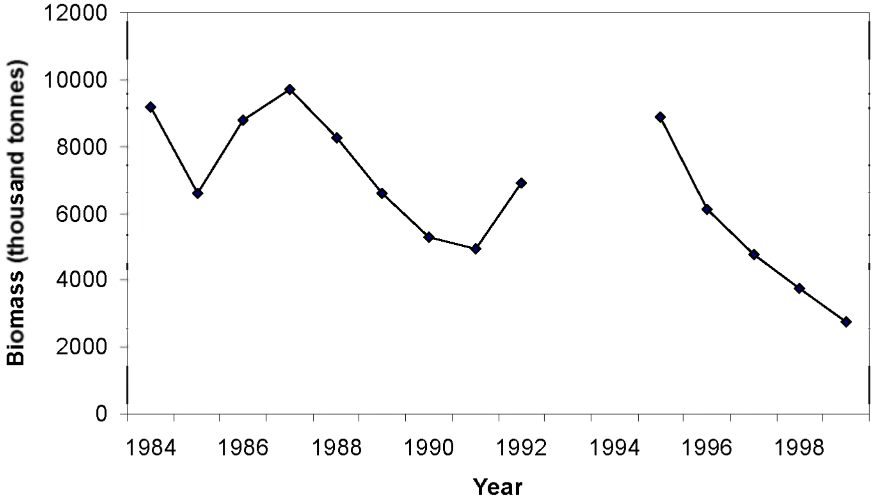

Fig. A5.3 Walleye pollock spawning stock biomass in the northern Sea of Okhotsk (Avdeev *et al.* 2001).

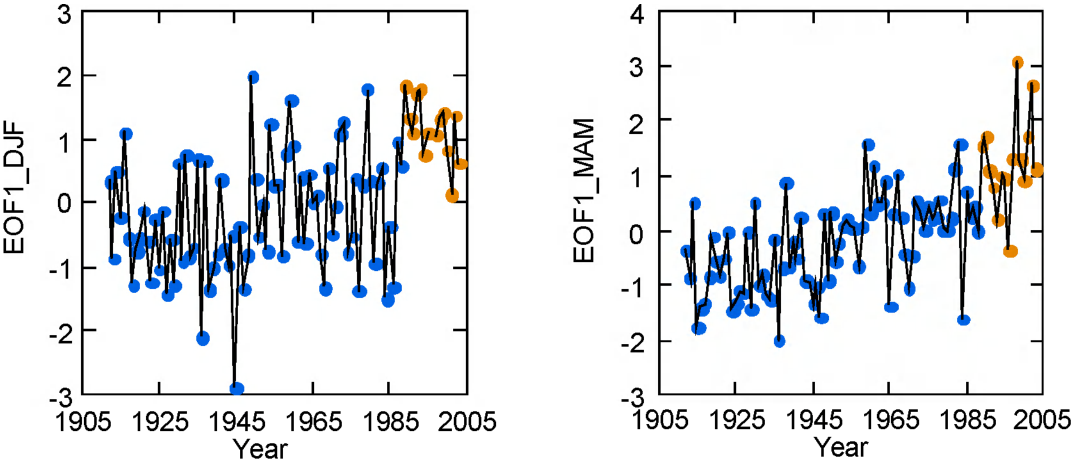

Fig. A5.4 Annual coefficients from the first component of an empirical orthogonal function (EOF) analysis of average seasonal air temperatures around the Japan/East Sea (left, December–February; right, March–May). Red dots indicate years after 1988. Data obtained from http://www.giss.nasa.gov/data/update/gistemp/station_data.

Physical oceanography

Temperatures in the deeper parts of the Tsushima Current region have been increasing steadily since the 1930s to 1995. The mean sea surface temperature (SST) has been increasing off the Korean Peninsula during the last 35 years (1968–2002), at a rate of 0.2°C per decade. Conversely, the temperature at 100 m depth has decreased at a similar rate. In the Tsushima Current region, winter temperature anomalies at 50 m depth were generally negative from 1968–87, but have shifted to a positive phase since 1988. These positive anomalies have continued through to 2004, without any remarkable change in the late 1990s (Ohshimo 2004). Time series of SST and sea level height at three locations (43°N, 37°N, and 35°N) along the Japanese coast indicated a decadal pattern, but no apparent changes around 1998 (Senjyu 2004). Salinity changes seem to be negligible off the Korean Peninsula.

Seasonal and interannual dynamics of the Oyashio Current, which are closely linked to climate change, influence the migrations and fluctuations of pelagic and demersal fishes in the northwestern Pacific. The spatial extent of the Oyashio Current has increased since the mid-1970s, and has remained in a positive phase until the present. The southern tip of the Oyashio coastal intrusion moved north during the mid-1960s, and shifted south from the late 1970s to 1980s, and then moved north again from the mid-1990s. The annual mean SST anomaly in the Oyashio Current area (37°–42°N, 141°–144°E) showed a similar change, from a positive phase to a negative phase in the late 1970s, and has been about zero after the late 1990s. SSTs along 40°N from 130°E to 180°E indicated a decadal pattern, with cooling during the late 1970s, warming in the late 1980s, and cooling detected during 1998–2002 (Watanabe 2004).

The Kuroshio Current often took the large meandering (LM) path in 1975–91, and kept the non-LM path from 1964–74 and 1991–2002, with a quasi-LM path in 1999–2001. Time series of SST anomalies in the Kuroshio Current region south of Japan indicated a remarkable warming trend from 1982–99, and after (Watanabe 2004). The Kuroshio Current may play an important role in varying heat transport, which subsequently affects the atmosphere–ocean climate system (Yasuda *et al.* 2000).

Lower trophic levels

In the Tsushima Current region, a particularly early spring algal bloom occurred in 1998 when winds were weaker and insolation higher than in other years. Delay and extended periods in spring algal blooms since 2002 may imply an arrival of a new regime since 1998, if there is a lag of several years. However, it is premature to conclude this because 2002 and 2003 were El Niño years (Yamada *et al.* 2004).

Meso-zooplankton biomass in the Oyashio Current region was low from the early 1950s to the mid-1960s, increased in the late 1960s, and sustained high values until the late 1970s, decreasing in the early 1980s, and thereafter sustained low values. In 1999, the net primary production increased to the level observed in the early 1970s (Tadokoro *et al.* 2004), though there was no evidence for an increase in the meso-zooplankton biomass.

In the Kuroshio Current region, winter biomass of large copepods was relatively high before the mid-1970s, became low during 1980s and early 1990s, then increased from 1999 to the level observed in the early 1970s (Hidaka 2004). However, copepod biomass in the inshore waters did not increase; this difference may be related to Kuroshio Current meandering.

Invertebrates

Although there was a significant increase in zooplankton abundance along the Korean Peninsula after 1988, it suddenly decreased from 1997–98. It was also a year with extremely poor catch per unit effort (CPUE) and catch of the Japanese common squid (*Todarodes pacificus*), which is the most dominant species, occupied around 45% of the Korean catch during the 1990s. However, squid had recovered to an average level since the late 1990s, and reached a maximum in 1998–2000 for the winter and autumn cohorts (Kidokoro *et al.* 2004). In general, the increase in squid catch has been accompanied by an increase in SST, as well as zooplankton biomass, since the late 1980s.

Fishes

While Japanese anchovy stock in the Tsushima Current region increased in 1998 and declined after a few years, no drastic changes were observed for other small pelagic fishes, including jack mackerel (*Trachurus symmetricus*), chub mackerel (*Scomber japonicus*), spotted mackerel (*Scomberomorus munroi*), Japanese sardine and round herring (*Etrumeus teres*) (Ohshimo 2004). The mean trophic level of the fish community decreased continuously from 3.6 in the mid-1980s to 3.5 in the late 1990s.

The reproductive success rate (recruit per spawners) of sardine, mackerel and Pacific saury (*Cololabis saira*) in the Kuroshio/Oyashio Current area decreased in the late 1990s, and recovered in 2000, except for Pacific saury, whose CPUE remained below average (Yatsu and Ueno 2004). The Japanese common squid CPUE and catch were at high levels from the early 1990s, but suddenly dropped in 1998, with a moderate recovery after that (Kidokoro *et al.* 2004). It was unclear if any changes occurred in 1998 for demersal fishes (Nihira 2004; Nishimura *et al.* 2004).

Higher trophic levels

There were no significant changes in the diet composition of seabird populations on Teuri Island (Hokkaido) in the late 1990s, which have been observed since 1984.

A5.4 Bohai Sea, Yellow Sea, and East China Sea

The Bohai, Yellow, and East China Seas are marginal seas of the Pacific Ocean, bounded by the Korean Pennisula and China. The Yellow Sea is a semi-enclosed shelf sea with distinct bathymetry, hydrography, productivity, and trophically-dependent populations. Shallow, but rich in nutrients and resources, the Yellow Sea is the most favorable for coastal and offshore fisheries, and has well-developed multi-species and multi-national fisheries. However, over the past several decades, many changes in productivity, yield biomass, species composition, and shift in dominance have been found. Over-exploitation is the principal source of changes in the state of the ecosystem, but natural environmental perturbation should be considered an important driving force causing changes in species composition and biomass yields, at least for pelagic species and shellfish.

Atmospheric influences

The climate system of the Yellow Sea and East China Sea region is strongly affected by processes in the Northwest Pacific Subtropical High system, Equatorial Current system, and the land climate system. The Asian monsoon is dominant in summer, and the northern cold air system is important in winter. Therefore, the long-term variation in the East China Sea and Yellow Sea is very complex, and we provide a brief review of the decadal characteristics of climate change in this area.

Empirical orthogonal function (EOF) analyses of the North Central Eastern Pacific (NCEP) monthly averaged sea surface air temperature (SSAT), available as gridded data (Fig. A5.5), characterizes the temporal and spatial processes in the East China Sea. The first and second modes of the EOF explain 68.5% and 15% of variance, respectively. The first mode (EOF1) shows the dominant variation in air temperature (Fig. A5.6).

The spatial pattern of EOF1 is a simple cycle and illustrates that the East China Sea and Yellow Sea share the same climate system (Fig. A5.6). An obvious low frequency variation is present in the EOF1 coefficients: a negative temperature anomaly period occurred from 1956–87; since 1988, a positive anomaly period has dominanted. A maximum anomaly was observed around 1998. Since then, the trend has been decreasing, and it appears a negative period has begun. It is important to note that there has been an overall long-term warming trend since 1956 (Fig. A5.6).

Though the monthly air temperature in Qingdao represents a single station, there is a high correlation (r = 0.69) with EOF analyses results, reported above, for the gridded air temperature dataset over the East China Sea and Yellow Sea region (Fig. A5.7). This correlation is helpful since the meteorological record in Qingdao is longer than 100 years and is a more reliable dataset.

A Butterworth low-pass filter was used to assess correlation in low frequency bands. The improved correlation (r = 0.85), illustrates that the air temperature in Qingdao shares the same climate system with the whole Yellow Sea and East China Sea region (Fig. A5.8).

The monthly SSAT in Qingdao (36°04′N; 120°18′E) is correlated (r = 0.66) with SST in Qianliyan (36°16′N; 121°23′E). A Butterworth low-pass filter improves the correlation to 0.89. The good correlation (Fig. A5.9) implies that the SST in the Yellow Sea is dominated by the local climate system. Overall, the long-term trend of SST at Qianliyan Station suggests an increase in temperature since the late 1980s. This positive trend has continued through 2003.

The El Niño–Southern Oscillation (ENSO) index (available from the Japan Meteorology Administration), and the Pacific Decadal Oscillation (PDO) index (available from the Climate Diagnostic Center; Zhang *et al.* 1997), show patterns similar to the Qingdao air temperature series (Fig. A5.10). However, the correlation between either ENSO or PDO with SSAT in the Yellow Sea and East China Sea region are not strong (r < 0.15). Given the correlations between Qingdao air temperature, Qingdao SST, and EOF1 temporal coefficient of the SSAT in this region, the long-term change in the Yellow Sea and East China Sea must be determined by a locally dominant system. Wang *et al.* (1998) pointed out that the air temperature change in China is obviously different than that of the global system. The main reason is that temperatures around China are caused not only by ocean processes, but also by a land climate system.

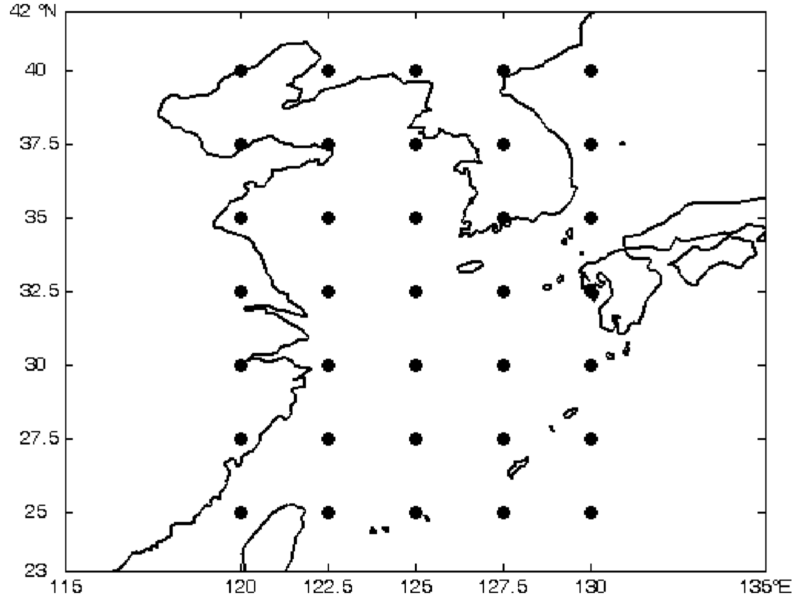

Fig. A5.5 Outline of gridded data set of North Central Eastern Pacific air temperatures for the East China Sea and Yellow Sea region.

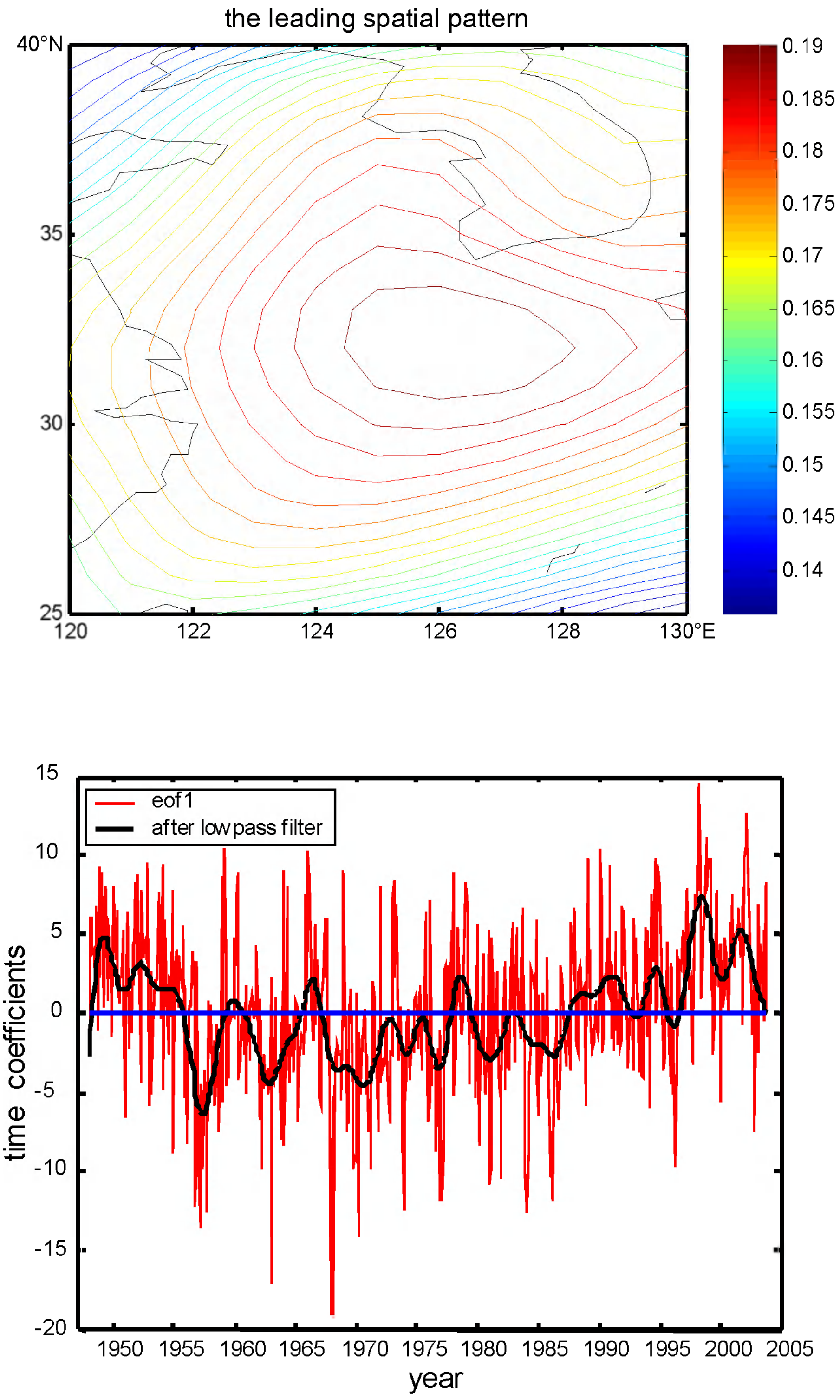

Fig. A5.6 The first mode of empirical orthogonal function anlaysis (EOF1) of air temperature in the East China Sea and Yellow Sea region. Top panel is a spatial pattern of EOF1 and bottom panel is EOF1 coefficients over time.

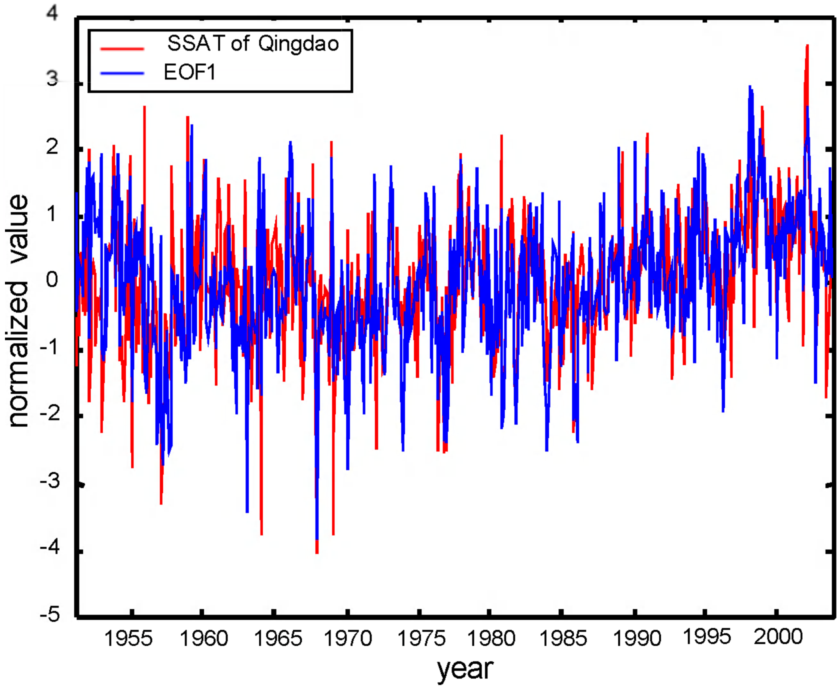

Fig. A5.7 Normalized time series of the first empirical orthogonal function (EOF1) time coefficient and monthly sea surface air temperature (SSAT) in Qingdao.

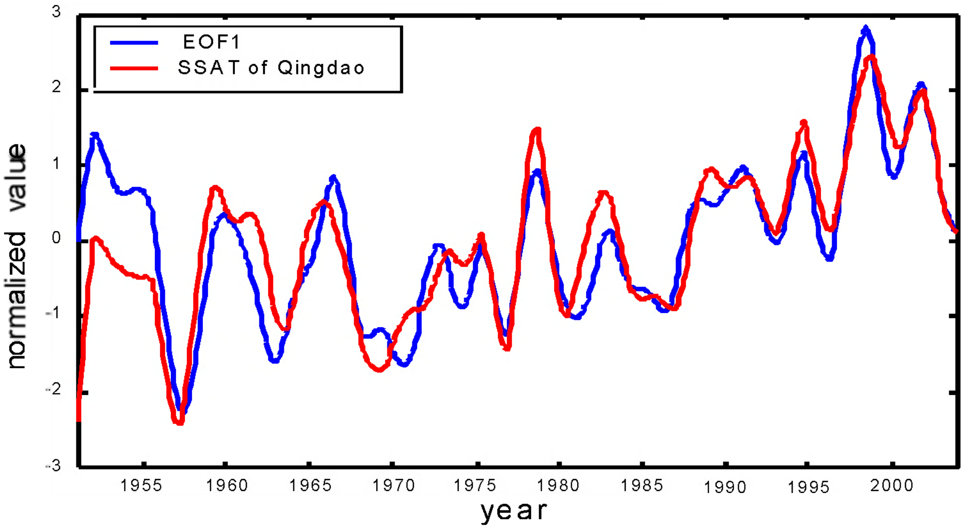

Fig. A5.8 Normalized time series of the first empirical orthogonal function (EOF1) time coefficient and monthly sea surface air temperature (SSAT) in Qingdao. A Butterworth low-pass filter was used to assess correlation at low fequency bands.

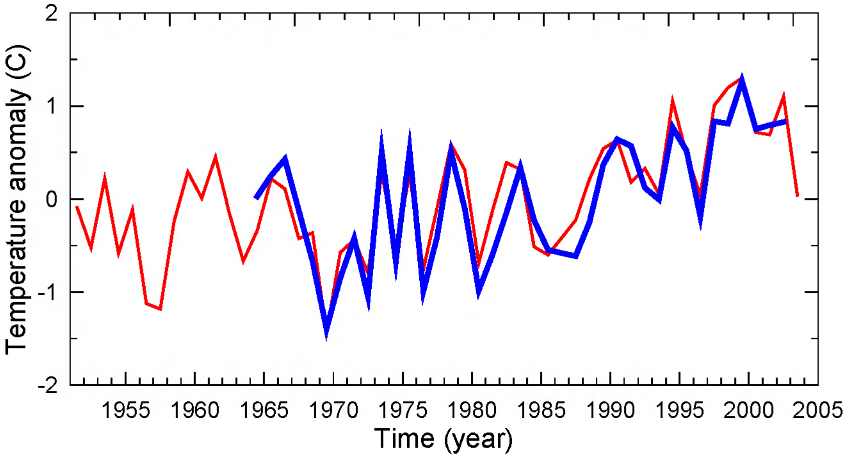

Fig. A5.9 Mean annual sea surface air temperature (SSAT) anomalies in Qingdao (red line) and mean annual sea surface temperature (SST) anomalies in Qianliyan (blue line).

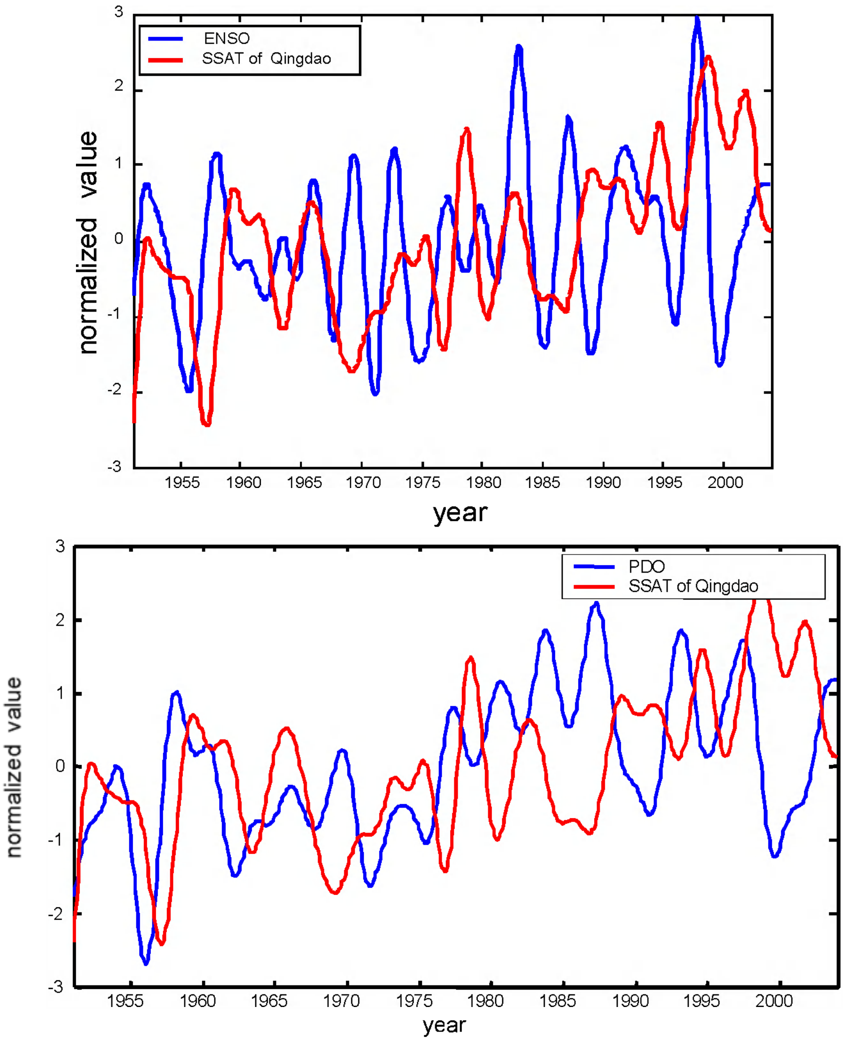

Fig. A5.10 Correlation of Qingdao air temperature with the El Niño–Southern Oscillation (ENSO) index (upper panel) and Pacific Decadal Oscillation (PDO) index (bottom panel). The data used in both figures were filtered with Butterworth low-pass filter.

Physical oceanography

SST in the Yellow Sea

There is strong evidence of a gradual increase in SST in the Yellow Sea since the early 1900s, with a recent cooling period. Warming in the surface layer has been conspicuous in the Yellow Sea since 1989, but seawater temperature anomalies switched to negative values in 2000 (PICES 2004). For the last 35 years (1968–2002), the increase in temperature for surface waters and at 50 m depth in the Yellow Sea were 0.27°C per decade and 0.12°C per decade, respectively (H.D. Jung, NFRDI, pers. comm.).

SST and salinity in the East China Sea

Sea surface temperatures in the coastal areas of the East China Sea have exhibited decadal-scale patterns: cooler periods during the 1960s and 1980s; warmer periods during the 1970s and 1990s. A rapid increase in SST occurred in 1993, and temperature reached a maximum around 1998. The temperature increase in coastal areas was much higher than that in offshore areas.

On the Korean side of the East China Sea, the SST has increased (0.23°C per decade), while temperature at 50 m depth has decreased (0.10°C per decade). Salinity at the surface seemed to decrease, however, changes at 50 and 100 m depth were negligible. Recently, the frequency of typhoons has increased over the Korean Peninsula. Increased typhoons, with heavy rain, and the construction of the Three Gorges Dam, may affect the regional salinity and alter the ecosystems in the Yellow Sea and the East China Sea.

Lower trophic levels

Phytoplankton

Annual variation of primary productivity in the Bohai Sea has been observed and overall, it has decreased noticeably from 1982–98 (Table A5.4). Over the past 40 years, a declining trend in phytoplankton biomass has been observed, and it appears to be correlated with the changes in nutrient concentrations (Fig. A5.11).

Harmful algal blooms (HABs) used to be uncommon in the Yellow Sea. However, the frequency and extent of outbreaks have increased, and the bloom season of red tide organisms has been prolonged from summer only (prior to 1995) to spring through fall (since 1995). Of particular note is the occurrence of the fish-killing dinoflagellate, *Cochlodinium polykrikoides*, which was present in October of 1998 and 1999.

Increased water temperatures in the late 1990s may have had a severe impact on the distribution and composition of large algal communities in the eastern portion of the East China Sea. Kiriyama *et al.* (2004) reported that large brown algae decreased in biomass, and warmwater species increased in biomass along the coast of northwestern Kyushu Island when temperatures increased, especially in the late 1990s. They also demonstrated that the feeding pressure of herbivorous fishes increased with increasing temperature.

Table A5.4 Annual variation in primary productivity (mg C m^{-2} d^{-1}) by season and area in the Bohai Sea (adapted from Tang *et al.* 2003).

	Winter	**Spring**	**Summer**	**Autumn**	**Mean**
1982–83	207	208	537	297	312
1992–93	127	162	419	154	216
1998		82	129	60	90
	Laizhou Bay	**Bohai Bay**	**Liaodong Bay**	**Central Part**	**Mean**
1982–83	412	162	325	394	312
1992–93	535	90	96	186	216
1998	76	90	96	89	90

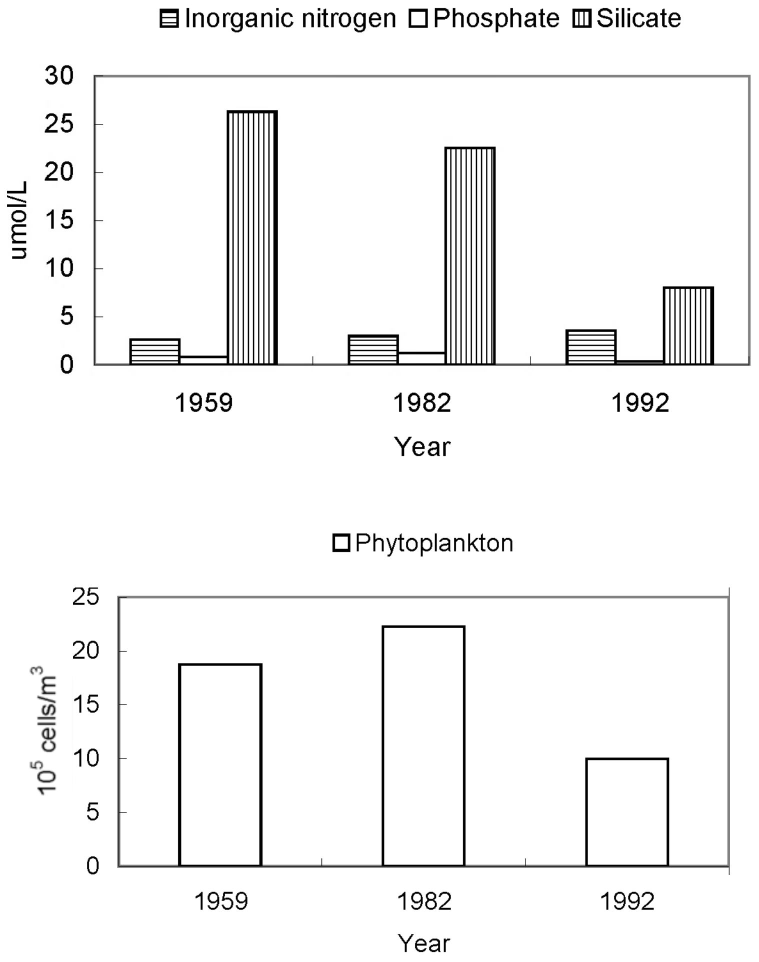

Fig. A5.11 Concentration of inorganic nitrogen, phosphate and silicate in the Bohai Sea (top panel). Phytoplankton density in the Bohai Sea (bottom panel) (adapted from Tang *et al.* 2003).

Zooplankton

In the Bohai Sea, the dominant zooplankton species include *Calanus sinicus*, *Euphausia pacifica*, *Sagitta crassa*, and *Themisto gracilipes*, all of which are important food for pelagic and demersal fish and invertebrates. The biomass of zooplankton in the Bohai Sea is lower than that of adjacent areas because of the influence of the warm current, and ranges from 5–50 mg m^{-3} in the north to 25–100 mg m^{-3} in the south. The annual biomass of zooplankton in the Bohai Sea has decreased noticeably since 1959; this is similar to the trend found in the East China Sea (Chen *et al.* 1991). However, there was a large increase in zooplankton biomass in the Bohai Sea in 1998 (Fig. A5.12; Tang *et al.* 2003), possibly due to a decline in the anchovy stock.

In the Yellow Sea, copepods (*Calanus sinicus*, *Paracalanus* sp., *Oithona atlantica*, *Corycaeus affinis*, *etc.*) were the major group comprising 70.1% of the total zooplankton biomass during the 1997–99 period. In 1997 and 1998, the biomass peaked in June, but in 1999, it peaked in October.

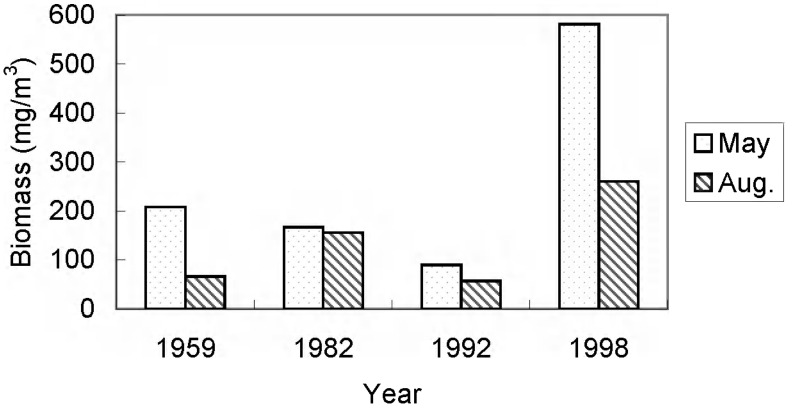

Fig. A5.12 Zooplankton biomass in the Bohai Sea (adapted from Tang *et al.* 2003).

Fishes

The Yellow Sea is one of the most intensively exploited areas in the world. With a remarkable increase in fishing effort and fisheries' expansion in the entire Yellow Sea, large declines in biomass and yields of resource populations in the ecosystem have been demonstrated (Xia 1978; Liu 1979; Chikuni 1985; Tang 1989, 1993; Zhang and Kim 1999).

Hairtail (*Trichiurus lepturus*) and small yellow croaker (*Pseudosciaena polyactis*) were historically the major commercial groundfish species in the Yellow Sea, with catches in 1957 reaching a maximum of about 200,000 and 64,000 tonnes, respectively. However, heavy exploitation caused the biomass of these two species to decline sharply since the mid-1960s. The biomass of the Yellow Sea hairtail was estimated to be only 1/30 of previous levels (Lin 1985), and this decline was accompanied by a substantial reduction in its distribution, and increase in growth rate, earlier maturation, and a decrease in the mean age and body length of adults (Mio and Shinohara 1975; Lee 1977; Zhao *et al.* 1990). After the resources of small yellow croaker (*P. crocea*) off the Jiangsu coast were depleted, the biomass yield of large yellow croaker increased, with the annual catches ranging from 40,000 to 50,000 tonnes, from 1965–75. Due to heavy exploitation of overwintering stocks, the biomass decreased sharply in the early 1980s, and spawning stock size declined to about 1/6 of that in the 1960s.

Concomittant with the decline in dominant Yellow Sea groundfish species, trawl surveys and commercial fishery information have indicated that the biomass of surface pelagic fish (Japanese anchovy, chub mackerel, Spanish mackerel (*Scomberomorus niphonius*) and horse mackerel (*Carangoides malabaricus*) increased continuously since the 1950s. It appears as though groundfish species have been replaced by small, surface pelagic fishes and invertebrates within 2–3 decades. Recent surveys indicate that the abundance of Japanese anchovy is declining (Zhao *et al.* 2003), while the biomass of sandlance (*Ammodytes hexapterus*) is increasing, and the stock of small yellow croaker is showing signs of recovery.

Pacific herring (*Clupea pallasii*), chub mackerel, Spanish mackerel, and butterfish (Stromateidae) are the major, larger-sized pelagic stocks in the Yellow Sea. The annual catch fluctuated widely from 1953–88, ranging from 30,000 to 300,000 tonnes per year, with Pacific herring and chub mackerel stocks fluctuating greatly, but with Spanish mackerel and butterfish stocks appearing to be relatively constant. Commercial use of Spanish mackerel stock began in the early 1960s when both the catch and abundance of small yellow croaker and hairtail decreased. In 1964, the catch was 20,000 tonnes, and has peaked at 200,000 tonnes in recent years, reflecting a steady increase in biomass. The mechanisms for the increase are unclear. However, Spanish mackerel feed on anchovy, which, as mentioned above, have increased in abundance.

Species shift in dominance and mechanisms

Mean trophic levels in both the Yellow Sea and the East China Sea showed an overall decrease. The mean trophic level was approximately 4.2 in 1959, 3.6 during the 1970s (corresponding to carnivores that consume small to large crustaceans), and approximately 3.2 by 1998. The mean trophic level rapidly decreased in the Yellow Sea, and slowly decreased in the East China Sea. Overall, species diversity in the Yellow Sea has decreased from the early 1980s to the late 1990s. Thus it appears as if external stress has affected the self-regulatory mechanism of these ecosystems.

As noted above, dramatic shifts in the dominant species of resource populations in the ecosystem has been observed over the past 50 years, from small yellow croaker and hairtail in the 1950s and early 1960s, to Pacific herring and chub mackerel in the 1970s. These larger, higher trophic level, commercially important species were replaced by smaller, lower trophic level, pelagic, less valuable species (Fig. A5.13). Although these large changes in biomass yield and shifts in species dominance are attributed principally to exploitation, it is not the case for all species. Fluctuation in recruitment of penaeid shrimp, which is a commercially important crustacean distributed in the Bohai Sea and Yellow Sea, provides a good example. Fluctuation in recruitment was related to both environmental influences, and spawning stock size. The relative importance of these two factors varied among years (Tang *et al.* 1989). Pelagic species, such as Pacific herring, are generally responsive to environmental variability, and fluctuations in recruitment can be very large. In the Yellow Sea, there is a long history of exploitation of Pacific herring and in the last century, the commercial fishery has experienced three peaks (*ca.* 1900, 1938, and 1972), followed by periods of little or no catch. Environmental variables such as rainfall, wind and daylight are the major factors affecting recruitment, and long-term changes in abundance may be correlated with the 36-year cycle of dryness/wetness oscillations in the eastern China (Tang 1993, 1995).

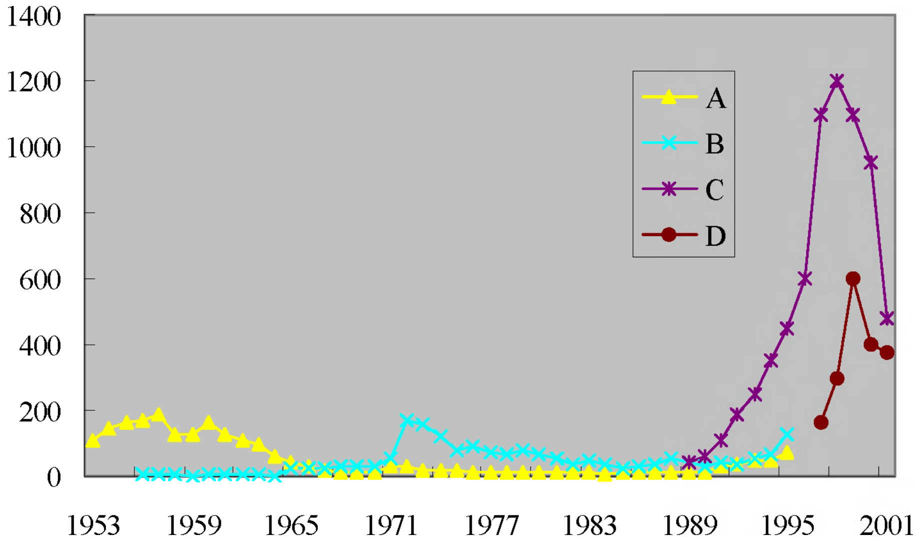

Fig. A5.13 Annual catch (tonnes) of dominant species in the Yellow Sea: (A) small yellow croaker and hairtail, (B) Pacific herring and Japanese mackerel, (C) anchovy, and (D) sandlance (adapted from Tang 2003).

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