PICES SPECIAL PUBLICATION 4

# Marine Ecosystems of the North Pacific Ocean 2003-2008

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Editors
Stewart M. McKinnell and Michael J. Dagg

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The views expressed in this report are those of the participating scientists. Contributions to the report were edited for brevity, relevance, language, and style and any errors that were introduced were done so inadvertently.

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# [Foreword]

**This book is a scientific product of the North Pacific Marine Science Organization (PICES).** The first version entitled “Marine Ecosystems of the North Pacific” was published in 2004 as PICES Special Publication Number 1[*]. It was a pilot project to determine whether a comprehensive overview of the status and trends in the North Pacific could be achieved through voluntary efforts, and once created, whether a report of this nature would be of value to PICES Member Countries. In 2007, following recommendations by the PICES Study Group on Ecosystem Status Reporting, Governing Council and Science Board endorsed the development of a second version of the North Pacific Ecosystem Status Report, adding that it should represent an incremental improvement over the first endeavour. Changes and improvements included:

- Providing a better balance of information among chapters,
- Developing a more comprehensive synthesis by facilitating analysis, inter-comparison, and reporting of results,
- Identifying clearly the target audience for the report,
- Providing better recognition to contributing scientists.

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[*] http://www.pices.int/publications/special_publications/NPESR/2005/npesr_2005.aspx

# [foreword]

The focus period of this book is 2003-2008. The basic information is organized around eight (originally nine) regional chapters. These summarize ecosystem status and trends in the four marginal seas, the four coastal boundary currents, and the large oceanic region at their centre. The boundary current chapters have a focus on the region from the coastline out to and including the continental slope and the adjacent boundary currents. The oceanic region includes everything beyond the boundary current/continental slope that is not in a marginal sea. The development of each regional chapter was the responsibility of a Lead Author who recruited a team of scientists with expertise in the region to contribute to the chapter. A common framework was provided by the editors to facilitate comparisons among the regions.

The schedule planned for a five month period of analysis/synthesis before a synthesis workshop was convened from December 1-4, 2009 in Honolulu, USA. The workshop was convened:

- to review findings within individual regions,
- to compare status and trends among regions,
- to review and discuss synthesis results from regional teams,
- to understand the cause(s) of variation/trends, with attention to regional, basin-scale, global forces,
- to reach agreement on what to include in the synthesis, and
- to write its first draft before leaving Honolulu.

The anticipated products of the project were:

- A PICES Special Publication containing the scientific synthesis and regional chapters.
- A collection of data files with the time series and other data that were used to create the figures in the Special Publication. These files would permit standardized figure formats in each chapter, and provide the data required for analysis and synthesis and the creation of figures for the synthesis.
- A scientific paper written jointly by the Lead Authors and rest of the synthesis team for the primary scientific literature.
- A PICES Brochure containing a summary of important highlights for non-scientific audiences.

The intended audience for this book is primarily scientists involved in the study of climate and marine ecosystems of the North Pacific Ocean, but also includes governments who deal with issues of understanding, use, policy, and management of North Pacific marine systems, and the general public. It is our hope and expectation that as the North Pacific ecosystem status report becomes more complete and more available, each of these groups will find that it stimulates and leads to new connections and new understanding of the North Pacific Ocean.

This book was made possible through the efforts of many volunteer scientists from PICES Member Countries, especially the Lead Authors of the regional chapters who were responsible for amassing such a diversity of information and the synthesis team that was responsible for summarizing the major findings. The Synthesis chapter received the benefit of comments provided by Roger Harris, Paul Harrison, James Overland, Franklin Schwing, and Jake Rice. The regional chapters did not have a formal review but they were subject to the scrutiny of the editors and advisors. Workshops hosted by our Korean colleagues at the Novotel Hotel in Busan in 2009 and by our American colleagues at the NOAA/Auke Bay Laboratories in Juneau, Alaska in 2009 made important contributions to this report. The North Pacific Anadromous Fish Commission (NPAFC) was invited and agreed to lead the development of the Pacific salmon sections of the Oceanic and Synthesis chapters. Their participation in this project is greatly appreciated. The North Pacific Research Board generously offered us access to their photograph collection. Special thanks to Wayne Barnes of Tofino Photography and to Mr. Y. Itayama (Yomiuri Shimbum), who have no affliation with PICES, for allowing us to use their photographs of a black bear with squid, and giant jellyfish.

Stewart M. McKinnell and Michael J. Dagg

Participants at the Synthesis workshop, December 1-4, 2009: [Front] Akihiko Yatsu, Sanae Chiba, Jennifer Boldt, Nick Bond, Sonia Batten, Young Jae Ro, Sinjae Yoo; [Middle] Jim Irvine, Frank Whitney, Hiroya Sugisaki, Dave Mackas, Mike Foreman, George Hunt, Steve Bograd; [Back] Skip McKinnell, Mike Dagg, Vyacheslav Lobanov, Oleg Katugin. Missing from the photograph are Phil Mundy, Ian Perry, Vladimir Radchenko, John Stein, Sun Song, and local participants Jeff Polovina, Mike Seki, Phoebe Woodworth.

# Marine Ecosystems of the North Pacific Ocean 2003-2008

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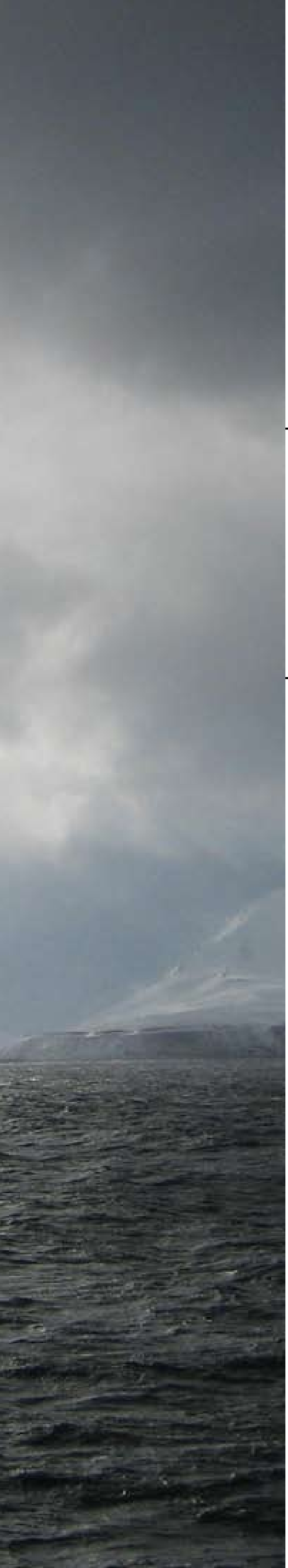

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# North Pacific Synthesis

Citation:

McKinnell, S.M., Batten, S., Bograd, S.J., Boldt, J.L., Bond, N., Chiba, S., Dagg, M.J., Foreman, M.G.G., Hunt Jr., G.L., Irvine, J.R., Katugin, O.N., Lobanov, V., Mackas, D.L., Mundy, P., Radchenko, V., Ro, Y.J., Sugisaki, H., Whitney, F.A., Yatsu, A., Yoo, S. 2010. Status and trends of the North Pacific Ocean, 2003-2008, pp. 1-55 In S.M. McKinnell and M. J. Dagg. [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

# highlights

An international, intergovernmental panel of scientists from PICES Member Nations has described the status and trends of climate and marine ecosystems in the North Pacific Ocean with special attention to a *focus period* from 2003-2008.

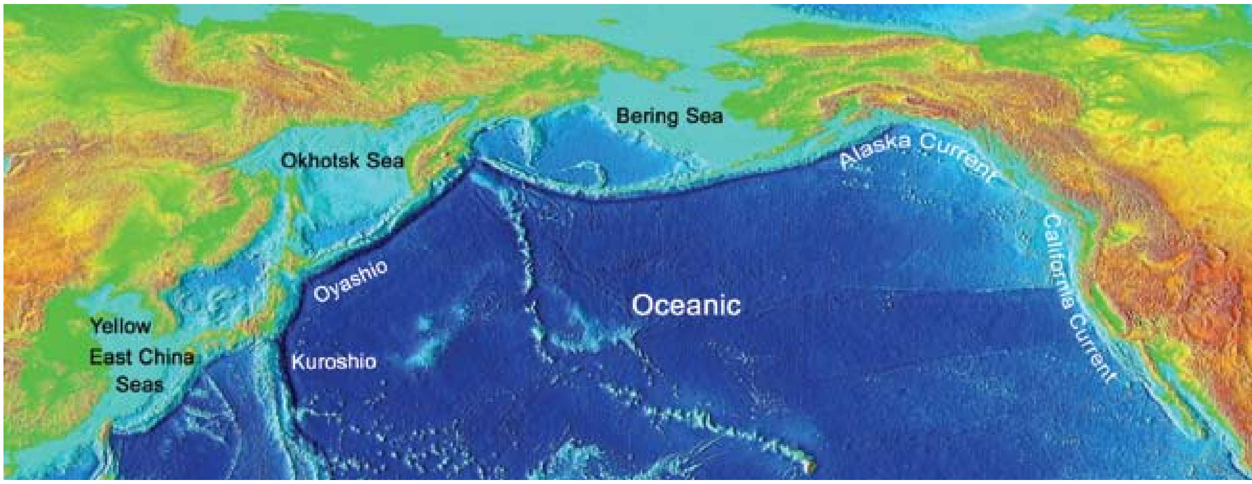
- The focus period was characterized by enhanced climatic and ecological variability, particularly in the eastern North Pacific where extreme values in some time series were observed. Within a span of three years, the annual average ocean surface temperature in the Gulf of Alaska went from one of the warmest in the last 100 years (2005) to one of the coldest (2008). In contrast, the surface layer of the Western Subarctic Gyre was warmer in 2008 than most of the last century. The marginal seas in the western North Pacific were warmer in recent years but much of the trend was due to an abrupt increase that occurred in the late 1980s.

- Following the 2002-2003 El Niño, the normally dominant Pacific Decadal Oscillation (PDO) climate pattern was markedly diminished and did not re-emerge until October 2007 when an abrupt shift to negative PDO values occurred.

- Areas of the subtropical North Pacific with low surface chlorophyll ($<0.07\ \mathrm{mg \cdot m^{-3}}$) expanded in size by about 2.2% $\mathrm{y^{-1}}$ from 1998-2006, accompanied by significant increases in average sea surface temperature.

- Apart from a relatively cooler period with more sea ice from 1998-2002, sea ice extent in the Sea of Okhotsk has continued a downward trend since 1978 in all ice seasons. Bering Sea ice extent was generally without trend during winters since 1978 but spring and fall saw abrupt and persistent declines in 1997. Small amounts of sea ice remained in the Bering Sea in July before the focus period but this disappeared during the focus period. The years from 2006-2008 saw increasing amounts of ice in the eastern Bering Sea.

- In general there were no significant changes in nutrient concentrations during the focus period, although there is a long-term downward trend in phosphate concentrations in the Oyashio region.
- During the summer of 2008 there was an atypical bloom of phytoplankton across the North Pacific. Its cause is a subject of ongoing investigation as this part of the North Pacific is classified as a high nitrogen, low chlorophyll region because of iron limitation.
- The amount of hypoxic water (low in oxygen) has increased along the North American continental margin. As a result, mobile species move to shallower depths where there is more oxygen. In extreme events like the summer of 2006, anoxia (no oxygen in the water) killed many benthic animals off the coast of Oregon. Oxygen concentrations at intermediate ocean depths are decreasing across the subarctic North Pacific and the cause appears to be the freshening of the mixed layer and reduced ventilation due to the effects of ocean/atmosphere warming at source locations of this water in the Sea of Okhotsk and northwestern Pacific.
- Productivity patterns in the California Current zooplankton community were relatively coherent throughout the region until the 1997-1998 El Niño. Thereafter the community south of the southern California Bight became inversely correlated with the community to the north. The change represents a remarkable reorganization and/or poleward shift of patterns of lower trophic level productivity that has persisted to the present.
- The most dramatic biological changes in the Asian marginal sea regions have occurred in populations of gelatinous macrozooplankton, where medium and large sized jellyfish have become very abundant in recent years.
- The first effects of water impoundment by the Three Gorges Dam (Changjiang River, China) that began in 2003 are being observed downstream in the East China Sea, with less discharge and reduced sediment volumes. One result of damming and fertilizer use is that much more nitrate and less silicate are being discharged into the coastal ocean which could increase blooms of nuisance algae.
- The total catch of Pacific salmon (*Oncorhynchus* spp.) in the North Pacific was the highest on record during the focus period. The increase is due to increased catches in Asia. In contrast, endangered species legislation is being used to try to prevent extirpations in the California Current region. Pacific salmon populations at the southern ends of their range on both sides of the Pacific Ocean generally have experienced low marine survival and reduced abundance.
- The biomass of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea declined because the focus period was part of an unprecedented sequence of years of low recruitment. The Oscillating Control Hypothesis (Hunt et al. 2002) had anticipated better recruitment during the warmer years of the focus period (2003-2005) but it did not materialize, and poor recruitment during the colder years (2006-2008) which did occur.



[Figure S-1] Regional organization of the chapters of the PICES report on Marine Ecosystems of the North Pacific Ocean, 2003-2008.

# Introduction

The report on which this synthesis is based, includes eight regional chapters (Fig. S-1) each of which was prepared under the guidance and supervision of a Lead Author. Each was asked to report on ecosystem status and trends according to a common framework of physical/ecological themes. Lead Authors were responsible for selecting regional specialists to participate as co-authors. After the regional chapters were completed, the Lead Authors met at a workshop in Honolulu, USA from December 1 to 4, 2009 to compare and contrast the nature of regional variability, and to develop thematic summaries of how, why, and where the North Pacific is changing, or not. This synthesis was written at or immediately after the workshop by an international group of senior scientists who were invited to volunteer for that purpose. After several iterations, a draft was sent to four readers who were not involved in the project and whose comments influenced what appears in this chapter and how it appears. The regional chapters were not sent for independent examination but their contents were made available to the synthesis team and were the subject of considerable attention. The period of greatest interest to this report (hereafter, the *focus period*) is 2003-2008, but analyses and descriptions of the focus period were interpreted within the context of historical observations.

If the 8 regions of the North Pacific Ocean can be considered as the rows of a matrix, the crosscutting synthesis activities reported in this chapter represent its columns (Climate, Physical, Chemical, Biological, Fishes and Invertebrates, Marine Birds and Mammals). The Climate section recognizes that the ocean and atmosphere form a single physical system but this section places greater emphasis on describing the atmosphere while the section on the Physical Ocean deals with circulation and hydrography and the forces, including climate, that cause these to vary. The section on the Chemical Ocean considers variability in some of the major nutrients that are dissolved in seawater. The Biological Ocean was split into chlorophyll/phytoplankton and zooplankton subsections in consideration of the diversity of taxa at these lower trophic levels. The Fish and Invertebrates section emphasizes the biological attributes of exploited species including their abundance (biomass), age, growth, and survival. Where these were not available, commercial catch often provided the only information on some species. Finally, the section on Marine Birds and Mammals was developed after the workshop by a survey of literature and/or researchers that may not have contributed to the regional chapters.

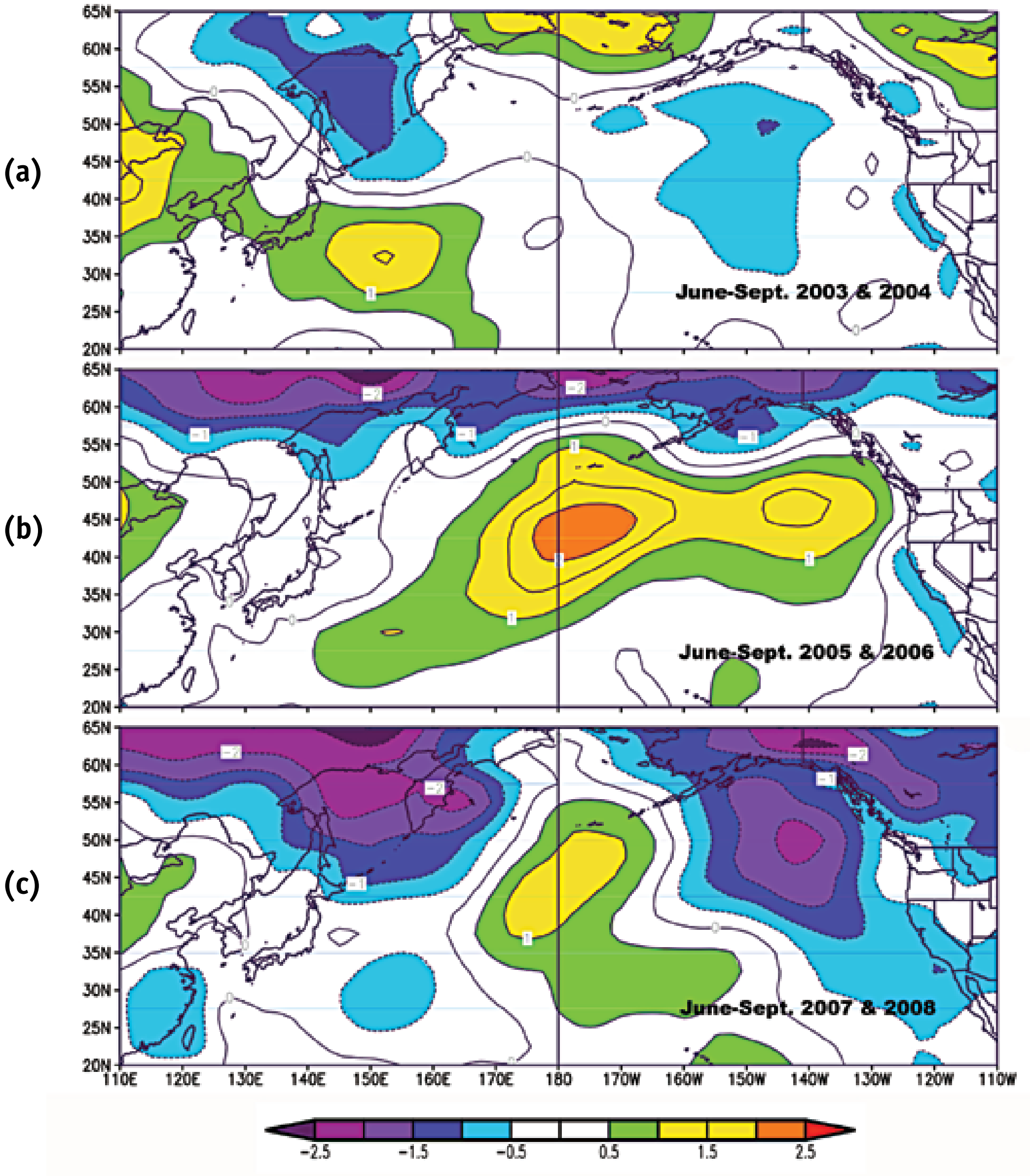
## 2.0 Climate *(Bond)*

The large-scale atmospheric forcing of the North Pacific during the boreal winter can be usefully characterized in terms of a few modes of variability. The Pacific-North American (PNA) pattern is associated with pressure, wind and temperature anomalies predominantly over the central and eastern North Pacific. The PNA relates to the strength and location of the Aleutian Low (AL), which itself is often characterized in terms of an area-averaged sea-level pressure (SLP), the North Pacific index (NPI). The PNA and NPI are correlated with, if not tightly coupled to, the tropical Pacific atmosphere-ocean system, i.e., El Niño/Southern Oscillation (ENSO). They also correspond with the primary mode of North Pacific sea surface temperature (SST) variability, the Pacific Decadal Oscillation (PDO). The atmospheric mode with the strongest expression in the western North Pacific is the West Pacific (WP) pattern. This mode consists of a north-south dipole in SLP and relates to the latitude and intensity of the entrance region of the Pacific jet stream. Its variations have not been linked to a specific oceanographic mode *per se*, but do relate to the temperature and latitude of the Oyashio, and the strength and latitude of the Kuroshio.

During the focus period of 2003-2008, the wintertime AL was initially strong (SLP was lower than average) but it weakened throughout the period. Some of this variability can be attributed to the extratropical influences of ENSO. The moderate El Niño of 2002-2003 and La Niña of 2007-2008 were accompanied by SLP patterns that are typical of past ENSO events, but the SLP and wind anomalies observed during the winter of 2006-2007 were atypical for the weak El Niño that was prevailing then. The extremely weak AL of late 2008 was coincident with relatively modest La Niña conditions. The lack of correspondence between the tropical Pacific atmosphere-ocean climate system and North Pacific atmospheric circulation during the focus period is a reminder that the latter has its own intrinsic variability and additional influences related to the underlying ocean (e.g., Nakamura et al. 2004), solar variability (e.g., Meehl et al. 2008) and others forcings.

### 2.1 Sea level pressure

The variability of the North Pacific atmospheric forcing during the warm season has not received much attention from the climate community. These variations tend to be smaller than their counterparts during the cold season, but may have a disproportionate effect on the biota since the oceanic mixed layer is shallow at this time of year. With this in mind, the atmospheric states during summers in the focus period are summarized as maps of mean SLP anomalies for June-September of 2003-2004 (Fig. S-2a), 2005-2006 (Fig. S-2b) and 2007-2008 (Fig. S-2c). Years were grouped based on the similarity of their SLP patterns. The summers of 2003-2004 had higher than normal SLP from east of Japan to the dateline and over the Bering Sea, which implies suppressed storminess and cloud cover (Norris 1998). Lower than average SLP was present over the Sea of Okhotsk and to a lesser extent over the eastern North Pacific. The summers of 2005-2006 featured relatively high SLP in the central North Pacific, indicating anomalous westerly (easterly) winds in the northern (southern) portion of the basin. The summers of 2007-2008 included anomalously high SLP in the central portion of the basin and low SLP in the Sea of Okhotsk and Gulf of Alaska. This pattern created greater low-level poleward flow in the northwestern Pacific and equatorward flow from the eastern Bering Sea through the western Gulf

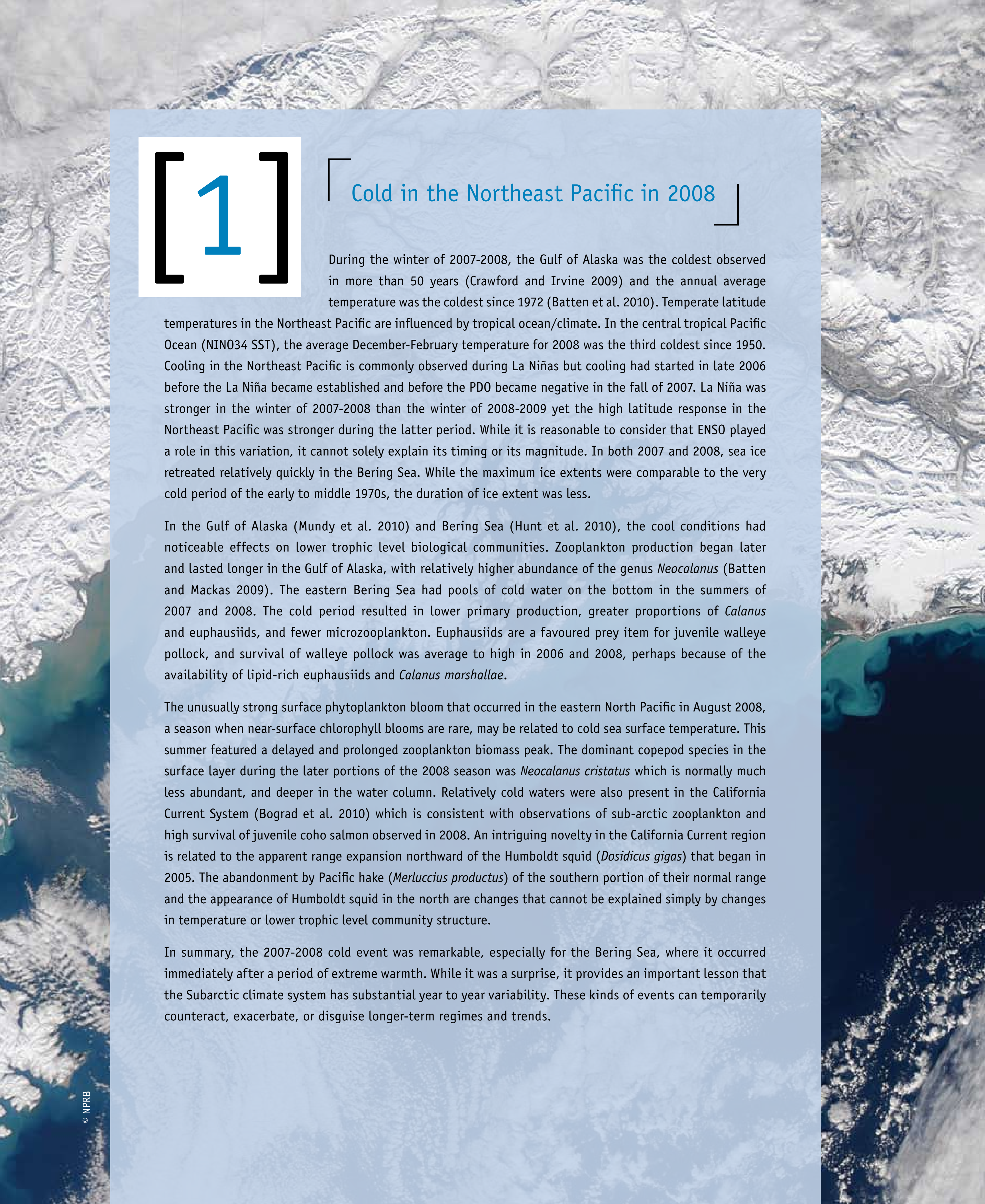


[Figure S-2] Average summer SLP anomalies (hPa) from June to September in (a, upper) 2003-2004, (b, middle) 2005-2006, and (c, lower) 2007-2008. Figures are courtesy of NOAA/ESRL Physical Sciences Division from NCEP/NCAR re-analysis data. The climatology used to compute the anomalies is 1968-1996.

of Alaska. In a general sense, the summer atmospheric conditions helped to reinforce what the winter had created in the northern part of the basin. In summary, the climate of the North Pacific from 2003-2008 can be characterized by relatively high frequency variability in the east, and with multi-year trends in the west, and overall weaker persistence than typical 6-year periods in the past. We now consider some highlights on how specific variations and trends were expressed.

## 2.2 Eastern Pacific

One of the most prominent climate events in the North Pacific during the focus period was the cooling of Bering Sea and Gulf of Alaska waters in 2007 that lasted through 2008 (and into 2009). Weaker Aleutian Lows tend to produce a cooler water column. Air masses associated with major storms tend to have a maritime origin and hence are warmer than those associated with high pressure centers which tend to be of continental or Arctic origin (Rodionov



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## [1]

## Cold in the Northeast Pacific in 2008

During the winter of 2007-2008, the Gulf of Alaska was the coldest observed in more than 50 years (Crawford and Irvine 2009) and the annual average temperature was the coldest since 1972 (Batten et al. 2010). Temperate latitude temperatures in the Northeast Pacific are influenced by tropical ocean/climate. In the central tropical Pacific Ocean (NINO34 SST), the average December-February temperature for 2008 was the third coldest since 1950. Cooling in the Northeast Pacific is commonly observed during La Niñas but cooling had started in late 2006 before the La Niña became established and before the PDO became negative in the fall of 2007. La Niña was stronger in the winter of 2007-2008 than the winter of 2008-2009 yet the high latitude response in the Northeast Pacific was stronger during the latter period. While it is reasonable to consider that ENSO played a role in this variation, it cannot solely explain its timing or its magnitude. In both 2007 and 2008, sea ice retreated relatively quickly in the Bering Sea. While the maximum ice extents were comparable to the very cold period of the early to middle 1970s, the duration of ice extent was less.

In the Gulf of Alaska (Mundy et al. 2010) and Bering Sea (Hunt et al. 2010), the cool conditions had noticeable effects on lower trophic level biological communities. Zooplankton production began later and lasted longer in the Gulf of Alaska, with relatively higher abundance of the genus *Neocalanus* (Batten and Mackas 2009). The eastern Bering Sea had pools of cold water on the bottom in the summers of 2007 and 2008. The cold period resulted in lower primary production, greater proportions of *Calanus* and euphausiids, and fewer microzooplankton. Euphausiids are a favoured prey item for juvenile walleye pollock, and survival of walleye pollock was average to high in 2006 and 2008, perhaps because of the availability of lipid-rich euphausiids and *Calanus marshallae*.

The unusually strong surface phytoplankton bloom that occurred in the eastern North Pacific in August 2008, a season when near-surface chlorophyll blooms are rare, may be related to cold sea surface temperature. This summer featured a delayed and prolonged zooplankton biomass peak. The dominant copepod species in the surface layer during the later portions of the 2008 season was *Neocalanus cristatus* which is normally much less abundant, and deeper in the water column. Relatively cold waters were also present in the California Current System (Bograd et al. 2010) which is consistent with observations of sub-arctic zooplankton and high survival of juvenile coho salmon observed in 2008. An intriguing novelty in the California Current region is related to the apparent range expansion northward of the Humboldt squid (*Dosidicus gigas*) that began in 2005. The abandonment by Pacific hake (*Merluccius productus*) of the southern portion of their normal range and the appearance of Humboldt squid in the north are changes that cannot be explained simply by changes in temperature or lower trophic level community structure.

In summary, the 2007-2008 cold event was remarkable, especially for the Bering Sea, where it occurred immediately after a period of extreme warmth. While it was a surprise, it provides an important lesson that the Subarctic climate system has substantial year to year variability. These kinds of events can temporarily counteract, exacerbate, or disguise longer-term regimes and trends.

et al. 2007). It is also interesting that the anomalous cooling in the Bering Sea and enhanced ice coverage during the winter of 2007-2008 came after a record minimum sea ice extent in the central Arctic (September 2007). While the delay in the development of ice in the Chukchi Sea did result in anomalously warm air masses early in winter, the atmospheric circulation was sufficiently unusual to swamp those effects. While the Bering Sea has remained cold through 2009, the Gulf of Alaska has been more moderate. In light of the El Niño conditions prevailing at the time of this writing (winter 2009-2010), the cold event is not likely to persist.

## 2.3 Western Pacific

The mean winter WP index was significantly higher during the focus period than in the period from 1950-2002 (Chiba et al. 2010). The index reflects variability in the latitude where the Pacific jet stream enters the North Pacific and the dynamics of the East Asian monsoon (Wallace and Gutzler 1981). A positive WP index is associated with positive westerly wind anomalies in a band between 40°N and 50°N across the North Pacific. Enhanced equatorward Ekman transports are one consequence of enhanced westerly winds in this band, where positive (negative) wind stress curl and Ekman pumping occur on the north (south) side of the band. Relatively cooler surface temperatures in the Oyashio and a latitudinal contraction of the transition zone between the Oyashio and Kuroshio occurred during the focus period (Chiba et al. 2010). Previous studies (e.g., Miller et al. 1998) have shown that variability in the strength of the Aleutian Low and resultant changes in thermocline depth from anomalous Ekman pumping can be communicated to the western North Pacific through upper-ocean Rossby waves. Chiba et al. (2010) and Sugisaki et al. (2010) describe how climate variability in the western North Pacific can also be important to regional ocean conditions. Easterly wind anomalies along 30°N and west of about 140°E that are associated with a positive WP index should have reinforced the effects of a weaker winter Aleutian Low in the last few years, tending to produce a weaker Kuroshio.

Average winter air temperatures in the Sea of Okhotsk region have been significantly warmer (approximately 1-3°C depending on location) during the last two decades (Fig. S-3; Radchenko et al. 2010). The increase was attributed to a preponderance of warm versus cold atmospheric circulation patterns in the region (Glebova 2006). The mean winter winds over the Sea of Okhotsk are from the north due to the east-west gradient in SLP between the Siberian High and the Aleutian Low. Strengthening (diminishing) this gradient is associated with colder (warmer) air temperature and greater (lesser) sea ice extent. Along with generally warmer winters, sea ice extent in the Sea of Okhotsk has been decreasing since the late 1970s (Radchenko et al. 2010) although different analyses are producing different results on this topic (Markus et al. 2009). While weaker Aleutian Lows in the winters of 2006-2008 tended to suppress the northerly winds in the Sea of Okhotsk, it appears that systematic changes in the Siberian High may also play a dominant role. The linear trend in average October-March SLP shown in Fig. S-4 reveals a marked decrease in average SLP over a broad area of Siberia and the Aleutian Low region and there are concomitant increasing trends in surface air temperature over roughly the same region. The magnitude of the increase is more than triple that observed at Sitka in southeast Alaska which is at an equivalent latitude (Mundy et al. 2010).

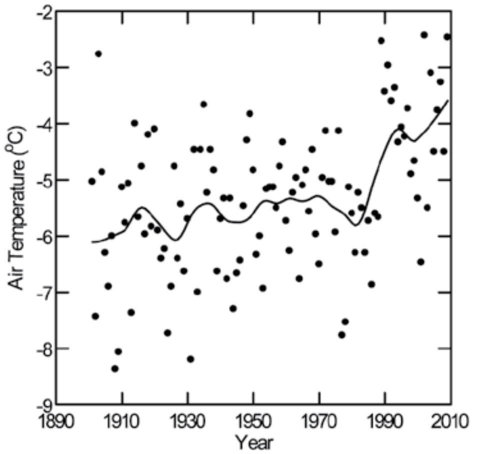
## 2.4 Disentangling climate variability

Improved understanding of the climate of the North Pacific during the last decade has led to a much greater appreciation of the diversity of sources of North Pacific climate variability. Understanding the relationships between the forces that give rise to the North Pacific Gyre Oscillation (NPGO) and other modes of the climate system such as the PDO and ENSO are improving (Di Lorenzo et al. 2008), especially in the central and eastern North Pacific. Conceivably, similar linkages will tie the western Pacific and East Asian summer and winter monsoons to other aspects of the large-scale atmosphere-ocean system. Nevertheless, predictability of the North Pacific climate system and its sub-regions is not well developed. ENSO events provide some measure of predictability but as was exemplified during the focus period, their remote influences are at least modulated and sometimes swamped by other effects. The extent to which these effects are mechanistic rather than stochastic in the climate system is an open question and the subject of ongoing research.

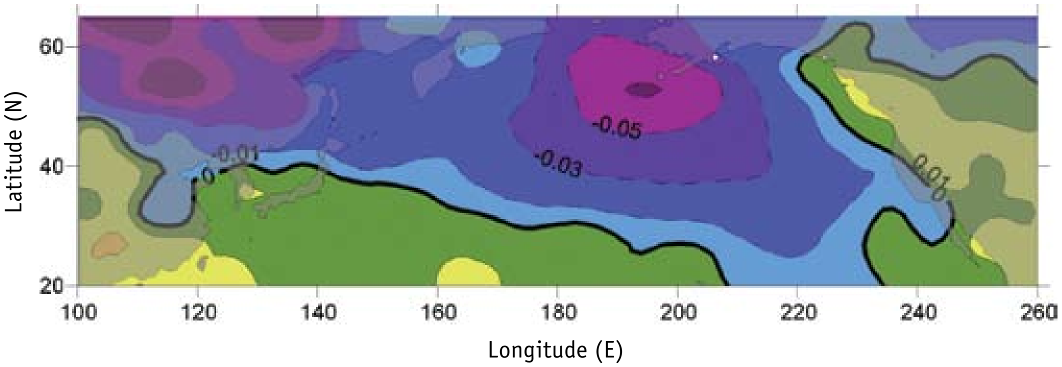
[2]

## Diminishing Sea Ice in the Sea of Okhotsk

The Sea of Okhotsk has the greatest amount of seasonal sea ice in the North Pacific and since the late 1970s, its maximum extent has been shrinking. This is likely due to changes in the mean state of the regional atmosphere (see Radchenko et al. 2010 for details). Average winter air temperatures in the region have been warmer, especially since 1989 (Fig. S-3). There is evidence that this reduction in sea ice could have significant feedback to the atmosphere, not just in a regional thermodynamic sense, but from a larger-scale circulation perspective (e.g., Honda et al. 1999). Regardless of whether sea ice anomalies have a significant effect on the overlying atmosphere, this region may be an important harbinger of climate change. Any high-latitude continental region should reveal the effects of climate change relatively early because wintertime temperatures are dominated by radiative effects, which are in turn relatively sensitive to carbon dioxide concentrations since water vapor concentrations are low in these regions. Whether or not the Sea of Okhotsk is a "canary in the coal mine" for climate change, observed changes in the chemistry and biology of the Sea of Okhotsk and Northwest Pacific Ocean are consistent with the ocean-atmosphere changes in the region. Weakened cooling slows the ventilation of the intermediate waters that form an upstream source of the Subarctic Gyre. Less oxygen in these source waters may ultimately contribute to more severe hypoxia and anoxia after they arrive in the eastern North Pacific (see Box 5).



[Figure S-3] Mean January-March air temperature at Abashiri, Japan (44°01'N 144°17'E) on the south coast of the Sea of Okhtosk. An abrupt shift to higher average winter temperatures occurred in 1989 following an untrended period from 1901-1988. The winter of 1989 also featured abrupt shifts in climate patterns (Victoria Mode and Arctic Oscillation). Data from Japan Meteorological Agency.



[Figure S-4] Contours indicate the sign and magnitude of linear trends (hPa·$y^{-1}$) in October-March average SLP from 1949-2009. While the trends (slopes) are of equivalent strength in the Siberian High and Aleutian Low regions, there is greater uncertainty in the Aleutian Low trend (not shown).

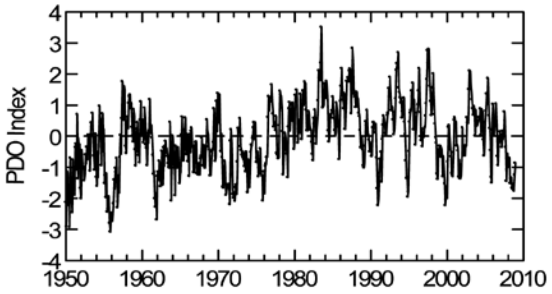
# 3.0 Physical Ocean *(Foreman)*

Each region in the North Pacific can be characterized by one or more physical properties or processes that are important to the productivity of its respective ecosystem. As many of these features are direct responses to atmospheric forcing, there are strong links to the oceanic variations described here and the climatic variations and trends described above.

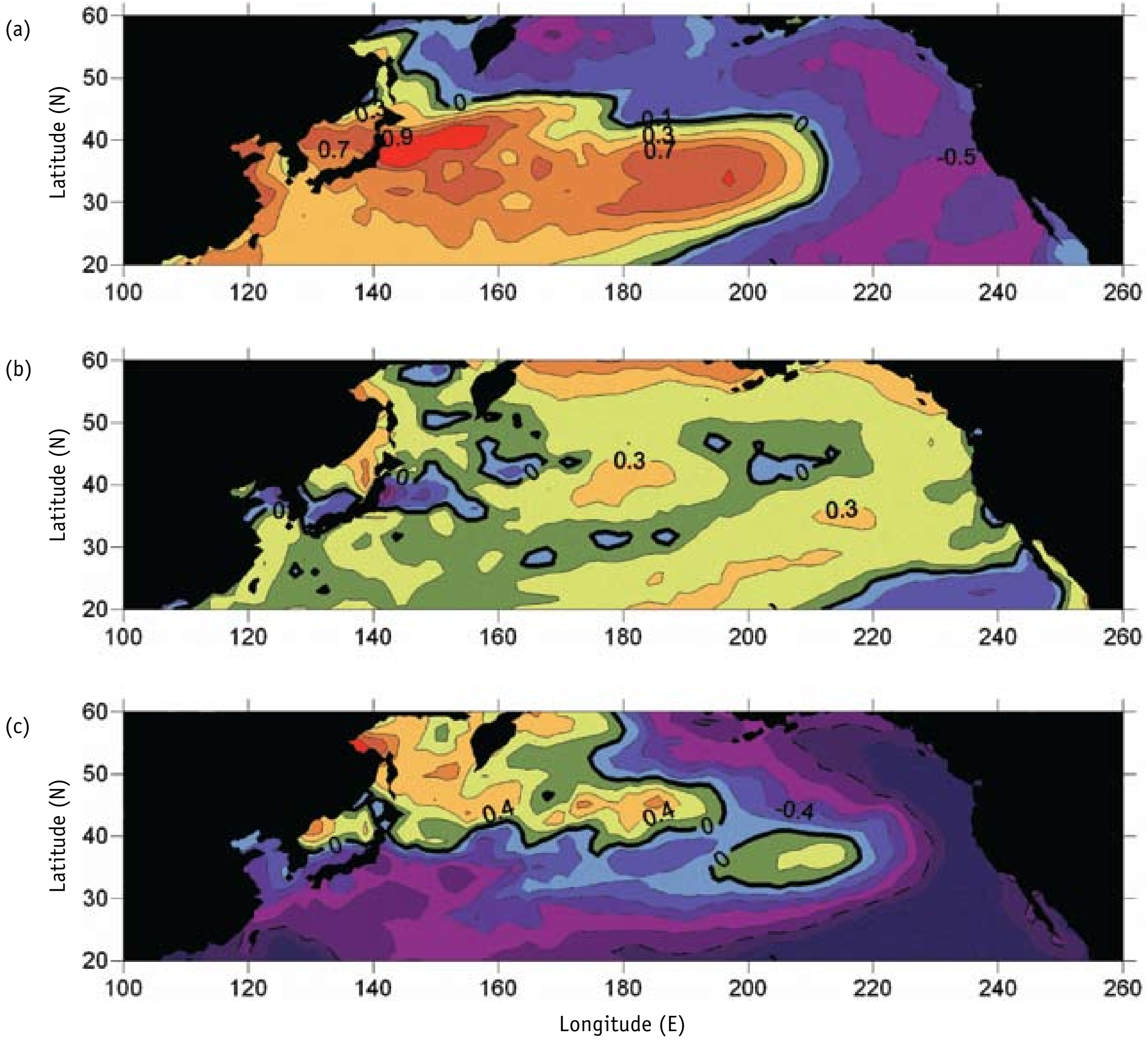
Temperature is a key water property that affects ecosystem productivity throughout the North Pacific and with the exception of the Kuroshio whose temperatures remained relatively constant over the focus period, there were significant temperature variations in all other regions. In the Oceanic region, temperature variations in space and time tend to exhibit the patterns of the PDO and Victoria modes (or the NPGO mode computed from sea surface height) as was the case after late 2007. In the California Current System, upwelling is the key process affecting ecosystem productivity, though the same PDO/NPGO and sometimes ENSO signals can be influential. In the Alaska Current region, freshwater input and oceanic eddies have important ecosystem roles because they affect ocean productivity. In both the Bering Sea and Sea of Okhotsk, the seasonal development of sea ice and the timing of its retreat are critical. Though both of these regions have relatively large freshwater inputs via the Yukon and Amur Rivers respectively, only the latter seems to play a significant role in ecosystem productivity as the Yukon plume generally moves northward toward Bering Strait and has relatively little effect on the sea. The most important physics affecting the Oyashio region are upstream conditions in the Western Subarctic Gyre and the Sea of Okhotsk where tidal mixing in the Kuril Island archipelago plays a key role in establishing the properties of water in the Sea of Okhotsk outflow. Meanders, eddies and transport strength are the most important characteristics in the Kuroshio. Finally, in the Yellow and East China Seas, inflows from the Kuroshio and Changjiang River are key factors in determining ecosystem productivity.

## 3.1 Ocean climate indices

Ocean climate indices reflect patterns of spatial and temporal variation in the sea that are caused by their interaction with the overlying atmosphere. The PDO is an important large-scale pattern of variation in sea surface temperature in the North Pacific. The PDO index tends to reflect whether the North American coastline is warm (cool) when the central and western North Pacific is cool (warm). The PDO index was positive following the 2002-2003 El Niño but diminished to become relatively neutral through most of the focus period. It switched abruptly to negative in September 2007 and remained negative through December 2008 (Fig. S-5). The focus period began with the 2002-2003 El Niño with warmer (cooler) surface temperature anomalies in the eastern (western) Pacific. However, Figure 6b shows that what followed through most of the focus period was a basin-wide warm SST pattern that, on average, was relatively uniform compared to the typical PDO patterns both before the focus period (Fig. S-6a) and after (Fig S-6c). The Bering Sea experienced unusually warm temperatures from 2002 to 2005 followed

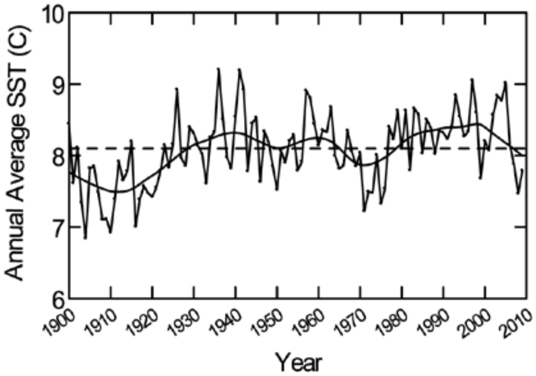


[Figure S-5] Monthly values of the Pacific Decadal Oscillation Index, 1950-2009.



[Figure S-6] Average SST anomalies within the periods: (a- upper panel) May 1998-August 2002, (b- middle panel) September 2002-September 2007, and (c- lower panel) October 2007-December 2008 (end of focus period). Periods were determined from zero crossings of the PDO index.

by cooling through 2006 to reach the coldest temperatures observed since the 1970s through the remainder of the focus period and into 2009. The relatively neutral PDO Index suggests that the PDO pattern was absent during most of the focus period. Beginning in the fall of 2007, region-wide surface temperatures in the Gulf of Alaska were colder than at any time since the early 1970s (Fig. S-7). The rapidity of this change is comparable to that which occurred in 1998, but that earlier transition was accompanying a strong shift from the intense El Niño of 1997 to the La Niña of 1998. The abrupt shift in the PDO was not accompanied by as dramatic a shift in ENSO. By way of comparison, the shift to negative PDO in 2007 is similar in magnitude to the strong positive shift that occurred around 1977.



[Figure S-7] Area-weighted annual average SST in the Northeast Pacific north of 50°N and east of 160°W from 1900 to 2009 with loess smoother indicating trend. Horizontal dashed line is the mean of the time series (8.1°C). Data source is Smith et al. (2007).

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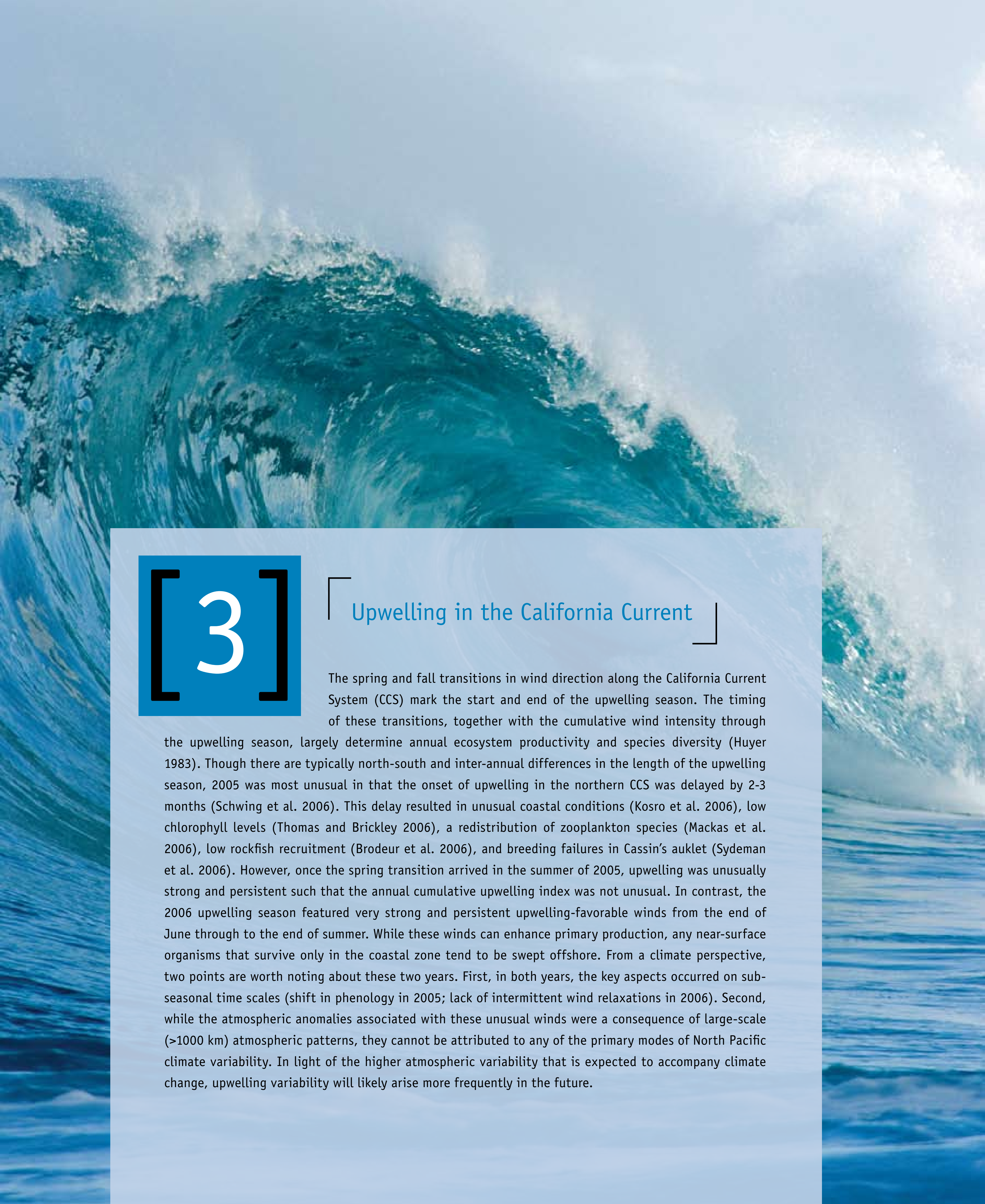
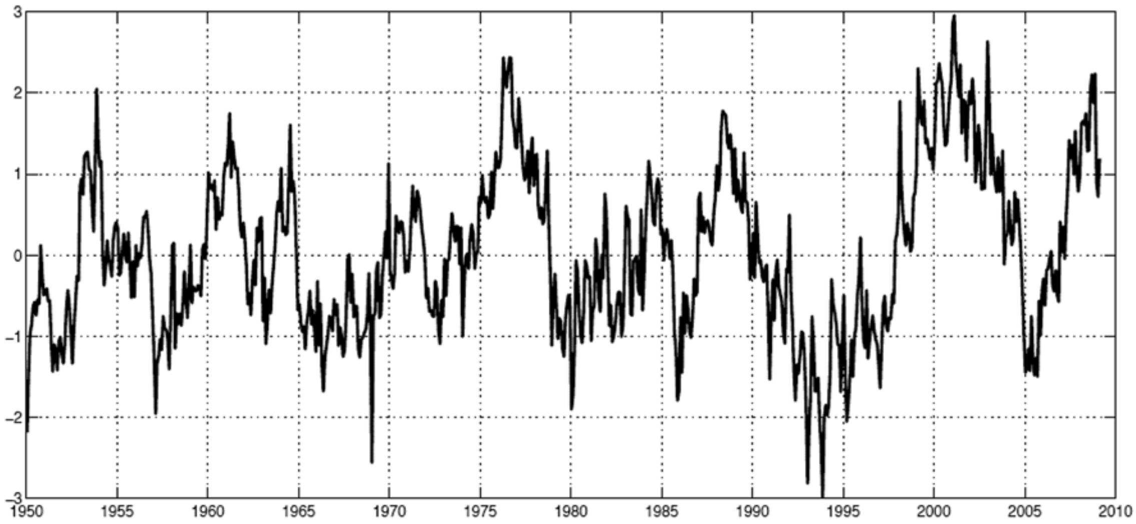


# [3]

# Upwelling in the California Current

The spring and fall transitions in wind direction along the California Current System (CCS) mark the start and end of the upwelling season. The timing of these transitions, together with the cumulative wind intensity through the upwelling season, largely determine annual ecosystem productivity and species diversity (Huyer 1983). Though there are typically north-south and inter-annual differences in the length of the upwelling season, 2005 was most unusual in that the onset of upwelling in the northern CCS was delayed by 2-3 months (Schwing et al. 2006). This delay resulted in unusual coastal conditions (Kosro et al. 2006), low chlorophyll levels (Thomas and Brickley 2006), a redistribution of zooplankton species (Mackas et al. 2006), low rockfish recruitment (Brodeur et al. 2006), and breeding failures in Cassin's auklet (Sydeman et al. 2006). However, once the spring transition arrived in the summer of 2005, upwelling was unusually strong and persistent such that the annual cumulative upwelling index was not unusual. In contrast, the 2006 upwelling season featured very strong and persistent upwelling-favorable winds from the end of June through to the end of summer. While these winds can enhance primary production, any near-surface organisms that survive only in the coastal zone tend to be swept offshore. From a climate perspective, two points are worth noting about these two years. First, in both years, the key aspects occurred on sub-seasonal time scales (shift in phenology in 2005; lack of intermittent wind relaxations in 2006). Second, while the atmospheric anomalies associated with these unusual winds were a consequence of large-scale (>1000 km) atmospheric patterns, they cannot be attributed to any of the primary modes of North Pacific climate variability. In light of the higher atmospheric variability that is expected to accompany climate change, upwelling variability will likely arise more frequently in the future.

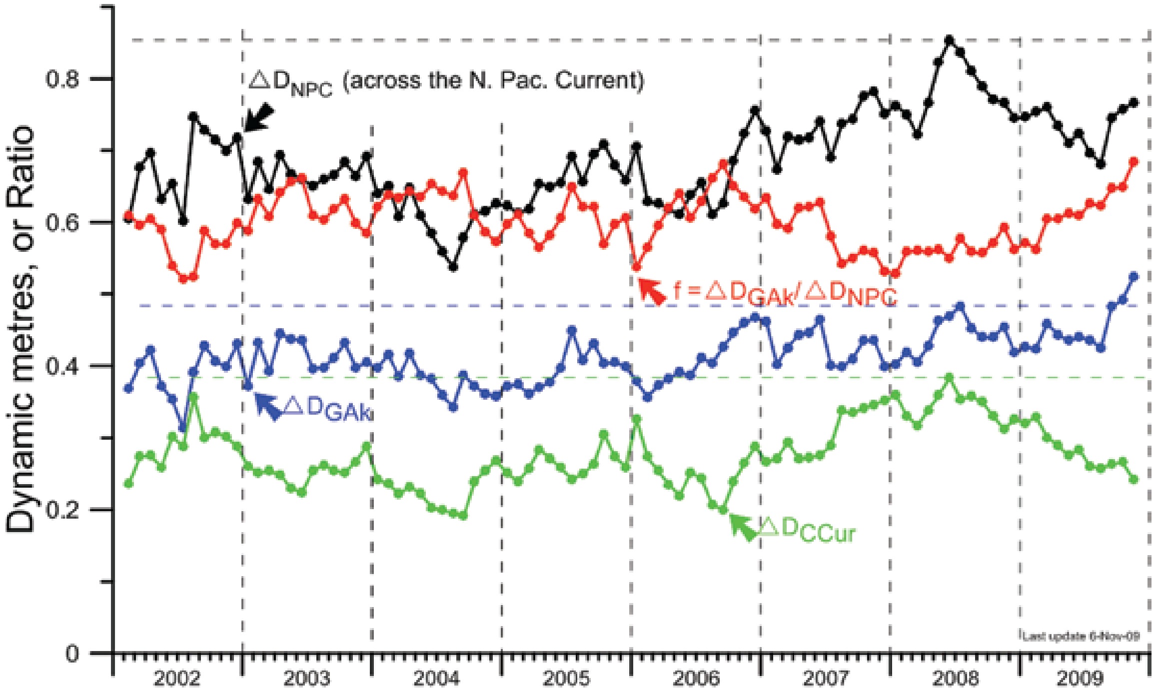


[Figure S-8] North Pacific Gyre Oscillation index (updated from Di Lorenzo et al. 2008).

## 3.2 Circulation

It is also instructive to look at the subdominant climatic pattern for the North Pacific. The NPGO index (Di Lorenzo et al. 2008) is the subdominant EOF of North Pacific sea surface height anomalies. As suggested by its name, it captures changes to the subpolar and subtropical gyres and has been shown to be strongly correlated with the strength of the North Pacific Current, salinity, upwelling winds, nitrate, and chlorophyll$_a$ in the CalCOFI region (Di Lorenzo et al. 2009), and salinity and nitrate along Line-P. The NPGO index was extended to February 2009 (Fig. S-8) and it reveals a relatively steady increase from minimally negative values in early 2005 to high positive values in November 2008. The NP index of SLP in November 2008 was also one of the largest observed in any November since the start of the time series in 1948. Whereas geostrophic currents associated with a positive PDO reflect anomalous poleward flows along the North American Pacific coast and thus stronger Alaska and weaker California Currents, the geostrophic flows associated with a positive NPGO reflect a stronger North Pacific Current and both stronger Alaska and California Currents.

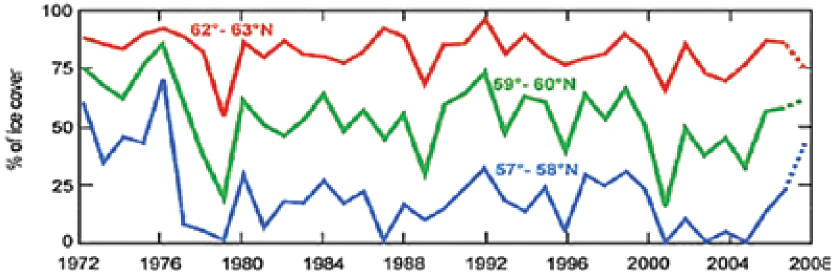
The establishment of the international Argo profiling float program in 2002 initiated an era of ocean sampling at finer spatial and temporal resolutions than was previously possible and permitted more complete time series of ocean temperatures, salinities and their derived quantities. Using Argo-based dynamic height gradients in the Northeast Pacific, Freeland (2006) estimated the relative strengths of the North Pacific, Alaska and California Currents. There were marked decreases in all three currents in 2004 and then an increasing trend in the North Pacific Current to mid-2008 (Fig. S-9) that is similar to the NPGO time series in Figure S-8. An increase in the California Current transport from late 2006 to mid-2008 is typical of periods when the NPGO is positive and stronger upwelling occurs along the west coast of the U.S. mainland.



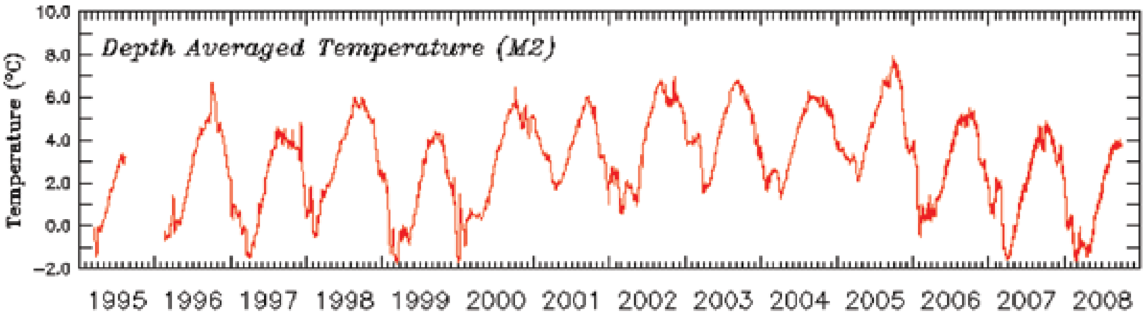
[Figure S-9] Indices of the relative strengths of the North Pacific Current (NPC), Alaska Current (GAk) and California Current (CCur) (updated from Freeland et al. 2006). ΔD= difference in dynamic heights across each current. f=ratio of dynamic height differences in the two boundary currents.

## 3.3 Eddies and meanders

Eddies and current meanders play important roles in ecosystem productivity. Eddies in the Alaska Current influence the distributions of nutrients, phytoplankton, and higher trophic level animals (Ream et al. 2005). Satellite altimetry is commonly used to estimate eddy kinetic energy. At a location east of Kodiak Island, Alaska, the ocean during the winters of 2002, 2003, 2004, and 2007 had relatively high eddy kinetic energy values; 2005 and 2006 were relatively calm, and no trend was evident. Calculations like these can also capture meanders. Had they been computed for the Kuroshio region, they would have shown a large signal in 2005 that was associated with a large meander and accompanied by the appearance of higher abundances of the coastal diatoms, *Chaetoceros* and *Cylindrotheca*. Eddy kinetic energy in the southern part of this system has also been linked to ecosystem productivity.



[Figure S-10] The yearly (December - May) average of Being Sea ice cover in 1° latitude bands. Weekly data on ice extent and concentration were obtained from the NOAA/National Ice Center.



[Figure S-11] Depth averaged temperature at Station M2 (56.9°N 164°W) in the southeastern Bering Sea.

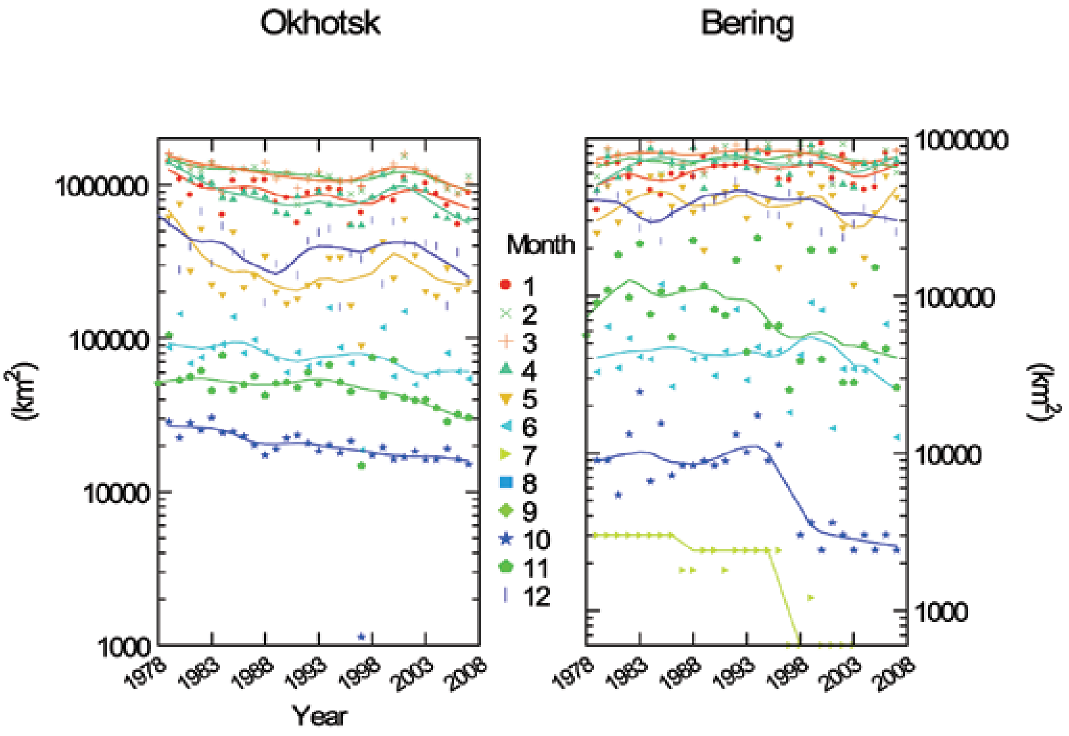
## 3.4 Sea ice

Winter sea ice extent, and its subsequent effect on summer temperatures, has a significant effect on ecosystem productivity in ice-covered marginal seas. The eastern Bering Sea exhibited relatively low sea ice extent and warmer temperatures in 2001-2005. Changes in winter winds reversed this pattern to one of extensive ice coverage (Fig. S-10) and cooler ocean temperatures (Fig. S-11) on the southeastern shelf in 2006-2009. Since 1997, there has been significantly less ice in the entire Bering Sea during the transitional seasons (late spring/early fall) (Fig. S-12). Small amounts of ice used to be seen as late as July but these occurrences disappeared during the focus period. Likewise the development of ice in the Bering Sea in October was significantly reduced after 1997 and the cause of this abrupt shift is unknown.

In the Sea of Okhotsk, sea ice extent had markedly negative anomalies from May - November 1997 in what has been a steadily decreasing trend in all months when sea ice is present (Fig. S-12). The 1997 anomaly did not persist in the Sea of Okhotsk as it did in the Bering Sea. April sea ice extent in 2009 in the Sea of Okhotsk was the least since 1957. Sea surface and intermediate water temperatures there have been generally increasing, at least during the years for which data are available.

## 3.5 Tides

The Sea of Okhotsk is a significant source of North Pacific intermediate water and dissolved oxygen at depth in the northwestern Pacific. To reach the North Pacific, water from the Sea of Okhotsk flows through the Kuril Island passes where strong tides mix large volumes of water. A well known 18.6-year cycle in the amount of tidal mixing contributes to variations in the formation and properties of this intermediate water (Yasuda et al. 2006; Osafune and Yasuda 2006). Similar variations arising from the lunar nodal tidal cycle have also been identified or suggested in the Seward Line time series (Royer 1993), Bering Sea (Foreman et al. 2006), and around the Northeast Pacific (McKinnell and Crawford 2007). In particular, there are suggestions of an 18.6-year signal in the declining trend of intermediate water oxygen concentrations at Station Papa (see Section 4.2).



[Figure S-12] Maximum ice extent (km²) in the Bering Sea and Sea of Okhotsk by month from 1978 to 2007. Loess smoothing is used to indicate trends. Plot points for months with no ice are excluded.

## 3.6 Freshwater runoff

Freshwater has important roles in several oceanic regions of the North Pacific. The most noteworthy example of a change during the focus period was the damming of the Changjiang River in 2003. Not only has the dam reduced annual discharge as water is diverted for other purposes, but it has also altered the shape of the annual hydrograph (Fig. S-13, Box 4). Though the Amur River in the Sea of Okhotsk, Fraser and Columbia rivers in the California Current region, and numerous rivers in the coastal Gulf of Alaska play important roles in the coastal circulation and nutrient supply of these regions, none of these rivers exhibited significant variations in their discharge over the focus period.

## 3.7 Mixed layer depth

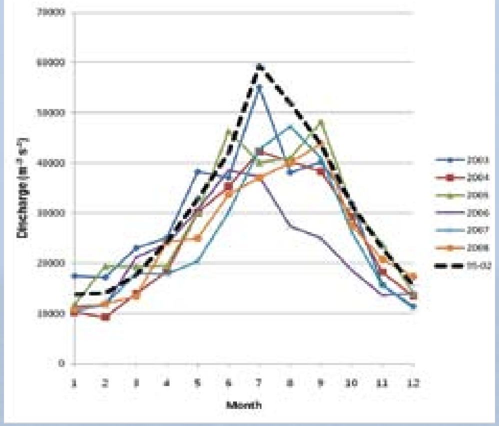
Seawater in the upper ocean has a nutrient concentration gradient that increases with increasing depth. Therefore variability in the depth of the winter mixed layer (MLD) is related to ecosystem productivity through variations in the quantities of nutrients that are available for phytoplankton growth near the surface each spring. In the Gulf of Alaska, there was high variability in MLD at a nearshore station (GAK-1) over the period of 1974 to 2006 and though there were deeper than average values in the winters of 2003-2004, 2004-2005 and 2005-2006, there is no statistically significant trend. This is in contrast to the 1956-1994 shoaling trend in MLD found by Freeland et al. (1997) at Station Papa in the center of the Alaska gyre, and also in the Oyashio and Kuroshio-Oyashio transition regions (Tadokoro et al. 2009). In the southern California Current region (CalCOFI), there is no consistent trend in MLD though values for the last five years of the focus period are about 5 m shallower than average. Monthly variations in western Subarctic Pacific MLDs occurred during the focus period though no long term trends were reported. The mixed layer shoals each spring with warming of the surface layer. As late as June each year there is considerable variability across the North Pacific in the extent of development of a stable water column.

# [4]

## Changjiang River – Anthropogenic Impacts on a Coastal Ecosystem

From its headwaters in Tibet, the Changjiang River runs 6,300 km eastward toward Shanghai before it enters the East China Sea. It is the world's third longest river with a watershed of 1.8 million km². The watershed encompasses one-third of China's population and 70% of its agricultural production. Huge amounts of sediment and nutrients are discharged to the sea annually which enhances biological productivity, including fisheries, on the East China Sea shelf. The amount of sediment entering the sea depends largely upon the amount of precipitation, sediment erosion, sediment impoundment by reservoirs, and sediment extraction.

Widespread use of fertilizers for agriculture resulted in increased nitrogen and phosphorus fluxes to the river after the early 1970s. Nitrate loads to the estuary have increased about threefold in 40 years. This eutrophication was also accompanied by an increase of N:P and N:Si ratios. These changes coincided with a rapid increase in the frequency of harmful algal blooms (HAB) near the estuary and a shift in the phytoplankton community from diatoms to dinoflagellates. The number of HAB events approached 90 in 2003 and the late 1990s and early 2000s also witnessed more frequent, disruptive jellyfish blooms. Furthermore, the summer of 2003 had one of the largest hypoxic areas ever observed near the estuary.



[Figure S-13] Monthly discharge of the Changjiang River measured at Datong station. Broken line denotes the average for the period from 1995 to 2002.

Floods in the Changjiang have caused major catastrophes costing hundreds of thousands of lives. As early as 1918, a dam was envisioned but construction began only in 1993 in the Three Gorges region. The Three-Gorges Dam (TGD) was built at a cost of US$25 billion from 1993 to 2003 to provide electricity, flood control, and improved navigation. It is the biggest hydropower development in the world. Some effects of water impoundment appeared on the coastal ecosystem immediately after it began in June 2003. In the long run, the TGD will exacerbate a nutrient imbalance in the sea which began long before the dam. The South-to-North Water Diversion Project will divert water from the Changjiang River to northern China where water is in short supply. Construction began in 2002 and when completed in 2050, about 44.8 billion tons of water will be diverted northward every year, with unknown affects for the coastal ocean currently receiving that discharge.

## 4.0 Chemical Ocean *(Whitney)*

Throughout the world's oceans, nutrients, oxygen and, in recent years, acidity are understood to be major chemical controls on life. In the surface ocean, primary producers utilize nutrients reclaimed from the deep ocean by various mixing processes, transported from land by rivers, or carried in the atmosphere as dust and vapors. These organisms then supply energy to virtually all other oceanic life forms, except those small enclaves supported by chemosynthesis (e.g. hydrothermal vent communities). Surface grazers and predators thrive in an oxygen rich environment due to the constant exchange of gases between atmosphere and ocean. In general, the surface ocean is within a few percent of being saturated by oxygen, creating a habitat suitable for metabolically active creatures.

Below the surface ocean, nutrition is transported to life either by vertical migrators (e.g. zooplankton, myctophids) or by the rain of detritus from the surface. At these depths, oxygen transport is a major habitat delineator. The Subarctic Pacific has one of the strongest oxygen gradients in the world's oceans, created by strong upper ocean stratification and weak ventilation (gas exchange with the atmosphere). Between 100 and 500 m oxygen declines from 100% saturation to < 20%, below the limit required for most marine organisms to thrive. This means that habitat is strongly compressed in the Subarctic Pacific, making marine creatures more vulnerable to predation and fishing. This compression is even stronger along continental margins where higher productivity, riverine inputs and upwelling can result in low oxygen water being found episodically on the continental shelf.

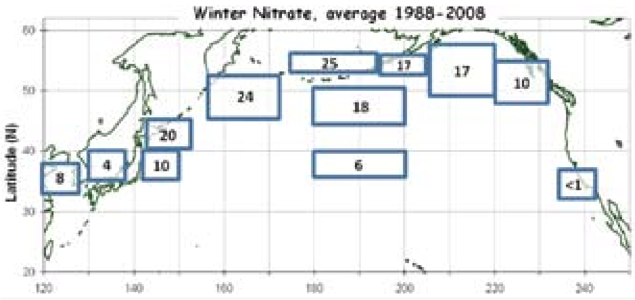
An emerging concern for the surface ocean is its exposure to increasing atmospheric carbon dioxide levels. Oceans are a major sink for $CO_2$ so, as more fossil fuels are combusted, more of this acid-producing gas dissolves into the upper ocean. Also, the interior ocean can become more acidic as oxygen is consumed by respiration. The intermediate waters of the Pacific contain about 400 µM more total $CO_2$ than the surface ocean. This is enough to decrease the pH from ~8.1 in the surface ocean to ~7.6 at 500 m (see Batten et al. 2010). These acidic/hypoxic waters are occasionally found on the continental slope during summer upwelling (Feely et al. 2008).

Generally, no strong anomalies in nutrients, oxygen or pH were observed during the focus period. Trends toward lower oxygen at intermediate depths persisted, except along the Asian coast where bidecadal variability (possibly enhanced tidal mixing due to a peak in the lunar nodal cycle in 2005-2007) appears to be slightly increasing ventilation. Nutrient levels in surface waters where ventilation is strong appear to have increased.

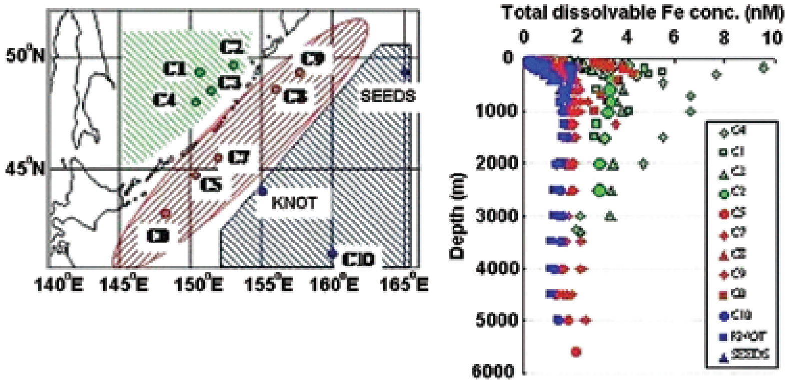
### 4.1 Nutrients

In the Subarctic Pacific, winter light levels are too low to support much phytoplankton growth, especially where the ocean's surface layer is strongly mixed by winter winds. High subsurface nutrient concentrations in the Bering Sea and Western Subarctic Gyre create nitrate concentrations of 20-25 µM and silicate concentrations of 40-45 µM at the surface during an average winter (Fig. S-14). By comparison, waters off the coast of British Columbia and in the Kuroshio region contain only 10 µM nitrate and 15 µM silicate prior to the start of spring growth. In the subtropical waters off California, nutrients do not accumulate in winter.

Since winter winds are the major cause of nutrient supply to the upper waters of the Subarctic, annual productive potential is largely established by early spring. In much of Subarctic Pacific, complete nutrient utilization by phytoplankton is prevented by a lack of iron creating what is known as an high nutrient-low chlorophyll region (HNLC). Measurements over the past decade show that shelf regions and the intermediate ocean are the major sources of iron, although dust transport from arid regions and volcanoes is thought to be a significant contributors. Mesoscale eddies carry iron-rich waters away from the BC and Alaskan coasts into the Alaska Gyre (Johnson et al. 2005), stimulating biological production (Crawford et al. 2007). Recent measurements in the Sea of Okhotsk and adjacent ocean (Nishioka et al. 2007) confirm that shelf regions are rich sources of iron (Fig. S-15). Sea-ice melt also provides dissolved iron to the ice edge region where productivity is high (Aguilar-Islas et al. 2008). The atypical, widespread high chlorophyll event that occurred in August 2008 required an iron source to support this phytoplankton growth. Possible mechanisms for such a large event include dust input from the volcanic eruption that occurred that summer in the Aleutian archipelago, or a widespread breakdown of upper ocean stratification by



[Figure S-14] Average winter nitrate (μM) in the surface waters of the North Pacific. Yellow Sea value comes from a single survey in 2008, others are measurements made by ships of opportunity between 1988 and 2008. Tsushima Current average is for the southern portion only. Winter nutrient data are difficult to obtain in ice covered regions of the Okhotsk and Bering seas.



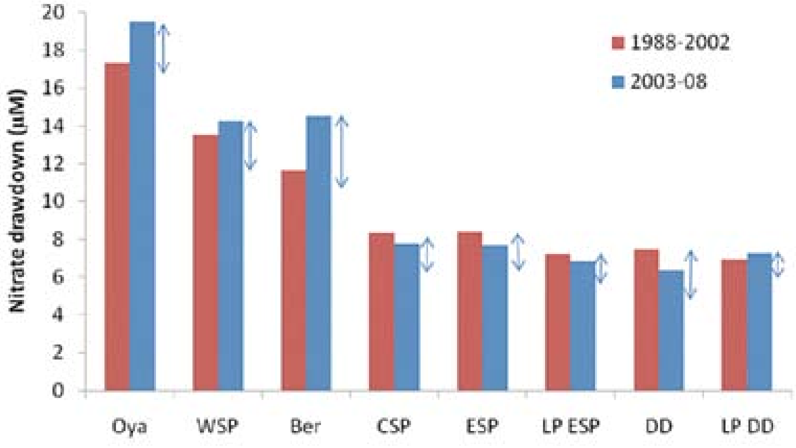
[Figure S-15] Vertical profiles of total dissolvable iron around the Kuril Island. Green symbols indicate the data from the Sea of Okhotsk, red symbols indicate the data from the Oyashio region and blue symbols indicate the data from oceanic regions of the western Subarctic Pacific (SEEDS Project Stations KNOT and C10). After Nishioka et al. (2007).

winds. Both occurred at times and scales that could have enhanced phytoplankton growth in 2008 (see Batten et al. 2010 and Section 5.1.4).

In coastal waters, nutrients are supplied to the photic zone by alongshore transport, upwelling, tidal mixing, estuarine circulation and river discharge. Organic matter sinking out of productive surface waters is turned over rapidly by these processes, making N, P and, to a lesser degree, Si repeatedly available to primary producers. Thus, coastal oceans are more productive than the open ocean because physical and biological mechanisms provide nutrients throughout the growing season. Off the Japanese coast, nutrient supply to the upper ocean was reduced in 2005-2006 when a Kuroshio meander was observed.

The rivers of central Asia are rich sources of N to coastal waters, whereas North American rivers discharging into the Pacific Ocean and Bering Sea tend to be weak sources of N and P, but strong sources of Si. The trend in the Changjiang River through the 1980s and 1990s has been for Si supply to decrease as N and P increase (Li et al. 2007). Between 1998 and 2004, the Si:N ratio declined from 1.5 to 0.4 near the mouth of the river; this trend being observed also in the Yellow Sea. It has been suggested that such changes can lead to a dominance of gelatinous zooplankton (Turner et al. 1998). Fertilizer use enhances N inputs, and dams or reservoirs reduce silicate since they provide areas for freshwater diatom growth. However, the 17% reduced flow of the river following the Three Gorges Dam construction (see Yoo et al. 2010) may cause a reduction in nutrient loading to coastal marine waters. By comparison, silicate inputs are sufficient to keep the entire shelf region from Oregon through Alaska replete in silicate, resulting in nitrate limited growth during summer (Whitney et al. 2005). A better understanding of which nutrient limits growth along the margins of the North Pacific may help to explain some of the regional ecosystem differences.

Sampling carried out by ships of opportunity (see Wong et al. 2002) and Line P survey cruises since 1988 suggest that nutrient supply to the surface waters of the North Pacific has not diminished (Fig. S-16). Comparing the 1970s and 1990s, Whitney and Freeland (1999) showed that less nutrient was being supplied during the warm winters in the 1990s, leading to a decrease in new production (nitrate supported primary productivity). However, nutrient levels have increased in recent cooler years. A comparison of the periods 1995-2002 to 2003-2008 hints at a recent increase in nitrate supply and drawdown in waters of the western Subarctic Pacific. A steady increase in Bering Sea salinity between 1995 and 2006 (data not shown) suggests that



[Figure S-16] A comparison of seasonal nitrate removal from surface waters (late winter to late summer) in domains of the subarctic Pacific (Oya=Oyashio, WSP=Western Subarctic Pacific, Ber=Bering Sea basin, CSP= Central Subarctic Pacific, ESP= Eastern Subarctic Pacific, DD= Dilute Domain off the coast of British Columbia). Data obtained from Line P surveys (LP) that pass through the southern edges of the ESP and DD regions are also used to estimate seasonal nitrate drawdown. Averages are shown for two time periods, arrows providing the standard deviation of the data set.

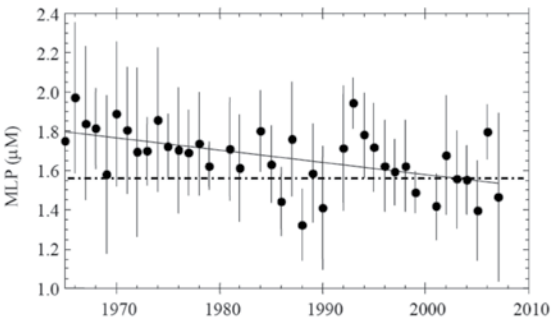
increased mixing towards the 2006 peak of the lunar nodal cycle has increased winter nutrient supply to waters along the Aleutian and Kuril Islands, as was proposed by Yasuda et al. (2006). Overall, diminished nutrients in the surface ocean might be expected since stratification is generally strengthening in the upper Subarctic ocean. Certainly, the expansion of oxygen minimum zones in the Subarctic Pacific is resulting in increased nutrient storage in intermediate depth waters (Whitney et al. 2007). One area showing a loss of surface layer nutrient is the Oyashio where phosphate levels have been declining for 40 years (Fig. S-17). Nutrient measurements are not sufficiently comprehensive in the upper ocean to determine which regions are gaining or losing nutrients as ocean circulation changes.

## 4.2 Oxygen

In the surface mixed layer, oxygen levels are generally within a few percent of saturation, with concentrations being governed more by ocean temperature than by primary production or respiration. In the subtropics, waters are well oxygenated to several hundred meters depth, whereas much stronger stratification in the Subarctic region only allows the upper ~100 m to be oxygenated by local mixing (winter winds). Oxygen supply to the intermediate Subarctic region is weak and occurs only where cold, saline waters are produced at the surface in winter. The largest ventilation area occurs along the Kuril Islands, extending into the western Bering Sea. Here, waters with a density of 26.5 $\sigma_\theta$ exchange gases with the atmosphere most winters. Oxygen and carbon dioxide exchange in this region will depend on the area of outcropping and its persistence.

A second but smaller region of ventilation occurs in the Sea of Okhotsk and accounts for oxygen transport to denser isopycnal surfaces. Winter ice formation produces dense water and a polynya permits gas exchange with the atmosphere. This oxygenated water passes through the deep passes of the Kuril Islands where strong tidal mixing blends Okhotsk waters with those of the East Kamchatka Current. The appearance of the 18.6-year lunar nodal cycle (Yasuda et al. 2006) in oxygen between 26.5 - 27.0 $\sigma_\theta$ reflects the strong tidal role in establishing water properties at these densities. At Station Papa, 4000 km downstream from ventilation sites, an oscillation of the same period is detectable on the 27.0 $\sigma_\theta$ isopycnal (Whitney et al. 2007). A lag of 6 to 7 years between oxygen peaks and valleys in these two data sets fits current understanding of deeper ocean circulation across the Subarctic Pacific.

Trends over the past 50 years or more show that oxygen levels are declining throughout the Subarctic and in the

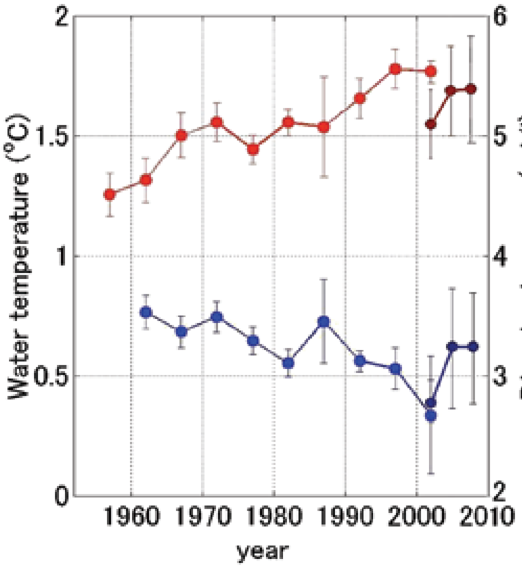


[Figure S-17] Mixed layer phosphate (MLP) in the Oyashio region off northern Japan; vertical bars indicate ±1 standard deviation.

northwestern marginal seas (e.g. Fig. S-18). At Station Papa, oxygen levels declined by 23% between 1956 and 2008 (updated from Whitney et al. 2007), with the strongest declines being seen between 150 and 400 m. The modeling work of Deutsch et al. (2005) found that the only reasonable explanation for this oxygen loss is reduced ventilation of the ocean. Where data series are long enough, it appears the surface ocean is freshening more than warming across the Subarctic. However, in the Sea of Okhotsk, declining ice cover may be reducing the period in which dense water can be produced and so its total volume is reduced.

As ventilated waters subduct below the fresher surface waters of the Subarctic Pacific, biota consume oxygen while consuming or decomposing the detrital rain produced in the surface layer. Oxygen consumption produces carbon dioxide and nitrate, and other nutrients such as phosphate and silicate. Oxygen consumption rates are high enough along the 26.5 $\sigma_\theta$ isopycnal that oxygen levels decline from 100% saturation off the Asian coast to 65% as they approach North America (Fig. S-19). As these waters come in contact with the North American continental margin, oxygen levels decline sharply due to increased oxygen consumption under the highly productive waters above. A south to north oxygen gradient occurs between Mexico and Alaska because the poleward, oxygen depleted California Undercurrent has less of an influence in the north. At least from southern California through BC, oxygen declines of >1% per year over the past 25 years have resulted in the 60 μM oxygen boundary (a level not tolerated by >80% of the BC groundfish community) shoaling by 3 m·y$^{-1}$ or 75 m since 1984 (Bograd et al. 2008). Data from the commercial groundfish fishery in BC suggests that demersal fish are losing habitat at the same rate (A. Sinclair, DFO emeritus, pers. comm.)

The consequences of expanding regions of hypoxia are several. Denitrification (an anaerobic process) increased between 1999-2006 in intermediate waters of the Sea of Okhotsk (Watanabe et al. 2009) and may also be increasing along the North American coast as anoxia becomes more common (Oregon shelf in 2006, Santa Barbara Basin). Hypoxia will cause sessile organisms to perish in their deeper ranges while mobile species will be displaced either into shallower or to northern habitats which could drive them from favoured breeding sites or protective habitat.

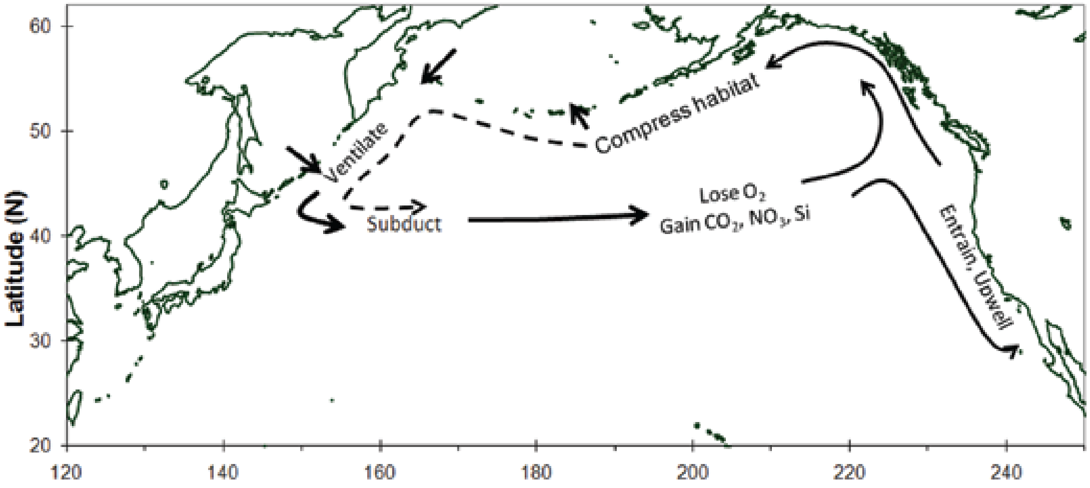


[Figure S-18] Time series of temperature (red line) and dissolved oxygen (blue line) of the intermediate water in the Sea of Okhotsk at 27.0 $\sigma_\theta$, corresponding to approximately 250-550 m depth, during the past 50 years. Additions for 2002, 2005, and 2008 indicate mean and 95% confidence interval calculated from data obtained during TINRO-Center surveys.

Oxygen consumption also results in waters becoming more acidic. Thus deep water corals or other organisms not able to tolerate this change may struggle. In the 1990s, the distribution of Pacific hake (*Meriluccius productus*) moved northward from California towards British Columbia and Alaska (Benson et al. 2002). Recently, the range of Humboldt squid (*Dosidicus gigas*) has expanded northward from Mexico to Southeast Alaska (Wing 2005).

With slope waters containing less oxygen and more nutrients, eutrophication will occur more frequently during upwelling periods. Fish and crab kills have become an almost annual event along the Oregon and Washington coasts in the past several years (Chan et al. 2008), with the strong 2006 upwelling season resulting in a substantial area of anoxia on the Oregon continental shelf.

Low oxygen is also being found under the plume of the Changjiang River in the Yellow Sea. The heavy nitrate loading of this river can be expected to create conditions similar to those seen in the Mississippi River plume in the Gulf of Mexico, where benthic habitat is lost as a result of agricultural sources of nutrients.



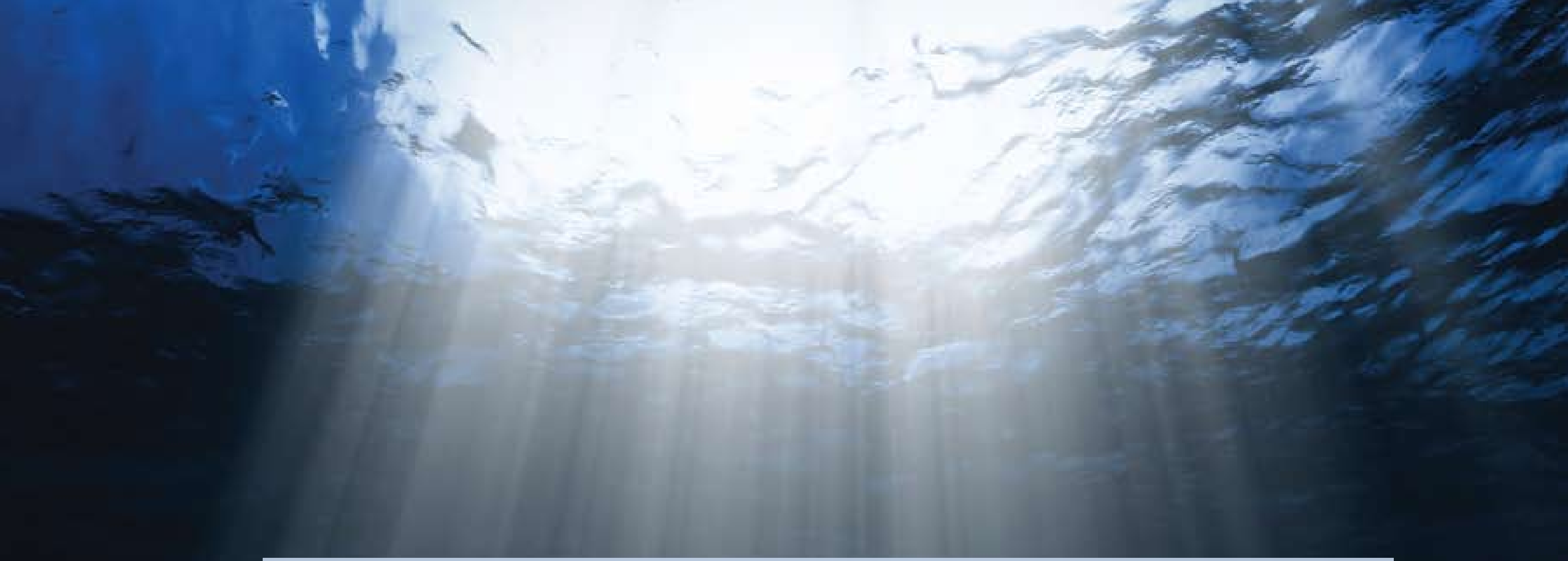
[Figure S-19] The formation and transport of ventilated waters from the Asian coast, across the Pacific towards the coast of North America. En route, waters lose oxygen and gain carbon dioxide plus nutrients as organic detritus is consumed. These waters can then be transported onto the continental shelf of North America via upwelling and estuarine entrainment.

## 4.3 Ocean acidification

Increasing atmospheric $CO_2$, the result of burning fossil fuels, is causing the surface ocean to become more acidic (Raven et al. 2005). Ocean acidification poses a complex, long-term biological problem because it affects shell formation of calcareous organisms (e.g. pteropods, foraminifera, mollusks), potentially leading to shorter food chains that favour invertebrates such as jellyfish. This is of special interest in the northern North Pacific since the depth at which exposed aragonite (an especially soluble form of calcium carbonate) currently dissolves is as shallow as 100 m (Feely et al. 2002; see also Hunt et al. 2010). The scant evidence available presently on trends in ocean pH suggests surface waters may have acidified by 0.1 pH units due to anthropogenic $CO_2$ emissions. Measurements over the past 15 years in Monterey Bay find a pH decrease of about 0.04. If the rate of carbon dioxide emissions continues to rise as predicted, the average pH could fall by 0.5 by the end of the century, equivalent to a three-fold increase in the hydrogen ion concentration (Raven et al. 2005).

The interior ocean is acidifying due to weakening gas exchange with the atmosphere. The spread of hypoxia throughout the Subarctic Pacific is also a spread of acidity. Ocean gradients of pH and oxygen suggest that for each ~50 µM loss of oxygen, pH will decrease by 0.1. In coastal waters off California and British Columbia, oxygen losses of 40 µM have been measured at a depth of 250 m over the past 25 years (Whitney et al. 2007; Bograd et al. 2008). Measurements in a tide pool on Tatoosh Island off the coast of Washington from 2000-2008 found a decline in surface ocean pH of nearly 0.4 (Wootton et al. 2008). This is a greater decline than most models suggest and may be in large part due to variation in ocean circulation, tidal mixing or upwelling. Regardless, the study showed that ecological changes were accompanying the changes in average pH. The abundance and mean size of the California mussel (*Mytilus californianus*), blue mussel (*M. trossulus*), and goose barnacle *(Pollicipes polymerus*) declined with declining pH. On the other hand, the abundance of ephemeral algae, filamentous red algae, foliose red algae, acorn barnacles (*Balanus glandula* and *Semibalanus cariosus*) and fleshy algae (*Halosaccion glandiforme*) increased with declining pH. Declining diversity and/or abundance of calcifying organisms will affect ecological structure and function in ways that have yet to be determined.

Ocean acidification must be considered an emerging issue, one which needs considerable additional study before its impacts can be understood. Besides biological impacts of acidification, a better idea of the mobility of calcareous sediments is needed. For example, input of calcium from the Amur River into the Sea of Okhotsk is credited with slightly increasing pH (decreasing acidity) of intermediate waters between 1999 and 2006 (Watanabe et al. 2009).



# 5

# Ecological Effects of Increasing Hypoxia

Oxygen levels are declining in the interior waters of the subarctic Pacific. Since there is no evidence of increased biological demand for oxygen, all studies conclude that the declines are due to reduced ocean ventilation. Two main ventilation sites are currently recognized: the waters east of the Kuril Islands and the Sea of Okhotsk. In the Sea of Okhotsk, warmer winter air temperature and diminishing ice cover are likely reducing the amount of dense, oxygenated water being produced. Various time series from the northwestern North Pacific suggest that the surface ocean is becoming fresher, perhaps due to increased transport of evaporated water from the tropics to the Subarctic, and/or to glacial meltwater in the mountains of North America.

Time series measurements at Station Papa (50°N, 145°W), some 4000 km from the ventilation sites, have recorded a 23% loss of oxygen from subsurface waters (100 to 400 m) between 1956 and 2008. After passing Station Papa, these waters flow toward North America where the hypoxic boundary is shoaling. The 60 μM oxygen level, for example, is a concentration that few fish can tolerate. It has been rising toward the surface at a rate of about $3\ \mathrm{m \cdot y^{-1}}$ over the past 25 years. This can be seen along both the California and British Columbia coasts. Only in these two locations have data been collected for enough time to identify this shoaling, but it is likely occurring from southern California to the Aleutian Islands, and could be affecting slope habitat along the Asian coast.

The ecological responses to expansions of hypoxia zones are predictable. Because the hypoxic boundary deepens toward Alaska (the 60 μM boundary is about 150 m off California and 400 m off southern Alaska), hypoxic stress could force northward shifts in distribution of species that live in slope habitat. Pacific hake (*Merluccius productus*), for example, is a demersal fish that feeds on euphausiids at depths of 200 to 300 m. Its distribution has shifted northward over the past two decades. Expanding hypoxic zones and changing prey distributions may explain the spread of Humboldt squid (*Dosidicus gigas*) from their usual Mexican habitat to as far north as Alaska over the past few years. These rapidly growing animals are adapted to low oxygen waters. They may use these waters to avoid predation and become a new grazing pressure on demersal and pelagic fishes from California to southern Alaska.

# 5.0 Biological Ocean

## 5.1 Phytoplankton and chlorophyll *(Yoo)*

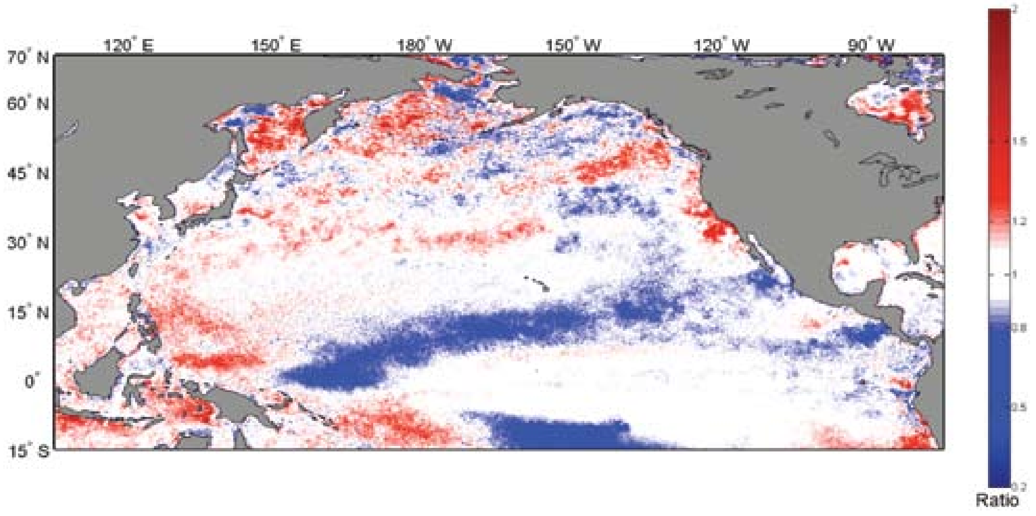
### 5.1.1 Basin-wide changes in satellite chlorophyll

To compare mean chlorophyll$_a$ concentrations during the focus period with those of the previous report (PICES 2004), annual mean chlorophyll$_a$ concentrations from SeaWiFS for each pixel and period averages were calculated for 1998-2002 and 2003-2007. The direction of change in the ratio (focus period as numerator) indicates that in the Subarctic region average chlorophyll$_a$ concentrations decreased in parts of the eastern North Pacific while they increased in the western North Pacific and the southern Gulf of Alaska (Fig. S-20). In most of the California Current region, average chlorophyll$_a$ concentrations increased during the focus period. An increase occurred in most of the Sea of Okhotsk and generally in the mid-latitude western North Pacific. There has been a noteworthy decline in average chlorophyll$_a$ across the entire tropical/subtropical zone from Indonesia to Baja California Sur.

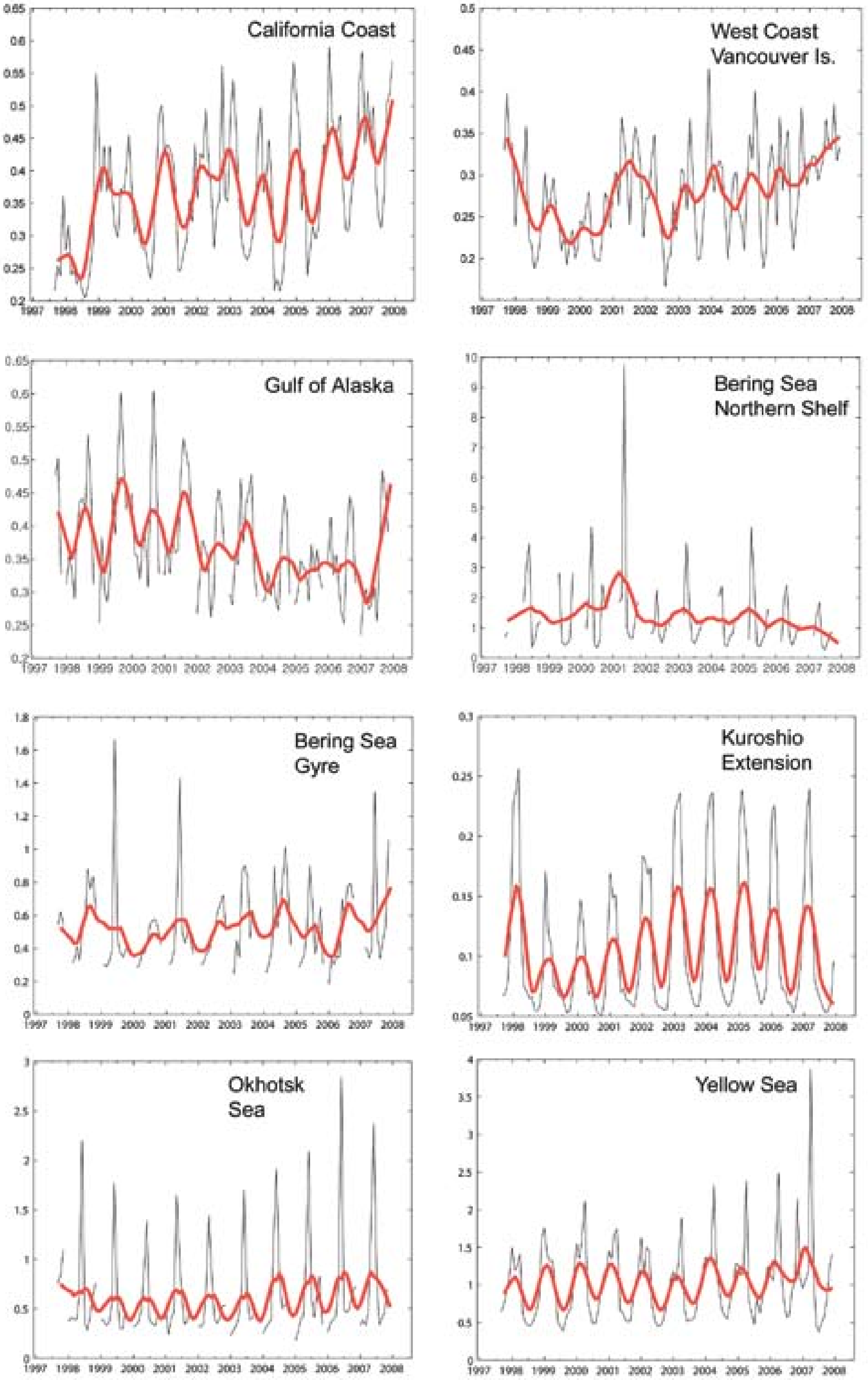
Time series of mean monthly chlorophyll$_a$ concentrations were extracted from the regions where chlorophyll$_a$ increased or decreased by more than 20% (Fig. S-20). In the California Current region, chlorophyll$_a$ increased after 2004 (Fig. S-21). On the west coast of Vancouver Island, chlorophyll$_a$ was low in 1998, 1999, and 2002 but increased after 2005. In the Gulf of Alaska, chlorophyll$_a$ decreased gradually after 1999. On the northern shelf of the eastern Bering Sea, chlorophyll$_a$ reached a maximum in 2001 and decreased after 2005. In the Bering Sea Basin, chlorophyll$_a$ was slightly higher in the focus period than in the previous focus period except for 2005. In the Kuroshio Extension region, chlorophyll$_a$ decreased in 1999 and 2000, but increased gradually until 2003. In the Sea of Okhotsk, chlorophyll$_a$ was low in 1999-2003 but increased after 2003. The peak value in 2006 was about two times higher than in 2000. In the Yellow Sea, chlorophyll$_a$ increased after 2003. In summary, there was little consistency in chlorophyll$_a$ from region to region.

### 5.1.2 Expansion of low surface chlorophyll area in the central North Pacific

Low surface chlorophyll$_a$ ($\leq 0.07$ mg·m$^{-3}$) is a major feature of the central North Pacific from 5°N to 45°N. From 1997-2008, the area of low chlorophyll has expanded by about 2% per year, a rate which is comparable with similar observations in the South Pacific, North Atlantic, and the South Atlantic. The expansion of low surface chlorophyll$_a$ waters is consistent with a global warming scenario of increased vertical stratification, but the rates observed already exceed long-term model predictions (Polovina et al. 2008). The expansion in the North Pacific occurred mostly in an eastward direction reaching 120°W longitude in 2006.



[Figure S-20] Ratio of mean chlorophyll$_a$ between 1998-2002 (denominator) and 2003-2007 periods. White color indicates minimal change between the two periods (ratios = 0.9-1.1).



[Figure S-21] Time series of monthly chlorophyll$_a$ concentrations extracted from the regions where significant changes (±20%) occurred. Thick red line is a 12-month moving average.

### 5.1.3 Increasing chlorophyll in the California Current region

Off central and southern California, a significant trend of increasing chlorophyll$_a$ was detected (see Bograd et al. 2010; Kahru and Mitchell 2008; Kahru et al. 2009). A recent study has shown that chlorophyll$_a$ concentrations within the CalCOFI domain in southern California were correlated with the NPGO up to 2005 (Di Lorenzo et al. 2008). Surface chlorophyll$_a$ concentrations in Monterey Bay have exhibited positive anomalies since the 1998 El Niño (Peterson and Schwing 2003; Chavez et al. 2003). At station NH-05 on the shelf west of Oregon, *in situ* measurements of surface chlorophyll concentrations from 2001 to 2008 were nearly double what they were from 1997 to 2000.

### 5.1.4 Variations in the timing and magnitude of annual peaks

Interannual variations in the location, timing and magnitude of seasonal peaks in surface chlorophyll$_a$ are characteristic of most regions of the North Pacific (Yoo et al. 2008). In the Bering Sea, blooms generally occur in April and May but they can also vary spatially. In the Middle Domain the bloom occurred in early March in 2003, whereas in 2007 in the Deep Basin it was not until May-June. Large fluctuations in the magnitude of spring blooms were observed in the Outer Domain. These variations in timing and magnitude seem to be related to cold or warm weather and the duration and extent of ice cover. The timing of the spring bloom in the eastern and western Bering Sea can also be affected by the location and strength of the Aleutian Low (Iida and Saitoh 2007). Overall, phytoplankton biomass appears to have been highest in 2003 for the eastern Bering Sea shelf (Middle and Outer domains) and higher in warm (2003-2005) than in cold years (2006-2008).

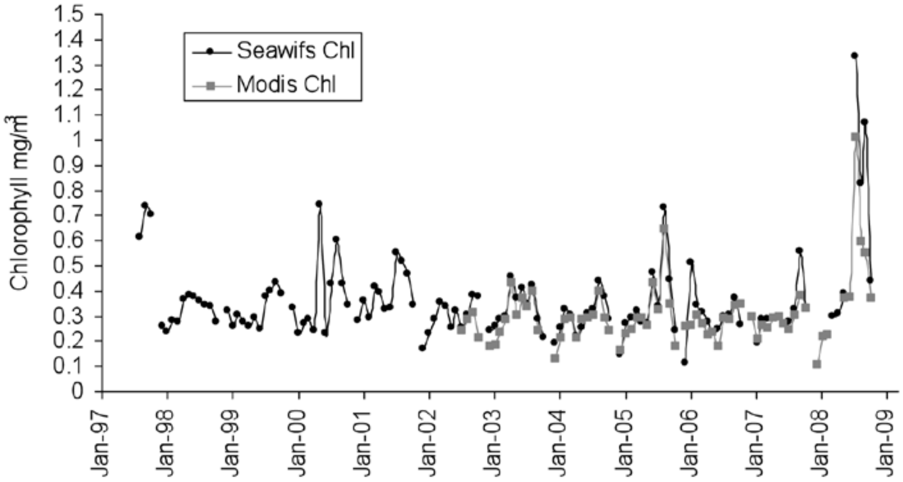
In the Sea of Okhotsk, Amur River discharge and ice dynamics tend to control phytoplankton dynamics. The discharge of large amounts of silicate and iron enhances biological production, especially by diatoms, in the East Sakhalin Current (Andreev and Pavlova 2010). In 2003 and 2008, chlorophyll$_a$ concentrations were low, corresponding to lower Amur River discharge. Near the Hokkaido coast, bloom timing was closely related to ice conditions. Chlorophyll$_a$ concentrations were higher in 1999, 2001 and 2003 when ice cover remained until early April and they were lower in 1998, 2000, 2002 and 2004 when the ice melted in early March (Mustapha and Saitoh 2008). Higher chlorophyll$_a$ concentrations occurred when sea ice melting was delayed.

In the Oyashio region, spring blooms generally occur at some time from April through June, and fall blooms from September through November, although the fall bloom tends to be indistinct in the southern region. The timing and magnitude of spring blooms were quite variable. Beginning from 2003, spring blooms were delayed from March to June over a broad area. This seems to be related to colder winters and delayed stratification. In the Kuroshio region, spring blooms occurred in late March-April. While the timing of spring blooms changed during the 1998-2008 period, the magnitudes of these blooms were rather similar.

In the central region of the Yellow Sea, chlorophyll$_a$ concentrations during spring blooms increased after 2003 (Fig. S-21). These were coincident with the start of water impoundment by the Three Gorges Dam. Whether the changes in chlorophyll$_a$ are related to the reduced Changjiang River discharge remains to be further investigated.

### 5.1.5 Events

A wide spread chlorophyll bloom occurred during the summer of 2008 in the Subarctic waters of the central and eastern North Pacific where summer chlorophyll$_a$ concentrations are typically from 0.3 to 0.5 $mg \cdot m^{-3}$ (Fig. S-22). The anomaly was confirmed by sampling at Station Papa where concentrations were 1.4 $mg \cdot m^{-3}$ in mid-August. Station Papa data indicated that little nutrient drawdown had occurred between February and June 2008, and that between June and mid-August, silicate drawdown was stronger than that of nitrate. A similar pattern of nutrient utilization was observed during an iron enrichment experiment at Station Papa in 2002. This unusual bloom has stimulated curiosity about how normal iron limitation might have been removed over a broad region of the Subarctic Pacific. The possibility of widespread deposition of dust from a volcanic eruption in the Aleutian Islands in early August of 2008 has been suggested as a potential source of additional iron. A second possibility is that the timing of spring and summer growth was delayed by an especially cold winter (Fig. S-7) that delayed the onset



[Figure S-22] Satellite-derived chlorophyll concentrations for a region of the NE Pacific centred on Ocean Station Papa (49.5-50.5°N, 144.5-145.5°W) from the MODIS and SEAWIFS satellites produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

of water column stratification. Both satellite and Project Argo data show that May remained much colder than average with deep mixing persisting longer than normal. May 2008 was the third coldest May in the Gulf of Alaska since 1950 and full development of seasonal stratification was delayed until June. How this might explain a bloom in August is not yet understood but the cold spring can help to explain the late development of the zooplankton community in 2008 (Section 5.2.6). Regardless, a bloom of the observed magnitude (1.4 mg·m$^{-3}$) would require significantly greater amounts of iron than are normally found in the surface waters during this season.

## 5.2 Zooplankton *(Mackas)*

### 5.2.1 Size categories and their trophic roles

Zooplankton are small to medium size animals that occupy middle trophic levels of the pelagic food web. They are divided, based on a combination of size, sampling method, taxonomy, and trophic level into three categories. The *microzooplankton* consist of single-celled protists and a few very small (<0.1 mm) metazoans, similar in size, capture methodology, and population turnover times (~ 1 day) to the phytoplankton. They are the primary grazers of total primary production in most open ocean areas, and important grazers of the smaller phytoplankton and bacteria in many coastal areas. Recent studies in the Bering Sea showed a twofold decline in summer microzooplankton biomass and grazing pressure in a cold year (2008) compared to previous observations in 1999 and/or 2004. In other regions, it is not possible to confirm whether or not there have been significant changes during the focus period.

The *mesozooplankton* form a large and diverse group made up of metazoans (many planktonic for their entire life cycle, some transient larval stages of benthos or nekton) in the size range ~0.1-10 mm. The dominant members of this group in the North Pacific are crustaceans, chaetognaths, cnidaria, ctenophores, chordates, and holoplanktonic mollusks. Nearshore areas also have seasonally abundant meroplanktonic larvae (e.g. barnacles, shrimps and crabs, echinoderms, and mollusks). Life cycles and/or duration of planktonic stages typically range from a few weeks to one year. Especially at higher latitudes, many of the dominant species undergo large seasonal/ontogenetic changes in vertical distribution, and some degree of metabolic dormancy. These can also lead to large seasonal changes in availability to predators, and in the dominant pathways within food webs. Recent research has also shown large interannual and longer time scale variability of community composition and total biomass. The temporal variability is quite important to higher trophic levels (including people) because nearly all larger pelagic predators feed on mesozooplankton directly as juveniles, and directly or indirectly (1-2 trophic steps) as adults.

The *macrozooplankton* form a group that includes larger planktonic animals (~2 cm-2 m) that are too fast/big/rare/fragile to be well-sampled by plankton nets, but whose horizontal position continues to be controlled more by advection than by active horizontal swimming. Many are strong diel vertical migrants that swim vertically several hundreds of meters twice per day. Time series of this group are rare due to difficulty of quantitative sampling with the plankton nets used for the mesozooplankton.

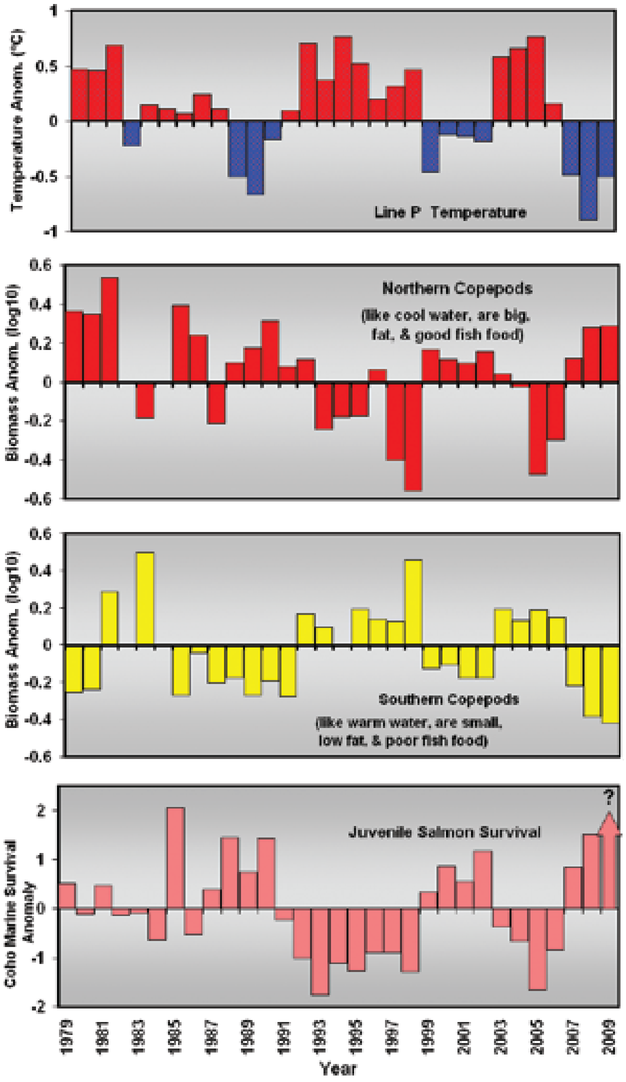
### 5.2.2 Oceanic North Pacific

Mesozooplankton time series sampling of the oceanic North Pacific during the past decade has been concentrated within three widely separated subregions: the Alaska Gyre (Continuous Plankton Recorder and Line P), near Hawaii (Hawaii Ocean Time Series, HOTS), and in the western Pacific from the subtropics to the Subarctic along 155°E (Hokkaido University T/S *Oshoro Maru*). The eastern (Alaska Gyre) data show strong responses by oceanic zooplankton to post-2005 cooling and circulation changes: higher spring-early summer biomass, and later and broader seasonal peaks of *Neocalanus* spp. This cooling also affected most of the eastern margin of the North Pacific, and the eastern Bering Sea. In the western Pacific, along the oceanic 155°E repeat sampling line, the temporal variability/trend depended on latitude: increasing biomass, mostly of small copepods, north of 42°N; a very large 2003 spike of salp biomass in the 40°-42°N Transition Region, and weak variability and no consistent trend between 36°-40°N. In the subtropical central Pacific, the HOT zooplankton time series showed a post-2005 leveling (or perhaps the start of a weak reversal) of the 1994-2004 upward trend of zooplankton biomass.

### 5.2.3 North American margin

Rapid swings between warm and cool periods were accompanied by large changes in zooplankton community composition and large-scale zoogeographic distribution. Cool conditions are associated with high abundance and productivity of zooplankton taxa that are endemic (and dominant in historic climatologies) while warm conditions are associated with reduced abundance of these endemic taxa, plus poleward movement and successful colonization by species endemic to warmer and/or more southerly environments. This pattern of meridional (north-south) displacement is not new or unique to the zooplankton; similar fluctuations have occurred in earlier portions of most existing time series. What is striking in the recent Northeast Pacific data is the amplitude and rapidity of alternations between the warm and cool patterns and communities. Another new realization is that the zooplankton time series story is a shared story involving strong covariability amoung the physical environment, zooplankton, and survival/growth of predators such as juvenile salmon, planktivorous seabirds, and sablefish (Fig. S-23; Mackas et al. 2007). The mechanism responsible for this linkage and the temporal coherence across trophic levels is likely the food quality provided by the zooplankton community (e.g., Trudel et al. 2005; Hooff and Peterson 2006). Many high latitude zooplankton are lipid rich (a prerequisite for prolonged winter-season dormancy). Their high energy content transmits rapidly upward through the food web, allowing predators to grow fast with greater survival. Food quality appears to be even more important than food quantity, although high zooplankton biomass has tended to covary temporally with high lipid content.

Earlier research (e.g., Chelton et al. 1982) showed a strong alongshore correlation of zooplankton biomass anomalies and an inverse local correlation of biomass with temperature anomalies throughout the CalCOFI sampling region. By implication, this coherence extended throughout the California Current System (mid-Baja California to Vancouver Island). CalCOFI coverage of Mexican waters became sporadic after 1970 and ended in the early 1980s, but resumed in 1997 (as a Mexican national monitoring program called IMECOCAL). The 2005 North Pacific warm event that also appeared in the California Current stimulated an updated region-wide comparison of zooplankton time series (Mackas et al. 2006). It showed strong alongshore coherence from southern Vancouver Island to the southern California Bight, but a negative correlation with the post-1997 Baja California region. Subsequent research (Lavaniegos, 2009; Baumgartner et al. 2008) has shown that this reversal of spatial coherence is real and has persisted to the present (Fig. S-24). The change represents a remarkable reorganization and/or poleward shift of patterns of lower trophic level productivity in the California Current System.



[Figure S-23] Northeast Pacific anomaly time series for upper ocean temperature, biomass of "Northern" (endemic) and "Southern" (colonizing) copepods, and coho salmon marine survival relative to ocean entry year (Updated from Mackas et al. 2007).

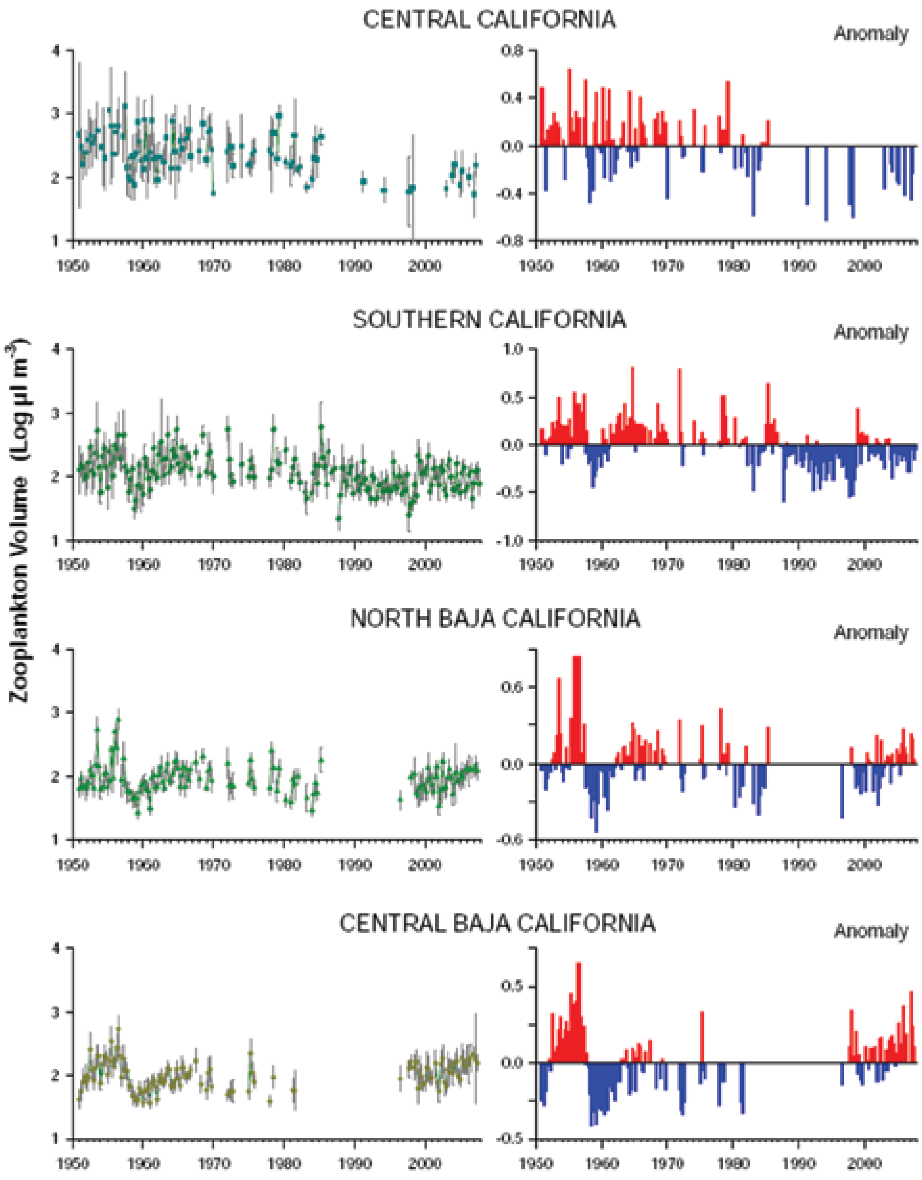
### 5.2.4 Northwest Pacific

Recent decadal trends of zooplankton biomass in the Oyashio and Kuroshio regions have been nearly neutral. However, within the Kuroshio region, the range of seasonal variability has declined by a factor of two over the past two decades. The past five years have had only weak March-April seasonal copepod maxima in abundance. Recent data also suggest the appearance of a weak secondary seasonal maximum in early autumn. Farther north, both the Oyashio and Kuroshio-Oyashio transition zone had reduced zooplankton biomass in 2005 and/or 2006. Trends for non-gelatinous mesozooplankton differed among regions in the Northwest Pacific. Biomass has either remained high or continued to increase all around the Korean Peninsula. The long-term trends in the sub-regions around Korea are correlated with surface warming that has been ongoing since the late 1970s. However, Russian data from Peter the Great Bay (near Vladivostok) show a strong step-like decrease between 1988-1996 and 1998-2004.

The most dramatic changes in the western marginal sea regions occurred in populations of gelatinous macrozooplankton, where medium and large sized jellyfish have become very abundant in recent years. Several taxa are involved, including the medium sized *Aurelia aurita* (abundant in summers since early 1990s), large *Cyanea capillata* (abundant spring-autumn since 2006), and large Dactylometra=*Chrysaora quinquecirrha* (abundant off the southern and eastern coasts of Korea). But the most extreme example is the recent (every year since 2002) population outbreak by the giant jellyfish *Nemopilema nomurai*. Blooms of this species begin in spring in the East China Sea and spread over about a month from there into the Yellow Sea and then northward through Tsushima Strait. A fraction of these sometimes reach Tsugaru Strait and pass into the coastal northwest Pacific. The jellyfish blooms have large human/economic impacts, causing major problems by clogging fishing nets, and stinging both fisherman and beach-goers. Recent changes in gelatinous zooplankton were less pronounced in other regions of the North Pacific, although the annual summer sampling along 155°E revealed a very intense bloom of salps within the Transition Region (40°-42°N) in 2003. Data from 2009 from the eastern Bering Sea show increased jellyfish abundance following 8 years of low abundance (Hunt et al. 2010).

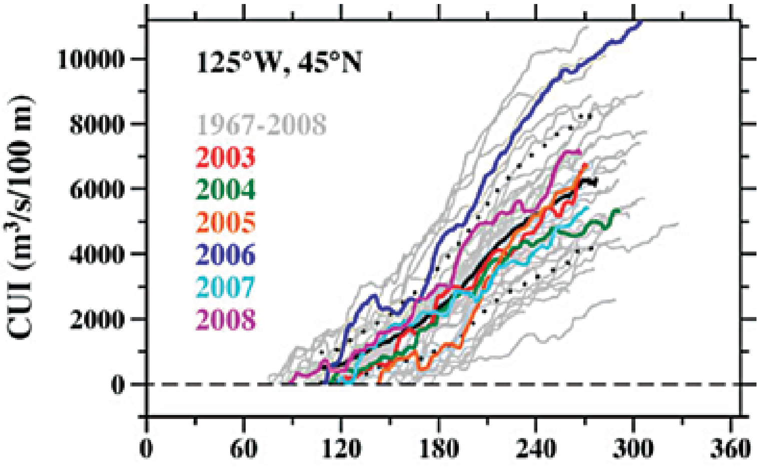
### 5.2.5 Ice cover and large zooplankton

The two regions most affected by seasonal ice cover (Okhotsk and Bering) share some important commonalities in their zooplankton community structure and sensitivity to timing of ice formation/melting. Both regions exhibit large interannual variability in the extent and duration of winter ice cover. In both regions, the long-term average zooplankton community is dominated by large copepods (*Neocalanus* spp. in deep water, *Calanus* in eastern Bering Sea shelf waters) and by euphausiids. But large changes



[Figure S-24] Comparison of zooplankton anomaly time series between CalCOFI and IMECOCAL sampling regions. Correlation was positive among all regions prior to ~1970, but became strongly negative between the southern and northern areas sometime between 1980 and 1997. (from Baumgartner et al. 2008).

in the zooplankton dominance hierarchy have occurred in both the eastern and western Bering Sea. In the western Bering Sea, euphausiids have been relatively more abundant in colder years and copepods more abundant in the warmer years (Shuntov and Temnykh 2009). On the eastern Bering Sea shelf, warm years (~2000-2005) were dominated by small copepods, but recent cooling (2006-2008) was accompanied by large increases in the abundance of both large copepods and euphausiids. The mechanism responsible for switches in dominance between euphausiids and small and large copepods is not yet clear. Globally, although euphausiids form a large fraction of total zooplankton in several oligotrophic open ocean environments (Longhurst 1985), they reach their largest biomass along a subset of more productive ocean regions (primarily in upwelling systems or cold winter shelf systems, Nicol and Endo 1997). Both of these environments undergo large seasonal cycles of food supply, yet euphausiids do not have a dormancy period like many of the large copepods.



[Figure S-25] Cumulative upwelling indices (CUI) off the coast of Oregon versus day of year for 1967-2008 at 45°N 125°W. CUI is computed by integrating the daily-averaged upwelling index from January 1 to December 31. Years in the focus period are colour-coded. The black solid and dotted lines are the long-term (1967-2007) mean and standard deviation of CUI(t) each day. CUI curves are shown from first zero-crossing to the date of maximum CUI (i.e., end of upwelling season).

### 5.2.6 Variability of zooplankton seasonal timing

The past decade has seen increased interest in zooplankton phenology, and its relation to environmental forcing. Two patterns are emerging. First, Subarctic copepods (*Neocalanus* and *Calanus* spp.) have strong associations between timing of their annual maximum abundance/ biomass, onset of seasonal dormancy, and upper ocean temperature during their growing season. Throughout the Subarctic Pacific, the consistent pattern is of an earlier and somewhat narrower population peak in warm years, later and broader in cold years. However, the east-west dipole of the PDO temperature anomaly pattern causes the copepod phenology time series to be out-of-phase between the eastern and western parts of the subarctic Pacific. Second, zooplankton seasonal timing within the California Current System is tightly coupled to the timing of the spring transitions of alongshore transport and upwelling intensity. Years such as 2005 in which upwelling is delayed (Fig. S-25) can also delay (and sometimes prevent) development of the annual cohort of resident cool-water zooplankton species. Thus, as the Northeast Pacific shifted from warmer to cooler temperatures during the focus period, the annual biomass peaks of *Neocalanus* shifted from earlier to later in the year. The timing and magnitude of the change are a function of location (earlier near the continental shelf, later farther in the Gulf of Alaska).

## 6.0 Fish and Invertebrate Fisheries

*(Yatsu, Irvine, Boldt)*

The biomass and abundance of marine fishes and some invertebrates exhibit annual and/or decadal-scale variability in recruitment, growth, natural mortality, and fishing mortality. Survival rates of larvae and juveniles are not only subject to the abundance and condition of spawners but to environmental changes as well. For most marine species, with the exception of many invertebrates whose life-span is one year or less, it generally takes several or more years to accumulate biomass. Therefore, biomass and catch responses to environmental changes can be delayed considerably, while recruitment levels, particularly for age-0 animals, tend to have much shorter time lags.

The objective of this section is to compare fish and invertebrate species and/or species groups among regions during the focus period (2003-2008, or shorter) with the period from 1990 to 2002. The ability to make comparisons was affected by the availability of data, the occurrences of climatic regime shifts in 1988-1989 (Hare and Mantua 2000) and 1998-1999 (Peterson and Schwing 2003), and potential delays in observing the responses of target animals and fisheries. Stock abundance, biomass, recruitment levels, length and weight at age, and survival rates of fishes and invertebrates were available for some, but not all commercial species. Where these data were not available, commercial catch or catch-per-unit-effort (CPUE) were used. Commercial catch and CPUE data can be useful indicators of abundance trends if fisheries are stable and sustainable, which is often not the case, particularly in some Asian fisheries. Fishing intensity can also be evaluated with catch:biomass ratios. Fish and invertebrates were examined at the species level when possible, or pooled as species groups with similar life-history traits. In addition to the data from each regional chapter, other relevant data (online Appendix http://www.pices.int/publications/special_publications/2010/npesr_2010.aspx) were assembled and summarized in two ways: inter-regional comparisons in average levels of abundance or abundance indices with environmental conditions, and inter annual and inter-regional comparisons in abundance of selected species or a species group, that have broad geographic distributions among most regions and relatively good data quality. Implications of regional similarities and differences detected in these comparisons are discussed.

## 6.1 Inter-regional comparisons

Most changes in fish and invertebrate abundance between the two periods were in the north-south direction. In the Sea of Okhotsk and Oyashio regions many taxa increased in abundance (Table S-1), probably as a result of warmer sea temperatures and reduced ice conditions in a generally cold place (Sea of Okhotsk). In contrast, the abundances of many fish and invertebrates decreased in the California Current, Yellow Sea and East China Sea, again possibly due to warming sea temperatures, though temperatures became cooler after 2006 in the northeastern Pacific. A warming trend was not detected in the Kuroshio/Oyashio in recent years.

Distributional shifts of some fish species in the eastern Pacific may also be related to temperature whereas some may be driven by other factors. Mueter and Litzow (2008) and Mueter et al. (2009) demonstrated that the distribution of eastern Bering Sea groundfish and invertebrates shifted to the north and into shallower waters over time (1982-2008). Temperature was identified as a factor but not the only one affecting this shift. Community dynamics and density-dependent responses may also affect trophic interactions, with economic implications (Mueter and Litzow 2008; Mueter et al. 2009; Spencer 2008). In the Gulf of Alaska, observed changes in rockfish distribution were not related to temperature or depth but their distribution was more contracted in 2007 than in previous years (Rooper 2008). There also appeared to be a trend of continued movement of the mean-weighted distribution towards the west, possibly indicating a change in rockfish distribution around the Gulf of Alaska (Rooper 2008). This change in distribution is especially apparent in juvenile Pacific ocean perch (*Sebastes alutus*) (Rooper 2008). Along the North American coast, the northward range extension and increased abundance of Humboldt squid during the focus period is hypothesized to be associated with the northward expansion of the coastal hypoxic area in addition to warming in the Northeast Pacific (see Box 5).

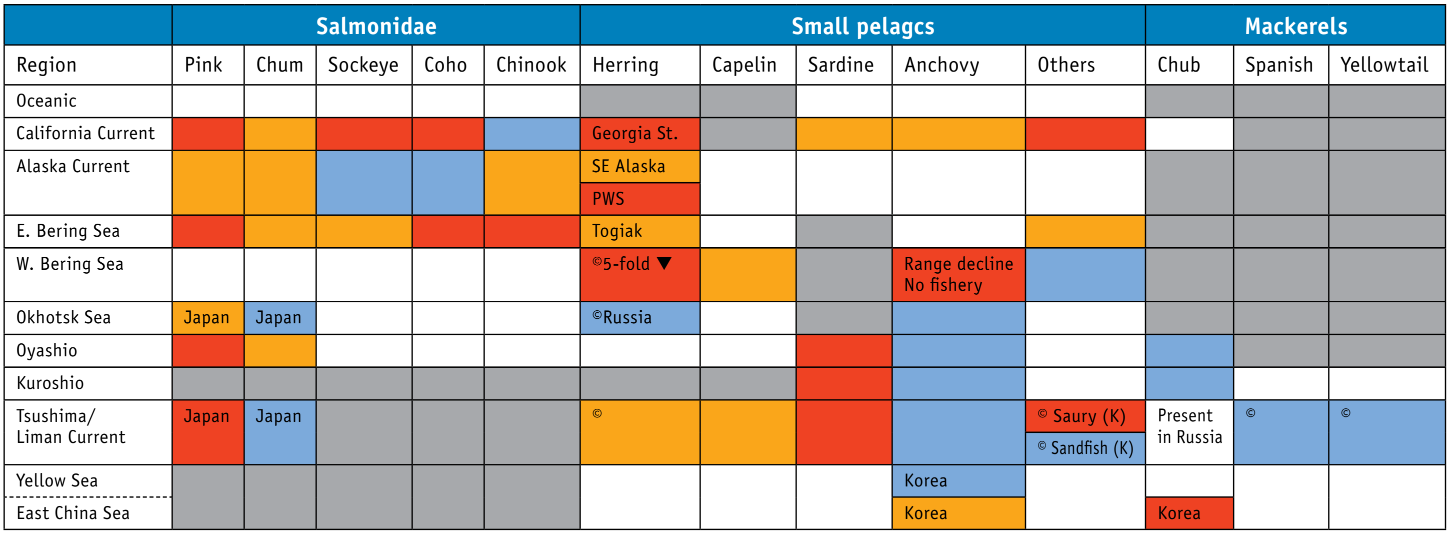
Along the west coast of Japan, increased catches and an expansion of the northern range of yellowtail (*Seriola quinqueradiata*) and Spanish mackerel (*Scomberomorus niphonius*) were apparent. In addition to increasing water temperatures in the Yellow Sea and East China Sea, eutrophication, blooms of giant jellyfish (*Nemopilema nomurai*) in 2002-2007, and 2009 and overfishing are potential factors causing declines in fish stock abundances. The recent dominance of cephalopods (mainly common squid, *Todarodes pacificus*) and blooms of giant jellyfish may be signs of ecosystem reorganization from environmental change and over-fishing. East-West differences were evident in the Bering Sea (Table S-1, Hunt et al. 2010), where out-of-phase patterns of environmental conditions can appear. Distributional shifts of species exemplify the dynamic nature of marine fish communities and the influence of environmental forcing.

## 6.2 Trends of major species

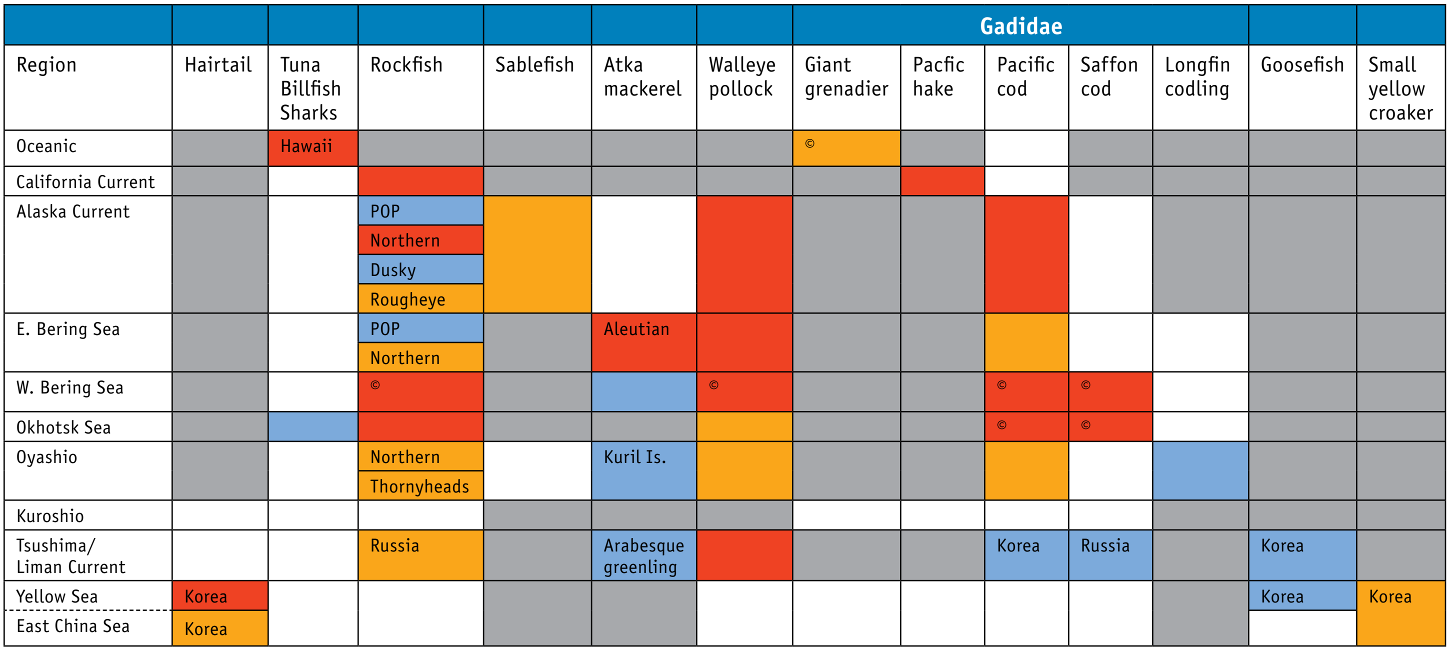
To examine these phenomenon across the entire North Pacific, long time series of abundance (or commercial catch) were examined using species that are commonly found in most regions of the North Pacific.

### 6.2.1 Pacific salmon

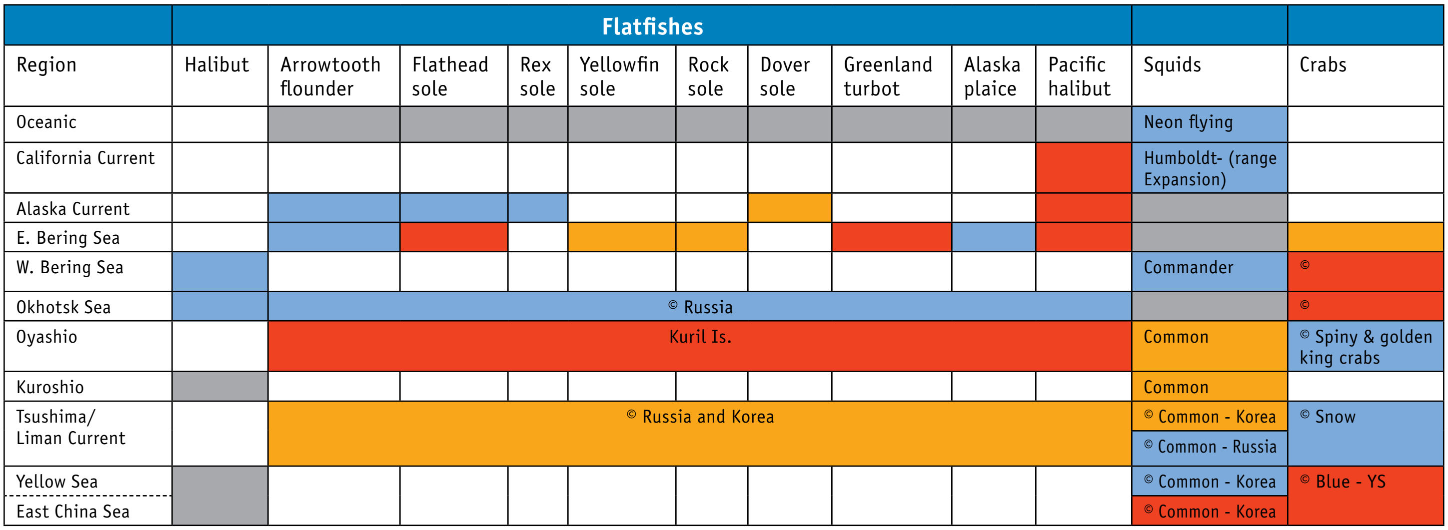
Aggregate commercial catches of Pacific salmon in the North Pacific during the focus period were the highest ever recorded (Fig. S-26, Irvine et al. 2009). Exceptional total catch during the focus period was a result of fisheries for pink salmon (*O. gorbuscha*) and chum salmon (*O. keta*) in Asia. There, the number of salmon released annually from hatcheries during this period was relatively stable (Fig. S-27), so some of the increase, particularly for Japanese chum salmon, must be a consequence of improved marine survival (Saito and Nagasawa 2009), or perhaps to improved hatchery rearing and releasing practices, especially in Russia.



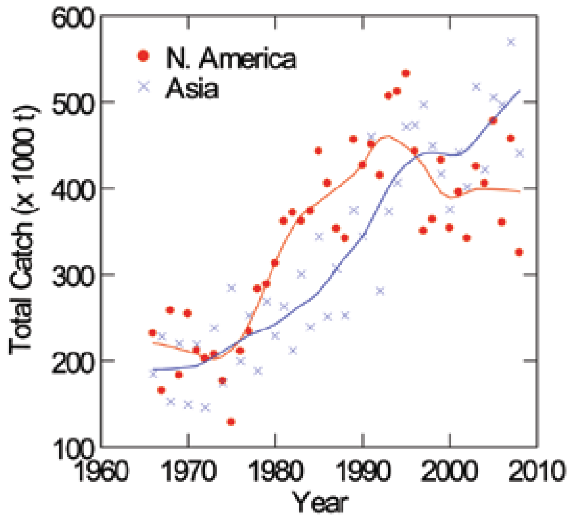
| | Salmonidae | | | | | Small pelagcs | | | | | Mackerels | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | Pink | Chum | Sockeye | Coho | Chinook | Herring | Capelin | Sardine | Anchovy | Others | Chub | Spanish | Yellowtail |
| Oceanic | | | | | | ▨ | ▨ | | | | ▨ | ▨ | ▨ |
| California Current | 🟥 | 🟧 | 🟥 | 🟥 | 🟦 | 🟥 Georgia St. | ▨ | 🟧 | 🟧 | 🟥 | | ▨ | ▨ |
| Alaska Current | 🟧 | 🟧 | 🟦 | 🟦 | 🟧 | 🟧 SE Alaska<br>🟥 PWS | | | | | ▨ | ▨ | ▨ |
| E. Bering Sea | 🟥 | 🟧 | 🟧 | 🟥 | 🟥 | 🟧 Togiak | | ▨ | | 🟧 | ▨ | ▨ | ▨ |
| W. Bering Sea | | | | | | 🟥 ©5-fold ▼ | 🟧 | ▨ | 🟥 Range decline No fishery | 🟦 | ▨ | ▨ | ▨ |
| Okhotsk Sea | 🟧 Japan | 🟦 Japan | | | | 🟦 ©Russia | | ▨ | 🟦 | | ▨ | ▨ | ▨ |
| Oyashio | 🟥 | 🟧 | | | | | | 🟥 | 🟦 | | 🟦 | ▨ | ▨ |
| Kuroshio | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟥 | 🟦 | | 🟦 | | |
| Tsushima/ Liman Current | 🟥 Japan | 🟦 Japan | ▨ | ▨ | ▨ | 🟧 © | 🟧 | 🟥 | 🟦 | 🟥 © Saury (K)<br>🟦 © Sandfish (K) | Present in Russia | 🟦 © | 🟦 © |
| Yellow Sea | ▨ | ▨ | ▨ | ▨ | ▨ | | | | 🟦 Korea | | | | |
| East China Sea | | | | | | | | | 🟧 Korea | | 🟥 Korea | | |



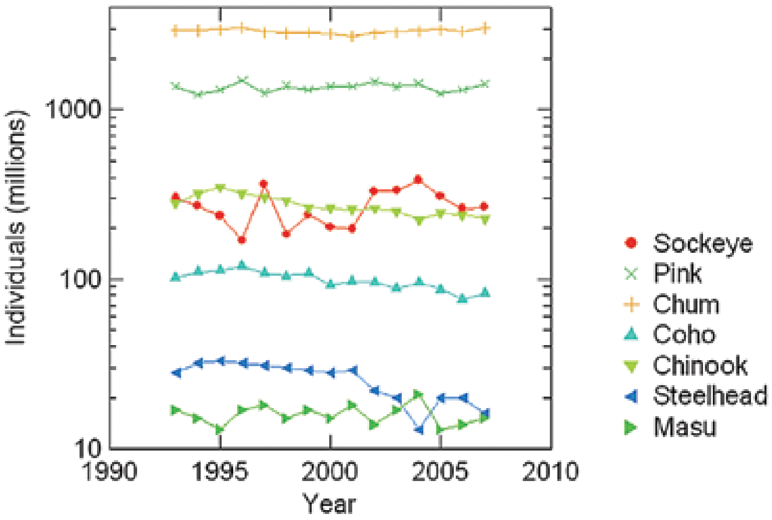
| | | | | | | | Gadidae | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | Hairtail | Tuna Billfish Sharks | Rockfish | Sablefish | Atka mackerel | Walleye pollock | Giant grenadier | Pacfic hake | Pacific cod | Saffon cod | Longfin codling | Goosefish | Small yellow croaker |
| Oceanic | ▨ | 🟥 Hawaii | ▨ | ▨ | ▨ | ▨ | 🟧 © | ▨ | | ▨ | ▨ | ▨ | ▨ |
| California Current | ▨ | | 🟥 | ▨ | ▨ | ▨ | ▨ | 🟥 | | ▨ | ▨ | ▨ | ▨ |
| Alaska Current | ▨ | | 🟦 POP<br>🟥 Northern<br>🟦 Dusky<br>🟧 Rougheye | 🟧 | | 🟥 | ▨ | ▨ | 🟥 | | ▨ | ▨ | ▨ |
| E. Bering Sea | ▨ | | 🟦 POP<br>🟧 Northern | ▨ | 🟥 Aleutian | 🟥 | ▨ | ▨ | 🟧 | | | ▨ | ▨ |
| W. Bering Sea | ▨ | | 🟥 © | ▨ | 🟦 | 🟥 © | ▨ | ▨ | 🟥 © | 🟥 © | | ▨ | ▨ |
| Okhotsk Sea | ▨ | 🟦 | 🟥 | ▨ | ▨ | 🟧 | ▨ | ▨ | 🟥 © | 🟥 © | | ▨ | ▨ |
| Oyashio | ▨ | | 🟧 Northern<br>🟧 Thornyheads | | 🟦 Kuril Is. | 🟧 | ▨ | ▨ | 🟧 | | 🟦 | ▨ | ▨ |
| Kuroshio | | | | ▨ | ▨ | ▨ | | | | | ▨ | ▨ | ▨ |
| Tsushima/ Liman Current | | | 🟧 Russia | ▨ | 🟦 Arabesque greenling | 🟥 | ▨ | ▨ | 🟦 Korea | 🟦 Russia | ▨ | 🟦 Korea | ▨ |
| Yellow Sea | 🟥 Korea | | | ▨ | ▨ | | | | | | ▨ | 🟦 Korea | 🟧 Korea |
| East China Sea | 🟧 Korea | | | | | | | | | | | | |



| | Flatfishes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | Halibut | Arrowtooth flounder | Flathead sole | Rex sole | Yellowfin sole | Rock sole | Dover sole | Greenland turbot | Alaska plaice | Pacific halibut | Squids | Crabs |
| Oceanic | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟦 Neon flying | |
| California Current | | | | | | | | | | 🟥 | 🟦 Humboldt- (range Expansion) | |
| Alaska Current | | 🟦 | 🟦 | 🟦 | | | 🟧 | | | 🟥 | ▨ | |
| E. Bering Sea | | 🟦 | 🟥 | | 🟧 | 🟧 | | 🟥 | 🟦 | 🟥 | ▨ | 🟧 |
| W. Bering Sea | 🟦 | | | | | | | | | | 🟦 Commander | 🟥 © |
| Okhotsk Sea | 🟦 | 🟦 © Russia | | | | | | | | | ▨ | 🟥 © |
| Oyashio | | 🟥 Kuril Is. | | | | | | | | | 🟧 Common | 🟦 © Spiny & golden king crabs |
| Kuroshio | ▨ | | | | | | | | | | 🟧 Common | |
| Tsushima/ Liman Current | | 🟧 © Russia and Korea | | | | | | | | | 🟧 © Common - Korea<br>🟦 © Common - Russia | 🟦 © Snow |
| Yellow Sea | ▨ | | | | | | | | | | 🟦 © Common - Korea | 🟥 © Blue - YS |
| East China Sea | | | | | | | | | | | 🟥 © Common - Korea | |



[Figure S-26] Trends in total commercial catch (× 1000 t) of Pacific salmon, by continent. The combined total was as high or higher during the focus period than at any other time in the historical record. Loess trend lines indicate the general trends in each region (Data source: NPAFC, see Irvine et al. 2009).

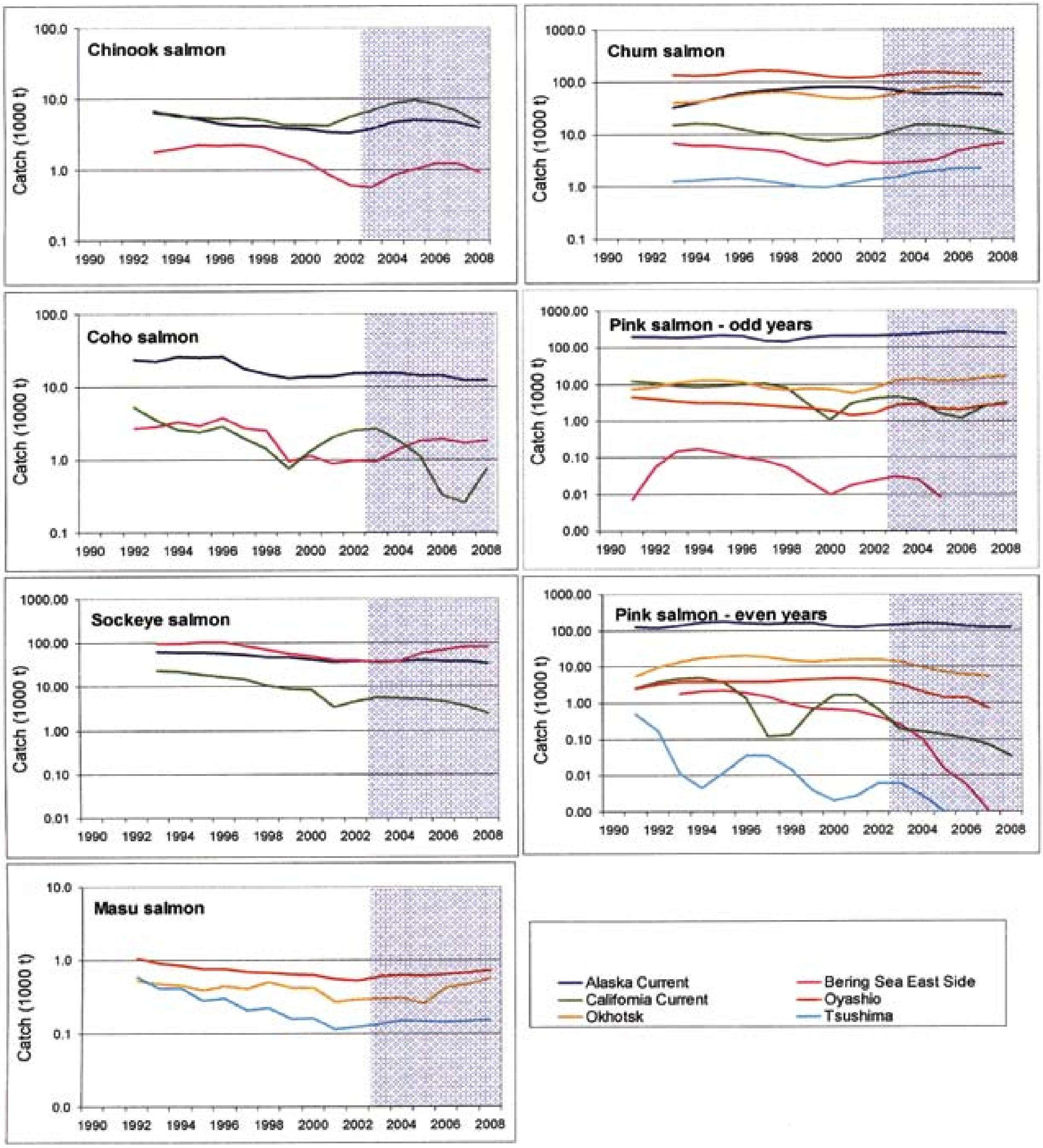


[Figure S-27] Numbers of salmon by species released by all hatcheries in the North Pacific during 1993-2007. The average during the focus period (2003-2007 only) was ~5.0 billion annually (Data source: NPAFC, see Irvine et al. 2009).

Kaeriyama et al. (2009) found that the carrying capacity for sockeye, pink, and chum salmon was positively correlated with the average winter intensity of the Aleutian Low pressure system so they predicted that carrying capacity will be synchronized with long-term trends in climate change. The Aleutian Low became less intense through the focus period but catches were at record high levels. This mismatch between observations and hypothesis may have arisen because some of the broods that were released during the focus period have yet to return so the final outcome is not yet known.

Lengthy time series of marine survival for Pacific salmon are uncommon in Asia. Hiroi (1998) and Kaeriyama (1998) reported increasing return rates for Japanese hatchery chum salmon from Hokkaido and Honshu from the late 1970s through the early 1990s. Chum salmon return rates to hatcheries along the Pacific side of Japan are affected by interannual temperature variability during the latter part of the period of coastal residency in the year of their release. Return rates for salmon released on the west side of Hokkaido decreased following the 1992 release year while those for chum salmon released on the west side of Honshu have been consistently low. Along the Japanese coast of the Sea of Okhotsk, survival of chum salmon at sea is significantly higher during years when the coastal ocean (< 100 km) is warmer or if the fry are released at a larger size (Saito and Nagasawa 2009). The abrupt and relatively persistent warm period that began in the northwestern Pacific around 1989 (Fig. S-3) should have been favourable for sustaining higher survival and better catches. Only in Russia has the number of chum and pink salmon released from hatcheries shown a gradual increase during the last 15 years. The number of chum salmon released from Japanese hatcheries has been a relatively constant 2 billion per year since the late 1980s (Hiroi 1998). Kaev and Ignatiev (2007) attributed increasing return rates (adult catches÷juveniles released) to Sakhalin chum salmon hatcheries to the recent practice of releasing fry in better condition, rather than from a more favorable ocean. Regardless of the mechanism responsible for improved survivals, the benefits in terms

[Table S-1] (Opposing page) Interregional comparison of levels in biomass or abundance indices of fishes and invertebrates since 2003, compared to 1990-2002. Colour codes are: blue (increase), red (decrease), orange (change <|10%|), grey (not relevant to the region), and white (no data). The symbol © indicates that the evaluation for that taxon/region is based on catch data. In some regions, flatfish data were not reported by species, so any trends that are indicated apply only to the aggregate of flatfish species caught in that region, andnot necessarily the individual species listed in the column headers.



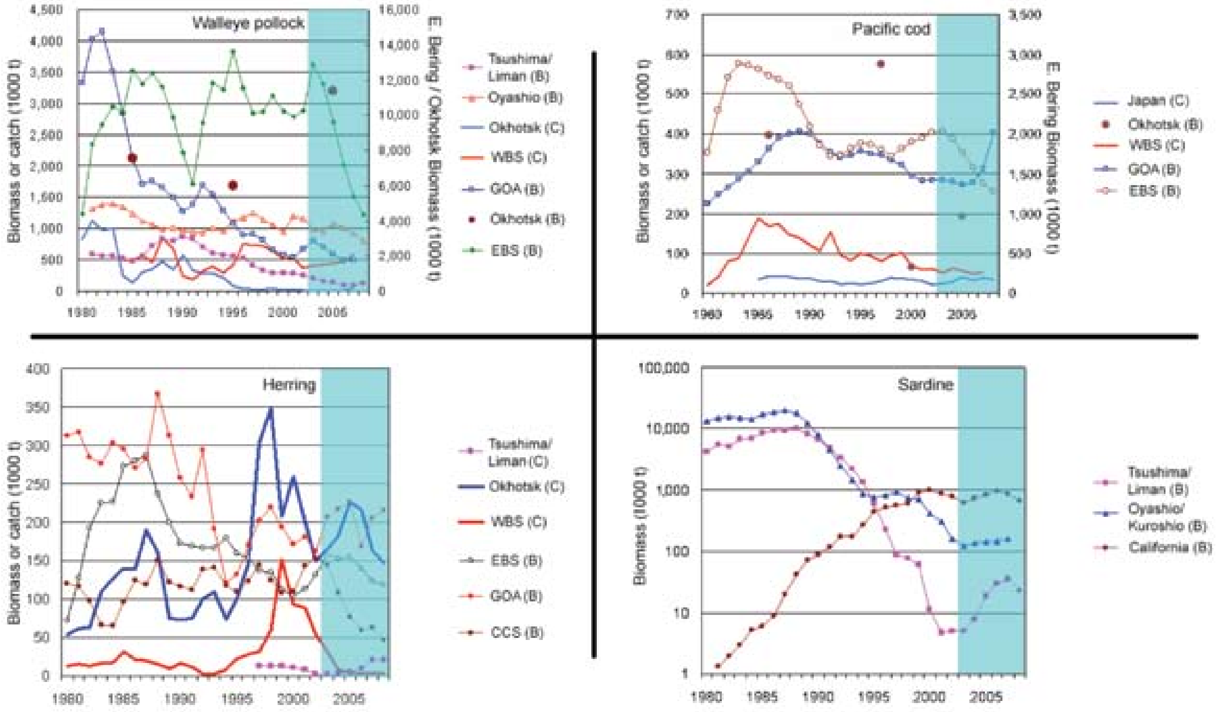
[Figure S-28] Year-to-year variations in catch of Pacific salmon species by oceanic region. Russian catches are excluded because they could not be partitioned into the regions of interest. Running averages are plotted (final year of 4-year moving window for sockeye, chinook, and chum salmon, 3 year for coho and masu salmon, and 2 year for pink salmon). The shaded regions indicate the focus period, 2003-2008. (Data source: NPAFC, see Irvine et al. 2009) of salmon catch have been significant. Chum salmon caught near Sakhalin are now largely of hatchery origin, a major switch from the catches of wild salmon in the 1960-1990 period (Kaev and Ignatiev 2007). In the Republic of Korea, chum salmon return rates were <0.4% during 1986-1988, increasing to 1.6% in 1990 (Lee et al. 2007). Lee et al. (2007) attributed declining return rates after 2000 to high temperatures in the coastal area when young chum salmon are present. The much less abundant and apparently declining masu salmon (*O. masou*) are caught only in Asia.

Contrast the Asian experience with what has occurred in North America (Fig. S-28). Except for chum salmon, recent trends are downward for commercial catches of sockeye salmon (*O. nerka*), coho salmon (*O. kisutch*), chinook salmon (*O. tshawytcha*) and pink salmon (*O. gorbuscha*) in most of the California Current region. Commercial salmon fisheries that have operated for more than a century have been severely curtailed or shut down in this region during the last decade. The survival and abundance trends in the California Current region seem to suggest that the ocean has become less hospitable to Pacific salmon or the salmon have become less resilient. Declining commercial catches of coho salmon from Canada southward are partly a consequence of restrictions on fishing, but their survival in the ocean has also declined or is at low levels. Sockeye salmon populations along the northern British Columbia coast (southernmost part of the Alaska Current region) are generally better off than those in the south but there are some rare and unexplained deviations from this pattern. Returns of several major populations of sockeye salmon to the Fraser River collapsed in 2009 (most went to sea in 2007) while sockeye salmon returns to the Columbia River in 2009 (and 2008), which shared the same ocean entry year as the fateful Fraser run, were very good. The contrast is as yet unexplained. In April 2008 the governor of the State of California declared a “State of Emergency” over the diminished abundance of fall run chinook salmon to the Sacramento River (central California) and in 2009, returns reached record lows. Poor marine survival, at least in the northern California Current region, is related to ecosystem variability that arises from contrasting subarctic and subtropical oceanic influences (Mackas et al. 2007). Marine survival tends to be better when the coastal ocean is more characteristic of a Subarctic ocean than a subtropical ocean. During the focus period, the California Current region shifted abruptly to a more Subarctic ocean with the PDO shifting to strongly negative (Fig. S-5, S-6c) in the fall of 2007. The full consequences of that shift have yet to be seen but survival of Pacific salmon in the California Current region should be better in these years (Fig. S-23).

### 6.2.2 Walleye pollock

The biomass of walleye pollock has a decadal-scale pattern of variation that shows little relation to climatic regimes (Yatsu et al. 2008; Beamish 2009). Declining trends in biomass were commonly observed during the 1990s to early 2000s in all stocks examined except for the eastern Bering Sea where the stock remained at a high level from the mid-1980s until recently. In West Kamchatka and the Pacific side of Japan, there were short-term recoveries in the mid or late 1990s (Yatsu et al. 2008). During the focus period however, declining trends were a general feature (Fig. S-29) except for Russian catches in the western Bering Sea (Navarin area) and Sea of Okhotsk which began to increase in 2003 and 2007, respectively. The biomass of walleye pollock in the Sea of Okhotsk in the 2000s was almost double that of the 1990s, associated with warmer conditions that were caused by an intensification of the West Kamchatka Current (increased inflow of Pacific water) and a relatively ice-free winter. Since the age of recruitment of walleye pollock is age-2 or older, the accumulation of biomass takes several years.

The Oscillating Control Hypothesis (Hunt et al. 2002) anticipates stronger walleye pollock recruitment in the eastern Bering Sea when there are warmer sea temperatures and increased zooplankton prey availability. Recruitment is also favoured by northward transport of eggs and larvae (Wespestad et al. 2000; Mueter et al. 2006). The eastern Bering Sea walleye pollock stock has declined during the focus period due to an unprecedented period of poor recruitment that spanned the warm years of the focus period (2003-2005) and the cold years of 2006-2009 (Ianelli et al. 2009). This indicates that at least one cause of recruitment variability was not anticipated by the Oscillating Control Hypothesis. Recent studies indicate that the condition of juvenile walleye pollock (Ianelli et al. 2009; Moss et al. 2009) and the abundance, bloom timing, composition, and distribution of their zooplankton prey may also contribute to recruitment success.



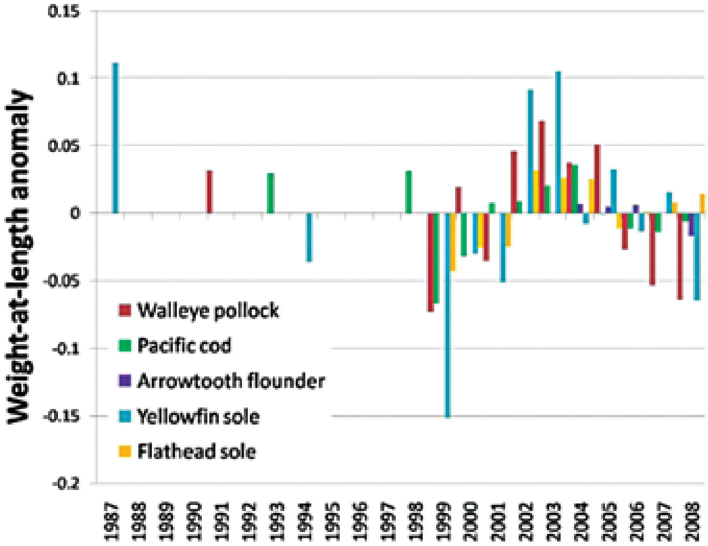
[Figure S-29] Year-to-year variations in biomass (B) or catch (C) of selected non-salmonid fishes by region CCS=California Current region, EBS=eastern Bering Sea, GOA=Gulf of Alaska, WBS=western Bering Sea. EBS herring biomass is Togiak herring; GOA herring biomass includes Prince William Sound, Southeast Alaska, and northern BC (Prince Rupert, Queen Charlotte Islands, and Central Coast), CCS herring biomass includes southern British Columbia stocks (Strait of Georgia and West Coast of Vancouver Island). WBS walleye pollock data are from Navarin.

### 6.2.3 Pacific cod

Pacific cod biomass in the eastern Bering Sea was relatively stable or slightly increasing during 1980-2003 after which it decreased (Thompson et al. 2008a). Biomass in the Gulf of Alaska increased from 1980 to 1989, then decreased until 2001, was relatively stable until 2006, and then increased (Thompson et al. 2008b). Pacific cod catch in the western Bering Sea, which may reflect biomass trends, increased from 1980 to 1985 and decreased from 1986 to 2007. Biomass in the Sea of Okhotsk varied considerably among the four surveys conducted from 1986 to 2005. The 2005 value was second lowest, recovering from the lowest one in 2000. The Japanese catch from Hokkaido and northern Honshu was relatively stable. Periodic shifts in key physical variables that change on scales from several years to a few decades appear to affect Alaska's Pacific cod stock (Thompson et al. 2008a; 2008b). However, establishing the links between environmental variables, biomass and recruitment of Pacific cod in the eastern Bering Sea and Aleutian Islands areas is difficult as there are only weak correlations between age-1+ recruitment and the PDO index (Thompson et al. 2008a, 2008b). It was also difficult to find a linkage between fluctuations of year-class strength and environmental factors in Russian stocks (Beamish 2009) although similarity in recruitment trends of walleye pollock and Pacific cod in the eastern Bering Sea and Gulf of Alaska suggest the existence of common oceanic factors.

### 6.2.4 Pacific herring

Gulf of Alaska herring biomass has been variable in the last five years (Fig. S-29); declining stocks include Prince William Sound, approximately half of the southeastern Alaska stocks, and British Columbia stocks, while increasing stocks include about half the southeastern Alaska stocks (Moffitt 2008; Hebert and Dressel 2009; J. Cleary, Fisheries and Oceans Canada, pers. comm.). Herring biomass in the California Current (southern British Columbia stocks) has decreased in the last five years; one stock is above the fishing threshold reference point and the other is below



[Figure S-30] Weight-at-length anomalies for five groundfish species in the eastern Bering Sea (see Hunt et al. 2010). Anomalies were computed by estimating log (weight) at a given size for each year from linear regressions of log (weight) on log (length).

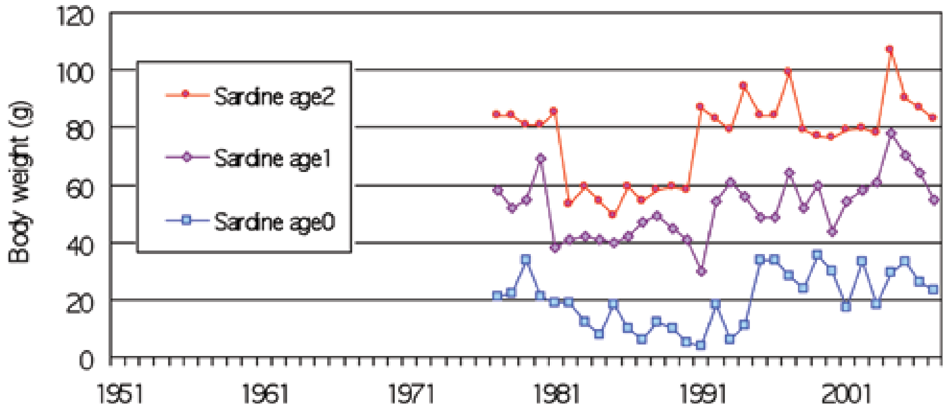
(J. Cleary, Fisheries and Oceans Canada, pers. comm.). Eastern Bering Sea herring biomass has been below the long-term average and decreased in the last five years (Buck 2008). Western Bering Sea herring catch has been variable but perhaps became stable during 2002-2004. Herring catch in the Russian Primorye region indicates that the Primorye stock is one of the few stocks in the region that has shown an increase since 2002. The herring catch in the Sea of Okhotsk has been highly variable, peaking in 1998 and generally decreasing afterwards, with decreased catches since 2005.

The variability of recruitment of Pacific herring in the Alaska and California Current systems is probably related to large-scale environmental factors (Williams and Quinn 2000), but also to smaller-scale environmental factors (Norcross et al. 2001), disease (Marty et al. 2003, 2004; Moffit 2008), and in some cases changes in spawning locations (Hebert and Dressel 2009). Williams and Quinn (2000) found that Pacific herring populations in the North Pacific are closely linked to environmental conditions with temperature having the strongest correlation. There is evidence that factors affecting the larval stage and/or juvenile stages of herring life history may determine year-class strength (Cushing 1975; Iles and Sinclair 1982; Schweigert et al. 2009a).

Herring populations throughout British Columbia have all shown a long-term decline in size-at-age suggesting that reductions in food supply may have occurred over the past two decades (Schweigert et al. 2009b). In addition, there have been few years of strong recruitment during this period; stock assessment results indicate that natural mortality rates have increased over this period, suggesting that there may be increasing predation pressure on these populations (Schweigert et al. 2009b).

### 6.2.5 Sardine

Catch and biomass trends of Japanese sardine and Pacific (California) sardine were in phase from the 1910s until the early 1990s (Yatsu et al. 2008). However, since the early 1990s only the Pacific sardine increased, while the Japanese sardine remained at a low level (Fig. S-29) due to excess fishing pressure and warmer than optimal sea temperatures in the Kuroshio Extension (Yatsu and Kaeriyama 2005). According to the Optimum Temperature Hypothesis (Takasuka et al. 2008), the in-phase annual catches of sardine from the early 1980s to the 1990s between the eastern and western North Pacific can be explained by the coherent out-of-phase SST trend. The optimum temperature for sardine in the west is cool and the optimum temperature for the eastern population is warm (Yatsu et al. 2008). The out-of-phase pattern in sardine catch between the east and west after the 1980s was due to increased SST in both areas. The relationship between SST and sardine biomass has continued in recent years, though current biomass levels of Japanese sardine could increase if fishing mortality was lowered. Prey and predators are also hypothesized to affect the population dynamics of the Pacific stock of Japanese sardine off Japan. In cool periods: 1) temperature and prey conditions



[Figure S-31] Body weight-at-age of the Pacific stock of Japanese sardine off Japan (see Chiba et al. 2010).

in the nursery grounds (Kuroshio Extension and Kuroshio/Oyashio transition zone) are favourable for early growth, 2) the southward expansion of the Oyashio provides an increased feeding ground, and 3) cooler conditions prevent mass arrivals of subtropical predators such as skipjack tuna (*Katsuwonus pelamis*) and common squid (Yatsu et al. 2008; Takahashi et al. 2009).

## 6.3 Biological indices

Weight-at-age of several species in the eastern Bering Sea increased corresponding to warmer temperatures and reduced ice from 2001 to 2005, and became negative during cold years from 2006 to 2008 (Fig. S-30). Size-at-age of some small pelagic fishes in the Oyashio/Kuroshio increased after the 1988-1989 regime shift (Fig. S-31), when zooplankton biomass increased and Japanese sardine and Japanese chub mackerel (*Scomber japonicus*) biomass decreased. These examples suggest a swift response in the condition of fish species to climatic shifts. In the central North Pacific, CPUE of medium- and large-sized fishes has been reduced, in contrast to an increase in CPUE of neon flying squid (*Ommastrephes bartrami*), suggesting a declining average longevity of high trophic level species in this region.

# 7.0 Marine Birds and Mammals

*(Hunt)*

Trends in the distribution, population size or productivity of marine birds and mammals provide an indication of changes in the resources on which they depend (Piatt et al. 2007). However, they are long-lived animals that may delay the start of reproduction for several years after becoming independent. To assess what the observed changes in marine bird and mammal indices are telling us about the marine environment, we must be sensitive to the time scales of reaction to environmental changes. Thus, most reproductive parameters of marine birds reflect food availability in the same season, whereas population changes may reflect events several years in the past. Likewise with many pinnipeds, prey availability in a given year will influence pup production in the same year, although the effects of nutritional stress may be delayed by a year (or more) and may show up then as reduced pup production. The evidence of ecosystem change provided by marine birds is, in most cases, relatively free of the effects of harvesting or predation, though, in some colonies birds of prey or terrestrial predators can have major impacts on reproductive performance. In the case of pinnipeds and whales, many populations have been subject to harvests in the past, and present trends may reflect a rebound from those past declines. Likewise, most species of pinnipeds and small whales are subject to predation by killer whales, the top predator in many North Pacific marine ecosystems (e.g., Springer et al. 2003). Given the

[Table S-2] Trends in the numbers or productivity of planktivorous species of marine birds and baleen whales. [CA= California, USA; BC= British Columbia, Canada; PRBO= Point Reyes Bird Observatory in California, K = carrying capacity]

| Location | Species | Metric | Dates used | Trend | Reference |
|---|---|---|---|---|---|
| **California Current** | | | | | |
| Farallon Is., CA | Cassin's auklet | Population trend | 1998 - 2008 | No trend | PRBO - pers. comm. |
| Farallon Is., CA | Cassin's auklet | Productivity | 2002 - 2008 | Down | PRBO - pers. comm. |
| California & Oregon | Blue whale | Population trend | 1991 - 2008 | Up <3% $y^{-1}$ | Calambokidis 2009 |
| California, Oregon & Washington | Blue whale | Population trend | 2001 - 2005 | No trend | Caretta et al. 2009 |
| California, Oregon & Washington | Fin whale | Population trend | 2001 - 2005 | No trend | Caretta et al. 2009 |
| California & Oregon | Humpback whale | Population trend | 1990 - 2008 | Up 7.5% $y^{-1}$ | Calambokidis 2009 |
| California, Oregon & Washington | Humpback whale | Population trend | 1999 - 2003 | Up | Caretta et al. 2009 |
| **British Columbia and Southeast Gulf of Alaska** | | | | | |
| Triangle Is., BC | Cassin's auklet | Population trend | 1999 - 2009 | No trend | Hipfner, pers. comm. |
| Triangle Is., BC | Cassin's auklet | Productivity | 1998 - 2006 | No trend | Hipfner, pers. comm. |
| British Columbia | Humpback whale | Population trend | | Up 4.1% | Ford et al. 2009 |
| **Northern and western Gulf of Alaska** | | | | | |
| Northern Gulf of Alaska | Humpback whale | Population count | 1987 - 2003 | Up 6.6% $y^{-1}$ | Allen & Angliss 2009 |
| Shumagin-Kodiak areas | Fin whale | Population count | 1987 - 2003 | Up 4.8% $y^{-1}$ | Allen & Angliss 2009 |
| **Sea of Okhotsk** | | | | | |
| Talan Island | Crested auklet | Population count | 1989 vs 2008 | Down | Andreev et al., In Press |
| Talan Island | Ancient murrelet | Population count | 1989 vs 2008 | Down | Andreev et al., In Press |
| Talan Island | Parakeet auklet | Population count | 1989 vs 2008 | Down | Andreev et al., In Press |
| **Western North Pacific** | | | | | |
| Asia stock | Humpback whale | Population count | 1991-93 vs. 2004-06 | Probably Up | Allen & Angliss 2009 |

generally sparse data, the effects of killer whales are not easily separated from those of bottom-up impacts of prey variability (DeMaster et al. 2006; Small et al. 2008; Wade et al. 2009).

Broadly speaking, marine birds and mammals can be separated into species that filter-feed on mesozooplankton and micronekton and those that bite-feed, primarily on fish varying in size from forage fish (capelin, eulachon, smelts, sand lance and juvenile herring, pollock and salmonids) to adult Pacific cod, walleye pollock, Atka mackerel, and other large fishes. Planktivores were distinguished from piscivores when tabulating data by region (Tables S-2 and S-3). The measures of trend are often unique to individual studies, as are the periods for which such information is available. There are numerous other populations for which point measures are available, but without a time series they are not particularly informative for a synthesis of the type attempted here.

Many of the planktivore populations in the eastern North Pacific Ocean have shown either increasing trends or no trend during the focus period, implying fairly stable populations (Table S-2, Fig. S-32). Although humpback whales have continued to increase throughout the North Pacific in all regions for which data are available, blue and fin whales in California, Oregon and Washington waters, after an initial rebound from the 1970s to the 1990s subsequent to the cessation of modern whaling (Calambokidis 2009), have shown little sign of increase in recent years. In contrast, there is evidence that these whales are still increasing in Alaskan waters.

There are few data available on trends of planktivorous species of marine birds and mammals in the western North Pacific. In the northern Sea of Okhotsk, three species of planktivorous seabirds have experienced severe population declines, whereas the Asian stock of humpback whales is most likely increasing. Breeding failure of planktivorous seabirds may indicate decreased abundance of euphausiids and large species of copepods. Many planktivorous seabird species prey on euphausiids, which may be favored by cold water (Drobysheva 1967, 1994; Coyle et al. 2008). In the California Current region, large Subarctic zooplankton and euphausiids are favored when the flow of the California Current and coastal upwelling of cold nutrient-rich water are strong (Ainley et al. 1995; Abraham and Sydeman 2004; Lee et al. 2007). Cassin's auklets nesting along the British Columbia coast suffer reproductive failures and colony abandonment when euphausiids and large sub-arctic copepods are not available (Bertram et al. 2001; Wolf et al. 2009). In the Bering Sea, elevated levels of stress hormones and reproductive failure were recorded in planktivorous alcids nesting on the Pribilof Islands during the warm year of 2004 (Benowitz-Fredericks et al. 2008; Hunt et al. 2008). Likewise, in the Sea of Okhotsk, euphausiid-eating seabirds thrived in cold years when euphausiids were abundant, whereas fish-eating species had higher reproductive success in warm years (Kitaysky and Golubova 2000). The recent sharp decline in planktivorous alcids in the northern Sea of Okhotsk (Table S-2) most likely reflects a steep decline in the availability of euphausiids to birds nesting on Talan Island. If the decline in euphausiids is widespread there, it may have implications for the recruitment of commercially important fish, such as walleye pollock, that consume euphausiids and large copepods both as juveniles and as adults (Aydin et al. 2007; Hunt et al. 2008; Moss et al. 2009). The mechanisms responsible for changes in euphausiid abundance most likely differ among the California Current, the eastern Bering Sea and the Sea of Okhotsk, but in each of the regions, measures of the reproductive parameters of marine birds provided notice that this important component of marine food chains had declined.

Changes in the timing of the availability of zooplankton can also negatively affect marine bird reproduction (e.g., Sydeman et al. 2006; Wolf et al. 2009). In the focus period, 2005 was notable for the extraordinarily late start of upwelling in much of the California Current region (see Box 3). A consequence was the late commencement of primary production and an apparent early-season lack of euphausiids (Sydeman et al. 2006). Limited data from the central California coast and British Columbia in 2005 indicated planktivorous auklets failed to attend their colonies at all, or those that did try to breed, failed (Sydeman et al. 2006). Unusually high numbers of seabirds washed up on beaches of California, Oregon and Washington, with species of both planktivorous and piscivorous species among those found dead (Parrish et al. 2007).

In the case of piscivorous species of marine birds (rhinoceros auklets and common murres) (Fig. S-33) and pinnipeds (sea lions, northern fur seals, harbour seals

[Table S-3a] Piscivorous species in the North Pacific [PRBO= Point Reyes Bird Observatory in California, USA; K= carrying capacity; CA= California, USA; WA= Washington State, USA; BC= British Columbia, Canada; GOA= Gulf of Alaska; DFO= Canadian Department of Fisheries & Oceans]

| Location | Species | Metric | Dates used | Trend | Reference |
|---|---|---|---|---|---|
| California, Oregon & Washington | California sea lion | Population trend | 2000 - 2006 | No trend | Caretta et al. 2009 |
| San Miguel Is., CA | Northern fur seal | Population trend | 1998 - 2005 | Up | Caretta et al. 2009 |
| San Miguel Is., CA | Northern fur seal | Pup production | 1972-76 vs 2002-06 | Up - interrupted by El Niño | Olesiuk 2009 |
| Channel Islands, CA | California sea lion | Population trend | 2004 - 2008 | Up | Bograd et al. 2010 |
| Channel Islands, CA | Northern elephant seal | Population trend | 2000 - 2005 | Up | Caretta et al. 2009 |
| Farallon Is. CA | Common murre | Population trend | 1998 - 2008 | Up | PRBO – pers. comm. |
| Farallon Is., CA | Common murre | Productivity | 2002 - 2008 | No trend | PRBO – pers. comm. |
| Farallon Is, CA | Rhinoceros auklet | Population trend | 1998 - 2008 | Unknown | PRBO – pers. comm. |
| Farallon Is., CA | Rhinoceros auklet | Productivity | 2002 - 2008 | No trend | PRBO – pers. comm. |
| Farallon Is. CA. | California sea lion | Population trend | 1998 - 2008 | No trend | PRBO – pers. comm. |
| Farallon Is., CA | Northern fur seal | Population trend | 1998 - 2008 | Up | PRBO – pers. comm. |
| Farallon Is., CA | Northern elephant seal | Population trend | 1998 - 2008 | No trend | PRBO – pers. comm. |
| Central California | Steller sea lion | Non-pup count | 1996 - 2004 | No trend | Caretta et al. 2009 |
| Northern California & Oregon | Steller sea lion | Non-pup count | 1996 - 2002 | No trend, at K | Caretta et al. 2009 |
| California | Harbour seal | Population trend | 1995 - 2004 | No trend, at K | Caretta et al. 2009 |
| Oregon & Washington | Harbour seal | Population trend | 1995 - 2004 | No trend, at K | Caretta et al. 2009 |
| Tatoosh Is., WA | Common murre | Productivity | 1998 - 2008 | Up | Parrish, pers. comm. |
| Triangle Is., B.C. | Rhinoceros auklet | Population trend | 1999 - 2009 | Up ? | Hipfner, pers. comm. |
| Triangle Is., B.C. | Rhinoceros auklet | Productivity | 1998 - 2007 | Up ? | Hipfner, pers. comm. |
| British Columbia | Steller sea lion | Pup count | 1980s - 2006 | Up 7.9% $y^{-1}$ | DFO, 2008 |
| British Columbia | Steller sea lion | Non-pup count | 1998 - 2002 | Up | Allen & Angliss 2009 |
| St. Lazaria Is., E GOA | Rhinoceros auklet | Population trend | 1994 - 2006 | Up | Slater, pers. comm. |
| St. Lazaria Is., E GOA | Rhinoceros auklet | Population trend | 1998 - 2006 | Up 5% $y^{-1}$ | Dragoo, pers. comm. |
| St. Lazaria Is., E.GOA | Rhinoceros auklet | Productivity | 2002 - 2006 | Up ? | Dragoo, pers. comm. |
| St. Lazaria Is., E GOA | Unid. murre | Population trend | 1998 - 2006 | No trend | Dragoo. pers. comm. |
| St. Lazaria Is., E GOA | Unid. murre | Population trend | 1994 - 2006 | Down | Slater & Byrd 2009 |
| St. Lazaria Is., E GOA | Unid. murre | Population trend | 2001 - 2006 | No trend | Slater & Byrd 2009 |
| Southeast Alaska | Steller sea lion | Pup counts | 1996 - 2009 | Up 5.0% $y^{-1}$ | DeMaster, 2009 |
| Southeast Alaska | Harbour seal | Population trend | 1990s - 2002 | Variable no trend | Allen & Angliss 2009 |
| Eastern GOA | Steller sea lion | Pup count | 2001 - 2009 | No trend | DeMaster 2009 |
| Central GOA | Steller sea lion | Pup count | 1994 - 2009 | Down 0.6% $y^{-1}$ | DeMaster 2009 |
| Middleton Is., GOA | Unid. murre | Population count | 1998 - 2007 | Down | Hatch, pers. comm. |
| Middleton Is., GOA | Rhinoceros auklet | Population count | 1998 - 2007 | Up | Hatch, pers. comm. |
| Middleton Is., GOA | Black-legged kittiwake | Population count | 1998 - 2007 | Down | Hatch, pers. comm. |
| Western GOA | Steller sea lion | Pup count | 1998 - 2009 | Up 2.6% $y^{-1}$ | DeMaster 2009 |
| Prince William Sound | Harbour seal | Population trend | 1984 - 1997 | Down | Allen & Angliss 2009 |
| Kodiak Region, GOA | Harbour seal | Population trend | 1993 - 2001 | Up 6.6% $y^{-1}$ | Allen & Angliss 2009 |
| Semidi Is, W GOA | Black-legged kittiwake | Population trend | 1998 - 2007 | No trend | Dragoo, pers. comm. |
| Semidi Is., W GOA | Common murre | Population trend | 1999 - 2007 | No trend | Dragoo, pers. comm. |

[Table S-3b] Piscivorous species in the eastern Bering Sea and Aleutian Islands

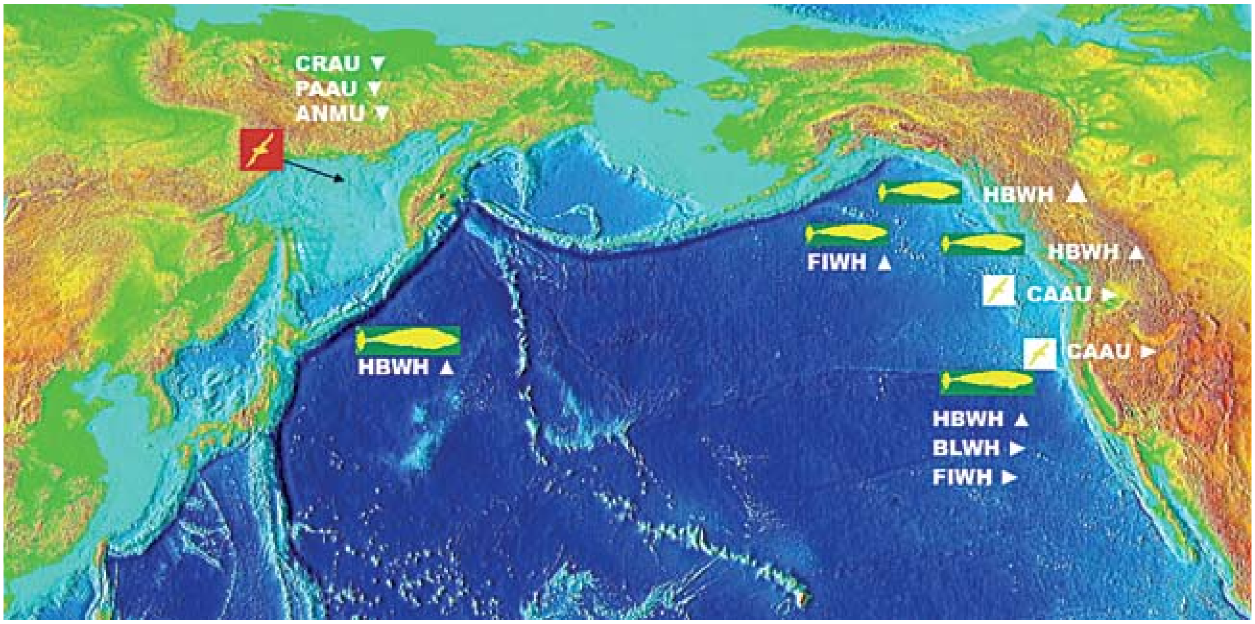
| Location | Species | Metric | Dates Used | Trend | Reference |
|---|---|---|---|---|---|
| St. Paul Is., E Bering | Black-legged kittiwake | Population trend | 1999 - 2008 | No trend | Dragoo, pers. comm. |
| St. Paul Is., E. Bering | Common murre | Population trend | 1999 - 2008 | No trend | Dragoo, pers. comm. |
| St. George Is., E. Bering | Black-legged kittiwake | Population trend | 1999 - 2008 | No trend | Dragoo, pers. comm. |
| St. George Is., E. Bering | Common murre | Population trend | 1999 - 2008 | No trend | Dragoo, pers. comm. |
| Pribilof Is., Bering Sea | Northern fur seal | Pup count | 1972 - 76 vs. 2002 - 06 | Down 2.7% $y^{-1}$ | Olesiuk 2009 |
| St. Paul Is., Pribilofs | Northern fur seal | Pup count | 1998 - 2006 | Down 6.1% $y^{-1}$ | Allen & Angliss 2009 |
| St. George Is., Pribilofs | Northern fur seal | Pup count | 1998 - 2006 | Down 3.4% $y^{-1}$ | Allen & Angliss 2009 |
| Bogoslof Is., Bering Sea | Northern fur seal | Population trend | 1972 - 76 vs. 2002 - 06 | Rapid growth | Olesiuk 2009 |
| Bogoslof Is., Bering Sea | Northern fur seal | Pup count | 2005 - 2007 | Up | Allen & Angliss 2009 |
| Bering Sea | Harbour seal | Population trend | 1980s - 1990s | Probably down | Allen & Angliss 2009 |
| Aiktak Is., Eastern Aleutian Islands | Unidenitified murre | Population trend | 1998 - 2007 | No trend | Dragoo, pers. comm. |
| Eastern Aleutian Islands | Steller sea lion | Pup count | 1998 - 2009 | Up 4.2% $y^{-1}$ | DeMaster 2009 |
| Eastern Aleutian Islands | Harbour seal | Population trend | 1977 - 82 vs. 1999 | Down 45% | Allen & Angliss 2009 |
| Koniuji Is., C. Aleutian Islands | Black-legged kittiwake | Population trend | 1998 - 2007 | No trend | Dragoo, pers. comm. |
| Koniuji Is., C. Aleutian Islands | Unidentified murre | Population trend | 2001 - 2007 | No trend | Dragoo, pers. comm. |
| Ulak Is., C. Aleutians | Unidentified murre | Population trend | 1998 - 2008 | Up 6.2% $y^{-1}$ | Dragoo, pers. comm. |
| C. Aleutian Islands | Harbour seal | Population trend | 1977 - 82 vs. 1999 | Down 66% | Allen & Angliss 2009 |
| Buldir Is., W. Aleutians | Black-legged kittiwake | Population trend | 1998 - 2007 | No trend | Dragoo, pers. comm. |
| Bering Sea Stock | Harbour seal | Population trend | 1980s - 1990s | Probably down | Allen & Angliss 2009 |
| Western Aleutian Islands | Harbour seal | Population trend | 1977 - 82 vs. 1999 | Down 86% | Allen & Angliss 2009 |
| Aleutian Islands | Steller sea lion | Pup count | 1994 - 2009 | Down 1.6% $y^{-1}$ | DeMaster 2009 |
| Western Aleutian Islands | Steller sea lion | Pup count | 1997 - 2008 | Down 10.4% $y^{-1}$ | DeMaster 2009 |

[Table S-3c] Piscivorous species in the western Pacific, including western Bering Sea, Sea of Okhotsk, Oyashio, and Yellow Sea

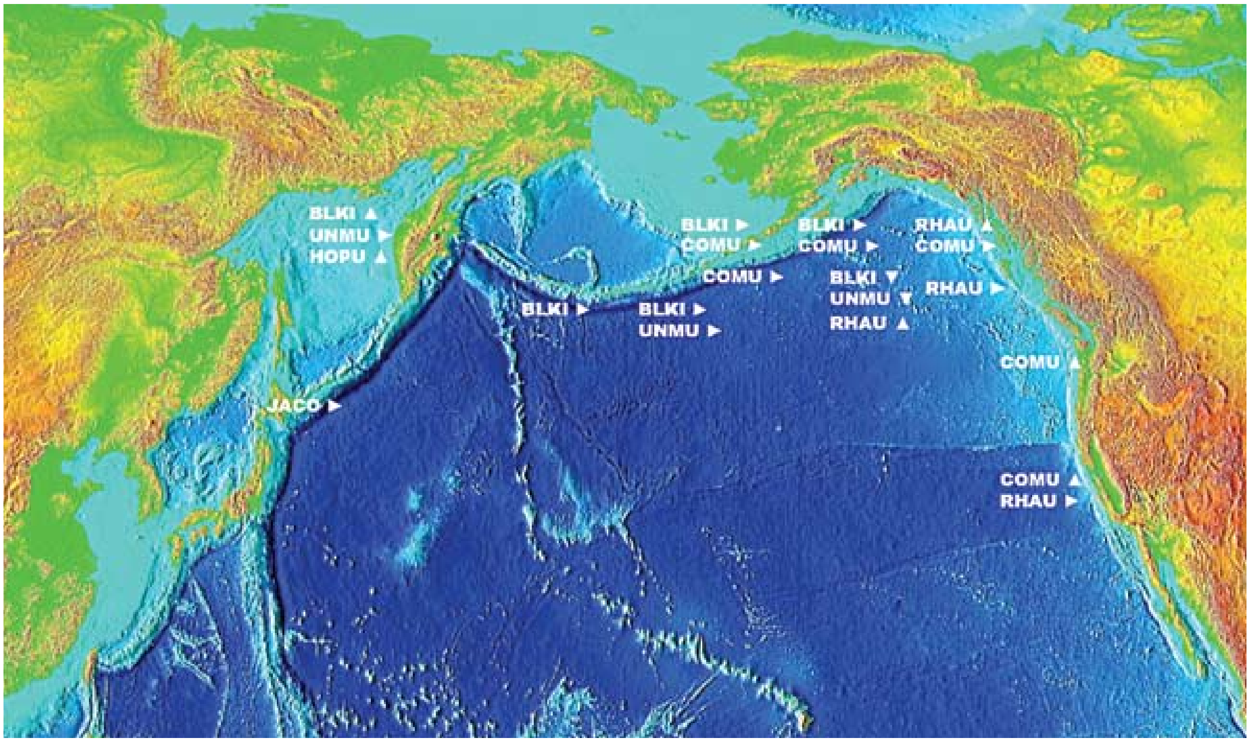
| Location | Species | Metric | Dates Used | Trend | Reference |
|---|---|---|---|---|---|
| E. Kamchatka | Steller sea lion | Non-pup count | 2001 – 2008 | No trend | Burkanov et al. 2009 |
| Commander Islands | Steller sea lion | Non-pup count | 2000 - 2008 | No trend | Burkanov et al. 2009 |
| Commander Islands | Northern fur seal | Pup production | 1972 - 76 vs. 2002 - 06 | No trend | Olesiuk 2009 |
| Kuril Islands | Northern fur seal | Pup production | 1972 - 76 vs. 2002 - 06 | Up, 3% $y^{-1}$ | Olesiuk 2009 |
| Robben Is., Okhotsk | Northern fur seal | Pup production | 1972 - 76 vs. 2002 - 06 | No trend | Olesiuk 2009 |
| Kuril Islands | Steller sea lion | Non-pup count | 2000 – 2007 | Up | Burkanov et al. 2009 |
| N. Okhotsk | Steller sea lion | Non-pup count | 1996 – 2006 | Up | Burkanov et al. 2009 |
| Sakhalin Island, Okhotsk | Steller sea lion | Non-pup count | 2000 – 2009 | Up | Burkanov et al. 2009 |
| Talan Is., Okhotsk | Horned puffin | Population count | 1989 vs 2008 | Up | Andreev et al., In Press |
| Talan Is., Okhotsk | Black-legged kittiwake | Population count | 1989 vs 2008 | Up | Andreev et al., In Press |
| Talan Is., Okhotsk | Unidentified murre | Population count | 1989 vs 2008 | No trend | Andreev et al., In Press |
| Teuri Is., W. Hokkaido | Japanese cormorant | Nest count | 2007 - 2008 | No trend | Watanuki, pers. comm. |
| Teuri Is., W. Hokkaido | Rhinoceros auklet | Population count | 1985 -1997 | Up | Watanuki, pers. comm. |

and northern elephant seals) (Fig. S-34), trends in the California Current region were mostly increasing (6 cases), or stable (10 cases) (Table S-3a). Steller sea lion (northern California and Oregon) and harbour seal (California to Washington) were considered to be at carrying capacity (Caretta et al. 2009). Within this region, El Niño events have had a powerful influence on the reproduction of both marine birds and pinnipeds, and in some cases, on population size. These effects were particularly noticeable in California sea lions and in northern fur seals on the Channel Islands in southern California in 1998. In addition to impacts from El Niño events, the survival of adult California sea lions has been adversely affected by domoic acid poisoning (e.g., in 1998, Scholin et al. 2000; and subsequent years, Thomas et al. 2010). Evidence is accumulating that domoic acid may also affect sea lion reproduction (Brodie et al. 2006; Goldstein et al. 2009). In 2002, 2,239 marine mammals were stranded in southern California in association with a bloom of domoic acid producing phytoplankton (*Pseudo-nitzschia* spp.) (Torres de la Riva et al. 2009).

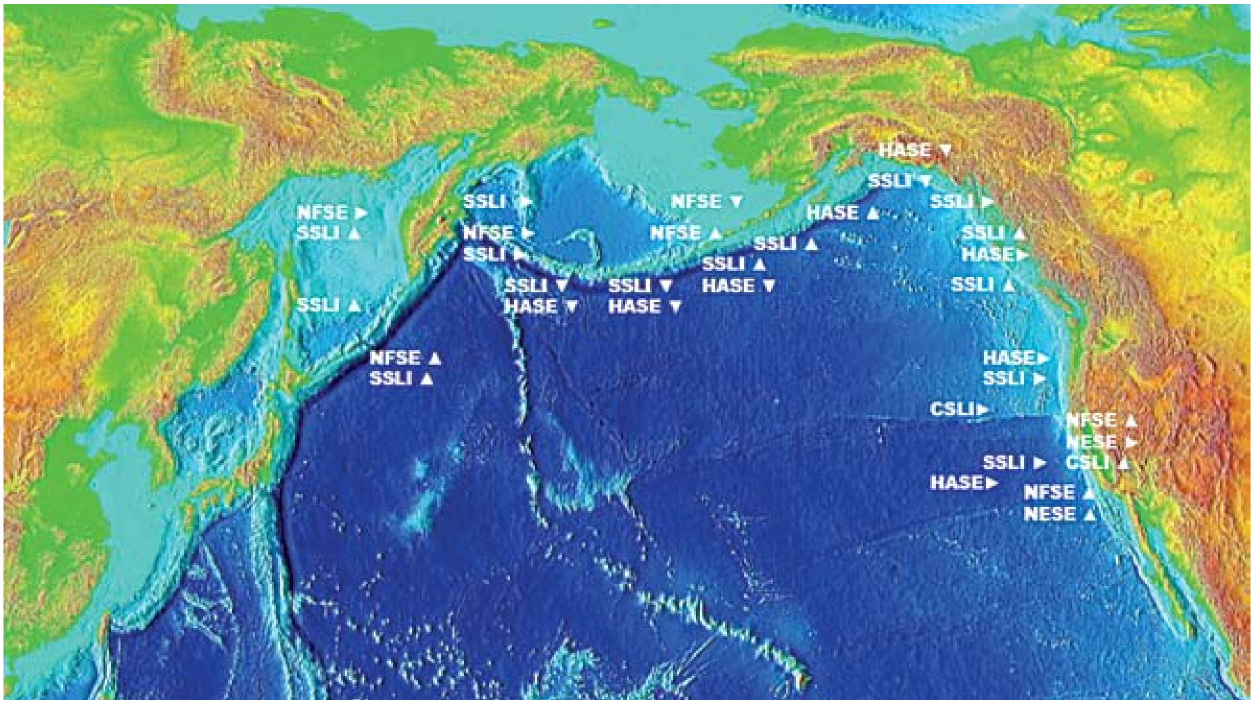
Moving northward and westward from the British Columbia coast to southeast Alaska and the Gulf of Alaska, an increasing number of piscivorous species show a shift from increasing population trends to either no trend or a decreasing trend (Table S-3a). For example, Steller sea lion populations have positive trends in British Columbia and Southeast Alaska, stable populations in the eastern Gulf of Alaska, and negative trends in the central and western Gulf of Alaska. Similarly, harbour seals show no trend in southeast Alaska, but a possible negative trend in Prince William Sound, though their numbers are increasing in the Kodiak Island area where Steller sea lions are declining. In general, the data available suggest little or no trend for most marine bird species, except for Middleton Island, where several species have shown declines (Table S-3a). There are conflicting data as to whether murres are increasing in the eastern and western Gulf of Alaska.



[Figure S-32] Trends in abundance of planktivorous air breathing animals in the North Pacific Ocean. Trends are indicated by ▲(upward), ▶(without trend), and ▼(downward). Codes for marine birds are: ANMU=ancient murrelet, CAAU= Cassin's auklet, CRAU=crested auklet, PAAU=parakeet auklet. Codes for marine mammals are: FIWH=fin whale, HBWH= humpback whale, BLWH= blue whale. Information sources for trends can be found in Table S-2.



[Figure S-33] Abundance trends in populations of piscivorous marine birds. Trends are indicated by ▲ (upward), ▶ (without trend), and ▼ (downward). Taxonomic codes are: BLKI=black-legged kittiwake, COMU=common murre, HOPU=horned puffin, JACO=Japanese cormorant, RHAU=rhinoceros auklet, UNMU=unidentified murre. Information sources for trends can be found in Table S-3.



[Figure S-34] Abundance trends for pinnipeds in the North Pacific Ocean. Trends are indicated by ▲ (upward), ▶ (without trend), and ▼ (downward). Species codes are: CSLI=California sea lion, HASE= harbour seal, NESE=northern elephant seal, NFSE=northern fur seal, and SSLI=Steller sea lion. Information sources for trends can be found in Tables S-3, S-4.

In the southeastern Bering Sea and the Aleutian Islands, there appears to be an east to west trend toward stable or declining populations (Table S-3b). At the Pribilof Islands, seabird populations have stabilized after a period of decline followed by recovery, particularly on St. George Island (Byrd et al. 2008). However, northern fur seals at both St. George Island and particularly St. Paul Island have continued a long-term decline extending at least as far back as the mid-1970s, though at nearby Bogoslof Island, the fur seal population is expanding rapidly (Table S-3b). Recent retrospective studies of fur seals at the Pribilof Islands suggest that the fur seal declines may be related to competition with arrowtooth flounder and possibly by disruption of foraging opportunities by fishing effort in the walleye pollock trawl fleet.

In the Aleutian Archipelago, there is a strong east to west decline in the population trends of both Steller sea lions and harbour seals (Table S-3b). Several hypotheses have been put forward to explain the declines in the western population of these two pinnipeds but there is presently insufficient information to allow a clear choice between top-down (Springer et al. 2003) and bottom-up (Trites and Donnelly 2003; Trites et al. 2006) mechanisms (DeMaster et al. 2006; Small et al. 2008; Wade et al. 2009). However, for piscivorous murres and black-legged kittiwakes there is no evidence for a similar negative trend; most populations monitored are stable, with the exception of murres on Ulak Island in the central Aleutian Islands which are increasing.

In the western North Pacific region, there are relatively few time series to draw upon. In the Commander and Kuril Islands, northern fur seals are stable or increasing, as are numbers from Robben Island in the Sea of Okhotsk (Table S-3c). Steller sea lions are, in general, stable along the Asian coast, except where they are increasing (northern Sea of Okhotsk, Sakhalin Island, and the Kuril Islands)(Table S-3c) Likewise, and in contrast to the declines in the planktivorous auklets there, population trends in piscivorous black-legged kittiwakes and murres are positive at Talan Island in the Sea of Okhotsk. These trends, though few in number, suggest that fish-eating species of marine birds and pinnipeds in the northwestern Pacific Ocean have stable populations.

Taken as a whole, where adequate data are available, North Pacific populations of marine birds, pinnipeds and cetaceans appear to be stable or increasing. Notable exceptions are Steller sea lions and harbour seals in the central and western Aleutian Islands, northern fur seals at the Pribilof Islands, and possibly harbour seals in Prince William Sound, Gulf of Alaska (Fig. S-34). Also down are planktivorous auklets in the Sea of Okhotsk (Fig. S-32). While the decline in these auklets is likely due to warming sea temperatures in the Sea of Okhotsk and declining euphausiid populations there, there are no certain answers as to why Steller sea lions and harbour seals are declining in the western Aleutians or why northern fur seals have declined in the Pribilof Islands. These are important issues worthy of resolution. There are a number of species of marine birds and mammals in the North Pacific that are of conservation concern and are so listed in the IUCN Redbook (Table S-4). Additionally, individual PICES nations have their own lists of endangered and threatened species. The existence of these threatened and endangered species suggests that there is still much to do to secure the sustainability of North Pacific marine ecosystems.

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[Table S-4] IUCN endangered, threatened and vulnerable marine birds and mammals of the PICES regions of the North Pacific (IUCN 2009).

| English Name | Latin Name | Status | Population Trend | Region |
|---|---|---|---|---|
| **Marine birds** | | | | |
| Short-tailed albatross | *Phoebastria albatrus* | vulnerable | increasing | Oceanic North Pacific |
| Laysan albatross | *Phoebastria immutabilis* | vulnerable | decreasing | Oceanic North Pacific |
| Black-footed albatross | *Phoebastria nigripes* | endangered | decreasing | Oceanic North Pacific |
| Ashy storm-petrel | *Oceanodroma homochroa* | endangered | decreasing | California Current System |
| Kittlitz's murrelet | *Brachyramphus brevirostris* | critically endangered | decreasing | Gulf of Alaska, Bering Sea |
| Marbled murrelet | *Brachyramphus marmoratus* | endangered | decreasing | California to Alaska |
| Long-billed murrelet | *Brachyramphus perdix* | near threatened | decreasing | Sea of Okhotsk mainly |
| Craveri's murrelet | *Synthliboramphus craveri* | vulnerable | decreasing | S. California Current |
| Xantus's murrelet | *Synthliboramphus hypoleucus* | vulnerable | decreasing | S. California Current |
| Japanese murrelet | *Synthliboramphus wumizusume* | vulnerable | decreasing | Kuroshio & Oyashio |
| Steller's eider | *Polysticta stelleri* | vulnerable | decreasing | Bering Sea and Arctic Ocean |
| **Marine mammals** | | | | |
| Steller sea lion | *Eumetopias jubatus* | endangered | decreasing | Coastal North Pacific |
| Sei whale | *Balaenoptera borealis* | endangered | unknown | Sub-arctic North Pacific |
| Blue whale | *Balaenoptera musculus* | endangered | increasing | World Oceans |
| Fin whale | *Balaenoptera physalus* | endangered | unknown | World oceans |
| North Pacific right whale | *Eubalaena japonica* | endangered | unkown | Northern North Pacific, Bering Sea |
| North Pacific right whale | *Eubalaena japonica* | critically endangered | decreasing | Northeast Pacific subpopulation |
| Bowhead whale | *Balaena mysticetus* | endangered | unkown | Sea of Okhotsk subpopulation |
| Grey whale | *Eschrichtius robustus* | critically endangered | unknown | Western North Pacific subpopulation |
| Beluga whale | *Delphinapterus leucas* | critically endangered | decreasing | Cook Inlet, Gulf of Alaska |

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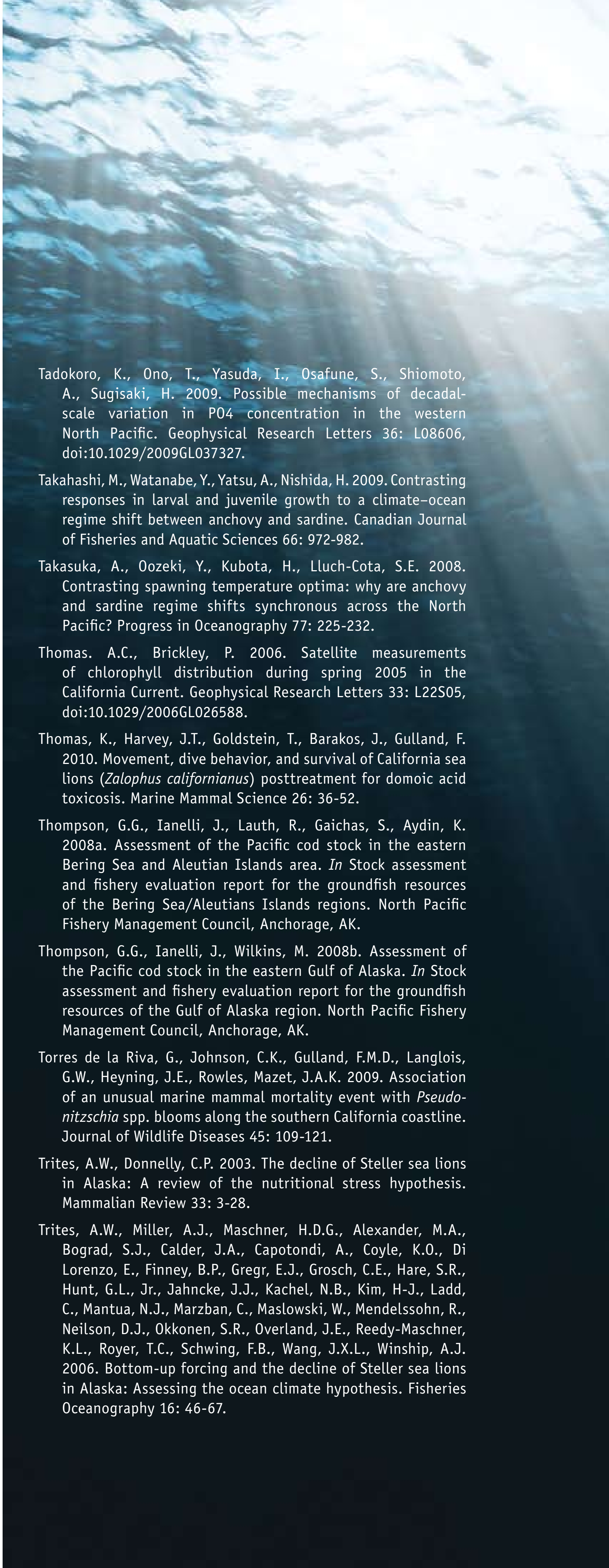

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# Oceanic

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# highlights

- The focus period includes a span of years when the atmosphere and ocean were highly variable, particularly in the eastern North Pacific; sea surface temperature anomalies were generally positive (warmer) in the western North Pacific throughout the focus period, positive until 2006-2007 in the eastern North Pacific and then sharply negative in 2008.

- The North Pacific subtropical low chlorophyll region expanded during the focus period because of increased vertical stratification and warmer temperatures.

- The eastern North Pacific was fresher and oxygen levels (>250 m) were lower than the long term average. Surface chlorophyll$_a$ values there were higher than average in winter, and similar to average in the spring and summer. There was a noticeable high chlorophyll event in the summer of 2008 that extended across the central and Northeast Pacific but the cause has yet to be determined. It was accompanied by elevated mesozooplankton biomass in August and September.

- Zooplankton biomass in the western North Pacific increased at the Subarctic Front. The increase could be due to faster development by zooplankton in warmer temperatures or more northerly movement of the Transition Zone communities. To the north, biomass was higher generally in the second half of the focus period but this could also be a seasonal or latitudinal shift rather than an increase in absolute biomass.

- Zooplankton communities in the eastern North Pacific responded to the highly variable ocean climate. In the warmer years of 2003-2005, the seasonal development of biomass peaked early and had a narrow peak while the converse (later with a broad peak) was true in the cooler years and very evident in 2008. Abundances of Subarctic copepods and cool-water chaetognaths increased with upper-ocean cooling and with increases in the strength of the North Pacific Current. The suite of southern "California Current species" that occurs offshore was high in 2003-2006 and low in 2008.

- Data on fish and squid stocks are neither abundant nor comprehensive for the open ocean. Catches of neon flying squid in the western Pacific were relatively high in the focus period. The most abundant species of Pacific salmon (sockeye, pink, chum) rear in the Subarctic region. Total catches of sockeye salmon were average or above average, chum catches were average and pink salmon catches were above average in the western North Pacific and below average in the eastern North Pacific. Some western stocks of chum salmon appeared to be decreasing in size. North Pacific albacore tuna stocks were relatively high during the focus period, but predictions are for them to decline by 2015 if fishing pressure is not reduced. Most data for the central North Pacific fisheries (tuna/billfish) showed declining catches during the focus period when compared with previous data.

- Seabird diversity and abundance increased in the eastern North Pacific, at least up to 2006 but this could reflect a change in distribution. Changes in seabird community structure and relative abundance on Line P may be related to changes in the underlying mesozooplankton community. The reproductive success of Laysan and black-footed albatrosses that rear their young in the Hawaiian archipelago in the central North Pacific was stable and relatively high in the early part of the focus period. Seabirds are considerably more abundant in the western than the eastern North Pacific but trend data there were not available.

# Introduction

The Oceanic Region of the North Pacific Ocean is defined to include the area of deep waters located beyond the continental margins and major coastal boundary currents. It is characterized by strong latitudinal gradients in surface temperature and salinity (high in the south and low in the north), multiple water masses, major oceanic gyres, large (~200 km) mesoscale eddies, and a complex bathymetry of deep trenches and remote sea mounts. Natural variability in the Oceanic Region is intimately linked to variability in the global climate system. Biological production in this region is responsible for major commercial fisheries for tunas and Pacific salmon.

Sub-regions in the Oceanic Region are treated separately in this chapter where the availability of data warrants it. The Aleutian Island chain constricts the main gyre and causes a re-circulation as two sub-gyres; the Western Subarctic and Alaskan Gyres. These gyres have distinct characteristics, often supporting different species and patterns of production. The North Pacific Transition Zone to the south represents a physical and biological transition between the subtropical and Subarctic gyres. It is a physically complex region bounded to the north by the Subarctic Frontal Zone which stretches east to west across the central North Pacific, and to the south by the Subtropical Frontal Zone. The latter is the southern limit of the Oceanic Region described in this chapter. It is characterized by zonal gradients (fronts) in temperature and salinity. Some of its more abundant species [e.g., flying squid (*Ommastrephes bartrami*), Pacific pomfret (*Brama japonica*), blue shark (*Prionace glauca*), Pacific saury (*Cololabis saira*)] undergo extensive seasonal migrations between summer feeding grounds at the Subarctic fronts (or within the Subarctic) to winter spawning grounds in the subtropics. The North Pacific subtropical gyre supports a diverse assemblage of apex predators including tunas, billfishes, sharks, marine mammals and seabirds. This chapter contains a review of the status and trends of the Oceanic Region from 2003-2008, hereafter the *focus period*.

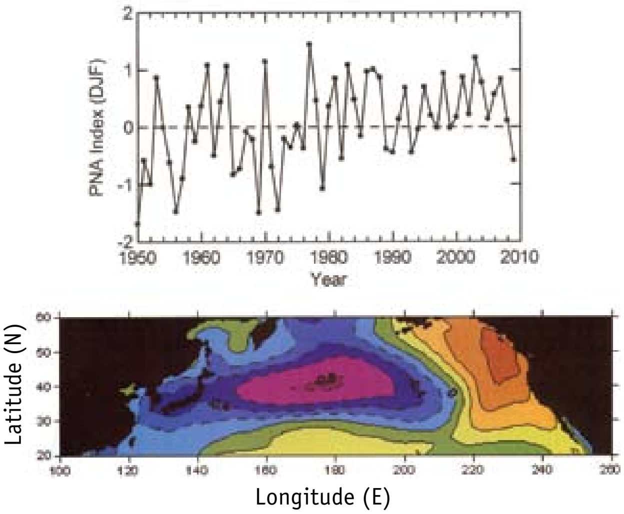
## 2.0 Large-scale Indices *(McKinnell)*

Many of the large-scale monthly and seasonal atmospheric climate indices in the North Pacific are highly correlated, particularly in winter because each reflects similar aspects of a common dominant climate pattern. To recognize the pioneers in this field and to reduce redundancy, priority for selecting indices to report is given to those that were first established for that purpose.

### 2.1 Atmospheric

#### 2.1.1 Pacific North American pattern

The PNA index (Fig. OC-1) is calculated from the 500 hPa height anomalies and its value provides an indication of the state of a dominant mode of low frequency climate variability in the North Pacific (Wallace and Gutzler 1981). Its positive phase tends to produce above-average air temperatures over western North America, Alaska, and to a lesser extent from the Hawaiian latitudes and southward (Fig. OC-1b) and below-average temperatures in the western Pacific, especially across Korea and Japan at latitudes in the range 35-45°N; strongest near the date line. The PNA-surface air temperature correlation pattern bears a strong resemblance to the Pacific Decadal Oscillation spatial pattern (based on ocean surface temperature) indicating a strong atmosphere/ocean interconnection in the Pacific.

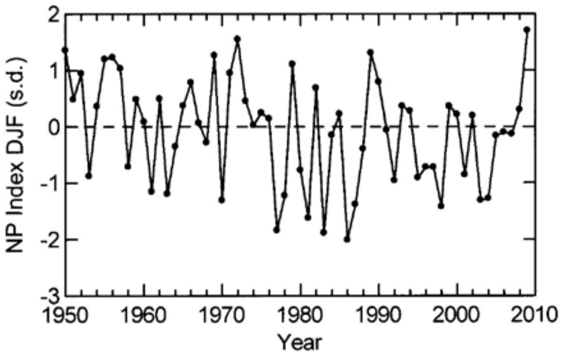


[Figure OC-1] Average December to February Pacific-North American (PNA) index variation from 1950-2009 (upper panel) and spatial correlation pattern of PNA with mean air temperature (lower panel).

During the focus period, the average winter PNA index was persistently >0 but it declined to its lowest value in 30 years during the winter of 2008-2009.

#### 2.1.2 North Pacific index

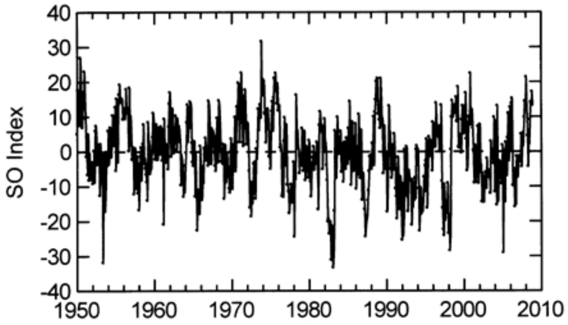
The NP index is the area-weighted monthly average sea level pressure (minus 1000 hPa) in the region 160°E-140°W, 20°-65°N (Trenberth and Hurrell 1994). Low values of the index represent lower than average sea level pressures and generally stormier months (the inverse of the PNA index). NP index values were converted to monthly anomalies using the 1950-2009 mean, then standardized. Average winter sea level pressures in the North Pacific increased during the focus period reflecting a trend toward declining storminess (Fig. OC-2). The winter of 2008-2009 had the highest average value of the index in the record. Some extreme monthly values occurred during the focus period: the two lowest values since 1950 in July occurred during 2004 and 2007, and the highest value observed in any December during that period occurred in 2008. There was no significant linear trend in the NP index in any month except July and that was due to the influence of the two extremes at the end of the timeseries.



[Figure OC-2] Standardized winter (DJF) NP index anomalies from 1950-2009.

### 2.1.3 Southern Oscillation index

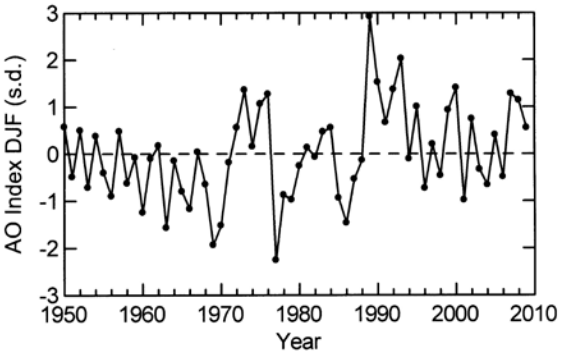
The SO index is the difference of the sea level pressure anomalies at Tahiti and Darwin, Australia divided by the standard deviation of their difference (Troup 1965). It reflects the strength of a zonal atmospheric circulation cell in the tropical Pacific known as Walker Circulation. Since the 2002-2003 El Niño, the SOI has varied between brief periods of El Niño and La Niña conditions, including an El Niño in the winter of 2006-2007 (Fig. OC-3). This El Niño has received scant attention in the North Pacific because it appears to have had very little extra-tropical boreal influence. In the fall of 2007, the SOI shifted abruptly to a strong La Niña and that state persisted through the end of 2008.



[Figure OC-3] Monthly Southern Oscillation Index variation from 1950-2008.

### 2.1.4 Arctic Oscillation index

The AO index is defined as the dominant eigenvector of the covariance matrix of the area-weighted monthly non-seasonal sea level air pressure anomalies northward of 20°N (Thompson and Wallace 1998). It is characterized by negative covariation in sea level pressures over the Arctic and over temperate latitudes of the Atlantic and Pacific oceans. Variation in the AO is seasonal with stronger expression in winter. There is a weak autocorrelation at lag= 1 month (r= 0.29). The mean winter (DJF) values tended to be negative during the first few years and positive for the last two winters and the start of the winter of 2008/09 (based on Dec. 2008 value only) (Fig. OC-4). Positive AO anomalies are correlated with higher than average SLP over the temperate latitudes of the North Pacific. The AO value for October 2008 was the highest observed in any October in the time series. The AO value for December 2009 was the lowest observed in any December since 1950.

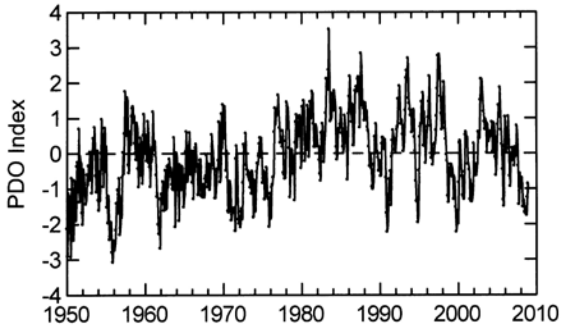


[Figure OC-4] Winter (DJF) average Arctic Oscillation index from 1950-2009.

## 2.2 Oceanic

### 2.2.1 Pacific Decadal Oscillation index

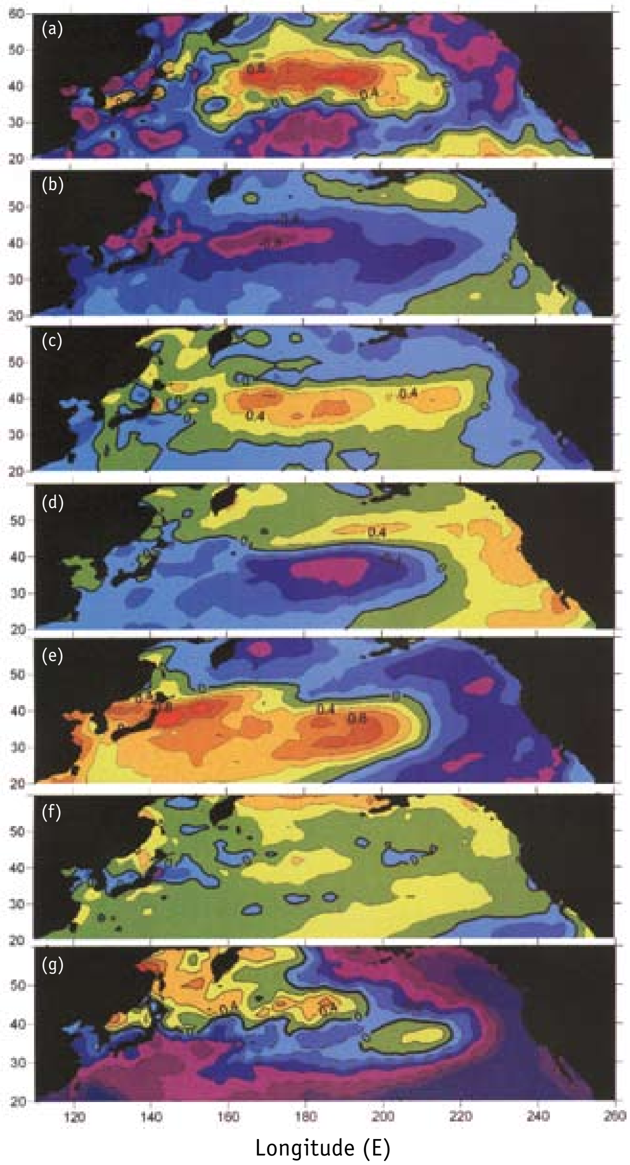
The PDO index (Fig. OC-5) is derived from the dominant eigenvector of the covariance matrix of area-weighted monthly anomalies of sea surface temperatures (SST) from 20°-65°N in the Pacific (Mantua et al. 1997). In winter, it is highly correlated with North Pacific atmospheric indices (NPI, PNA). During the last three decades, the PDO index has varied between positive and negative phases with greater frequency than was observed at the time of its first description. Average SST anomalies within these ~5-year stanzas (Fig. OC-6) varied in typical PDO fashion until the 2002-2003 El Niño. Positive PDO values (warm in the eastern Pacific, cool in the central and western Pacific) at the beginning of the focus period diminished after about 6 months and remained near neutral or slightly positive. A broad pattern of weak to strong positive SST anomalies throughout most of the basin persisted until September 2007 when the PDO index shifted abruptly to negative. The negative PDO pattern (cold along the North American continent and Gulf of Alaska and warm in the central and western Pacific) persisted through most of 2009 in spite of El Niño-like conditions at the Equator.



[Figure OC-5] Monthly variation in the Pacific Decadal Oscillation index from 1950-2008.

### 2.2.2 Basin-scale average SST anomalies

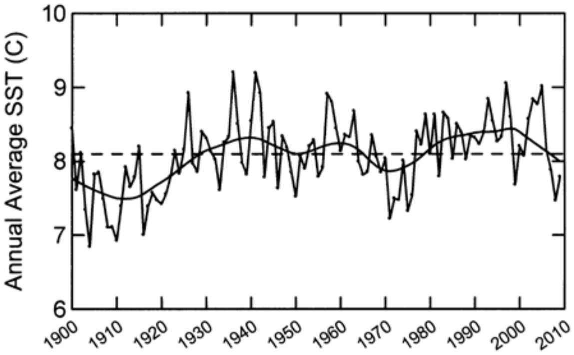
Since the advent, in the early 1980s, of blended SST measurements that are primarily determined by satellite remote sensing, the North Pacific Ocean has been oscillating more frequently (~10-11 y) between warm and cool phases of the PDO than the multi-decadal period that is normally associated with the PDO. Based on an EOF analysis of these SST data to determine phase shifts, the corresponding average SST anomalies within stanzas are: Jan/82-Jun/82, Jul/82-Dec/87, Jan/88-Sep/91, Oct/91-Apr/98, May/98-Aug/02, Sep/02-Sep/07, and Oct/07-Dec/08 (Fig. OC-6a-g). Average anomalies within each phase feature a PDO-like pattern except for the period from September 2002 - September 2007 (Fig. OC-6f) when the PDO pattern in SST anomalies was largely absent for a period of about 5 years. After September 2007, the negative phase of the PDO re-appeared and was sustained through the focus period to 2009 (Fig. OC-6g).



[Figure OC-6] Average SST anomalies: (a) Jan/82-Jun/82, (b) Jul/82-Dec/87, (c) Jan/88-Sep/91, (d) Oct/91-Apr/98, (e) May/98-Aug/02, (f) Sep/02-Sep/07, and (g) Oct/07-Dec/08 (Data from Reynolds et al. 2002).

### 2.2.3 Gulf of Alaska annual SST

Area-weighted annual average surface temperatures in the Gulf of Alaska from 1900-present (Fig. OC-7) reveal a pattern of high variability during the focus period. Three years of higher than average temperatures from 2003-2005 were followed by an abrupt shift to cool in 2006 to cold in 2007 and even colder in 2008. The surface of the Gulf of Alaska has not been as cold since 1972.



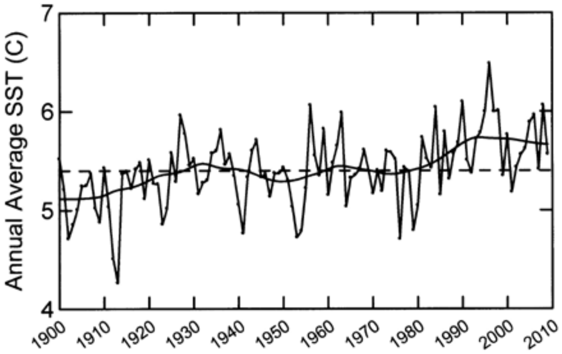
[Figure OC-7] Area-weighted annual average SST in the NE Pacific (50-60°N, 160°W to coast) from 1900-2009 (Data from: Smith et al. 2008) with loess smoother indicating trend. Horizontal dashed line is the mean of the time series (8.1°C).

### 2.2.4 Western Subarctic Gyre annual SST

Area-weighted annual average of monthly SST in the core of the Western Subarctic Gyre suggests 3 periods: below average years before 1914, followed by an untrended period near the long-term average until 2002, followed by a recent period where negative annual anomalies are rare (Fig. OC-8). All months except August-October show significant positive linear trends since 1950. During the focus period, monthly anomalies were positive in all years; the positive anomaly in 2008 was the fourth largest since 1900.

### 2.2.5 Spring timing estimated from water column stability

Gargett et al. (2001) defined an index of water column stability based on average density differences between 0-20 m and 60-80 m for individual CTD casts. This index was computed for each of about 75,000 Argo profiles in the North Pacific. The index values were grouped by year, by week, and by block (5° latitude × 10° longitude). Within each block, for each year, a loess smoother of stability index versus week was used to generate a seasonal timing curve of increasing stability from winter through spring/summer. Within each block-year, the week when water column stability reached 40% of its maximum was noted.

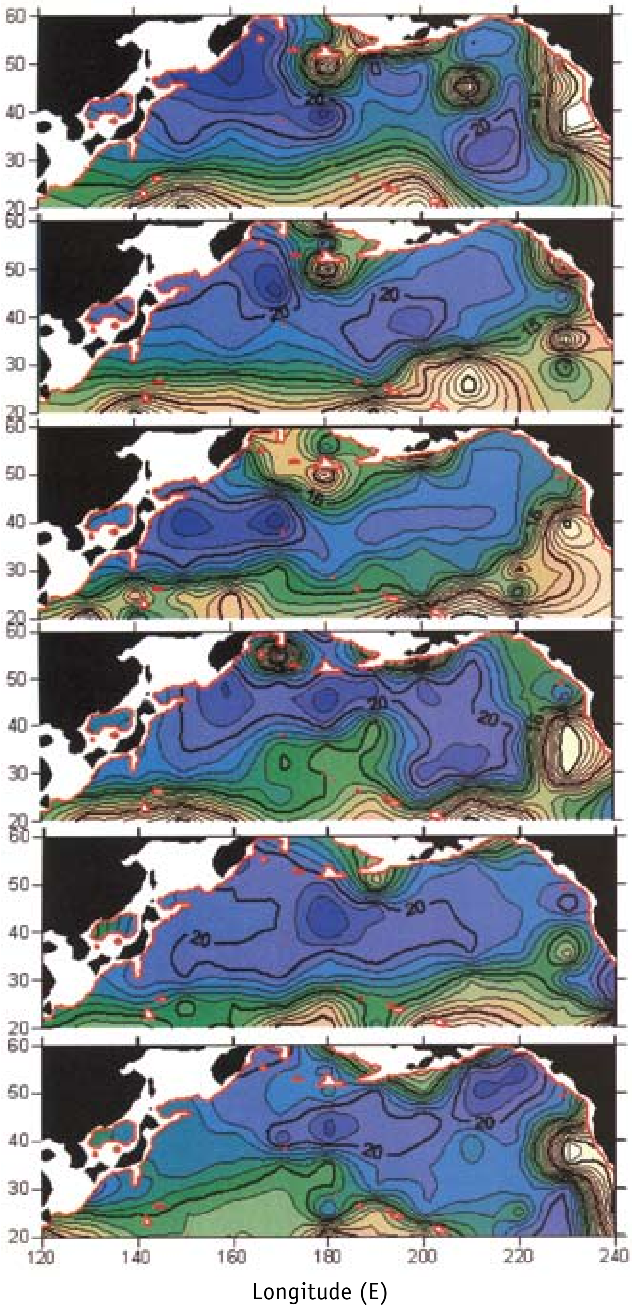


[Figure OC-8] Area-weighted annual average SST in the Western Subarctic Gyre from 1900-2009 (Data from: Smith et al. 2008) with loess smoother indicating trend. Horizontal dashed line is the mean of the time series (5.4°C).

During the focus period, water column stability developed earliest along the North American coast and in the subtropical region where surface warming occurs earlier (Fig. OC-9). A zonally oriented region centred on about 40° N tended to stabilize later in the year, with a tendency for the northwestern Pacific to be later than the northeastern Pacific (indicated by size of region >20 week contour). In the Gulf of Alaska, stability arrived latest in 2008. In general, there appear to be later springs (more blue) from 2006-2008 than in 2003-2005.

### 2.2.6 Western Subarctic Gyre mixed layer depth

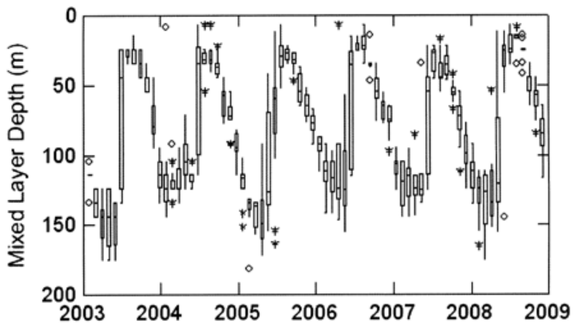
Mixed layer depths (defined as the distance from the surface to a depth required to observe a $\Delta\sigma_\theta = 0.0125$) were deepest in the core of the Western Subarctic Gyre in early spring (MAM). During the focus period, the month of June had the greatest variability (some areas deeply mixed and others very stable). By July of each year from 2003-2008, a stable water column had developed fully that lasted for several months. Only 2005 differed from this pattern with water column stability developing in May in some locations rather than June (Fig. OC-10).



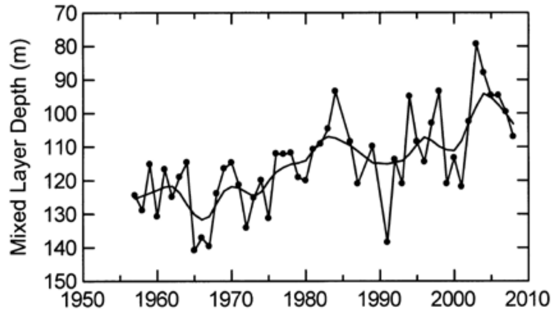
[Figure OC-9] Contours indicate week of year when the water column reached 40% of its maximum stability. Years appear sequentially; the top panel is 2003 and the bottom panel is 2008. Colours are chosen such that blue is later, green is intermediate, tan is earlier. Week 20 is approximately mid-May. The red lines indicate the 2000 m contour (few floats here). Remember that fewer profiles occurred in the earlier years as Argo met its target number of floats about 2007 so comparisons with years before 2003 were not made. Argo profiles were acquired from the US Global Argo Data Server.

### 2.2.7 Northeast Pacific mixed layer depth *(Whitney)*

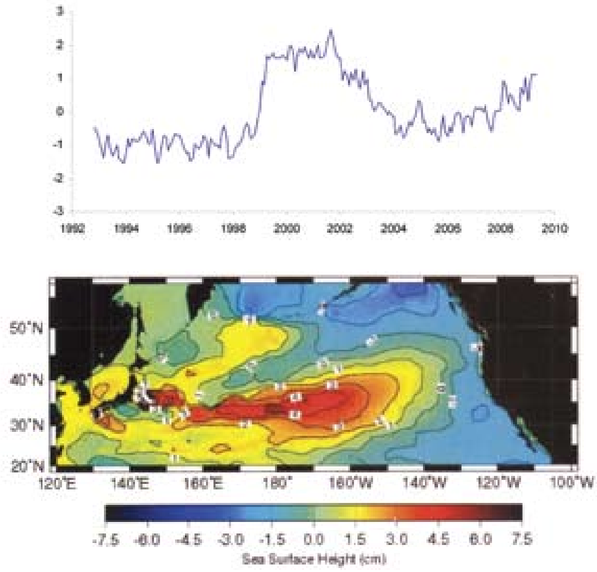
Deeper mixing at Station Papa (50°N 145°W) in 2008 coincided with SSTs <5° C for most of January through May and a persistent outcropping of the 25.8 isopycnal. In the Alaska Gyre, the 26.2 isopycnal surfaced which would have resulted in oxygen influxes and carbon dioxide outgassing from waters that do not frequently come in contact with the atmosphere in the eastern subarctic Pacific. Mixed layer depths from 2002 onwards were calculated from Argo data. Mean values after 1976 were shallower than the earlier part of the time series (108 ±12 m vs 125 ±9 m), with the shallowest mixed layer depth of the entire time series occurring during the focus period in 2003 (Fig. OC-11). Through the rest of the focus period, mixed layer depth has steadily increased although still remaining shallower than the earlier part of the time series.



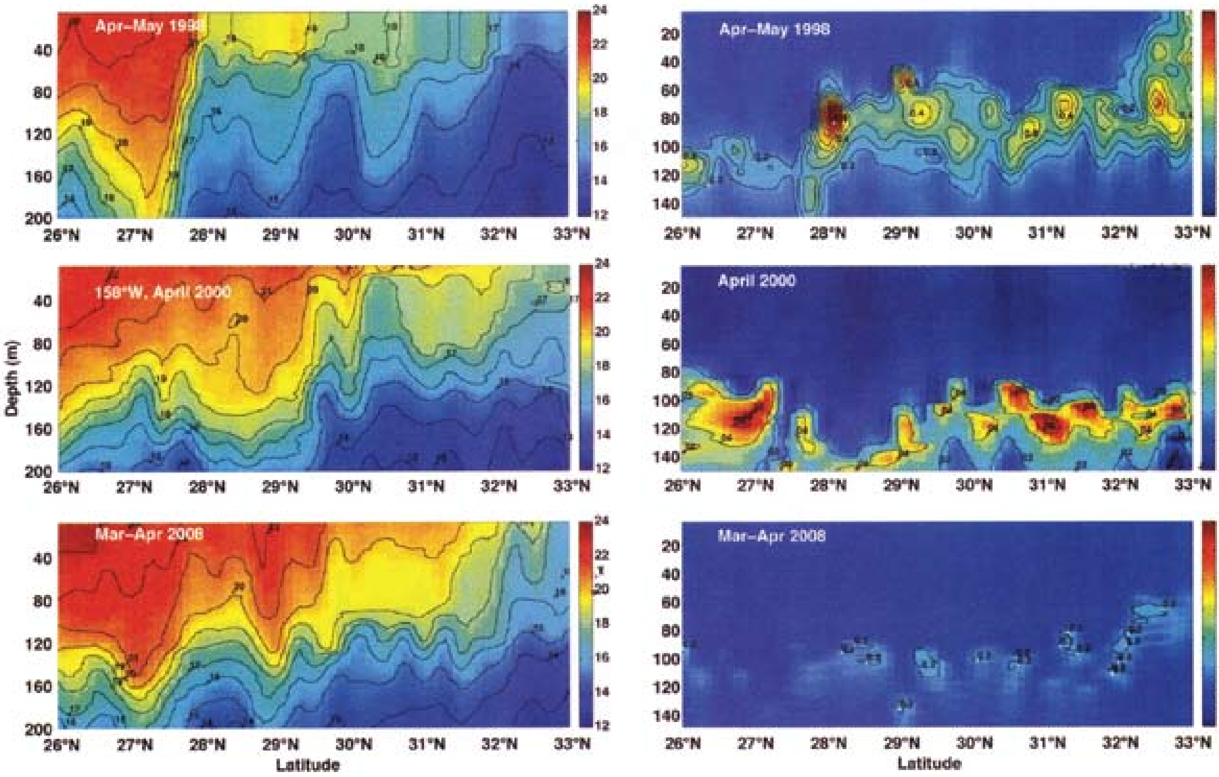
[Figure OC-10] Box and whisker plots indicating variability of monthly mixed layer depth across the North Pacific during the focus period. The greatest range of values occurred in spring when some areas stabilized and others were still mixing deeply. Argo data used to calculate mixed layer depths were acquired from the US Global Argo Data Server.



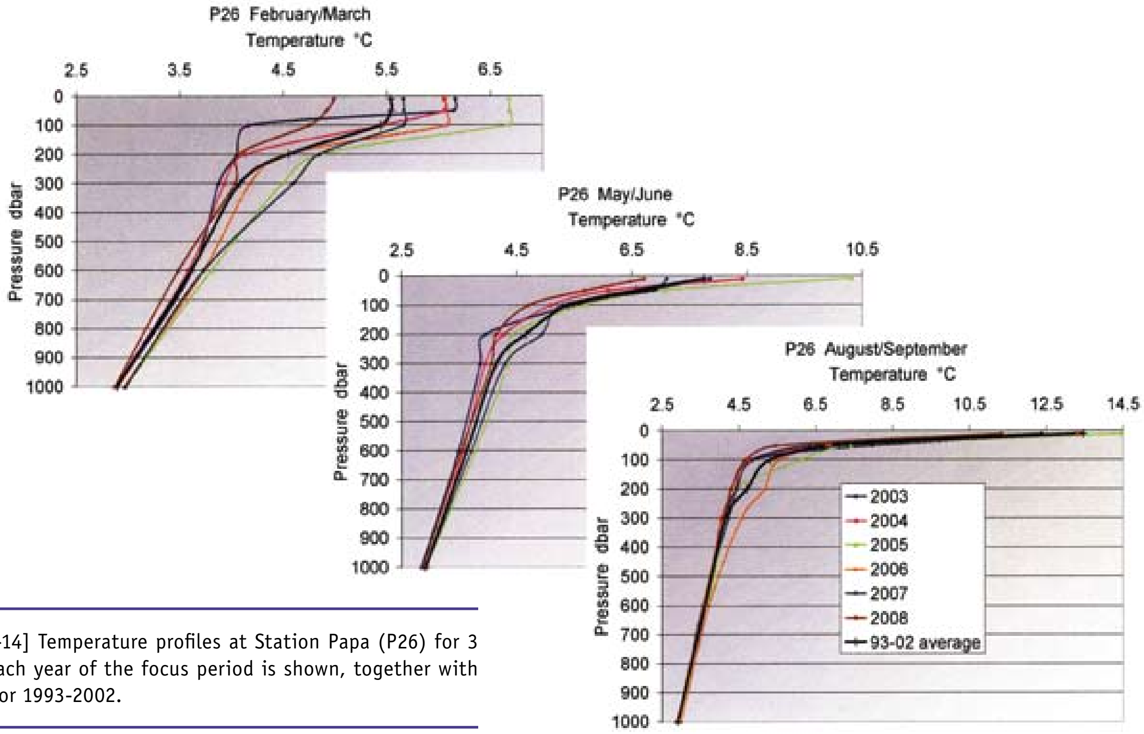
[Figure OC-11] Mixed layer depth at Station Papa, updated from Freeland et al. (1997). Depth profiles were obtained at least weekly before 1982 by hydrocast. After 2001, they were estimated from Argo profile data extrapolated to Station Papa. From 1982 to 2001 annual winter mixed layer depths were determined from hydrocasts deployed during single winter cruises to Station Papa. A loess trend line is indicated.



[Figure OC-12] Time series of the detrended variation of the first mode of the EOF analysis of sea surface height (upper panel) and the spatial pattern of the first mode of the sea surface height EOF (lower panel).



[Figure OC-13] Comparative vertical sections of temperature (°C) (left) and chlorophyll (mg·m⁻³) (right) from annual surveys April-May 1998, April 2000, and March-April 2008 along 158°W longitude.



[Figure OC-14] Temperature profiles at Station Papa (P26) for 3 seasons. Each year of the focus period is shown, together with the mean for 1993-2002.

# 3.0 Oceanography

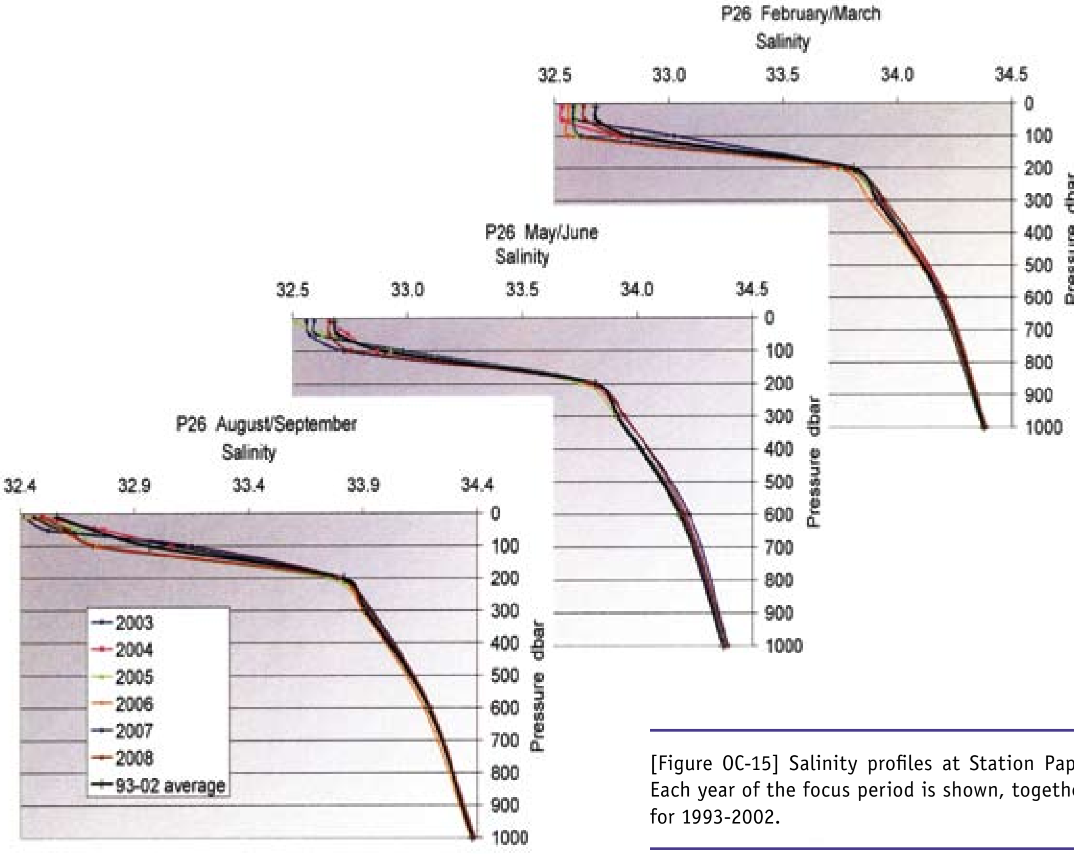
## 3.1 Subarctic North Pacific

## 3.2 Central North Pacific *(Polovina)*

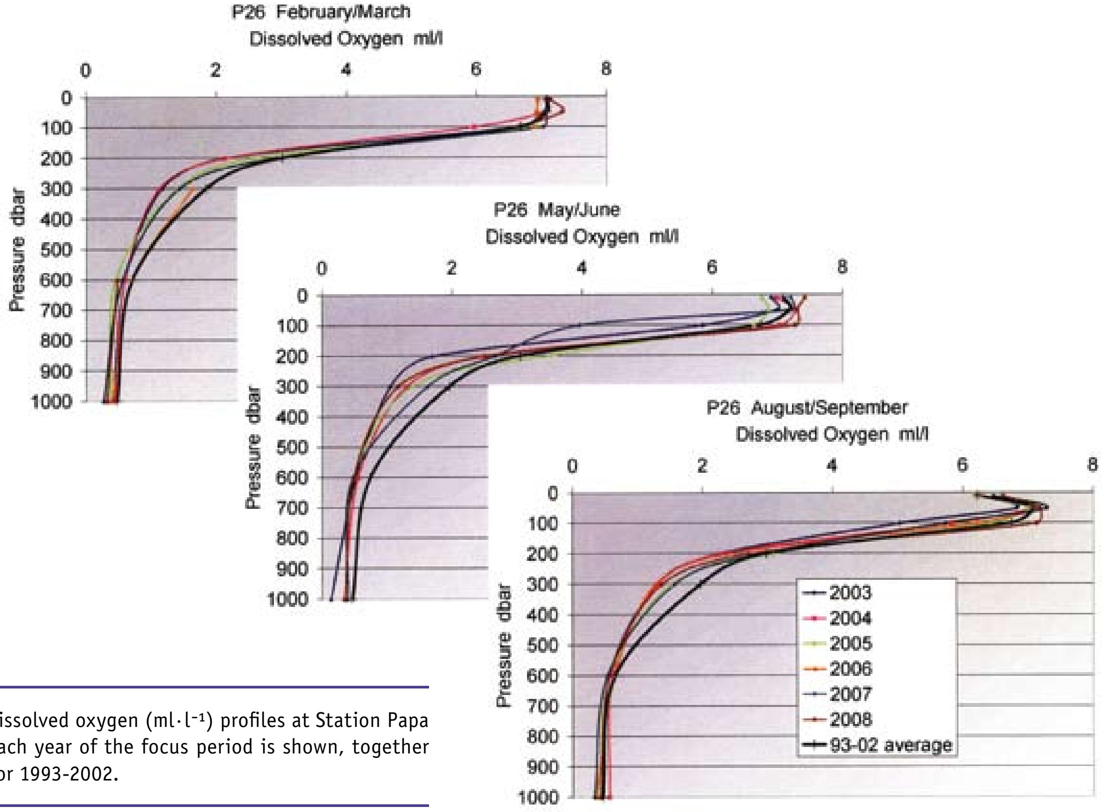
The first EOF of sea surface height (SSH) shows that the central Pacific and Transition Zone region exhibits a pattern of low frequency variation characterized as a horseshoe-like spatial pattern with the central Transition Zone out of phase with areas to the south, east and north (Fig. OC-12). During the period 1992-1998 SSH was low in the central Transition Zone and high in the surrounding areas. Between 1999-2003 SSH rose abruptly in the central Transition Zone and dropped in the surrounding regions. Between 2003-2007 the SSH pattern returned to the pattern observed in the 1992-1998 period, and then in 2008 and 2009 the SSH pattern reverted to more closely resemble the 1999-2003 pattern (Fig. OC-12). Changes in SSH reflect changes in the vertical structure of the ocean with a rise (drop) in SSH reflecting increased (decreased) vertical stratification. The period 1999-2003 was a strong La Niña period while 2008 and early 2009 was a moderate La Niña event and the observed SSH rise in the central Transition Zone appears to represent a mid-latitude La Niña response. Three longitudinal sections of temperature-depth and chlorophyll-depth taken along 158°W longitude during spring 1998, 2000, and 2008 show a northward shift over time in the vertically stratified warm water and low surface chlorophyll waters (Fig. OC-13). This pattern is consistent with the mid-latitude rise in SSH, representing an increase in vertical stratification, observed in 2000 and 2008 relative to 1998 (Figs. OC-12, OC-13).

## 3.3 Water properties along Line P *(Robert)*

The Line P program began in 1959 when hydrographic casts were made at a series of stations along a transect leading to Station Papa (Freeland 2007). This is one of the world's longest deep-ocean time series in existence and is now sampled 2-5 times per year, usually in late winter (February/March), spring (May/June) and summer (August/September). Data shown here are mainly from Station Papa (station P26) but data from landward stations P16 (49° 17'N, 134° 40'W, water depth 3550 m) and P12 (48° 58.2'N, 130° 10'W, water depth 3300 m) are also included.



[Figure OC-15] Salinity profiles at Station Papa for 3 seasons. Each year of the focus period is shown, together with the mean for 1993-2002.



[Figure OC-16] Dissolved oxygen (ml·l⁻¹) profiles at Station Papa for 3 seasons. Each year of the focus period is shown, together with the mean for 1993-2002.

### 3.3.1 Temperature

Profiles for each season and each year at Station Papa are plotted in Figure OC-14 together with the mean for 1993 to 2002. In late winter (February/March) all years of the focus period, except 2008, were warmer than the 1993-2002 average at the surface (to ~50 m). 2005 was exceptionally warm through the upper 200 m at Station Papa and was the warmest or second warmest year at P16 and P12 in all seasons (2003 and 2004 were other warm years). However, surface waters were coldest in 2008 at all stations and in all seasons, in agreement with the basin scale anomaly (Fig. OC-7).

### 3.3.2 Salinity

The surface waters were fresher in all seasons and all years of the focus period (Fig. OC-15) than the average for 1993-2002 (to ~70 m in February/March, to ~30 m in May/June, to ~40 m in August/September). Mean salinity over the surface 1000 m was also less in all seasons and all years than the average for 1993 to 2002 (except for summer 2004) suggesting that the quantity of salt in the water column has decreased. Surface waters were also fresher than the long-term mean at P16 and at P12 in winter and spring of each year, though summer surface waters were slightly more saline than the mean in 2004, 2006 and 2008 at P12.

### 3.3.3 Density

Warmer temperatures and fresher water resulted in least dense surface waters in 2005. Conversely, the cold conditions and slightly higher salinities in 2008 caused the most dense surface water during the focus period. Only 2008 had denser surface waters in winter than the average for 1993-2002 and this was the case at all 3 stations.

### 3.3.4 Dissolved Oxygen

Declining oxygen levels in sub-surface waters of the Subarctic Pacific are occurring (Whitney et al. 2007) and are evident in the Line P dataset (Fig. OC-16). With the exception of summer 2004, all years and all seasons had lower dissolved oxygen below about 250 m at Station Papa than the average for 1993-2002. The warm temperatures of 2005 led to the lowest surface oxygen levels of the focus period, while cold conditions in 2008 led to generally the highest surface oxygen levels.

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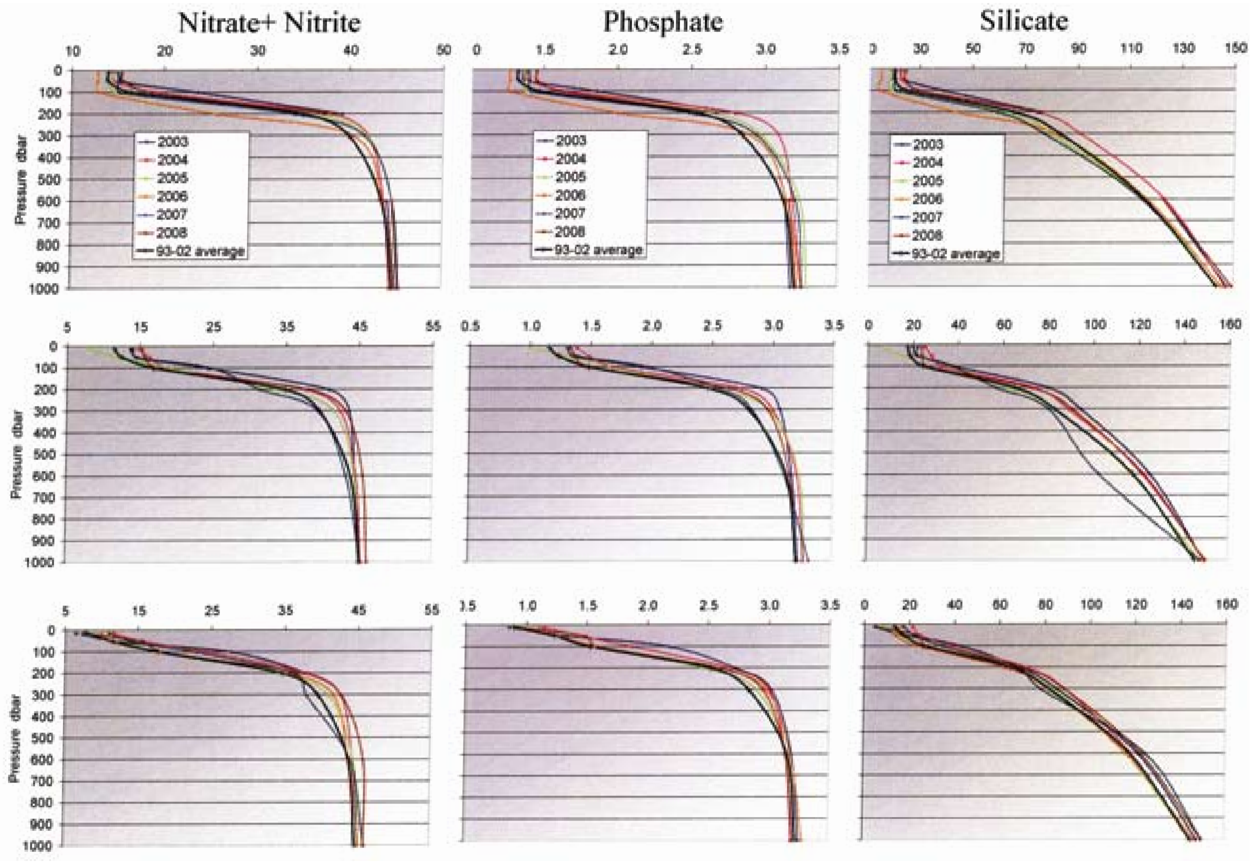


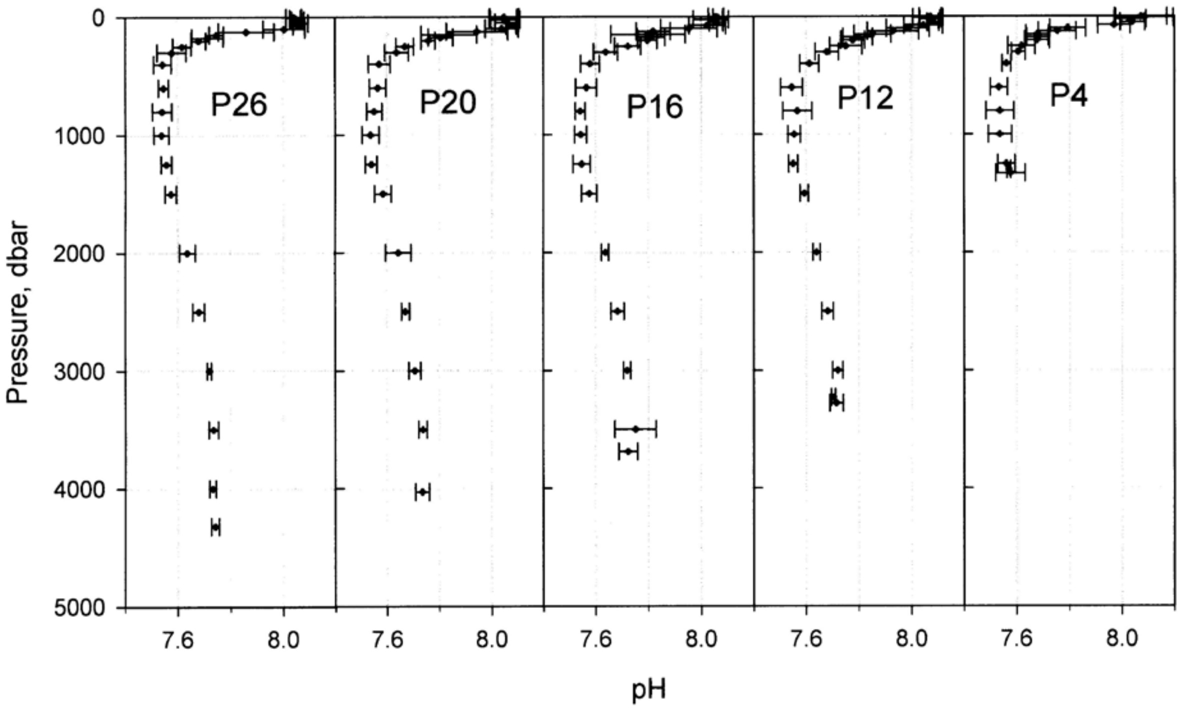
[Figure OC-17] Nutrient profiles (μmol·l⁻¹) at Station Papa. Top row = winter, centre row = spring, bottom row = summer.

### 3.3.5 Nutrients

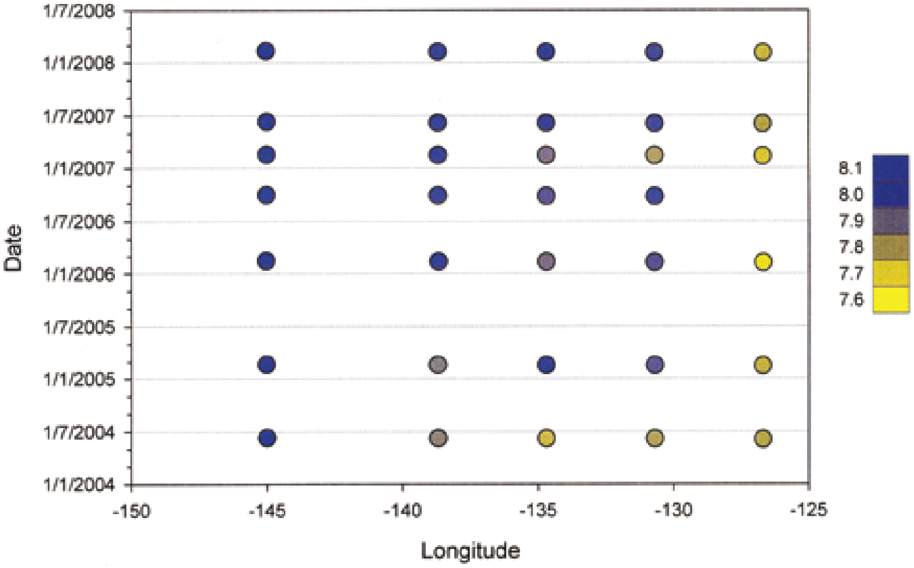
As a general rule the level of nitrate (plus nitrite) was higher during the focus period than the 1993-2002 average for most years and most seasons (Fig. OC-17). The 2008 concentrations of nitrate were particularly high at depth, especially in spring and summer. The 2006 concentrations were particularly low, especially in winter, but also at the lower end in summer (no cruise in spring 2006). Most phosphate concentrations during the focus period were higher than the 1992-2003 mean although the concentrations in 2006 were quite low in winter. Similarly high levels of silicate occurred, except in spring 2007 below 150 m, and in 2005 when concentrations were similar to the long-term mean. Note that spring 2005 was the only spring with lower values of nitrate, phosphate, and silicate than the 1993-2002 average, and it had the lowest dissolved oxygen during the focus period.

### 3.3.6 pH *(Miller)*

The time period between 2003 and 2008 is too short to confidently identify a pH decrease in the oceans due to anthropogenic carbon dioxide emissions. However, these data will provide a valuable comparison to the historical data, dating back to the summer of 1956, when they have been quality-controlled and released. Average profiles of pH data collected along Line P show that the pH distribution is consistent with depth across the transect. Surface values are around 8.05, with a minimum of about 7.55 at 500-1000 m, rising to above 7.7 in deep waters (Fig. OC-18). This pattern parallels the oxygen profiles and is primarily a result of varying spatial distributions of photosynthesis and respiration. The greatest variability is seen in the surface waters and at the pycnocline. Note that because of the depth distribution of pH, bottom communities nearer the coast live in lower pH waters than those off the coast.

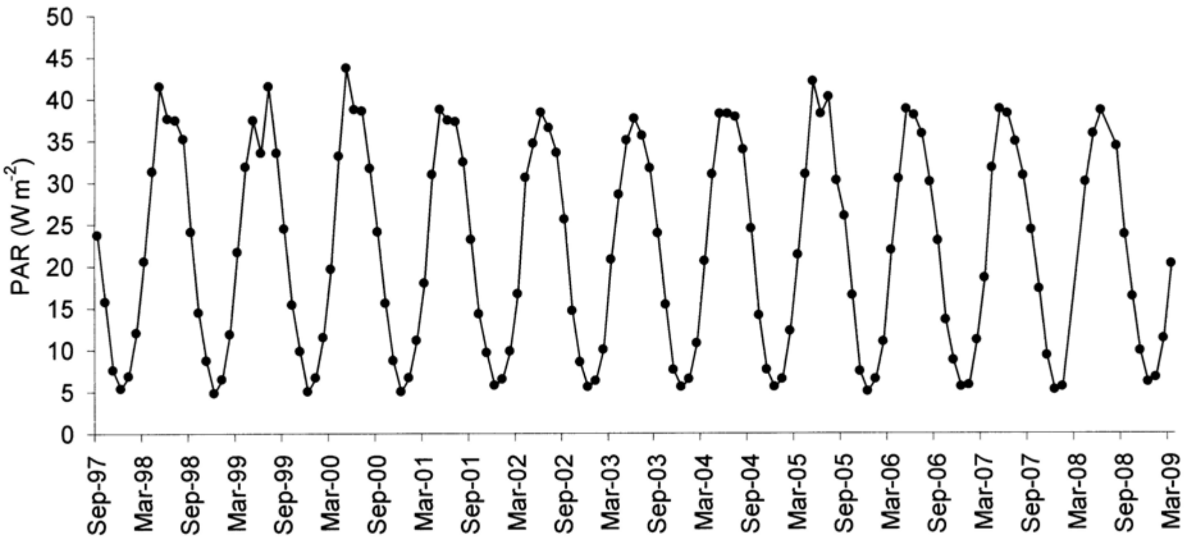


[Figure OC-18] Profiles of *in situ* pH along Line P. Error bars give ±1 standard deviation between seasonal (spring, summer, and fall) cruises, 2004-2008.

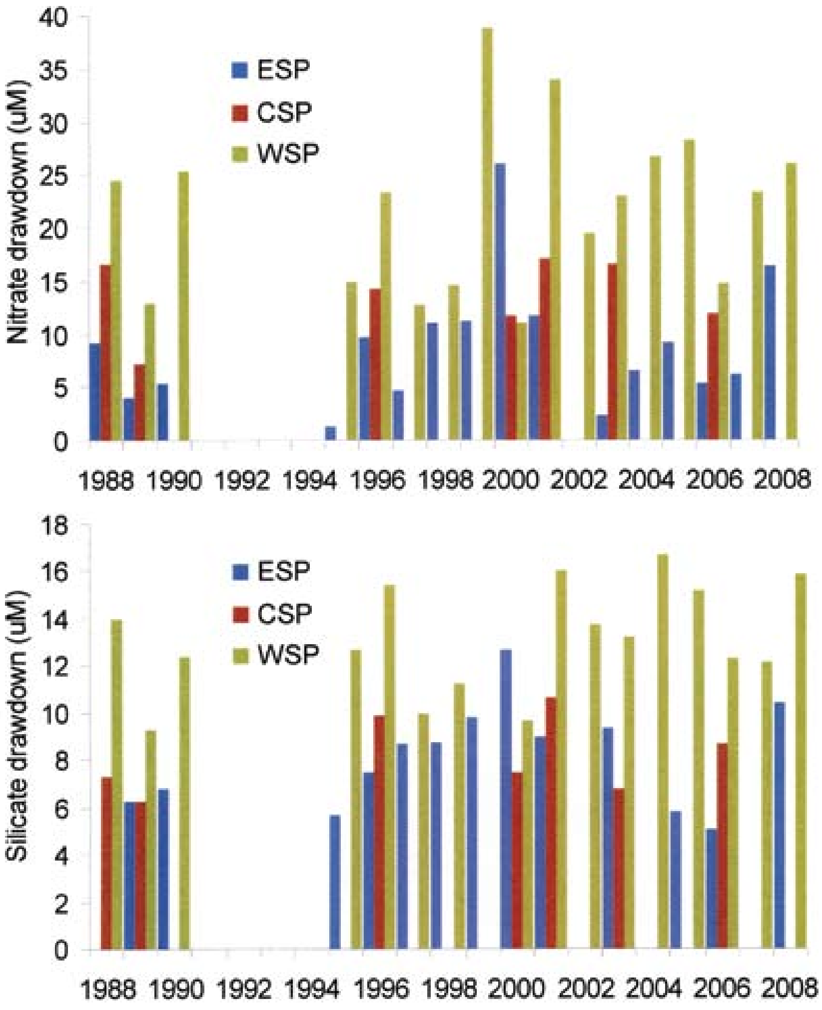


[Figure OC-19] pH on the 26.0 $\sigma_\theta$ surface along Line P over time.

On the 26.0 $\sigma_\theta$ density surface, which is roughly the source of coastal upwelling water and coincident with the permanent pycnocline, pH appears to have increased between 2004 and 2008 (Fig. OC-19), contrary to the long-term global trend. This increase is also contrary to the change in salinity, which was decreasing and would have lowered pH, if acting alone. Interestingly, dissolved oxygen also increased on the 26.0 $\sigma_\theta$ during this period, again contrary to the general trend over the last 50 years. If that increase in oxygen content in the pycnocline between 2004 and 2008 is the result of decreasing respiration rates, this would also explain the increase in pH.



[Figure OC-20] Monthly Photosynthetically Active Radiation from SeaWiFS for a region of the NE Pacific centred on Station Papa produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).



[Figure OC-21] Estimated seasonal nutrient drawdown for 3 regions of the North Pacific. Upper panel – nitrate drawdown, lower panel – silicate drawdown.

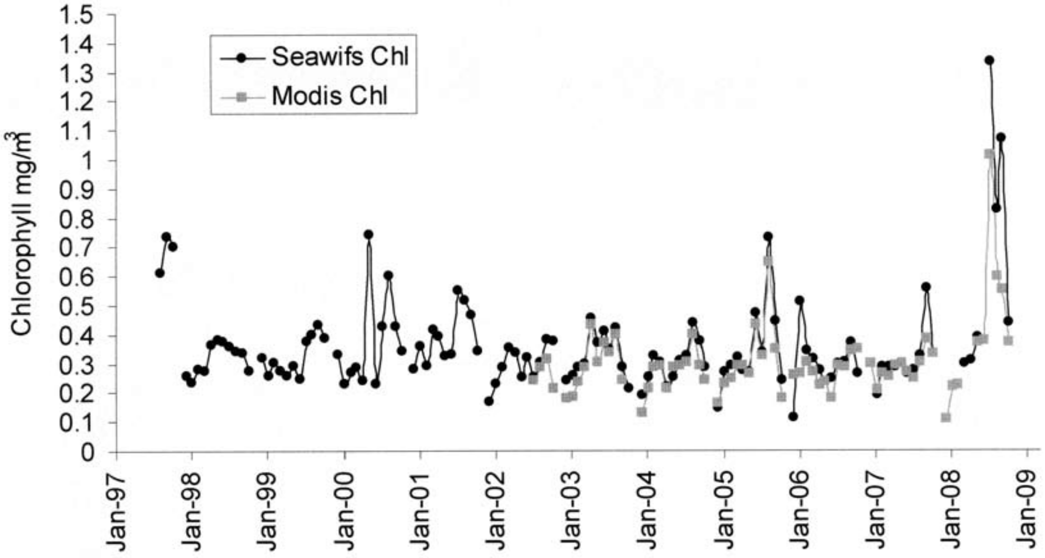
### 3.3.7 Photosynthetically active radiation *(Peña)*

The monthly time series of SeaWiFS Photosynthetically Active Radiation (PAR) shows highest values during May to July and little interannual variability (Fig. OC-20).

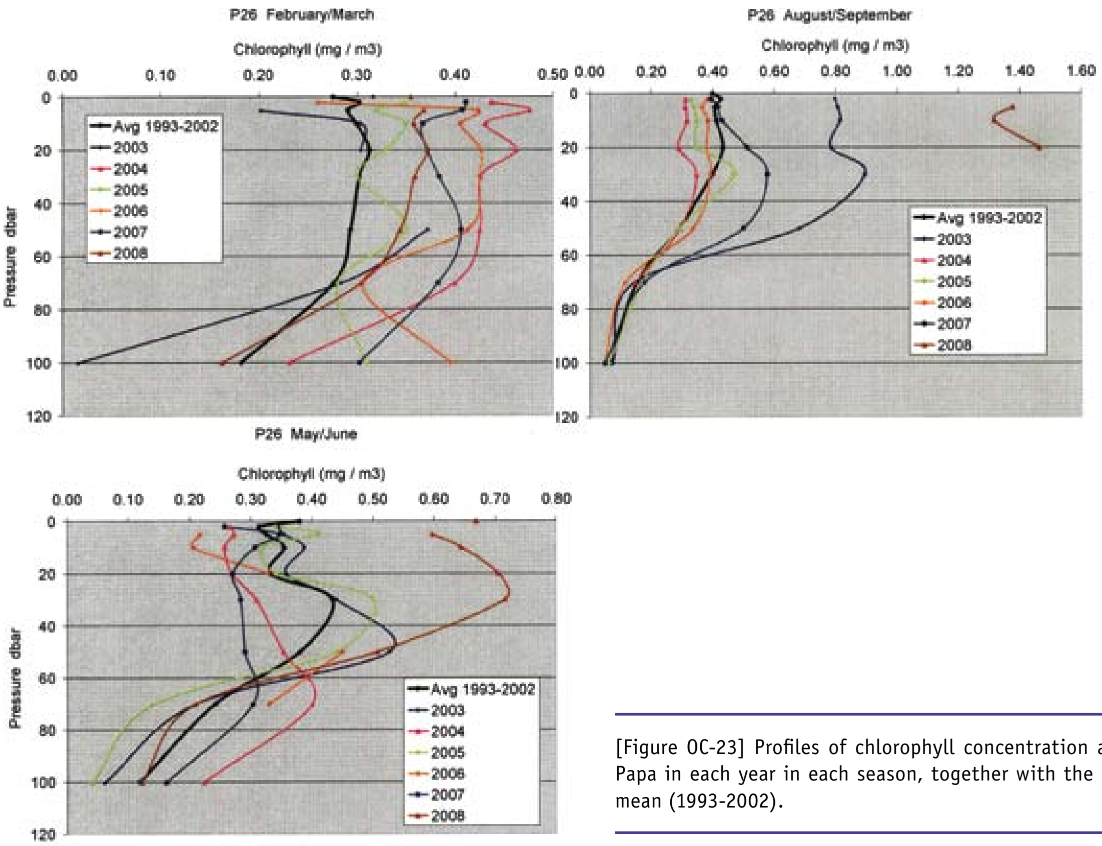
## 3.4 Nutrient data from ships of opportunity *(Whitney)*

Commercial ships crossing the North Pacific were used since 1987 to collect water samples that have been analysed for nutrient drawdown. Data for three geographical domains are included here; the Western Subarctic Pacific (WSP, 155-172°E, 45-53°N), the Eastern Subarctic Pacific (ESP, 140-155°W, 49.5-57°N) and the Central Subarctic Pacific (CSP, 45-51°N 160-180°W). Estimates of annual drawdown of silicate and nitrate were made by averaging all available data in each geographical domain for February and March (January was included if February and March data were scarce) and August/September (Fig. OC-21). Drawdown indicates nutrient use by phytoplankton in regions where winter storms are the dominant cause of mixing the ocean. It is not useful for this purpose in regions where tidal mixing is strong such as near the Aleutian or Kuril Islands.

Nutrient drawdown is stronger in the WSP where winter levels average 24 µM nitrate and 40 µM silicate, compared to the central and eastern domains where 18 µM nitrate and 26 µM silicate are typical winter levels. Transport of iron is stronger in the WSP due to prevalent current and wind directions, allowing 13 µM nitrate (18 µM silicate) to be drawn down seasonally compared to 8 µM nitrate (9 µM silicate) in the ESP. In all regions, strong or weak drawdown events were observed but no evidence of trends was found. The stronger stratification that reduced nutrient supply to surface waters along Line P in the 1990s, compared to the 1970s (Whitney and Freeland 1999) has broken down in recent years. Next to 2000, strongest nutrient drawdown in the ESP was in 2008.



[Figure OC-22] Satellite-derived chlorophyll concentrations for a region of the NE Pacific centred on Station Papa from the MODIS and SeaWiFS satellites produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).



[Figure OC-23] Profiles of chlorophyll concentration at Station Papa in each year in each season, together with the long term mean (1993-2002).

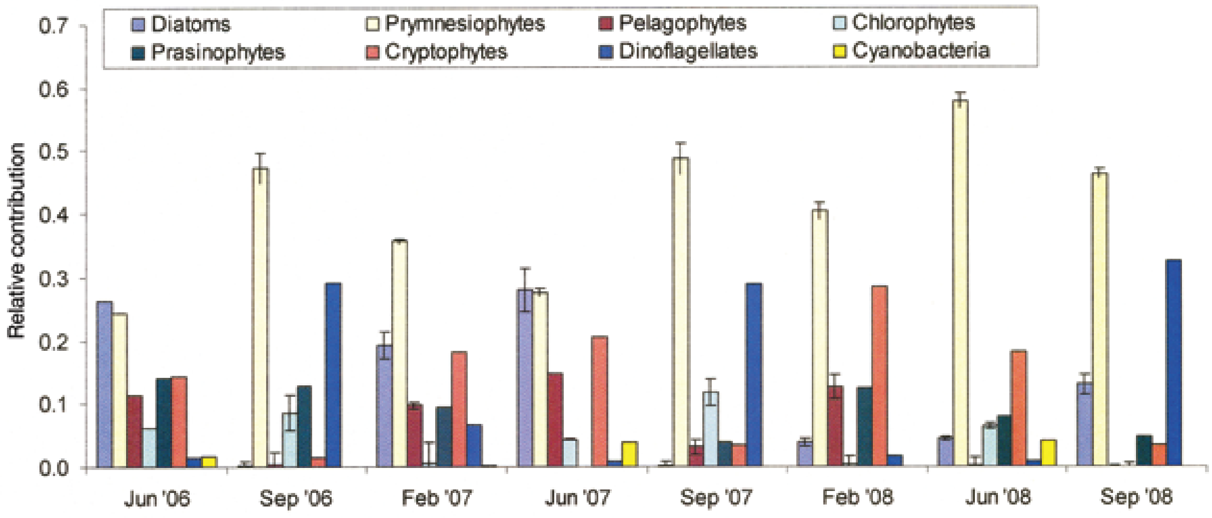
# 4.0 Phytoplankton

## 4.1 Chlorophyll at Station Papa *(Peña)*

Chlorophyll concentrations are usually low (<0.5 mg·m$^{-3}$) and show little seasonal variability in the eastern Subarctic Pacific (Fig. OC-22) and Station Papa field data (Fig. OC-23). Satellite data show four peaks in chlorophyll concentration: fall 1997, spring 2000, fall 2005 and summer 2008. The origins of the anomalous peak in 2008 are currently being investigated. Ship-based observations at Station Papa show chlorophyll concentrations in winters of 2004 to 2008 were slightly higher than the average for 1993-2002 (Fig. OC-23). This increase could be related to the shallowing of the winter mixed layer depth that has been previously reported (Freeland et al. 1997). In spring of 2003-2008, chlorophyll values were similar to the average, with the exception of 2008 which was higher. Late summer values were also similar to the long-term average except for 2003 and 2008 which were also higher.

## 4.2 Community composition at Ocean Station Papa *(Peña)*

Prymnesiophytes dominate phytoplankton biomass during the year (Fig. OC-24). In general, diatoms and cryptophytes are also abundant in spring whereas in summer dinoflagellates are the second most abundant phytoplankton group. Unusually high chlorophyll concentrations were observed by satellite data across the eastern Gulf of Alaska in August and September 2008 compared to these months the previous six years. The high concentrations observed by the satellite in August were confirmed by *in situ* observations (~1.3 mg·m$^{-3}$; Fig. OC-23). Despite the strong change in phytoplankton biomass in August 2008, the phytoplankton composition at Station Papa looks similar to that of August/September in the previous 2 years (Fig. OC-24). As before, prymnesiophytes and dinoflagellates contributed to most of the chlorophyll concentration (~70%). The main difference in composition compared to previous years was a slight increase (~10%) in diatoms at Station Papa, but not at the other offshore stations along Line P. Similarly, PAR values in August and September 2008 were not different to the values from previous years (Fig. OC-20).

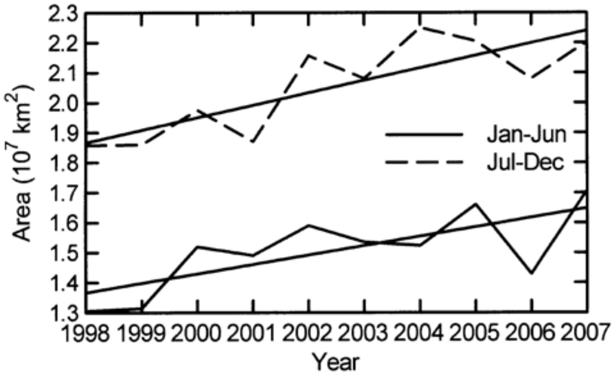


[Figure OC-24] Relative contribution of the main phytoplankton groups in the surface mixed layer at Station Papa obtained by CHEMTAX (Mackey et al. 1996) using pigment data from 5 and 10 m.

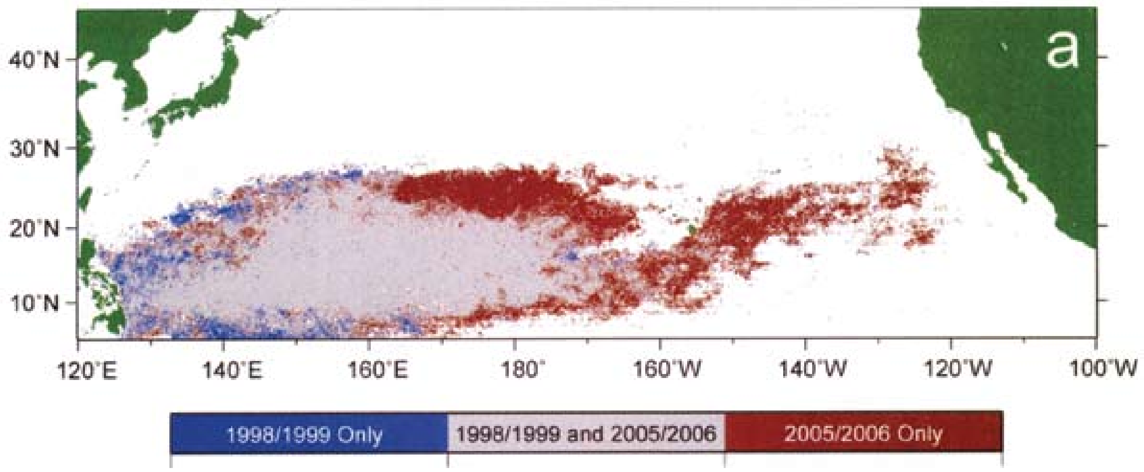
## 4.3 Chlorophyll in the Subtropics

*(Polovina, Woodworth)*

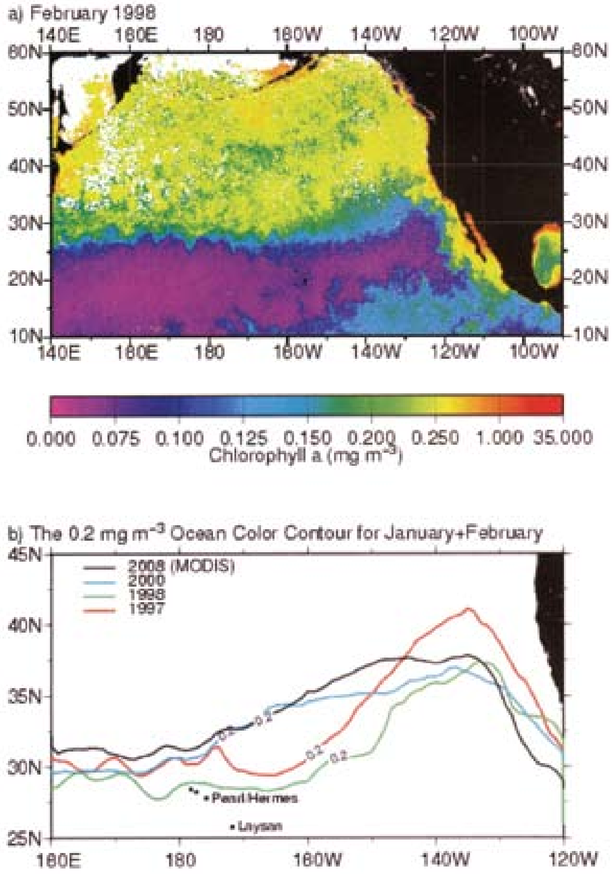
With limited information available from direct observations, satellite remote sensing of surface chlorophyll$_a$ provides the best insight into the phytoplankton dynamics of the Subtropical region. In the Subtropical central Pacific, surface concentrations are generally <0.15 mg·m$^{-3}$ and closer to the Subarctic they are >0.25 mg·m$^{-3}$. From the SeaWiFS ocean color sensor there is a time series of surface chlorophyll available from 1998 to the present. An increase was observed in the magnitude of the area of lowest surface chlorophyll waters in the central North Pacific (≤0.07 mg·m$^{-3}$) from 1998 to 2006 by about 2% per year in both the winter and summer seasons coherent with increases in sea surface temperature (Fig. OC-25) (Polovina et al. 2008). There was an eastward expansion of these low surface chlorophyll waters between the beginning and end of the time series (Fig. OC-26) that tracked similar expansions in the South Pacific, North Atlantic, and the South Atlantic, at rates ranging from 1-4% per year (Polovina et al. 2008). The expansion of low surface chlorophyll waters is consistent with a global warming scenario of increased vertical stratification but the observed rates already exceed long-term model predictions (Polovina et al. 2008).



[Figure OC-25] Area for the mean January-to-June and July-to-December seasons with surface chlorophyll ≤0.07 mg·m$^{-3}$ from SeaWiFS ocean colour sensor, 1998-2007. Straight lines indicate linear model fits to the data.



[Figure OC-26] The area ≤0.07 mg·m⁻³ surface chlorophyll in December 1998/1999 and 2005/2006 (grey), present in 1998/1999 but not in 2005/2006 (blue) and present in 2005/2006 but not in 1998/1999 (red).

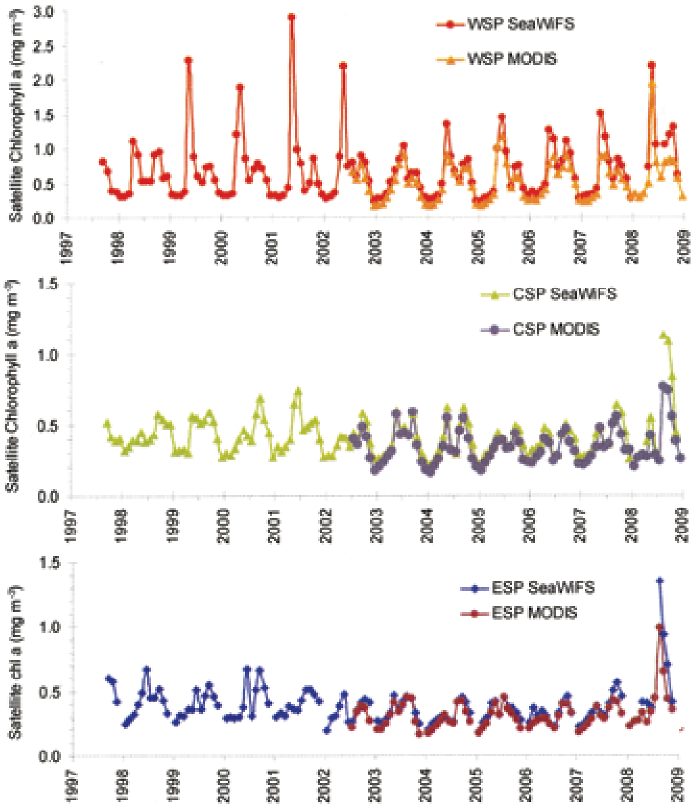


[Figure OC-27] Surface chlorophyll density (mg·m⁻³) estimated from SeaWiFS ocean colour for (a) February 1998 and (b) the mean position, averaged over January and February, of the Transition Zone Chlorophyll Front defined as the 0.2 mg·m⁻³ contour illustrating the south-shifted position in El Niño years 1997 and 1998, and the north-shifted position in La Niña years 2000 and 2008.

Between these regions of high/low surface chlorophyll lies the sharp basin-wide surface Transition Zone Chlorophyll Front (TZCF) (Polovina et al. 2001). The TZCF oscillates seasonally north to south about 1000 km with a latitudinal minimum in January-February and maximum in July-August (Polovina et al. 2001). The southernmost winter position of this biological front also exhibits considerable interannual variability. During the 1997-1998 El Niño, the southern extreme of the TZCF was south of 30°N, reaching the northwestern part of the Hawaiian Archipelago. During the 2000 and 2008 La Niña periods, however, the southern extreme of the TZCF shifted by as much as 500 km northward (Fig. OC-27). There is coherence between SSH EOF1, vertical temperature and chlorophyll sections, and the southernmost winter position of the TZCF (Figs. OC-12, OC-13, OC-27). The SSH rises (drops) reflecting an increase (decrease) in warm stratified water between 28-32°N latitude, and the TZCF southern minimum shifts northward (southward).

## 4.4 Chlorophyll in the Subarctic *(Whitney)*

Satellite-derived chlorophyll$_a$ estimates from SeaWiFS and MODIS satellites for the same three geographical domains discussed in Section 3.4 are included here (Fig. OC-28). Areas averaged are entirely oceanic for the Central Subarctic Pacific (CSP) and Eastern Subarctic Pacific (ESP), but cover a small area of coast in the Western Subarctic Pacific (WSP) which may enhance the spring bloom characteristics of this time series. Both concentration and seasonal variability were greatest in



[Figure OC-28] Chlorophyll$_a$ concentration for 3 regions (WSP, 155-172°E, 45-53°N; ESP, 140-155°W, 49.5-57°N; CSP, 45-51°N 160-180°W) estimated from ocean colour sensing satellites.

the WSP, a consequence of stronger nutrient supply in winter and enhanced iron supply. All three regions show a peak in 2008. The extraordinary event in the ESP and CSP is the chlorophyll spike in August 2008 (see also Section 4.1). This is a unique event in the satellite chlorophyll record and covered most of the ESP. The high nutrient-low chlorophyll waters of the ESP generally have stable chlorophyll levels of 0.3 to 0.5 mg·m$^{-3}$ throughout the year. When offshore chlorophyll peaks have been observed, they were associated with iron transport by mesoscale eddies. Surface currents move waters from the Asian coast toward the ESP, but when they arrive iron levels are extremely low. Spring and summer growth in the ESP is strongly controlled by the availability of iron, relying mainly on winter mixing to infuse small amounts that support slightly enhanced primary productivity in spring. Occasionally, an old eddy stimulates growth as was seen near Station Papa in 2000 (Whitney et al. 2005). Others have theorized that dust is a potentially significant iron source (Boyd et al. 1998), although no strong evidence has yet been shown of stimulated phytoplankton growth from volcanic eruptions or dust storms. At the moment, the definitive cause of the 2008 bloom in the ESP and CSP is not known. Leading candidates are volcanic ash* and vertical transport enhanced by the deepened mixing of the previous winter. Oddities in nutrient dynamics and phytoplankton in 2008 are summarized as follows:

- A very cold winter resulted in deeper winter mixing and a delay in spring stratification;
- Little nitrate or silicate was drawn down between February and June;
- A bloom event in August, perhaps affiliated with a volcanic eruption in the Aleutian Islands, drew down Si and N at a high ratio which is typical of the response seen during an artificial iron enrichment study at Station Papa (Boyd et al. 2004).

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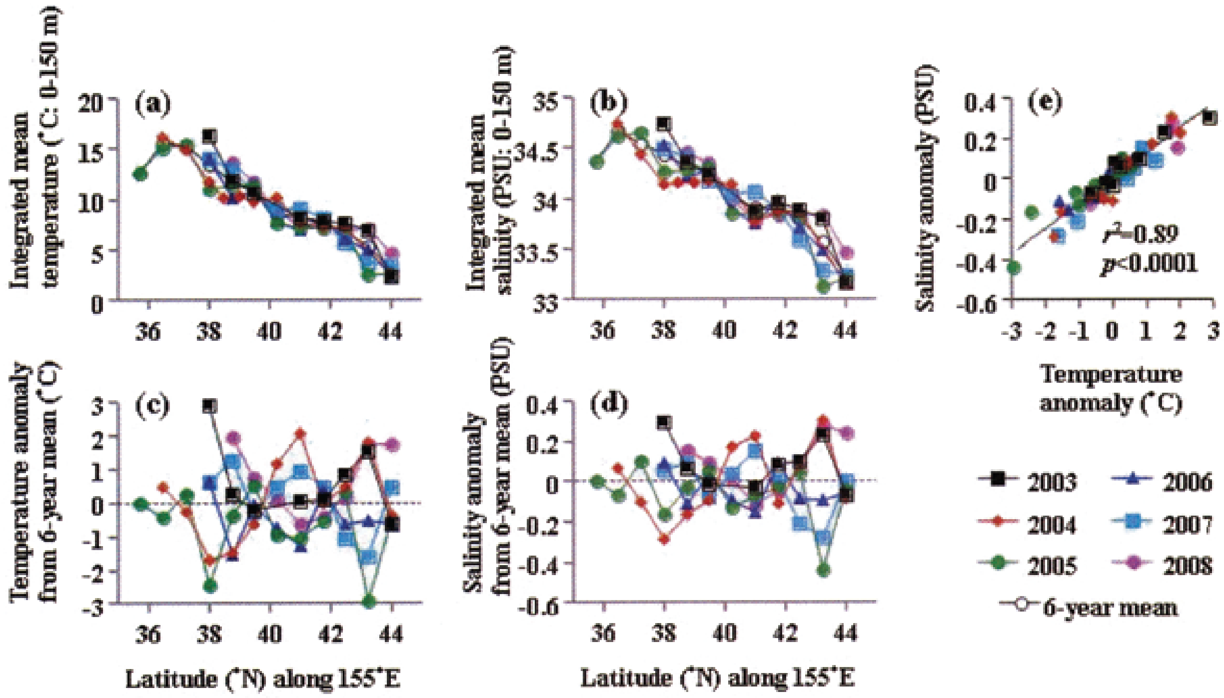
*Hamme, R. et al. 2010. Natural Volcanic Iron Fertiization of the Subartic North Pacific, EOS Transactions. AGU 91(26), Ocean Sciences Meeting Supplement, Abstract IT23C-01



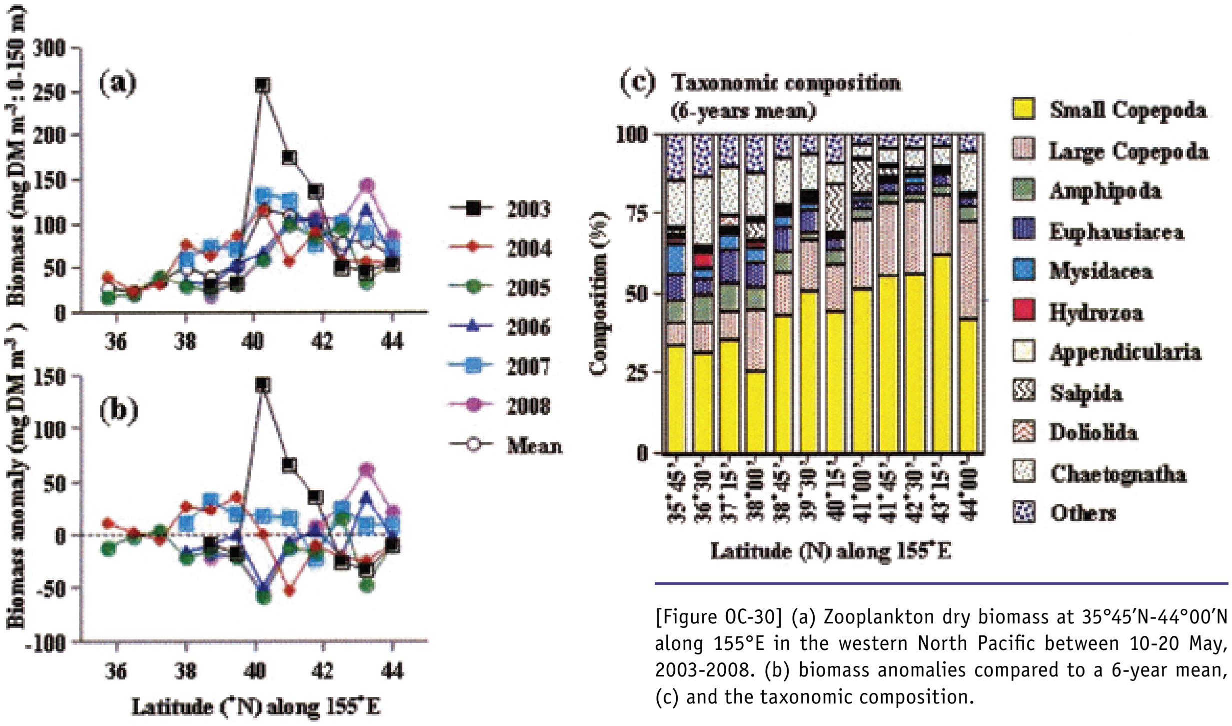
[Figure OC-29] Integrated mean temperature (a) and salinity (b) at 35° 45′N-44° 00′N along 155°E in the western North Pacific between 10-20 May, 2003-2008. Temperature (c) and salinity (d) anomalies from a 6-year mean are also calculated. Anomalies in salinity and temperature are highly correlated (e).

# 5.0 Zooplankton

## 5.1 Western North Pacific

### 5.1.1 Oshoro Maru *(Yamaguchi)*

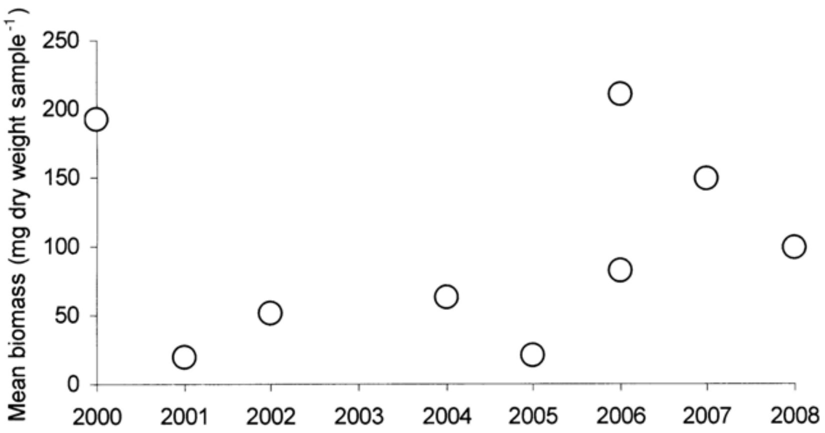
Zooplankton sampling was conducted using vertical tows of NORPAC nets (0.33 mm mesh) from 0-150 m at twelve stations every 83.3 km, between 35°45′N and 44°00′N along the 155°E line in the western North Pacific between 10-20 May, 2003-2008. Each study region was classified according to latitude as: Subarctic Front (SF: >42°N), Transition Domain (TR: 40-42°N), Subarctic Boundary (SB: 38-40°N) or Subtropic Current System (ST: <38°N). Temperature and salinity anomalies from 6-year means were correlated with each other, and were higher at SF in 2008 (Fig. OC-29). Zooplankton biomass was greater in the TR (ca. 100 mgDM·m$^{-3}$), followed by the SF (60 mgDM·m$^{-3}$) and the SB (45 mgDM·m$^{-3}$) (Fig. OC-30). High zooplankton biomass at the SF in 2008 (100 mgDM·m$^{-3}$) may be related to the high temperature during that period (a northward shift of the transition domain). Taxonomic composition of zooplankton biomass showed latitudinal variation and was dominated by small and large copepods in regions >40°N (SF and TR), while regions <40°N (SB and ST) were dominated by amphipods, euphausiids and chaetognaths as well as copepods. There was similar taxonomic composition at the TR and SF, while the high biomass in the TR might be a reflection of faster copepod development caused by high temperatures in the region. Prominent high values (130-260 mgDM·m$^{-3}$) were noted in the TR in 2003, caused by a dominance of salps (*Salpa fusiformis*). Temperature and salinity anomalies could not explain the dominance of salps.



[Figure OC-30] (a) Zooplankton dry biomass at 35°45'N-44°00'N along 155°E in the western North Pacific between 10-20 May, 2003-2008. (b) biomass anomalies compared to a 6-year mean, (c) and the taxonomic composition.

### 5.1.2 Continuous Plankton Recorder *(Batten)*

The Continuous Plankton Recorder (CPR) was towed behind a merchant ship on a transect crossing the open western Pacific at a latitude of ~50°N so that it is further north and east than the *Oshoro Maru* data described above and can be considered as fully Subarctic waters. Taxonomic abundance data were converted to biomass using taxon specific dry weights and summed to give total biomass per sample (~3 m³). Samples collected between 160° and 168°W from the surface ~10 m in the late spring/early summer of each year were averaged to give mean values for the region (Fig. OC-31). Sampling usually took place in June but occasionally in May and July in which case both values are shown for that year (2006 and 2008). There was considerable variability, a factor of 10 between the lowest and highest years. There is some agreement with the most northerly *Oshoro Maru* data in that the most recent 3 years (2006, 2007 and 2008) had higher biomass than the prior 3 years (2003, 2004 and 2005), but the sampling locations and methodologies were very different so not too much emphasis should be placed on this result.



[Figure OC-31] Mean zooplankton biomass from CPR sampling, 160-168°W in late spring/early summer of each year. May and July values in 2008 are superimposed.

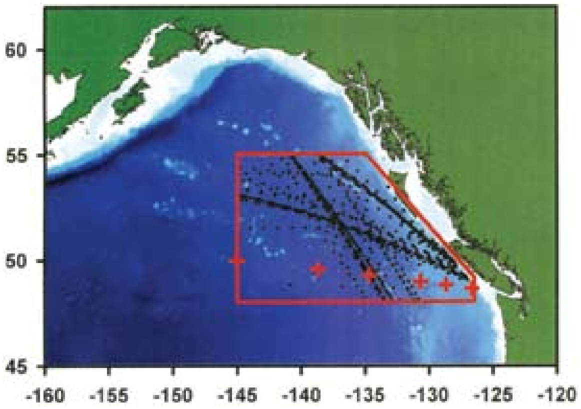
## 5.2 Eastern North Pacific *(Mackas, Batten)*

Frequent zooplankton sampling was conducted at Station Papa from 1956-1980 as part of the "Weathership" time series (Fulton 1983; Waddell and McKinnell 1995; McKinnell and Mackas 2003) but it ended with the retirement of weatherships. From 1980 to the late 1990s, most of the zooplankton sampling in the oceanic Alaska Gyre was either during two intensive but brief research projects; Project SUPER, 1983, 1987, and 1988 (e.g., Mackas et al. 1993, Miller 1993), Canadian JGOFS, 1996-1997 (e.g. ,Goldblatt et al. 1999) or the once-per-year sampling along 145°W that was done as part of the large scale Japanese *Oshoro Maru* surveys of the entire Subarctic Pacific (e.g., Sugimoto and Tadokoro 1997). More regular net tow sampling resumed along Line P in 1997, stimulated in part by the 1997-1998 El Niño (Mackas and Galbraith 2002). The present effort consists of three surveys per year: February, late May or June, and August or early September. For analysis purposes Line P was divided into two segments: outer Line P (stations P16, P20, and P26=Station Papa) ; this segment contains the HNLC stations that are usually iron limited from spring through autumn, and inner Line P (stations P4, P8, and P12). This segment has more exchange with the continental margin and often shows nitrate depletion in summer.

Monitoring zooplankton in the Alaska Gyre by the CPR began in 1997 with a pilot study in July-August (Fig. OC-32). Since 2000 sampling continued as a series of 6-8 survey lines per year. Both the "modern" Line P and the CPR time series are now about a decade in length, allowing relatively stable average seasonal cycles of zooplankton biomass and community composition to be computed. From these it is possible to examine interannual differences in seasonal timing of growth and dormancy of the dominant copepod *Neocalanus plumchrus* and to produce time series of taxon-specific deviations from the average seasonal abundance and biomass. Calculations used to convert raw net tow data to annual amount and composition anomalies are identical in sequence to those previously described for the longer continental margin time series (e.g., Mackas et al. 2001). Abundance, biomass and stage composition ratios can be used to measure changes in zooplankton seasonal timing (Mackas et al. 1998, 2007; Batten et al. 2003; Batten and Mackas 2009).

### 5.2.1 Seasonal cycles of amount and species composition

Based on presence-absence, the zooplankton taxa in the Line P time series samples are the same as those found in samples from the Vancouver Island continental margin. However, the dominance hierarchies differ between continental margin (Mackas et al. 2001) and oceanic regions (Mackas and Galbraith 2002). Seaward of the continental margin, the largest component of the annual total and spring-summer seasonal biomass (Fig. OC-33) consists of a small number of copepod species that can be characterized zoogeographically as "subarctic oceanic" (primarily *Neocalanus plumchrus*, *N. cristatus*, *N. flemingeri*, *Eucalanus bungii*, and *Metridia pacifica*, plus much smaller contributions from *Paraeuchaeta elongata* and *Racovitzanus antarcticus*). All have distributions that span the Pacific basin, north of the Subarctic Front. *Neocalanus*, *Eucalanus* and *Euchaeta* are large in individual size (~0.5-1 cm total length as late juveniles and adults), and both *Neocalanus* and *Eucalanus* have very distinctive life history strategies involving deep ontogenetic vertical migration, and 1-3 year life cycles (depending on location) including one or more prolonged seasonal dormancy periods (Fulton 1973; Miller et al. 1984; Miller and Clemons 1988; Miller and Terazaki 1989; Tsuda et al. 1999). The migration and dormancy strategies result in a distinct spring-early summer maximum of biomass, earliest and most pronounced for *N. plumchrus* and *N. flemingeri*; more prolonged for *Eucalanus* and *N. cristatus*.



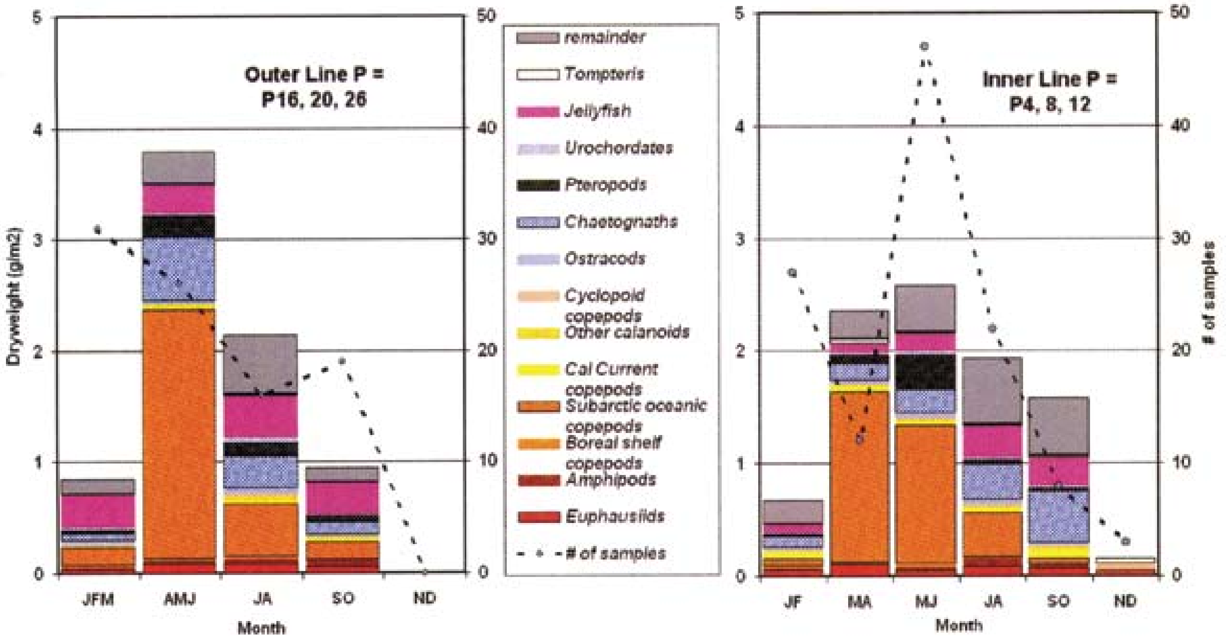
[Figure OC-32] Sampling locations for the recent Line P zooplankton monitoring program (red + are the Line P stations P26, P20, P16, P12, P8, P4 from west to east) and for the North Pacific CPR program (black dots are samples along north-south and east-west shipping routes, red box indicates the 48-55°N 'box' within which temporal coverage is best.

The second largest component of biomass is the chaetognaths, primarily two cool water species *Parasagitta elegans* and *Eukrohnia hamata*. These also peak in spring and summer, but slightly later than the copepods on which they feed. Other major contributors to total biomass are the pteropods (*Limacina helicina*, *Clione limacina*, and occasionally *Clio pyramidata*), gelatinous predators (siphonophores and medusae), and a "remainder" category dominated by large diel-migratory taxa such as shrimps, small squids, and small midwater fishes. Categories present but at lower average abundance/biomass than along the continental margin include euphausiids (with *Thysanoessa inspinata* replacing *Euphausia pacifica* and *T. spinifera* as the most common species), hyperiid amphipods, and "Boreal Shelf" and "California Current" copepod groups (see Mackas et al. 2001 or Mackas et al. 2007 for the species included in each group).

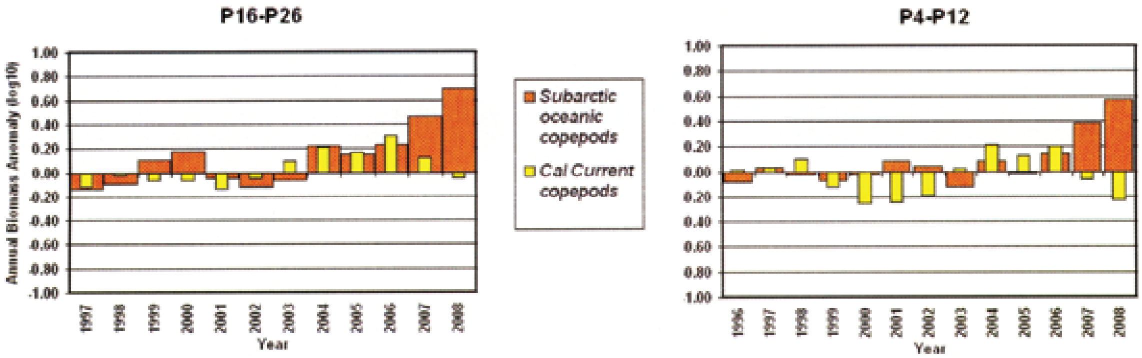
### 5.2.2 Anomalies of amount and species composition

Large interannual changes are seen in the "success" of various species and species groups (Fig. OC-34). The most striking results have been upward trends (equivalent to 3-5 fold increases) in the biomass of the large interzonal migrant "Subarctic oceanic" copepods (*Neocalanus cristatus, N. plumchrus, N. flemingeri, Eucalanus bungii*) and the cool-water chaetognaths (*Parasagitta elegans, Eukrohnia hamata*). These changes are correlated with the recent upper ocean cooling ($r^2$ = 0.3-0.4) but are even more strongly associated ($r^2$ = 0.5-0.65) with the recent strengthening of the eastward North Pacific Current that has been revealed by the Argo network of profiling drifters (H. Freeland pers. comm.).

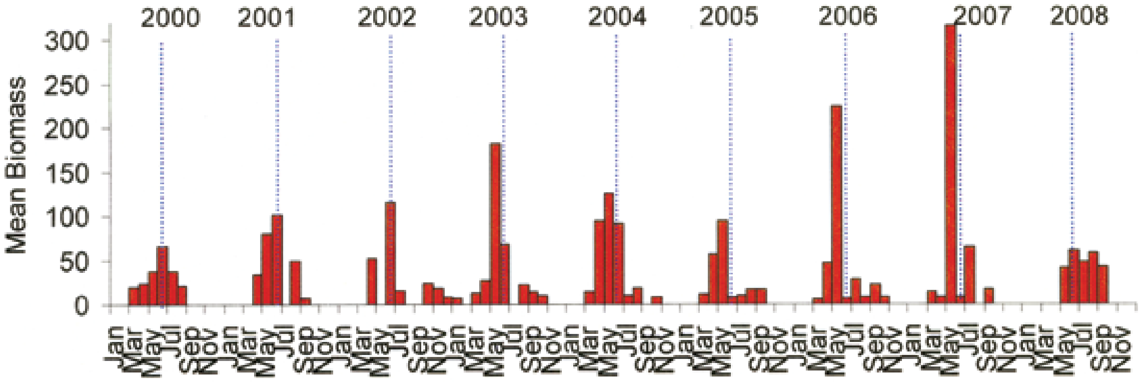
Within the Subarctic Oceanic copepod group, which includes the overall dominant members of the zooplankton community (Fig. OC-33), the strongest increases have been by the two largest-bodied species, *N. cristatus* and *E. bungii*. These species also have longer growing seasons and later entry into seasonal dormancy. Note also that anomaly magnitudes are greater for the more oceanic outer Line P subregion. This suggests that we are observing oceanic processes, rather than seaward propagation of changes originating at the eastern margin.



[Figure OC-33] Average seasonal cycles of mesozooplankton biomass (geometric mean dry weight $m^{-2}$) within various composite taxonomic groups, for "outer" and "inner" Line P. These are used as climatologies against which individual years are compared, to produce anomaly time series.



[Figure OC-34] Time series of annual anomalies of zooplankton biomass averaged within important species groups. The Subarctic oceanic copepods have increased considerably during the past decade, and are associated with increased transport by the North Pacific Current. Subtropical California Current copepods have fluctuated, and are most strongly associated with temperature variability.

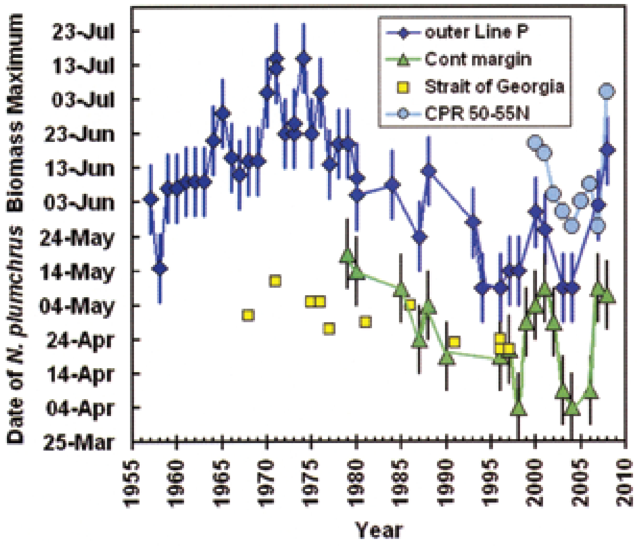


[Figure OC-35] Mean monthly mesozooplankton biomass for the Northeast Pacific from CPR sampling. The dashed lines indicate June of each year to emphasize the shift in peak timing and magnitude.

Biomass per sample was also calculated for the CPR samples according to procedure described in Section 5.1.2. Average monthly biomass (Fig. OC-35) was calculated for the region defined in Figure OC-31. In cool years the peak was late and protracted (2000, 2001 and 2008). In warm years the peak was early and narrow (2005, 2006). Variation within the focus period was considerable with the monthly profile of the adjacent years 2007 and 2008 very different from each other. The highest late summer biomass (August and September) in the CPR time series occurred in 2008.

### 5.2.3 *Neocalanus* seasonal timing

Upper-ocean temperature during spring (March-May) has a large effect on the seasonal timing of growth and dormancy for the dominant copepod *Neocalanus plumchrus* (Mackas et al. 1998, 2007). The fluctuations of zooplankton seasonal timing continue to be large (up to 3-4 months variation in the timing of a peak that is only about 1.5 month wide) and continue to be strongly associated with temperature (early in warm years, later in cool years). The timing fluctuations also appear to be spatially coherent throughout the Subarctic NE Pacific (separations up to ~1500 km). The focus period was especially variable with 2003-2005 seeing the earliest peaks in the 50 year Line-P record, while 2008 was much later reflecting the switch back to cool conditions (Fig. OC-36).

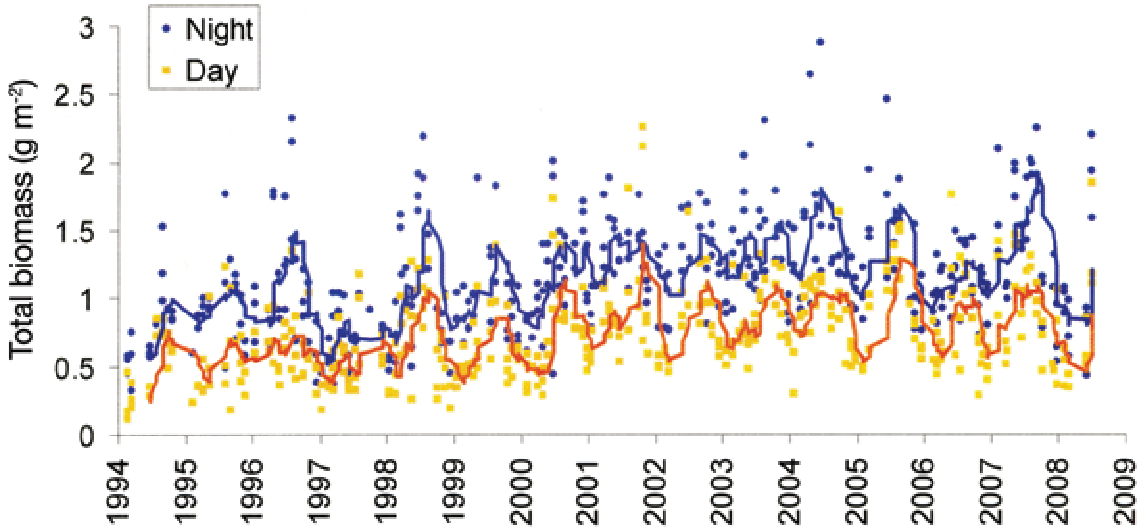


[Figure OC-36] Phenology time series for *Neocalanus plumchrus* populations in various subregions of the Northeast Pacific.

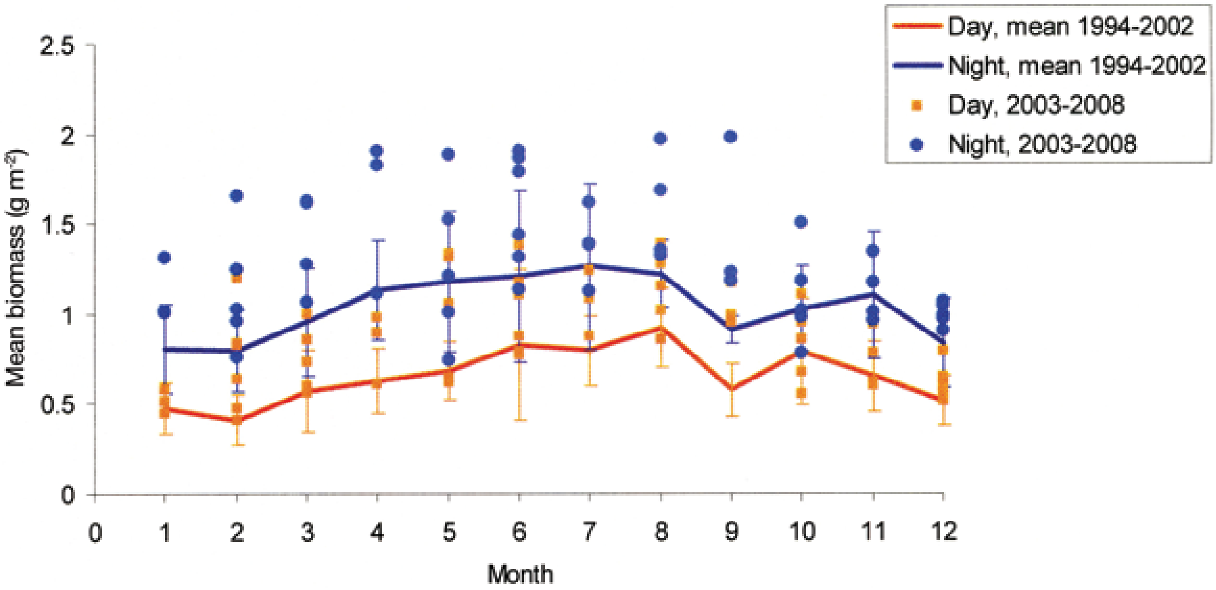
## 5.3 Central Subtropical zooplankton

*(Landry)*

Size fractionated zooplankton biomass has been measured at station ALOHA since 1994 as part of the Hawaii Ocean Time series (HOT) program. Cruises are conducted approximately once per month to the oligotrophic deep-water station ALOHA (22° 45'N, 158° 00'W) located 100 km north of Oahu, Hawaii. Three midnight (2200 - 0200) and 3 midday (1000 - 1400) oblique tows are collected through the euphotic zone on each cruise, and the catch is size-fractionated to give biomass for the 0.2-0.5 mm, 0.5-1 mm, 1-2 mm, 2-5 mm and >5 mm fractions. The mesh size of the net has been consistent at 202-µm, but the type of gear changed in 2005. The new gear may be easier to avoid by larger animals with fast escape responses and so some caution should be used in comparing the largest (>5 mm) size fraction before and after November 2005. The time series of total daytime (0530-1830) and nighttime zooplankton biomass extends from 1994 to June 2008 (Fig. OC-37). There is a clear seasonal cycle with the annual peak usually occurring June-August (Fig. OC-38). From 1994 to 2004, there was an increasing trend in biomass, which leveled, or even decreased after 2005. Although this coincides with the gear change, the pattern is the same if the largest size fraction is removed, with an increase in biomass through 2004 in size classes <5 mm, which subsequently reached a plateau. For the remainder of the focus period, biomass has remained relatively high (Fig. OC-37), with most months having values higher than the monthly mean for 1994-2002, although there is a suggestion that values were declining towards the end of the focus period. Among recent years, 2006 is notable in having a markedly depressed seasonal cycle, which typically shows a biomass peak in late summer or fall, as seen for example in 2005 and 2007. Within the full data set, only the period 1997 El Niño to 1998 La Niña conditions shows a sharper difference between nocturnal summer biomass values from one year to the next. Within the focus period, only two months had biomass values less than one standard deviation of the 1994-2002 monthly means; night samples in October 2006 and May 2008.



[Figure OC-37] Total zooplankton biomass with an 8-point running mean superimposed. Day (0530) and night (1830) are shown by red and blue lines, respectively.



[Figure OC-38] Monthly mean and standard deviations for the period of 1994 to 2002, with monthly means for the focus period superimposed as symbols (blue = night, orange = day, as above).

# 6.0 Fishes and Invertebrates

## 6.1 Northeast Pacific

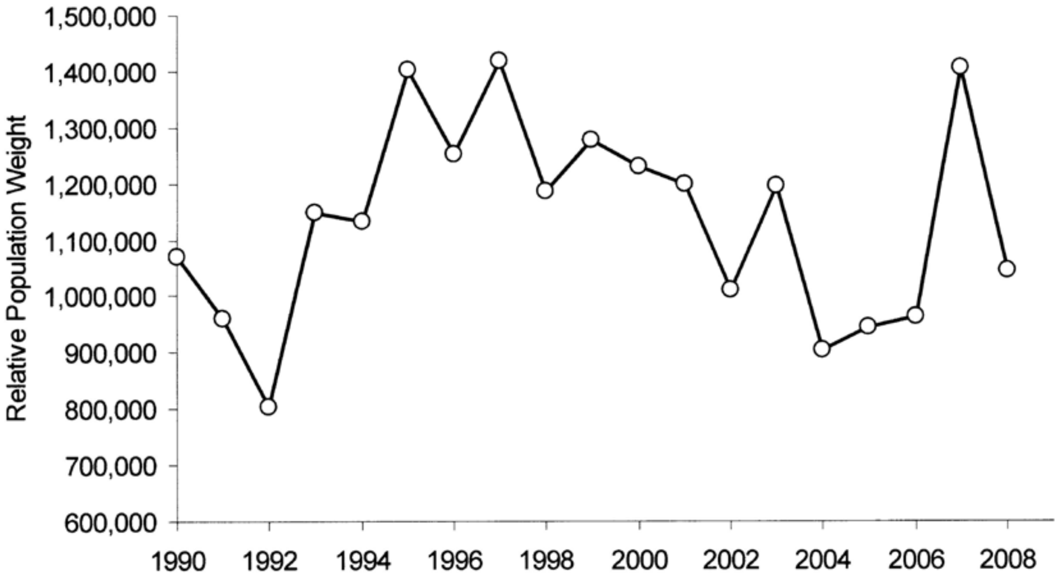
The fish fauna of the oceanic northeastern Pacific consists of a mix of temperate and subarctic species, resulting in a gradient in species composition along the shelf from the east to the west (Mueter and Norcross 2002). At least 383 species belonging to 84 families of marine and anadromous fishes have been reported from the Alaska continental shelf, slope, and offshore areas (Mecklenburg et al. 2002). The majority of fish biomass and commercial exploitation occurs on the continental shelf and slope in relatively nearshore areas. Few studies have been conducted to investigate long-term temporal patterns in fish abundance in the northeastern Oceanic Region. The central part of the Alaska Gyre provides the principal feeding habitat for many species, particularly salmon, throughout the year (Brodeur et al. 1999). South of the Alaska Gyre, the NPTZ once supported large-scale squid (*Ommastrephes bartrami*) driftnet fisheries until a moratorium prohibiting use of this gear was established by the United Nations General Assembly in 1992 (PICES 2004). Midwater trawling over seamounts in 1981 found low quantities of non-commercially valuable species of squid, bathypelagic fishes, and immature salmon (Hughes 1981).

Little is known about demersal species that inhabit the deeper parts of the continental slope and oceanic region. Due to the extreme depths in this region, there are few commercial fisheries and limited opportunities for fisheries research. Seamounts in the Gulf of Alaska represent one of the few areas in the oceanic region where exploitation of demersal fish species has occurred. Hughes (1981) first conducted exploratory fishing on Gulf of Alaska seamounts in 1979 using trawls and pots. Sablefish, (*Anaplopoma fimbria*) was the most common finfish found but rattails (family Macrouridae) were also caught. Other commercially important species encountered were several species of king crab (family Lithodidae) and tanner crab (*Chionoecetes tanneri*). Subsequent longline surveys conducted by Maloney (2004) on eight seamounts in the Gulf of Alaska from 1999-2002 produced high numbers of sablefish, giant grenadier (*Albatrossia pectoralis*), and Pacific grenadier (*Coryphaenoides acrolepis*). Tagging studies have verified that sablefish migrate among the continental shelf, slope region and seamounts but the route is unknown (Maloney 2004).

In 2005, the U.S. North Pacific Fisheries Management Council named 16 seamounts within the U.S. Exclusive Economic Zone off Alaska to be Alaska Seamount Habitat Protection Areas. These marine protected areas are now closed to all bottom contact fishing gear. Since the cessation of high seas driftnet fisheries and closure of seamounts to bottom contact fishing gear very little commercial exploitation has occurred. No time series information of abundance exists for fish species in this area. The best information likely comes from giant grenadier abundance estimates.

### 6.1.1 Grenadiers *(Lunsford)*

Grenadiers (family Macrouridae) are deep-sea fishes related to hakes and cods that occur world-wide in all oceans (Eschmeyer et al. 1983). Also known as "rattails", they are especially abundant in waters of the continental slope, but some species are found at abyssal depths. Of the seven species of grenadiers known to occur in Alaska, giant grenadier appear to be the most abundant and most common grenadier caught in the commercial fishery and in fish surveys (Clausen 2008). Survey information on giant grenadier in Alaska comes from comprehensive bottom trawl and longline surveys of the continental slope. Trawl surveys are too intermittent in time and depths sampled to show trends in abundance, but longline surveys provide estimates of relative biomass since 1990 up to depths of 1000 m (Clausen and Rodgveller 2008). Definitive trends in the relative abundance are difficult to discern, but generally there was an increasing trend from 1992-1997 and then somewhat of a decrease in subsequent years followed by a sharp increase in 2007 (Fig. OC-39). Both survey types show relatively high catch rates of giant grenadier in the deepest strata sampled, which indicates an unknown and possibly significant portion of the population may reside in deeper waters that have not been sampled (Clausen and Rodgveller 2008). A longline survey conducted in 2008 sampled depths up to 1600 m and found relatively high catch rates of giant grenadier at the deeper depths which supports the idea that an unknown portion of population resides in depths not sampled by traditional survey methods (D. Clausen, pers. comm.)



[Figure OC-39] Giant grenadier relative population weight in NMFS longline surveys in the Gulf of Alaska, 1990-2008. Values include data only for the upper continental slope at depths 201-1,000 m and do not include continental shelf gullies sampled in the surveys. Note: relative population weight, although an index of biomass (weight), is a unit-less value (from Clausen and Rodgveller 2008).

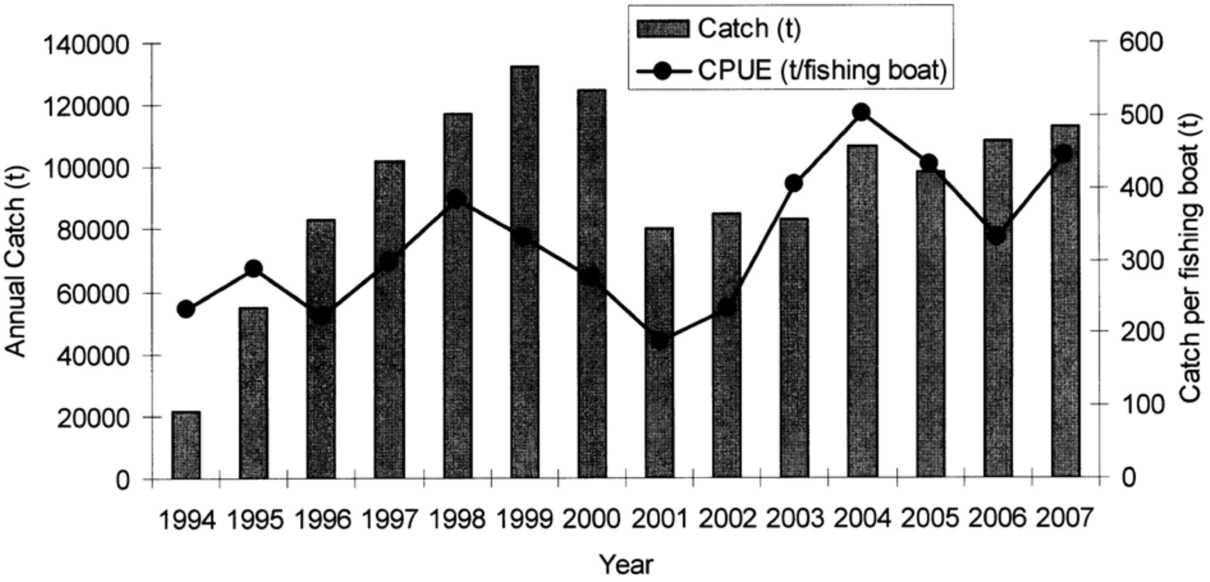
## 6.2 Central North Pacific

The primary fishery in the central North Pacific region is the pelagic longline fishery which includes fleets from the U.S. (based in Hawaii) as well as Japan and Taiwan. Several commercial fisheries currently operate in Transition Zone waters, including Japanese and U.S. vessels targeting tunas and billfishes, Japanese and U.S. troll vessels targeting tunas (notably albacore tuna), and a distant water Japanese (and to a much lesser extent U.S.) squid jigging fishery. The now defunct Asian high-seas driftnet fishing fleets targeting squid, tunas, and billfish also operated in Transition Zone waters. Information obtained by the multi-national observer program that monitored these fisheries provided the basis for much of our current understanding of the region's nektonic faunal composition (e.g., Yatsu et al. 1993).

### 6.2.1 Neon flying squid *(Chen, Ichii)*

The neon flying squid, *Ommastrephes bartrami*, is a large oceanic squid distributed in temperate and subtropical waters of the Pacific, Indian and Atlantic Oceans, and is especially abundant in the North Pacific. A large scale squid jigging fishery started in 1994, and a total of 23,000 t was landed. The maximum output in 1999 reached 132,000 t. The current fishing area is mainly located in the waters of 150°–165°E and 40°–46°N during August and November for the Chinese squid jigging boats, accounting for more than 65% of the total Chinese squid catch (Chen and Tian 2006). Data on catch per fishing boat and annual catch were obtained from the Chinese commercial jigging fleet operating in the area 150–165°E, 38–46°N during August and November from 1995 to 2007 (Fig. OC-40). Catch and CPUE remained relatively high and stable through the period 2003-2007 with the lowest CPUE in 2006 and the highest in 2004. However, the 2006 CPUE was similar to the previous highest CPUE in 1998.

A modified depletion model was fitted to the fisheries data to estimate the squid stock abundance during 2000–2005 (Chen et al. 2008). The proportional escapement ranged from 15.3% (in 2000) to 69.9% (in 2001), with an average of 37.2%, which was close to the management target of 40%. Thus, the current fishing mortality of the squid jigging fishery was considered to be sustainable and the annual maximum allowable catch was inferred to range from 80,000 to 100,000 t. The squid have been under-

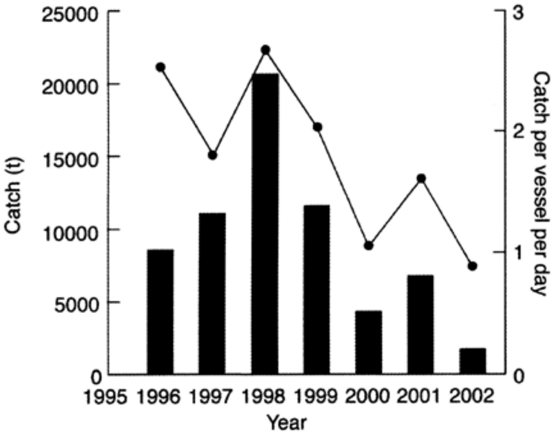


[Figure OC-40] Total annual catch of neon flying squid (*Ommastrephes bartrami*) caught by the Chinese squid-jigging fleet in the North Pacific, 1995–2007, and average CPUE in the area 150–165°E, 38–46°N for the same period.

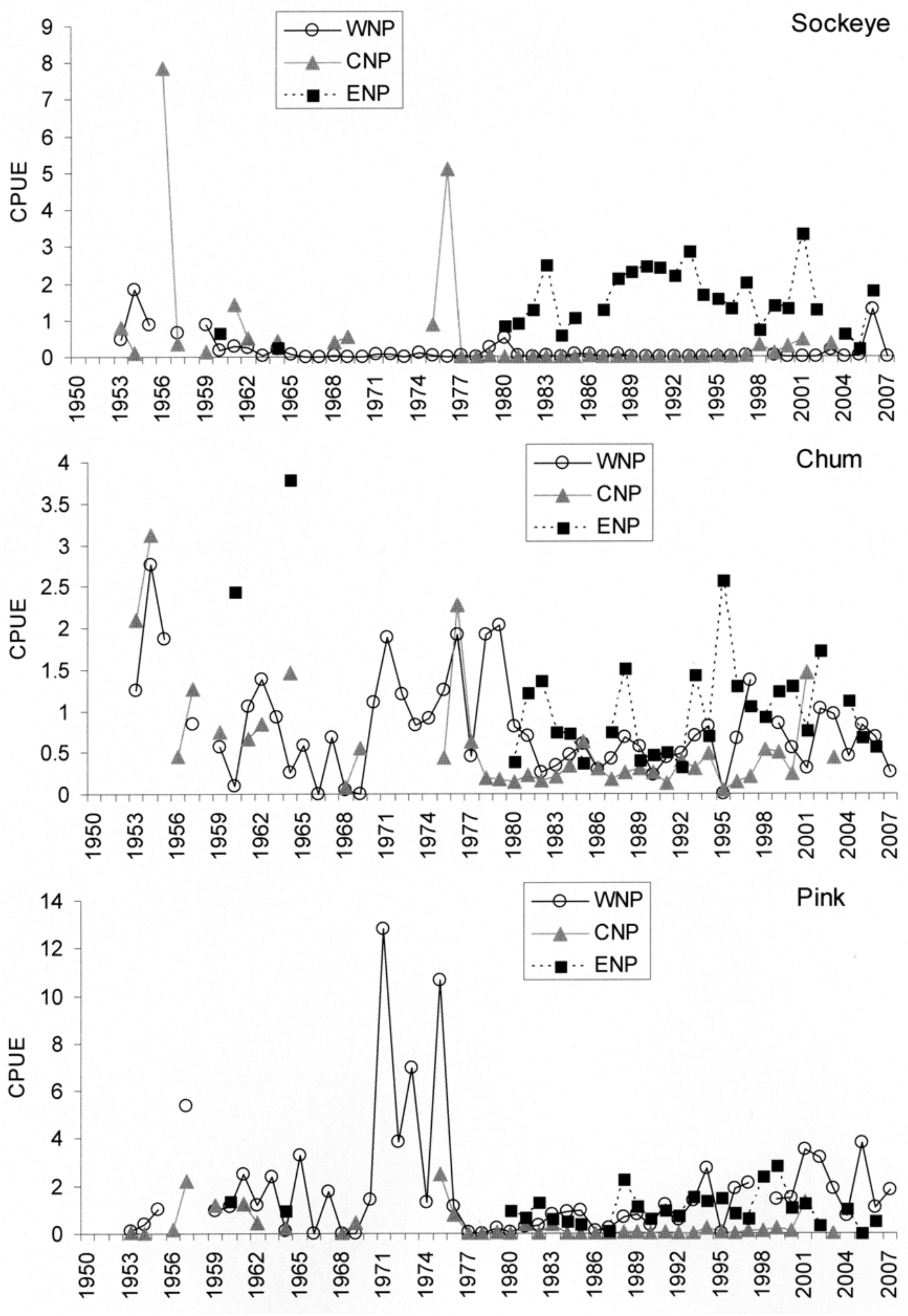
exploited in the waters east of 170°E since 1993, and are exploited fully in the waters between 150°E and 170°E.

Chen et al. (2007) concluded that a La Niña event would result in a decrease in squid recruitment through variability in environmental conditions on the spawning grounds, whereas an El Niño event would lead to environmental conditions favourable to squid recruitment. ENSO events also influenced squid distribution on the feeding grounds, resulting in a northward shift of the fishing grounds in La Niña years and a southward shift in El Niño years. A relationship between CPUE and the monthly proportion of favourable SST areas at the spawning and feeding grounds was quantified for the years 1995-2004 (Cao et al. 2009) and used to predict CPUE for 2005 and 2006, where it performed well. February was the most important month to influence recruitment during the spawning season. The proportion of favourable SST areas on the feeding grounds could influence CPUE during the fishing season because of squid aggregations.

In the Subtropical Transition Zone, catch and catch per vessel-day for neon flying squid from Japanese jig boats show a decline over the period 1998–2002 but apparently this decline is a result of a change in the Japanese squid fleet rather than a change in the abundance of flying squid (Fig. OC-41). There is some agreement between the Chinese and Japanese squid catch data in that the late 1990s saw relatively high catches while the early 2000s saw lower catches but the correlation was not significant.



[Figure OC-41] Catch (bars) and catch per vessel per day (line) of flying squid (*Ommastrephes bartrami*) by the Japanese jig fishery.



[Figure OC-42] Total catch (research, commercial, and other nets) as CPUE (individuals per net) of sockeye, chum and pink salmon in three regions of the oceanic North Pacific. WNP= western North Pacific, CNP= central North Pacific, and ENP= eastern North Pacific.

## 6.3 Pacific salmon

### 6.3.1 Oceanic surveys *(Kaeriyama, Matsuda)*

Hokkaido University has carried out continuous oceanographic and fishery surveys since 1957. Long-term changes have been measured in fork length of sockeye (*Oncorhynchus nerka*), chum (*O. keta*), and pink salmon (*O. gorbuscha*) collected by research gill nets from the T/V *Oshoro-maru* and the T/V *Hokusei-maru* in the North Pacific. Each species is distributed across 6 areas: the western Bering Sea (WBS), the eastern Bering Sea (EBS), the western North Pacific (WNP), the central North Pacific (CNP), the eastern North Pacific (ENP), and the Okhotsk Sea (OS). Only the WNP, CNP and ENP data will be considered here.

The age of a Pacific salmon is often identified as x.y where x is the number of years spent in freshwater and y is the number of years spent at sea. The fork length of chum salmon showed a significant declining trend since 1970 in 6 of 48 age-classes (age-0.3 and 0.4 female in WNP, age-0.3 female and age-0.2-0.4 male in CNP). The fork lengths of sockeye salmon and pink salmon did not show temporal changes (Table OC-1) although the mean length of odd-year pink salmon was larger than that of even-year broods. In 10 of 48 age-classes, significant correlations were observed between CPUE and fork length (8 were negative and 2 were positive, Table OC-2). Caution must be used to interpret these results as it is not clear that these measures of CPUE reflect the abundance of salmon. Sockeye salmon showed negative correlations ($r < -0.64$, $P<0.05$) for four age-classes in the ENP and the EBS. Chum salmon indicated negative correlation ($r = -0.75$, $P<0.05$) for a population in the CNP, and positive correlations ($r > 0.64$, $P<0.05$) for two age-classes in the ENP and EBS. Pink salmon showed negative correlations ($r < -0.37$, $P<0.05$) for two age-classes in the WNP and ENP (Table OC-2).

[Table OC-1] Correlations between year and fork length of sockeye, chum, and pink salmon in the North Pacific during 1970 to 2005 (*P<0.05, **P<0.01). WNP= western North Pacific, CNP= central North Pacific, ENP= eastern North Pacific.

| Species | Sex | Ocean age | WNP | CNP | ENP |
|---|---|---|---|---|---|
| Sockeye | Female | 1 | 0.70 | 0.29 | 0.24 |
| | | 2 | 0.16 | -0.10 | 0.16 |
| | | 3 | -0.48 | 0.16 | -0.16 |
| | Male | 1 | -0.70 | 0.48 | 0.03 |
| | | 2 | -0.10 | -0.25 | 0.20 |
| | | 3 | -0.94 | -0.56 | -0.07 |
| Chum | Female | 1 | 0.27 | 0.43 | 0.21 |
| | | 2 | -0.45 | -0.19 | -0.06 |
| | | 3 | -0.48* | -0.69** | 0.16 |
| | | 4 | -0.72** | -0.24 | -0.11 |
| | Male | 1 | 0.31 | 0.09 | 0.41 |
| | | 2 | -0.32 | -0.65** | -0.11 |
| | | 3 | -0.09 | -0.59** | -0.03 |
| | | 4 | -0.40 | -0.51* | -0.32 |
| Pink | Female | 1 | -0.37 | -0.21 | -0.13 |
| | Male | 1 | -0.30 | -0.07 | -0.26 |

[Table OC-2] Correlations between CPUE and fork length of sockeye, chum, and pink salmon in the North Pacific during 1970 to 2005 (*P<0.05, **P<0.01). WNP: Western North Pacific, CNP: Central North Pacific, ENP: Eastern North Pacific.

| Species | Sex | Ocean age | WNP | CNP | ENP |
|---|---|---|---|---|---|
| Sockeye | Female | 1 | -0.85 | -0.49 | -0.17 |
| | | 2 | -0.06 | 0.49 | -0.64** |
| | | 3 | -0.08 | 0.40 | -0.53* |
| | Male | 1 | -0.16 | 0.40 | -0.21 |
| | | 2 | -0.17 | 0.61 | -0.69** |
| | | 3 | -0.89 | 0.60 | -0.19 |
| Chum | Female | 1 | 0.22 | 0.18 | 0.71** |
| | | 2 | -0.29 | -0.35 | 0.32 |
| | | 3 | 0.30 | -0.32 | -0.35 |
| | | 4 | 0.15 | -0.19 | 0.24 |
| | Male | 1 | 0.04 | 0.07 | 0.64** |
| | | 2 | -0.24 | -0.75** | 0.24 |
| | | 3 | -0.04 | -0.37 | 0.04 |
| | | 4 | 0.27 | -0.20 | -0.22 |
| Pink | Female | 1 | -0.30* | -0.28 | -0.70** |
| | Male | 1 | -0.37* | -0.30 | -0.69** |

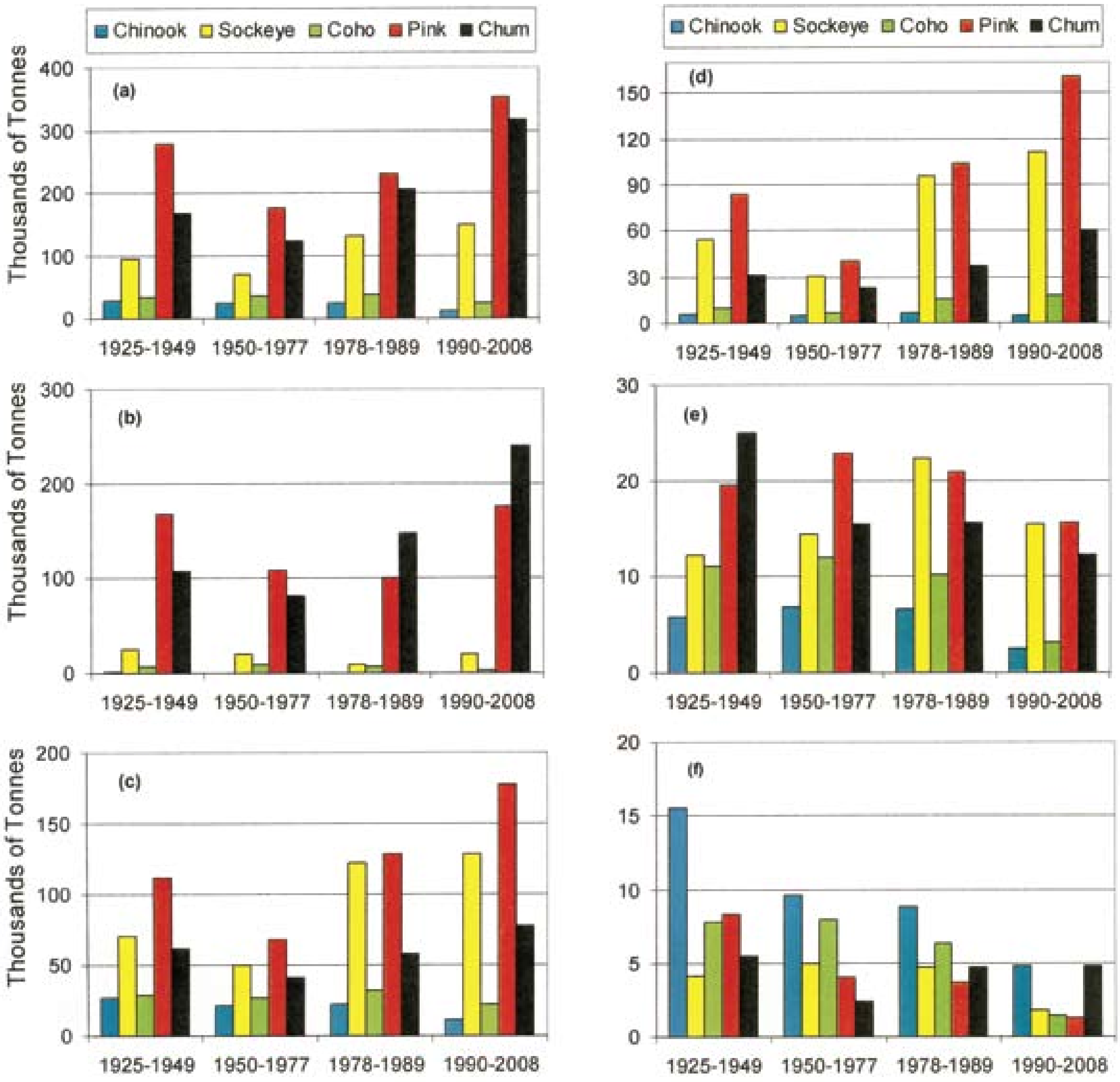
During the focus period, sockeye salmon CPUE was higher only in 2006 than the long-term mean (1950 to 2002) in the WNP and ENP (Fig. OC-42). Other years of the focus period were near average. CPUE of chum salmon during 2003-2007 was close to the long-term mean in the WNP and ENP. Pink salmon catches were relatively high in the WNP and relatively low in the ENP, compared to the 1990s, with the 2005 value in the WNP being the highest since 1975. Data for the CNP were only available for 2003 for all species.

### 6.3.2 Catch, hatchery production, and survival

*(NPAFC; Irvine et al. 2009)*

Aggregate commercial catches of Pacific salmon in the North Pacific are at or exceed all time highs (Fig. OC-43a) but the trends vary by species and region. Pink (*O. gorbuscha*), chum salmon (*O. keta*), and sockeye salmon (*O. nerka*) are generally the most abundant species in the North Pacific and their abundances remain high. Coho (*O. kisutch*), and chinook (*O. tshawytscha*) salmon are either decreasing or stable, depending on the region. Chum and pink salmon are most abundant in Asia (Fig. OC-43b) where significant increases were evident following the 1989 regime shift. In Russia, pink salmon catches have consistently been higher than catches of chum salmon, while the reverse has been true in Japan. Although Kaeriyama et al. (2009) suggested that the carrying capacity for Pacific salmon declined after 1998/99, the longer time series now available suggests that it has been reversed.

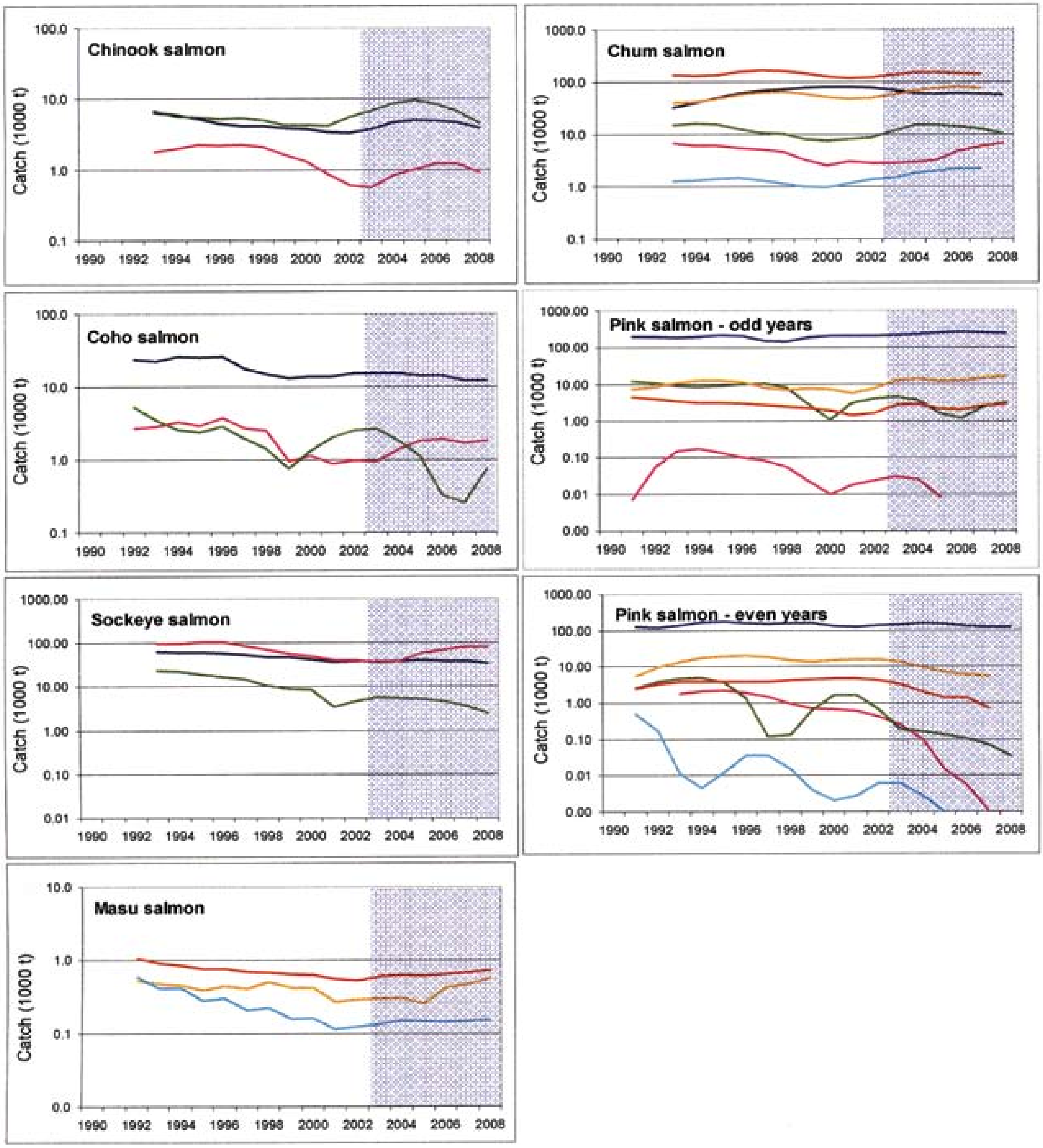
In North America, pink and sockeye salmon are generally the most abundant. Pink, sockeye, and chum salmon were more abundant following the 1989 regime shift than previously (Fig. OC-43c). Total catches in Alaska since the 1989 regime shift exceeded all previous periods (Fig. OC-43d). Catches of chum, pink, and sockeye salmon were highest during this period while chinook and coho salmon catches were similar to the previous period. Catches south of Alaska are small relative to those in Alaska. Canadian salmon abundances were relatively stable until 1989 when declines were experienced for all species (Fig. OC-43e). Abundances in Washington, Oregon, and California have declined throughout the time series (Fig. OC-43f). With the exception of chum salmon, catches along the U.S. west coast are at all time lows.



[Figure OC-43] Mean commercial catch (1000 t) of Pacific salmon by regime and species for (a) the North Pacific, (b) Asia, (c) North America, (d) Alaska, (e) Canada, and (f) U.S. west coast. (Data from Irvine et al. 2009).

To understand the latitudinal patterns of abundance within the North Pacific, the data were stratified by region (Fig. OC-44, note logarithmic axes). It was not possible to incorporate Russian catch data into this analysis, so regional patterns in the western North Pacific will not be considered. Chinook, coho, and sockeye salmon were caught in the three eastern regions (i.e. California Current, eastern Bering Sea, and Alaska Current). Catches since 1990 have declined for each species. Chinook salmon was the most abundant species in the California Current, coho salmon was the most abundant species in the Alaska Current region, and sockeye salmon was the most abundant in the eastern Bering Sea. The much less abundant and apparently declining masu salmon (*O. masou*) were reported only in western Pacific regions.

With the exception of even year pink salmon, temporal trends from 1990 are much less evident for the more abundant chum and pink salmon than for other species (Fig. OC-44). Chum salmon were generally more abundant during the recent focus period in the Alaska Current and western Pacific marginal seas where they are known to occur. All species are in decline in the California Current. Understanding reasons for changes in salmon catch and linking these to biological status is limited by a paucity of reliable information including estimates of fishing effort and the proportion of catch made up by hatchery-reared salmon.



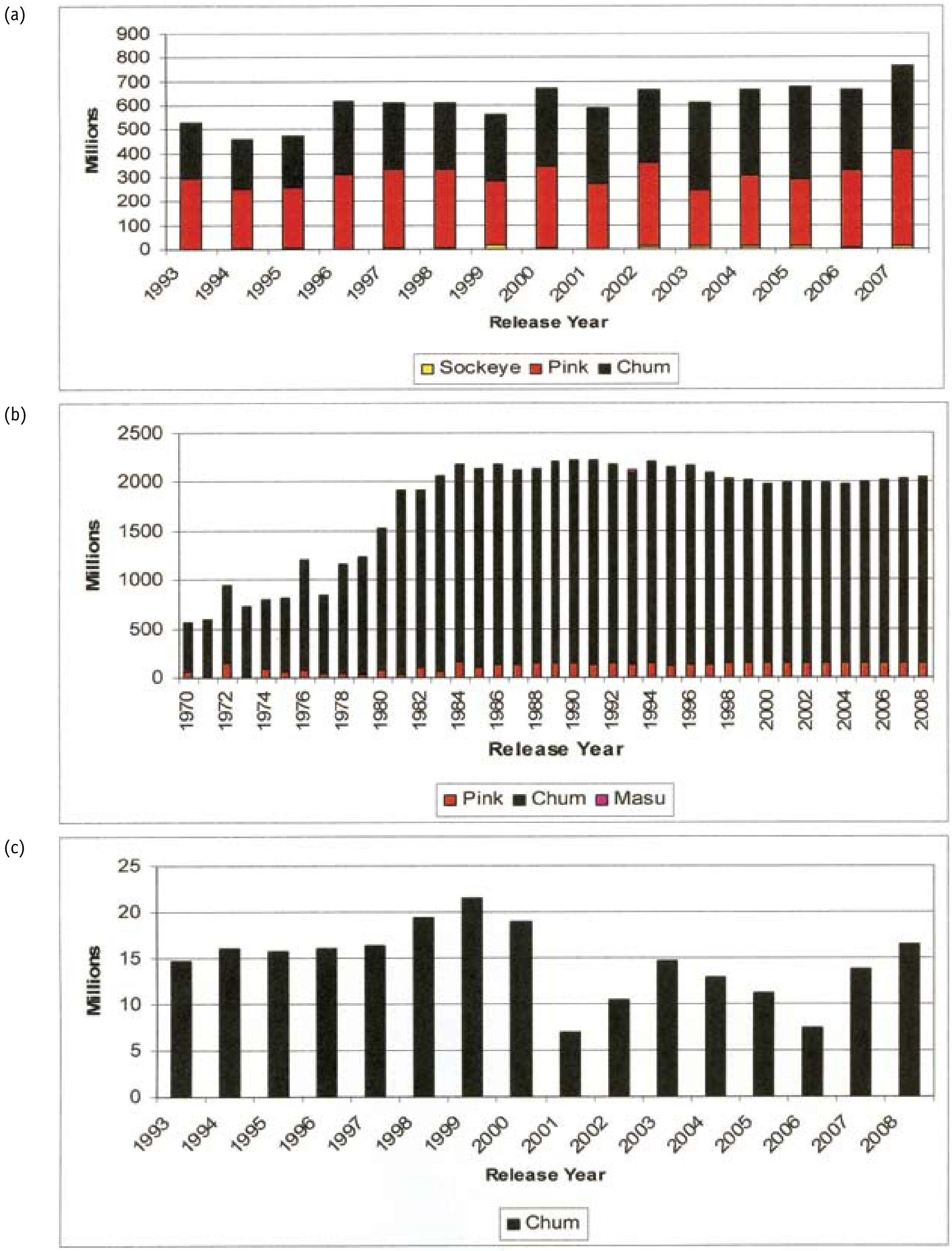
[Figure OC-44] Year-to-year variations in catch of Pacific salmon species by region (data from Irvine et al. 2009). Running averages are plotted (final year of 4-y moving window for sockeye, chinook, and chum salmon, 3-y for coho and masu salmon). The shaded region indicates the focus period.

Hatchery release numbers and survival time series have relatively short durations. Numbers of chum and pink salmon released from Russian hatcheries gradually increased during the last 15 years (Fig. OC-45a). Japanese hatcheries release greater numbers of chum salmon than other species. Their chum salmon fry releases increased rapidly in the late 1970s, but have been relatively stable for the last 25 years (Fig. OC-45b). Korean hatcheries tend to release chum salmon, but numbers released are relatively small (Fig. OC-45c). In Alaska, releases of pink and chum salmon in particular increased rapidly in the 1970s and 1980s but have been relatively constant since then (Fig. OC-46a). In Canada, release numbers declined after the 1990s but were reasonably constant thereafter (Fig. OC-46b). On the U.S. west coast, hatchery production has declined since the mid-1990s (Fig. OC-46c) where chinook salmon is the main species released.

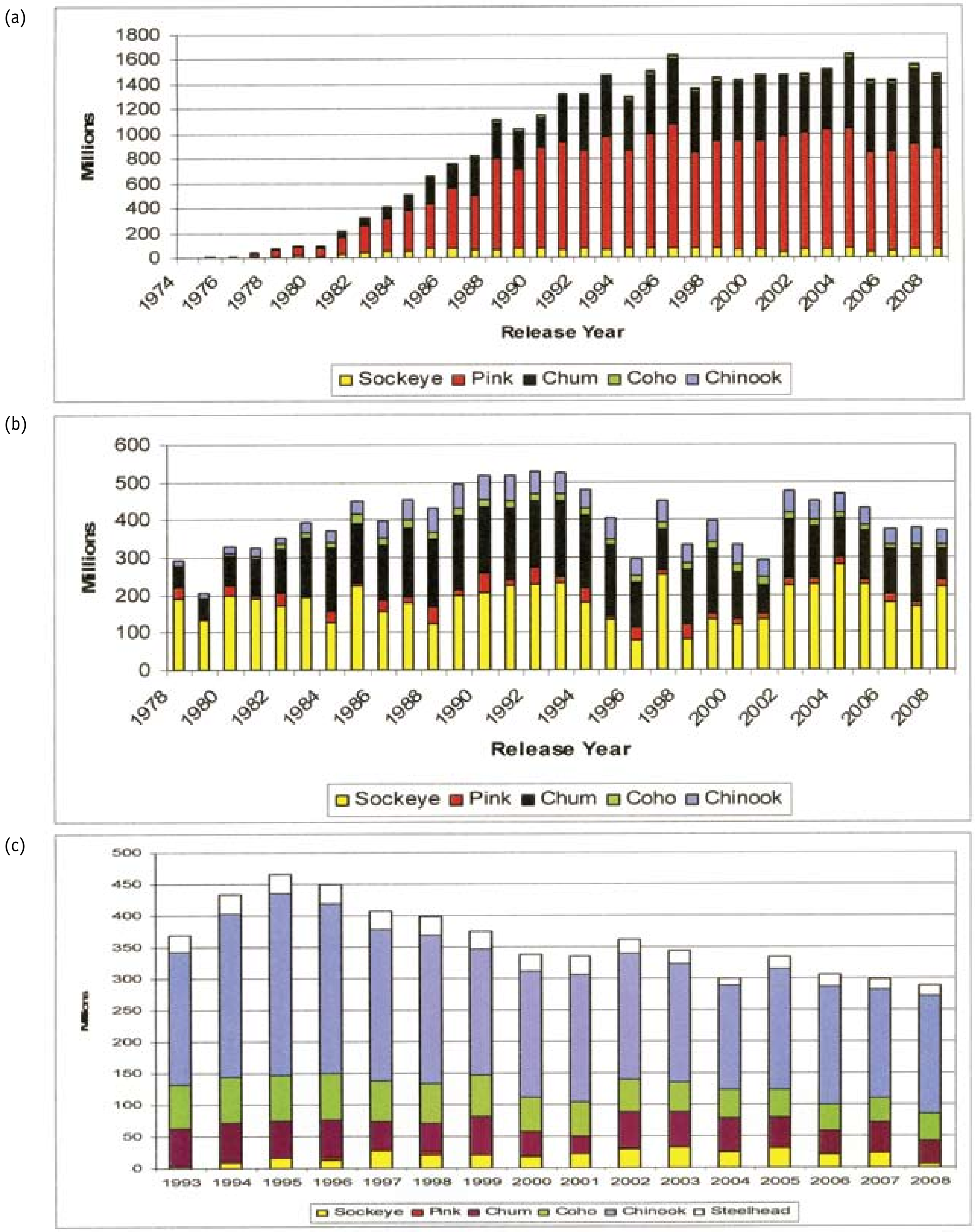
Long-term time series of salmon marine survivals are not commonly available for Asia. Hiroi (1998) and Kaeriyama (1998) report increasing return rates (adult catches/ juveniles released) for Japanese hatchery chum salmon from Hokkaido and Honshu respectively from the late 1970s through the early 1990s. A more recent review of Japanese hatchery chum survival (Saito and Nagasawa 2009) found that increased return rates for chum salmon from eastern Hokkaido were related, at least in part, to increases in the size of fry released. Chum salmon return rates from the Pacific side of Japan were influenced by interannual temperature variability during the late season of coastal residency after the release. Return rates for salmon released on the west side of Hokkaido decreased in recent years while those for chum salmon released on the west side of Honshu have been consistently low. Kaev and Ignatiev (2007) reviewed Sakhalin hatchery production information for pink and chum salmon. They attributed increasing chum salmon return rates to improvements in hatchery technology rather than more favourable natural marine conditions. Regardless of the mechanism responsible for improved survival, the benefits in terms of salmon catch have been significant. Chum caught near Sakhalin are now largely of hatchery origin, a major switch from the 1960s to 1980s (Kaev and Ignatiev 2007).

In Korea, chum salmon return rates were less than 0.4% during 1986-1988, increasing to 1.6% in 1990 (Lee et al. 2007). Declining return rates after 2000 were attributed to higher temperatures in the coastal area when young chum salmon are present. There is even less information on Asian pink salmon survivals. Since pink salmon recovery rate estimates are based on returns from a mixture of hatchery and wild fry, they are difficult to interpret. The data that are available do not indicate any significant temporal pattern, except for what appears to be a large increase for fish returning in 2007 (Irvine et al. 2009). Kaev and Geraschenko (2008) speculate that the unfavorable influence of a cold northern coastal current on juvenile feeding may be the reason pink salmon from southern Sakhalin Island appear to survive at higher rates than pink salmon from northeastern Sakhalin.

In the California Current region, lower catches of coho salmon are partly a consequence of reduced fishing effort, but low average marine survivals are contributing to the current situation. Temporal trends in the abundance of chinook salmon are positively associated with changes in survival. In some areas, changing exploitation patterns have affected spawner numbers. Sockeye salmon populations within Canada are generally better off in northern than in southern BC. Several major sockeye salmon populations in the Fraser River experienced very poor survival of the 2007 smolt year-class (returns in 2009). On the other hand, sockeye salmon returns to the Columbia River in 2008 and 2009 (2006 and 2007 smolt years) were extremely good and marine survival indices were high.



[Figure OC-45] Releases of hatchery salmon by (a) Russia, (b) Japan, and (c) Korea (Data from Irvine et al. 2009).



[Figure OC-46] Releases of hatchery salmon by (a) Alaska, (b) Canada, and (c) the U.S. west coast (Data from Irvine et al. 2009).

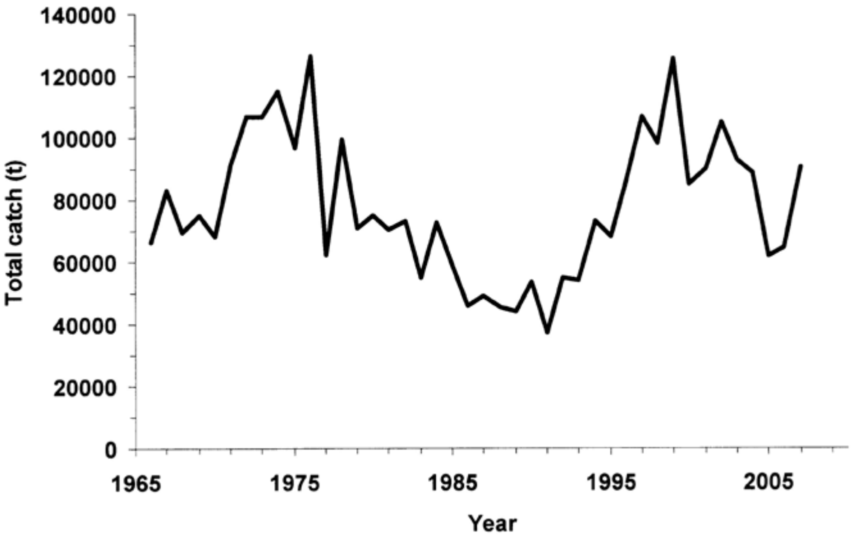
## 6.4 Tuna and billfish *(Holmes)*

Albacore tuna (*Thunnus alalunga*) is a widely distributed, economically important tuna species in the North Pacific Ocean. Of the large and highly migratory pelagic species (tunas, swordfish, marlins), the albacore has the most northerly distribution. The North Pacific stock is panmictic (a single population) without significant genetic structuring (Wu et al. 2009). Mature albacore spawn in tropical waters exceeding 24 °C between Japan and Hawaii, generally within 10 - 15° N of the Equator. Highest densities of larvae appear in the Kuroshio and its Countercurrent (10-25°N) from May through August (Ueyanagi 1969). Juvenile albacore (age 1+) are distributed across the North Pacific and are most abundant in the Kuroshio, the North Pacific Transition Zone, and the California Current. They undergo extensive seasonal migrations, including trans-Pacific movements by some individuals (Clemens 1961; Laurs and Lynn 1977). Albacore mature at 5-6 years of age and the adult fish are most abundant in the subtropical waters between Japan and Hawaii. Maximum life span is believed to be 11-12 years and maximum size is about 135 cm (Clemens 1961).

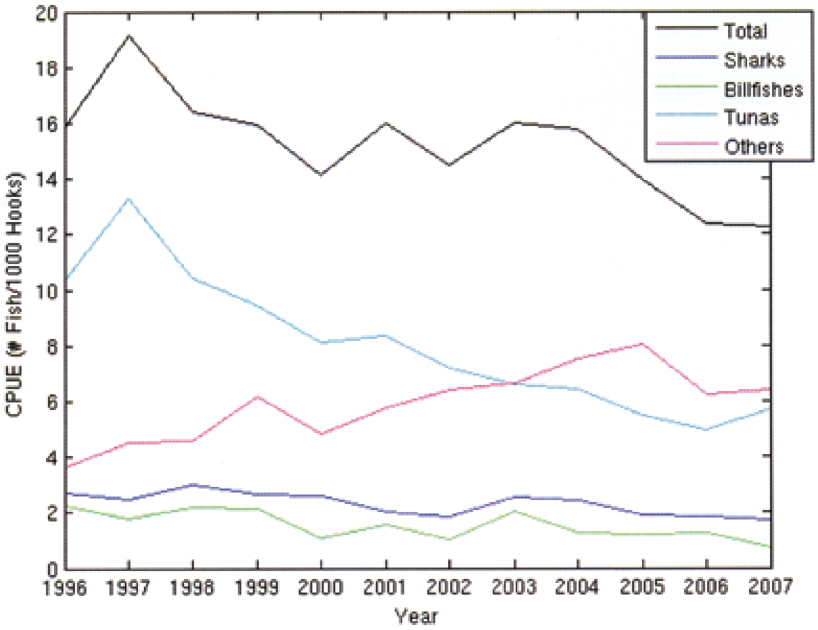
Albacore fisheries by Canada, the United States, Mexico, Japan, Korea, and China-Taipei (Taiwan) have caught up to 126,536 tonnes (t) in 1976 to a low of 37,320 t in 1991 (Fig. OC-47). The steep decline can be attributed to the development of high-seas driftnet fishing in the late 1970s and below average recruitment in the 1980s (Cox et al. 2002). In the early 1990s, catches increased again, peaking in 1999 at 125,576 t, and declining to 61,696 t by 2004. Modest increases in catches have occurred in recent years that may be related to strong recruitment from the 2001 and 2003 cohorts (ISC 2008) and catch has averaged 84,425 t since 2000.

The most recent (2006) stock assessment was carried out by scientists from Canada, Japan, China-Taipei, United States, Mexico, Korea and the Inter-American Tropical Tuna Commission (IATTC) using an age-structured model (ISC 2007). The results indicated that North Pacific albacore biomass is relatively high (~513,000 t), especially compared to the low values estimated for the late 1970s and 1980s. Spawning biomass (SSB) was estimated to be 153,000 t in 2006, which is 53% higher than the long-term average. The current estimate of fishing mortality (F2002-04 = 0.75 or F-17%) is high when compared with reference points commonly used in contemporary fisheries management. Although these high fishing levels have been sustained by good recruitment, total biomass and the SSB are expected to decline by 2015, even under optimistic recruitment assumptions. Fisheries for North Pacific albacore will have to be reduced (ISC 2007, 2008). However, since there is no formal guidance from managers on how these reductions will occur, the present scientific advice is that current fishing effort should not be increased and that all nations should adhere to precautionary fishing practices (ISC 2007, 2008).

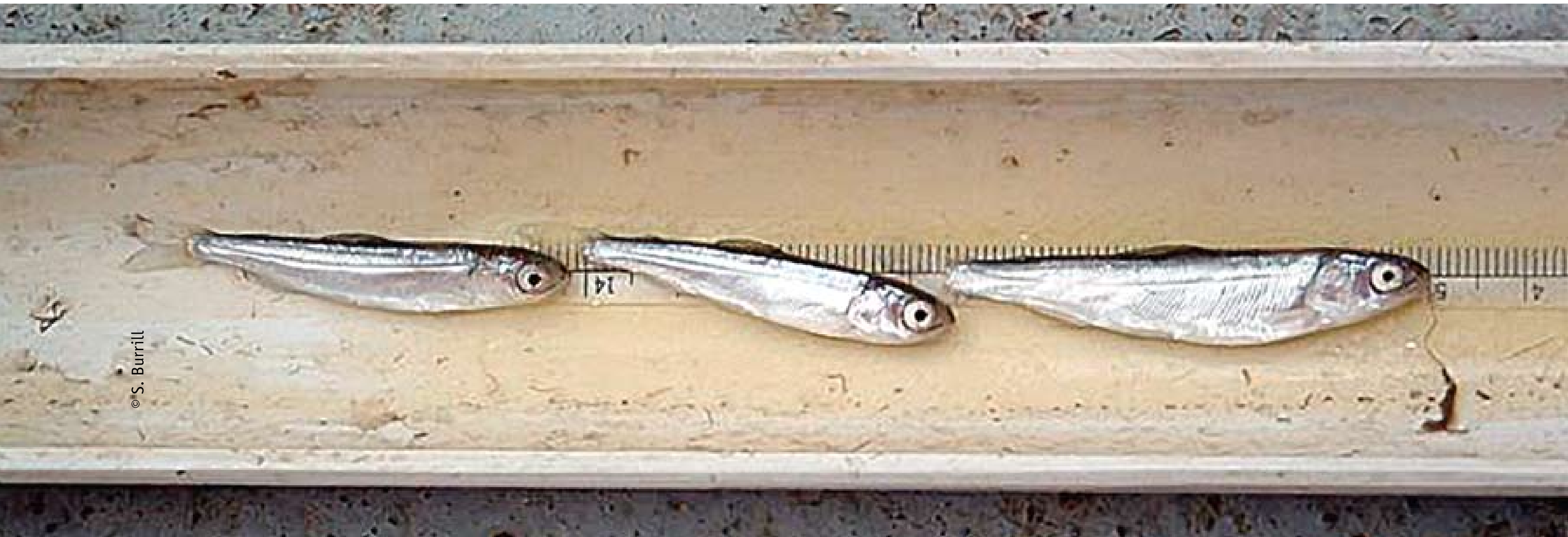
Catch and effort data for the high trophic level fishes in the central North Pacific are obtained from mandated logbooks and observer reports from the Hawaii-based longline fishery. An analysis of these data for the deep-set portion of this fishery that targets bigeye tuna shows the catch rate for all species combined has declined from about 18 fishes per 1,000 hooks to 12 fishes per 1,000 hooks (Fig. OC-48). The declines occurred for the top trophic level species, billfishes, sharks, and tunas, while a group of lower trophic level species (called “others” in the figure) including mahi mahi (*Coryphaena hippurus*), sickle pomfret (*Taractichthys steindachneri*), snake mackerel (*Gempylus serpens*), and escolar (*Lepidocybium flavobrunneum*), showed statistically significant increases in catch rates (Fig. OC-48). The decline in catch rates of the top trophic level fishes is attributed to fishing. The increase in catch rates in the next lower trophic level has been attributed to reduced predation. (Polovina et al. 2009).



[Figure OC-47] Total annual catch (tonnes reported) of North Pacific albacore tuna by all nations, 1966-2007 (Data taken from ISC 2008). This excludes substantial catch and bycatch in large-scale pelagic driftnet fisheries that operated until 1992 (Waddell and McKinnell 1994).



[Figure OC-48] Catch rates (number per 1,000 hooks) from Hawaii-based longline deep-set fishery logbook and observer logs 1996-2007. The "Others" group includes mahi mahi (*Coryphaena hippurus*), sickle pomfret (*Taractichthys steindachneri*), snake mackerel (*Gempylus serpens*), escolar (also called walu) (*Lepidocybium flavobrunneum*), and longnose lancetfish (*Alepisaurus ferox*); animals that feed at a lower level of the food web.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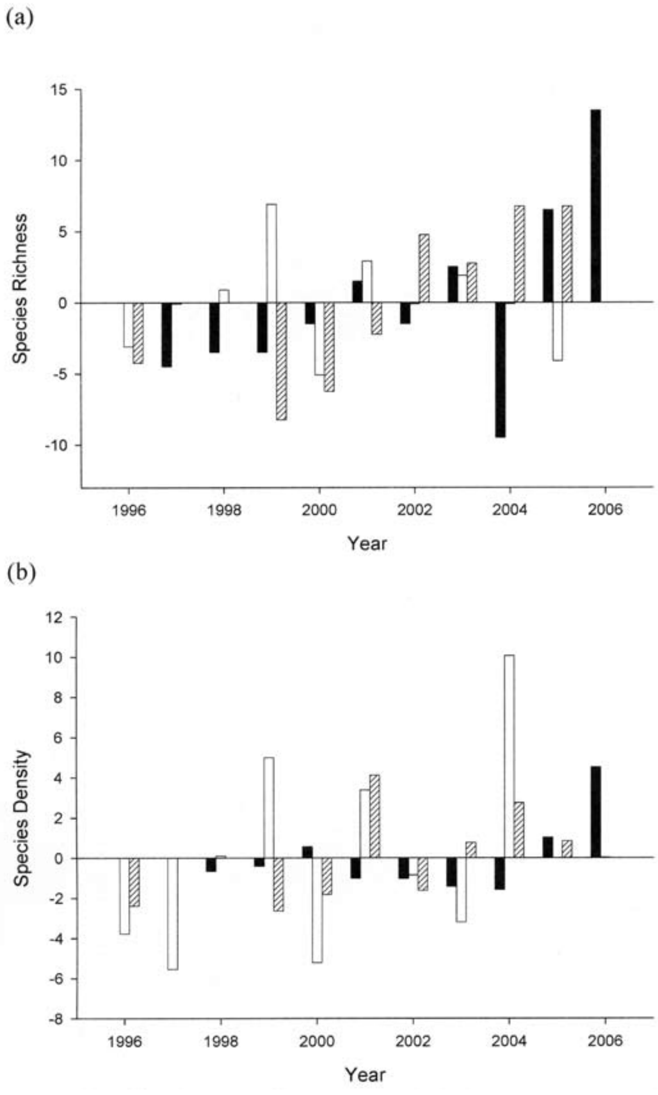


[Figure OC-49] (a) Seabird species richness seasonal anomalies and (b) seabird abundance anomalies (total numbers of birds km$^{-2}$) from winter (February), summer (June-July), fall (September-October) long-term Line P surveys in the GOA: Black bars= winter; open bars= summer, hatched bars= fall.

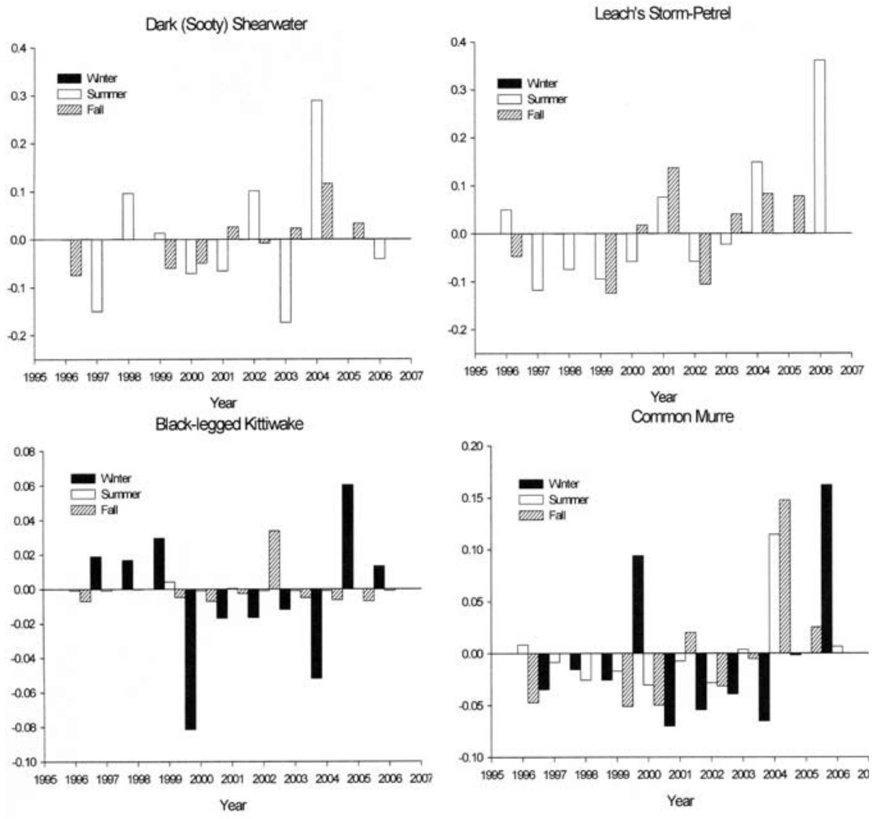
# 7.0 Marine Birds and Mammals

## 7.1 Seabirds *(Sydeman, Morgan, Thompson, Flint)*

### 7.1.1 Gulf of Alaska

Seabird distribution and abundance along Line P in the Gulf of Alaska has been surveyed since May 1996 as part of the Environment Canada pelagic seabird monitoring program. The Line P survey spans the transition between the California Current and the Gulf of Alaska ecosystems. Basic methods to survey and analyze seabird data on Line P may be found in O'Hara et al. (2006) and Yen et al. (2005). Relative abundance is expressed as density (number km$^{-2}$), with density estimated on a daily basis within each seasonal survey. Interannual changes in the overall seabird community (density, number of species observed, and relative abundance of the two most abundant seabird species in each season on Line P) were evaluated. For both summer (June-July) and fall (September-October) surveys, "dark" shearwaters (mostly sooty, *Puffinus griseus*) and Leach's storm-petrel (*Oceanodroma leucorhoa*) were the dominant species. Common murre (*Uria aalge*) and black-legged kittiwake (*Rissa tridactyla*) were dominant in winter.

The number of seabird species (richness) on Line P generally increased through time, especially from 2003-2006 (Table OC-3). Analysis of species richness revealed seasonal variability as well as a significant increase through time (Fig. OC-49a). Analysis of total seabird relative abundance also revealed seasonal variability and an increase though time (Fig. OC-49b). Changes in the relative abundance of the most abundant seabird species are summarized in Figures OC-50a-d. Leach's storm-petrel increased in summer (subdominant), dark shearwaters increased in fall (also subdominant after the storm-petrel), and there was no trend in common murre or black-legged kittiwake density through time in winter (Table OC-4). Dark shearwaters were most abundant during the relatively cool June of 2004 whereas storm-petrels were most abundant during the warm June of 2006. This reflects the water mass preferences of these species. Dark shearwaters prefer colder waters whereas the storm-petrel is most often found in warmer offshore habitats (Hyrenbach and Veit 2003).



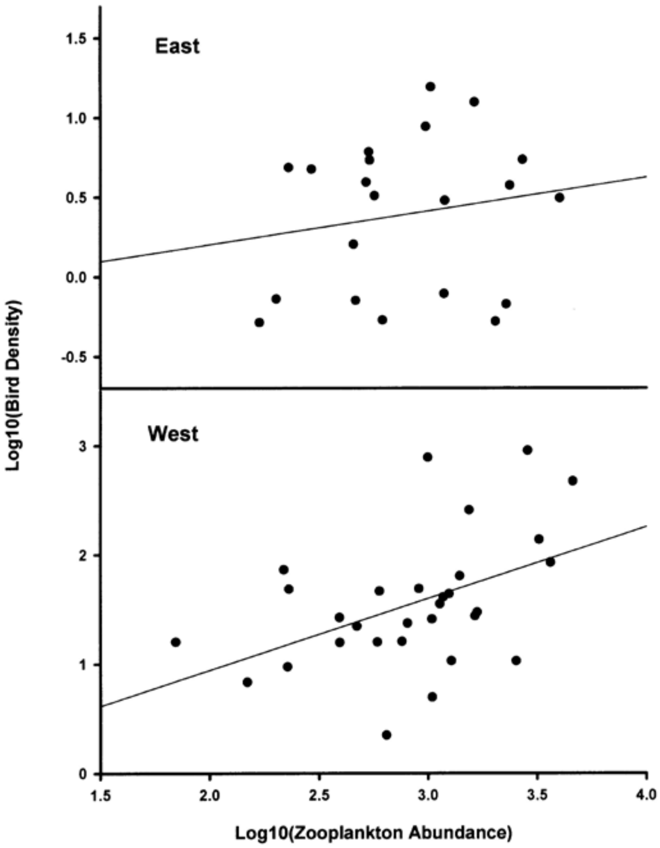
[Figure OC-50] Trends in the density (birds·km$^{-2}$) of the most abundant species in each season based on long-term Line P surveys in the GOA.

[Table OC-3] Trends in faunal diversity and relative abundance stratified by season for Line P surveys. Spearman rank correlations, sample size and P-values for the above datasets. Data are summarized by survey.

| | Winter | | | Summer | | | Fall | | |
|---|---|---|---|---|---|---|---|---|---|
| Dataset | N | Spearman rho | p<\|t\| | N | Spearman rho | p<\|t\| | N | Spearman rho | p<\|t\| |
| Line P Density | 10 | 0.07 | 0.85 | 10 | 0.42 | 0.23 | 8 | 0.71 | 0.05 |
| Line P Diversity | 10 | 0.63 | 0.05 | 10 | -0.07 | 0.85 | 8 | 0.90 | 0.00 |

[Table OC-4] Spearman rank correlations of trends in log(relative abundance) by day for the two dominant seabird species in each season on Line P, 1996-2006. Dark/sooty shearwaters and Leach's storm-petrel are dominant in summer and fall. Common murre and black-legged kittiwake are dominant in winter.

| | Winter | | Summer | | Fall | |
|---|---|---|---|---|---|---|
| Species | Spearman Rho | p>\|t\| | Spearman Rho | p>\|t\| | Spearman Rho | p>\|t\| |
| Dark/sooty shearwater | -0.15 | 0.11 | -0.05 | 0.50 | 0.23 | 0.02 |
| Leach's storm-petrel | 0.07 | 0.47 | 0.16 | 0.05 | 0.19 | 0.05 |
| Black-legged kittiwake | 0.02 | 0.82 | -0.07 | 0.40 | -0.02 | 0.82 |
| Common murre | 0.10 | 0.27 | -0.01 | 0.91 | 0.14 | 0.15 |



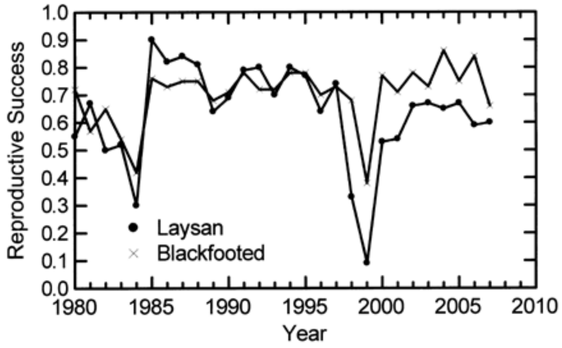
[Figure OC-51] The relationship between seabird density and zooplankton relative abundance as determined by the integrated CPR-MBM survey for June surveys in the eastern (Gulf of Alaska; not significant) and western ($r^2$=.21, P=0.01) North Pacific. Note the different scales on the ordinates between regions.

### 7.1.2 Pan-North Pacific

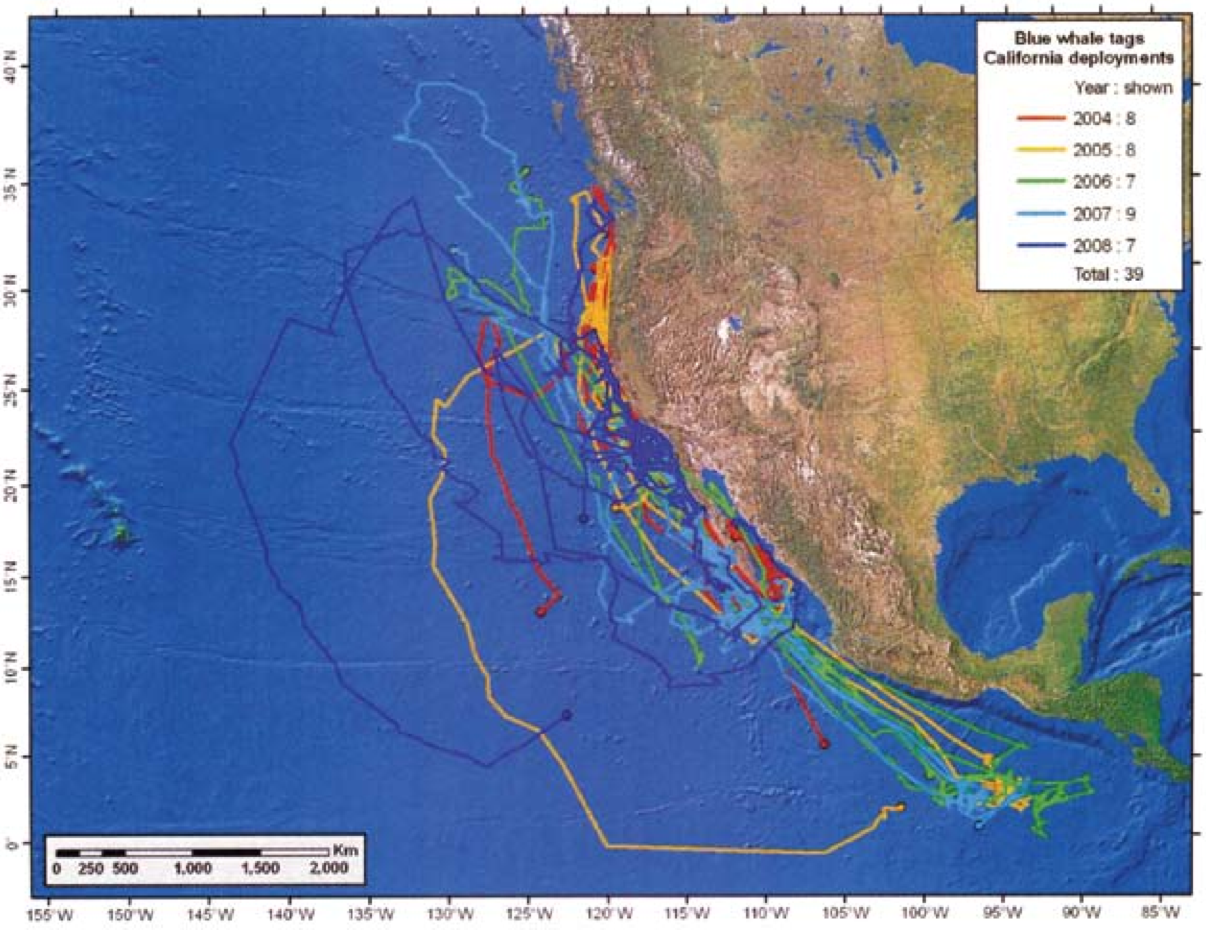
The Continuous Plankton Recorder Marine Bird and Mammal (CPR-MBM) survey was made three times per year and includes plankton and seabird observations on a 7,500 km transect along the "great circle route" from Vancouver, Canada to Tokyo, Japan (Batten et al. 2006). Methods used to survey and analyze seabird data from this vessel of opportunity program may be found in Hyrenbach et al. (2007). The CPR-MBM time series is, at present, too short to conduct trend analyses.

Seabirds are excellent sentinels of coupled climate-marine ecosystem change (Bertram et al. 2001; Piatt et al. 2007) in part because they may amplify variation in physical oceanographic attributes or biological productivity at lower trophic levels (Taylor et al. 2002). The relative abundance of seabirds at sea is thought to reflect water mass and prey base characteristics (Cairns 1987; Briggs et al. 1987; Hyrenbach and Veit 2003; Hedd et al. 2006). Trends in the Line P seabird community from 1996-2006 are consistent with interannual variability in water temperature, salinity, and overall ocean productivity (Fig. OC-51). Additionally, a significant increase in the abundance of Murphy's petrel (*Pterodroma ultima*), a predominantly southern hemisphere species, is evident in the eastern Gulf of Alaska over the past three decades (Morgan et al. unpubl.). An increase in shearwaters in fall may suggest that these migratory birds are staying longer in the Gulf of Alaska during the austral spring, instead of moving to the southern hemisphere where they reproduce. An increase in Leach's storm-petrel might indicate an increase in open ocean neuston production, as these birds take prey from the ocean surface. The increase in overall species richness and abundance may reflect a redistribution of seabird species from the south to the north. This may be a signal of marine climate change, or simply interannual variability over the study period.

Populations of Laysan albatross (*Phoebastria immutabilis*) and blackfooted albatross (*P. nigripes*) breed and nest at French Frigate Shoals in the Hawaiian Archipelago and forage in the North Pacific Transition Zone and beyond. A time series of reproductive success (proportion of chicks fledged per egg laid) for both these species show strong coherence and sharp declines in 1984 and 1999 (Fig. OC-52). Both years of low reproductive success occurred about one year after strong El Niños.



[Figure OC-52] Reproductive success of Laysan albatross and blackfooted albatross at French Frigate Shoals (Hawaiian Archipelago) from 1980-2007.



[Figure OC-53] Tracks of 39 blue whales tagged from 2003 to 2008 with satellite-monitored radio tags (www.argos-system.org) off the coast of central and southern California (Mate et al. 2007).

## 7.2 Blue whale *(Mate)*

The blue whale population feeding off California in the summer is estimated at 2,200-3,500 individuals (Barlow and Forney 2007). Unlike other large whale species, blue whales choose winter areas which are productive enough for them to forage throughout their reproductive season. Some of these areas, such as "down-stream" (west) from the Costa Rica Dome upwelling, are reasonably far off shore and their precise location may vary by hundreds of kilometres from year to year, due to changes in both currents and prevailing winds. Such remote and variable oceanographic structures probably contributed to the survival of this species during the intense whaling of the 20th century, when whalers probably could not find whales reliably in areas of previous hunting success. Satellite-monitored radio tags have revealed the movements and seasonal habitats of tagged whales, including feeding, reproduction, and migration areas (Fig. OC-53). The tagging technique is reviewed in Mate et al. (2007) and analyses of their area-restricted search and state space models have recently been completed (Bailey et al. 2009). The wide-ranging seasonal movements are generally south in the winter for reproduction and north in the summer for feeding. Numerous foraging "hot spots" coincide with seasonal krill concentrations over a 35° range in latitude (and pelagic red crabs off Baja California, Mexico in winter). Their large size allows them to survive through severe El Niño events, but can result in up to 50% of the population appearing emaciated, with lower reproduction evident for several years as whales recover their physiological "fitness". The relatively high sustained speed of blue whales allows them to move between foraging areas quickly (Irvine 2007). The E-W distribution of tagged whales (to within 800 km of Hawaii) suggests the ENP may be a single foraging area with most of the animals moving N-S between relatively near shore "hot spots", including areas off Vancouver Island, which have recently been described as re-populated (Calambokidis et al. 2009). Knowledge of the movements and habitat preferences of ENP blue whale is more extensive than for any other population in the world, yet the question of how many stocks may use the area is still unresolved.

The June to November feeding season is from 27-54°N (central Baja to Gulf of Alaska), followed by a diffuse migration south over a 4 month period to wintering areas east of southern Baja, in the Gulf of California, and at the Costa Rica Dome upwelling (~7-10°N). While krill is the dominant prey nearly everywhere, the color of blue whale feces off Magdalena Bay suggest feeding also on pelagic red crabs (Etnoyer et al. 2004, 2006). High productivity in wintering areas allows foraging for extended periods (Mate et al. 1999), allowing the world's largest newborn (8.5 m) to suckle sufficient quantities of its mother's rich milk to grow to 16 m in one year.

## Acknowledgements

Argo data were collected and made freely available by the International Argo Project and the national programs that contribute to it (http://www.argo.ucsd.edu, http://argo.jcommops.org). Argo is a pilot program of the Global Ocean Observing System. A representative of the North Pacific Anadromous Fish Commission (Dr. James Irvine) helped to make the most recent results of the Commission's work available to the project.

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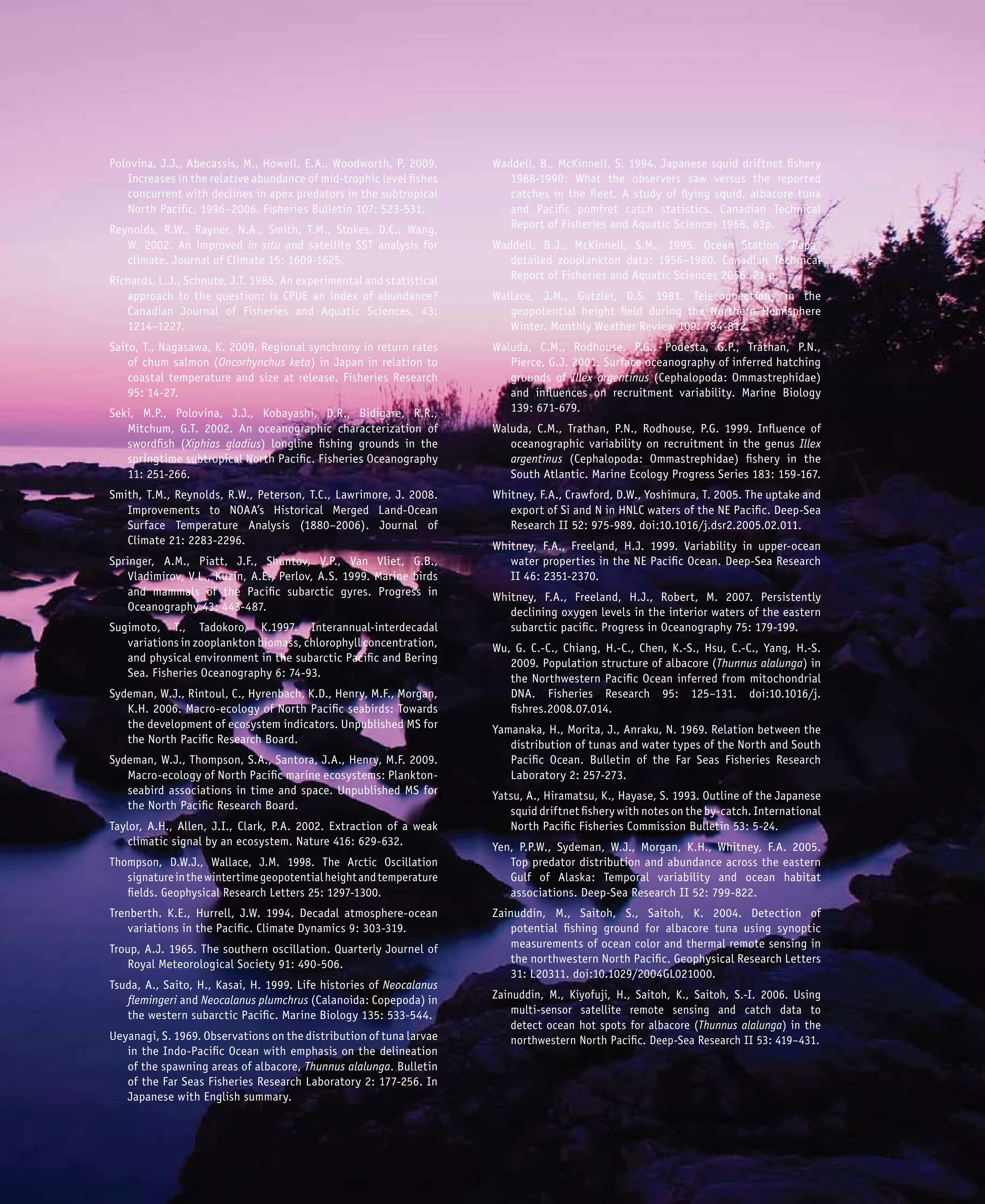

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# California Current

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# highlights

- The timing, duration and intensity of coastal upwelling have been highly variable, with significant intra-seasonal oscillations. Upwelling was delayed in 2005 in the northern California Current System (CCS) resulting in discernable, pan-trophic disruptions in productivity, breeding, and species distributions. Intense upwelling has prevailed in 2006-2008.

- Long-term ocean time series have revealed trends toward lower dissolved oxygen content in the upper pycnocline, from southern California to Line-P. These trends are consistent with predictions from global climate models driven under global warming scenarios. The hypoxic boundary has shoaled in parts of the CCS, possibly leading to habitat compression for some species. Increased occurrence of continental shelf hypoxia has been observed off Oregon, with lethal consequences for coastal benthic species.

- Satellite and *in situ* data on primary productivity has revealed a tendency towards increased surface chlorophyll$_a$ concentrations throughout most of the CCS. However, dinoflagellates became more dominant in Monterey Bay in 2004 and 2005 leading to ecosystem changes at higher trophic levels.

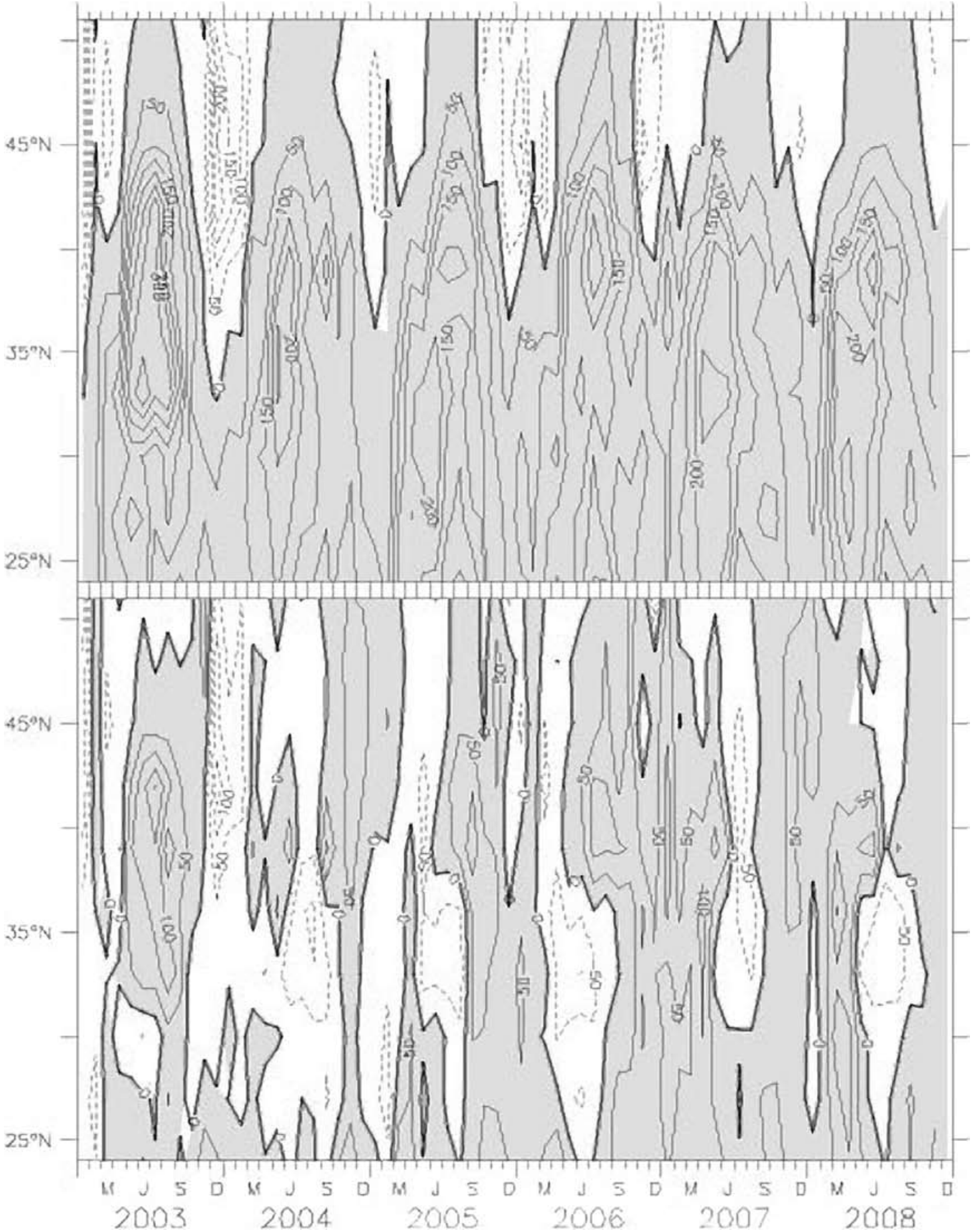
- Despite strengthened upwelling from 2003 to 2008 and cooler waters, the mesozooplankton (copepod) community off Oregon was comprised of many subtropical species up to 2008. In 2008, however, this community was dominated by species with "boreal", Subarctic zoogeographic affinities. Changes in *Neocalanus* phenology have been observed off British Columbia, with narrower and more short-lived peaks of abundance. The peak was significantly delayed in 2008.

- Rockfish production remained relatively low throughout the focus period. From Vancouver Island to Oregon, average marine survival of coho salmon was among the lowest observed since records began in the early 1970s. Sardine and herring recruitment and abundance have declined. Humboldt squid have continued their post-1998 range expansion into the northern CCS.

- Physical and biological data for the CCS have shown increasing ecosystem variability. Seabirds and marine mammals have shown dramatic responses including complete breeding failures (for the first time in 35 years) for Cassin's auklets off central California in 2005-2006 that were related to changes in upwelling phenology and corresponding changes in euphausiid populations. Cetacean populations have shown variable distributions, and the abundances of humpback whale is increasing.

# Introduction

The California Current System (CCS) extends 3000 km from Baja California Sur to the northern tip of Vancouver Island, and is composed of several distinct circulation features. The California Current is a year-round equatorward flow extending from the shelfbreak to ~1000 km offshore, with strongest speeds at the surface and extending to at least 500 m depth (Hickey 1998). It carries cooler, fresher, nutrient-rich water equatorward. A narrow, weaker surface poleward flow along the coast is known as the California Countercurrent south of Pt. Conception, and the Davidson Current north of Pt. Conception. Another narrow but deeper poleward flow, the California Undercurrent, extends the length of the coast along the continental slope. Maximum current speed is usually from summer to early fall for the California Current and California Undercurrent, and in winter for the California Countercurrent/Davidson Current. The CCS is largely a wind-driven system, with little freshwater input except at the Columbia River. Three major estuaries, San Francisco Bay, the Columbia River, and Puget Sound contribute significantly to local economies. Coastal upwelling, El Niño, and decadal-scale climate forcing result in highly variable productivity of the region and consequently, for many fisheries (Bakun 1993; Aquarone and Adams 2009). Several long-term observing programs provide time series of physical, biological, chemical and fisheries variables within the CCS (Peña and Bograd 2007). These include: CalCOFI (Hewitt 1988; Bograd et al. 2003; http://www.calcofi.org), Line P (Freeland 2007; http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/linepdata/default_e.htm), and U.S. GLOBEC Northeast Pacific Program (Batchelder et al. 2002; http://globec.coas.oregonstate.edu). Fishery resources include invertebrate populations, especially in nearshore waters, groundfish populations along the continental shelf, and migratory pelagic species such as salmon (*Oncorhynchus* spp.), Pacific sardine (*Sardinops caeruleus*), Pacific hake (*Merluccius productus*), and Pacific herring (*Clupea harengus*) at the northern end of the CCS. At the southern end, the northern anchovy (*Engraulis mordax*) and market squid (*Loligo opalescens*) are important. The CCS also supports large and diverse seabird and marine mammal populations. This chapter contains a review of the status and trends of the CCS from 2003-2008, hereafter the *focus period*.



[Figure CC-1] Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2003–December 2008. Shaded areas denote positive (upwelling-favourable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–1967 monthly means. Units are in $m^3 \cdot s^{-1}$ per 100 km of coastline.

# 2.0 Atmosphere

## 2.1 Climate indices

*(Di Lorenzo, McKinnell, Peterson, Sydeman)*

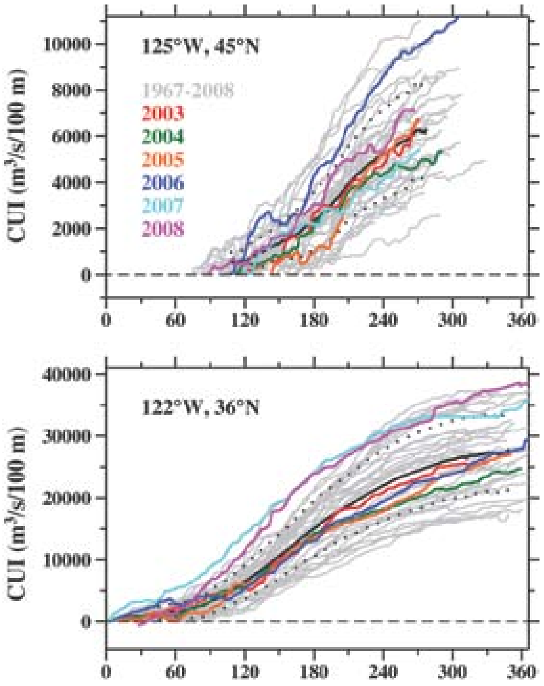
The wintertime North Pacific index (NPI) has increased during the focus period, indicating a trend toward higher than average sea level pressures from less intense and/or fewer winter storms in the subarctic North Pacific. The California Current region tends to have cooler surface ocean temperatures when the NPI is high. The Northern Oscillation index (NOI) has tended from negative to positive, indicating strengthening of the North Pacific High with relatively strong coastal upwelling, especially in 2007-2008. Correspondingly, the North Pacific Gyre Oscillation (NPGO) became positive in the past two years, while the Pacific Decadal Oscillation (PDO) became negative in the fall of 2007. The PDO has been in a generally positive state since 1977, with the exception of the periods 1999-2002 and 2006-2008. The Multivariate ENSO Index (MEI) has had relatively strong negative values in 2007-2008, reflecting La Niña conditions.

## 2.2 Coastal upwelling

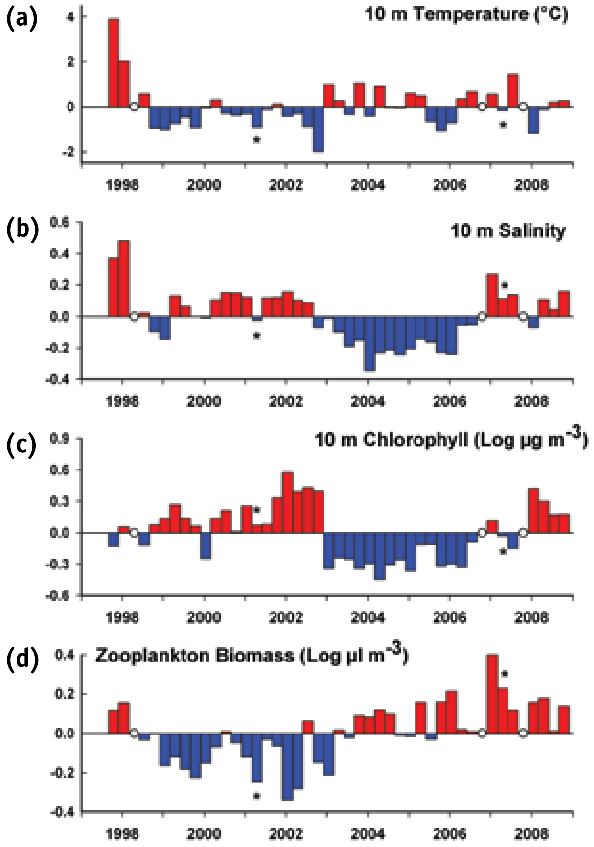
*(Bograd, Durazo, Lavaniegos)*

The intensity of coastal upwelling in the CCS was generally high during the focus period (Fig. CC-1). A strong upwelling season in 2003 was followed by strong winter downwelling in the northern CCS. The 2005 and 2006 upwelling seasons were unusual in terms of their initiation, duration and intensity. With the exception of a brief period of weaker than normal upwelling in the summers of 2007 and 2008, west coast upwelling index anomalies have been positive since the late summer of 2006. Wind patterns in early 2009 reflect anomalously strong high pressure over the Northeast Pacific and very high upwelling. At the southern end of the CCS, coastal upwelling off Punta Baja (30°N, 119°W) and Punta Eugenia (27°N, 116°W) has increased since April 2005.

The focus period was highly unusual in terms of the timing and duration (i.e., phenology) of coastal upwelling particularly in the northern CCS (Fig. CC-2). The phenology of coastal upwelling plays a particularly critical role in the region (Barth et al. 2007; Bograd et al. 2009). For example, the start of the upwelling season was significantly delayed in 2005 (Schwing et al. 2006) resulting in unusual coastal conditions (Kosro et al. 2006; Pierce et al. 2006) and ecosystem changes from primary production (Thomas and Brickley 2006) to zooplankton (Mackas et al. 2006) to fish, birds, and mammals (Brodeur et al. 2006; Sydeman et al. 2006; Wiese et al. 2006), respectively. In contrast, the upwelling season has begun either early or on time from 2006-2008 with particularly strong upwelling in the northern CCS in 2006 and in the central CCS in 2007-2008 (Fig. CC-2).



[Figure CC-2] Cumulative upwelling indices (CUI) vs. day of year for 1967-2008 at 125°W, 45°N (top) and 122°W, 36°N (bottom). CUI is computed by integrating the daily-averaged upwelling index from January 1 to December 31. Only the periods of positive CUI are plotted.



[Figure CC-3] Main physical and biological indicators of change in the Baja California pelagic ecosystem from quarterly IMECOCAL cruises between October 1997 and October 2008. Anomalies of the four variables calculated as deviations from the seasonal long-term means taken over the entire sample grid. Temperature and salinities at 10 m were taken from CTD profiles; chlorophyll concentrations are from water samples taken at 10 m; zooplankton biomass was measured as displacement volumes from standard oblique bongo net-tows (0-200 m). Biological variables were log-transformed. Open circles along the x-axis are missing cruises and asterisks indicate only data from the northern transects.

# 3.0 Oceanography

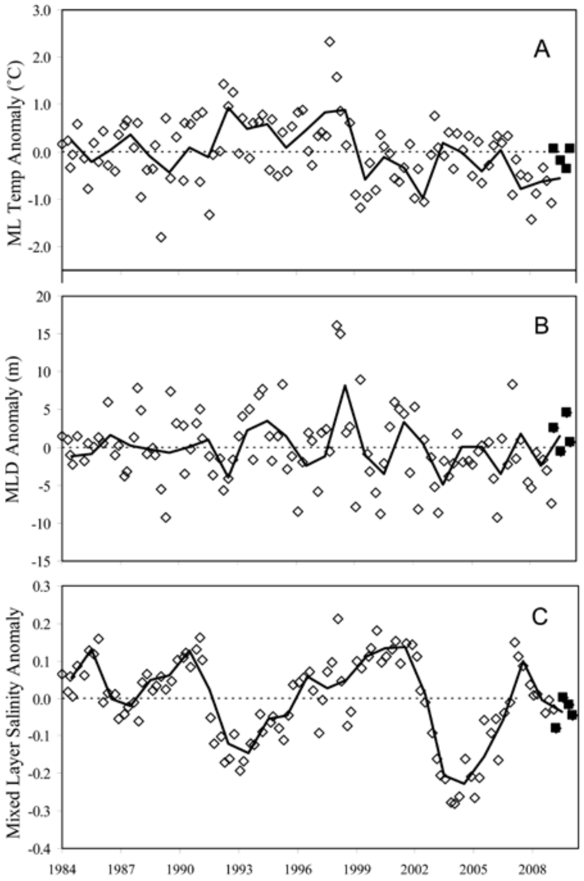
## 3.1 Hydrography

*(Bograd, Chavez, Crawford, Di Lorenzo, Durazo, Goericke, Koslow, Peterson, Suntsov, Whitney)*

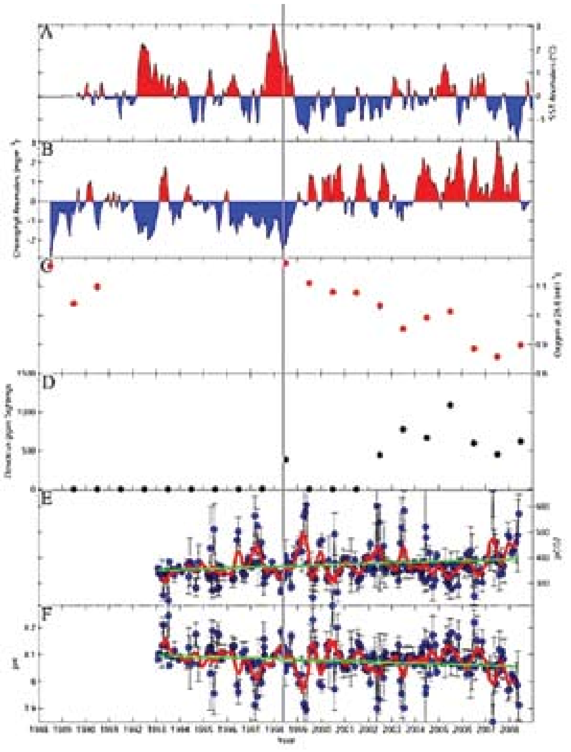
### 3.1.1 Temperature and salinity

Oceanographic time series off southern California and the Baja California Peninsula, Mexico are among the longest and richest in the world (Bograd et al. 2003; Peña and Bograd 2007). Field studies were initiated in the late 1940s to explain the collapse of the California sardine fishery and have continued under the auspices of the California Cooperative Oceanic and Fisheries Investigations (CalCOFI); since 1997 in Mexico, as the Investigaciones Mexicanas de la Corriente de California (IMECOCAL). These lengthy datasets allow the recent observations to be put into the context of interannual to decadal climate variability. Other time series of relatively shorter duration are also available.

Off Baja California, a period of relatively cool, saline near-surface waters extended between El Niños of 1997-1998 and 2002-2003, possibly a result of intensified coastal upwelling (Fig. CC-3). The period 2003-2006 was characterized by very fresh near-surface waters, while the El Niño events of 2002-2003 and 2006-2007 were characterized by much weaker temperature and salinity anomalies that those of the 1997-1998 event. Off southern California, mixed layer temperatures have been relatively cool (Fig. CC-4a). Mixed layer depth has not shown a consistent pattern but it has been ~5 m shallower than average during the past five years (Fig. CC-4b). Salinity in the mixed layer, on the other hand, has considerable low-frequency variability with a 5-10 year period that is correlated with the NPGO rather than the PDO (Di Lorenzo et al. 2008) (Fig. CC-4c). This is similar to the salinity variations observed off Baja California (Fig. CC-3).

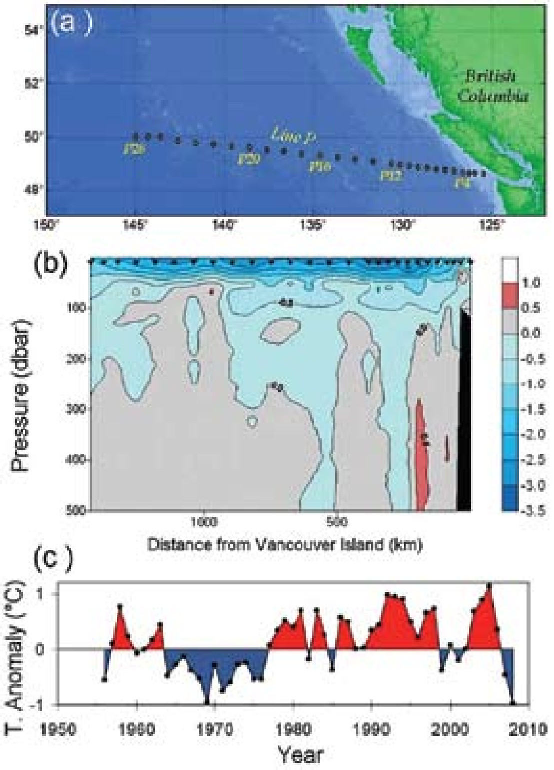


[Figure CC-4] Anomalies of (A) mixed layer temperature, (B) mixed layer depth, and (C) mixed layer salinity off Southern California (CalCOFI standard grid). Data from the last four CalCOFI cruises are plotted as solid squares, data from previous cruises are plotted as open diamonds. The solid lines represent the annual averages and the dotted lines, the climatological mean, which in the case of anomalies is zero.

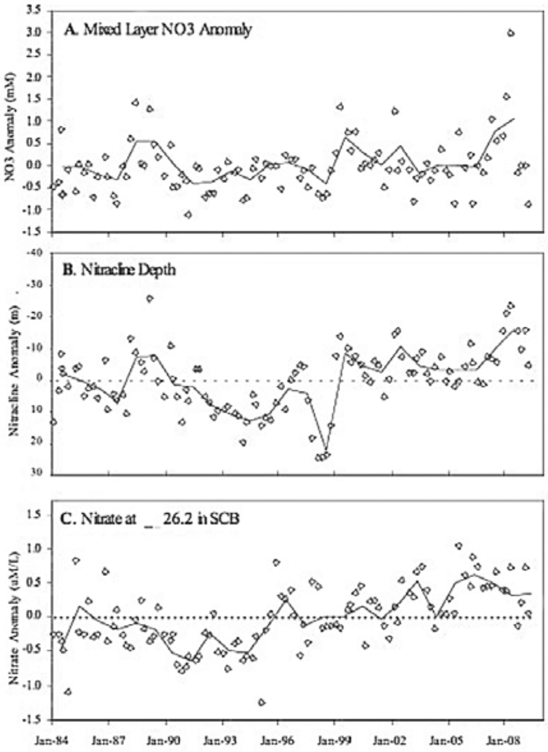


[Figure CC-5] Time series of SST, surface chlorophyll$_a$, oxygen on the 26.8 isopycnal surface, ROV sightings of the Humboldt squid (*Dosidicus gigas)*, surface pCO$_2$ and pH measured in Monterey Bay and the California Current. The sharp regime shift, indicated by the vertical line, to cooler and more productive waters is evident in the SST and chlorophyll time series. The oxygen time series is incomplete but suggests that a decrease in oxygen started after the shift. A similar shift can be seen in the sightings of the Humboldt squid. The human-driven increases in pCO$_2$ and acidity (pH decrease) are evident in the lower panels. These changes are similar to those measured in the open-ocean Atlantic and Pacific but are slightly faster, presumably due to the regime shift.

A time series from Monterey Bay consists of a 20 year record of measurements taken on a cross-shore transect from inner Monterey Bay to offshore in the California Current. SST anomalies were similar to patterns observed by IMECOCAL and CalCOFI, with warmer conditions in 2005-2006 and cooler conditions thereafter (Fig. CC-5a,b). At the northern end of the CCS, the winters of 2007-2008 and 2008-2009 had stronger than normal westerly winds, bringing cool ocean waters from the Gulf of Alaska to the British Columbia coast (Crawford and Irvine 2009). Temperatures off British Columbia and along Line P were the coldest in several decades (Fig. CC-6). Deep waters in the Strait of Georgia have also been below normal in recent years (not shown).



[Figure CC-6] Annual average temperature anomalies along Line-P at 10-50 m. (from Crawford and Irvine 2009).



[Figure CC-7] Anomalies of (A) mixed layer nitrate concentrations, (B) nitracline depth (the depth where concentrations of nitrate reach values of 1 µM, and (C) nitrate concentration in the Southern California Bight at the 26.2 $\sigma_\theta$ isopycnal. Data presented as described for Fig. CC-4.

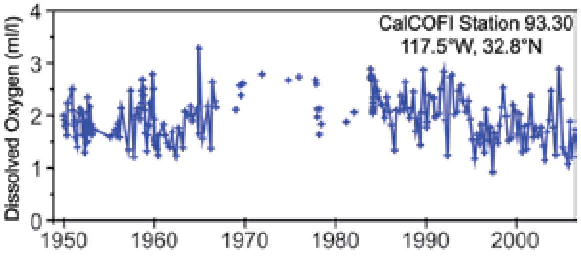
### 3.1.2 Dissolved inorganic nutrients and oxygen

Nutrient concentrations in the euphotic zone are a potential control on overall system productivity. Nitrate is the macronutrient often limiting phytoplankton biomass. In the southern CCS, concentrations of nitrate in the mixed layer (Fig. CC-7a) and the thermocline (Fig. CC-7b,c) have been above the long-term average since 1999. During the recent La Niña period, nitrate concentrations increased above the 1999-2008 average, likely driven by a shallowing of the nitracline depth (Fig. CC-7b).

Mean dissolved oxygen concentrations in the southern CCS have declined since the late 1980s (Fig. CC-8) resulting in substantial shoaling of the hypoxic boundary (Bograd et al. 2008). Potential mechanisms include isopycnal deepening driven by large-scale wind forcing and declining oxygen concentrations within the California Undercurrent source waters that are transported into the Southern California Bight. The decrease since 1984 was generally <10% at 50 to 100 m, but ranged from 10 to 30% at 200 to 300 m. The oxygen declines in the southern CCS are consistent with observations from several regions of the western and eastern Subarctic North Pacific, including off the Canadian west coast, where rates of oxygen decline have also exceeded 1% $y^{-1}$ at 200-300 m (Fig. CC-9; Crawford and Irvine 2009).

### 3.1.3 Hypoxia and anoxia

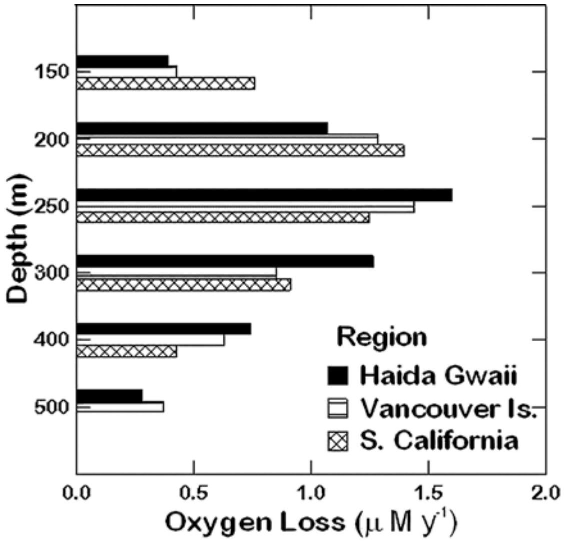
Some of the primary production in the surface layer of the California Current sinks and decays at depth so if production is higher (see Section 4), the increased decay of organic matter reduces subsurface oxygen, increases $CO_2$ and lowers pH. This process is clearly detectable at Monterey Bay (Fig. CC-5c). A repercussion of changes in ocean climate that enhances surface productivity is that continental shelf ecosystems off western North America, including important fishery species (e.g., Dungeness crab, rockfish), are now experiencing sporadic but nevertheless lethal anoxic conditions. These "dead zones" have long been known to occur beneath the extremely productive



[Figure CC-8] Dissolved oxygen concentrations ($ml \cdot l^{-1}$) at 200 m depth at a station off the coast of San Diego, CA (CalCOFI Station 93.30).

upwelling systems off Peru and Namibia, but are a new phenomenon in the CCS (Grantham et al. 2004; Barth et al. 2007; Chan et al. 2008). These changes in ocean climate reverberate through oceanic food webs leading to increases and redistributions of important predators like the Humboldt squid (*Dosidicus gigas*; Gilly et al. 2006; Field et al. 2007; Fig. CC-5d and see Section 4.3.4). Another repercussion of enhanced production is that the water being upwelled to the surface is more acidic, with as-yet unknown ecological consequences (see Section 3.1.4).

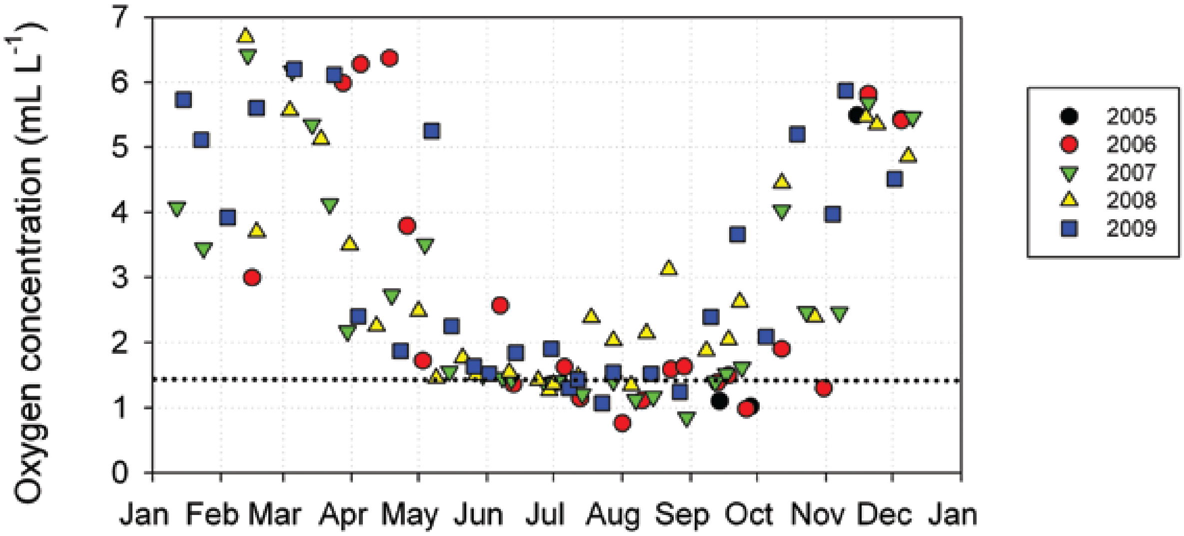
In the northern CCS, severe inner-shelf hypoxia and novel shoaling of water-column anoxia is related to enhanced upwelling, primary production and respiration. Demersal fish and benthic invertebrate communities off Oregon can be strongly affected by seasonally persistent anoxia and severe hypoxia. In August 2006, for example, surveys found no rockfish on rocky reefs and a near-complete mortality of macroscopic benthic invertebrates during one of the more severe anoxic events (Chan et al. 2008). Oxygen concentrations have been measured regularly along the Newport Hydrographic Line since September 2005. During the strong summer upwelling in 2006, water very low in oxygen was upwelled onto the shelf (Fig. CC-10). Oxygen concentrations were low in 2007 as well, another year of relatively strong upwelling off Oregon. Despite higher than average upwelling in 2008, oxygen concentrations fell below the hypoxic level on only two occasions.



[Figure CC-9] Rates of oxygen loss at three stations along the Pacific coast of North America (west coast of Haida Gwaii, west coast of Vancouver Is., and southern California). Redrawn from Crawford and Irvine (2009).

### 3.1.4 Ocean acidification

The slow and steady uptake of atmospheric $CO_2$ by the oceans has been observed in Monterey Bay (Fig. CC-5e) and in the open ocean time series off Hawaii and Bermuda. That it can be clearly detected in Monterey Bay is a surprise given the large high-frequency changes in $pCO_2$ due to coastal upwelling and biological production. The uptake of $CO_2$ by the oceans is lessening the atmospheric $CO_2$ problem but, in turn, the acidity of the oceans is slowly increasing (Fig. CC-5f) with potentially negative effects on some biota. In 2008, strong upwelling increased subsurface $pCO_2$ at Monterey Bay faster than what was seen in the atmosphere.



[Figure CC-10] Dissolved oxygen concentrations (ml·l$^{-1}$) at 50 m depth at Newport Hydrographic Line station NH-05.

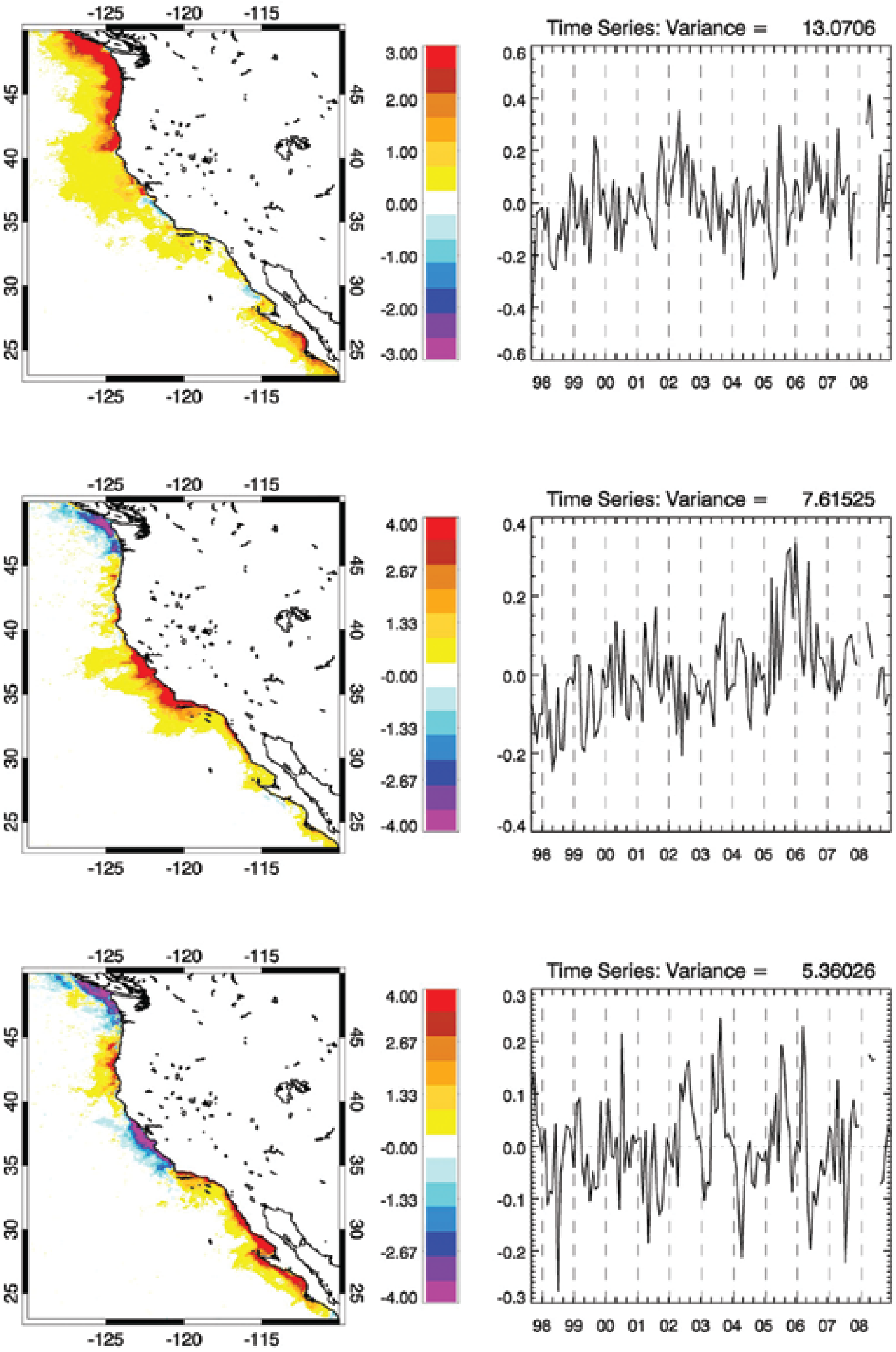
# 4.0 Biology

## 4.1 Phytoplankton *(Thomas, Kahru, Mitchell, Chavez, Durazo, Goericke, Koslow, Lavaniegos, Suntsov)*

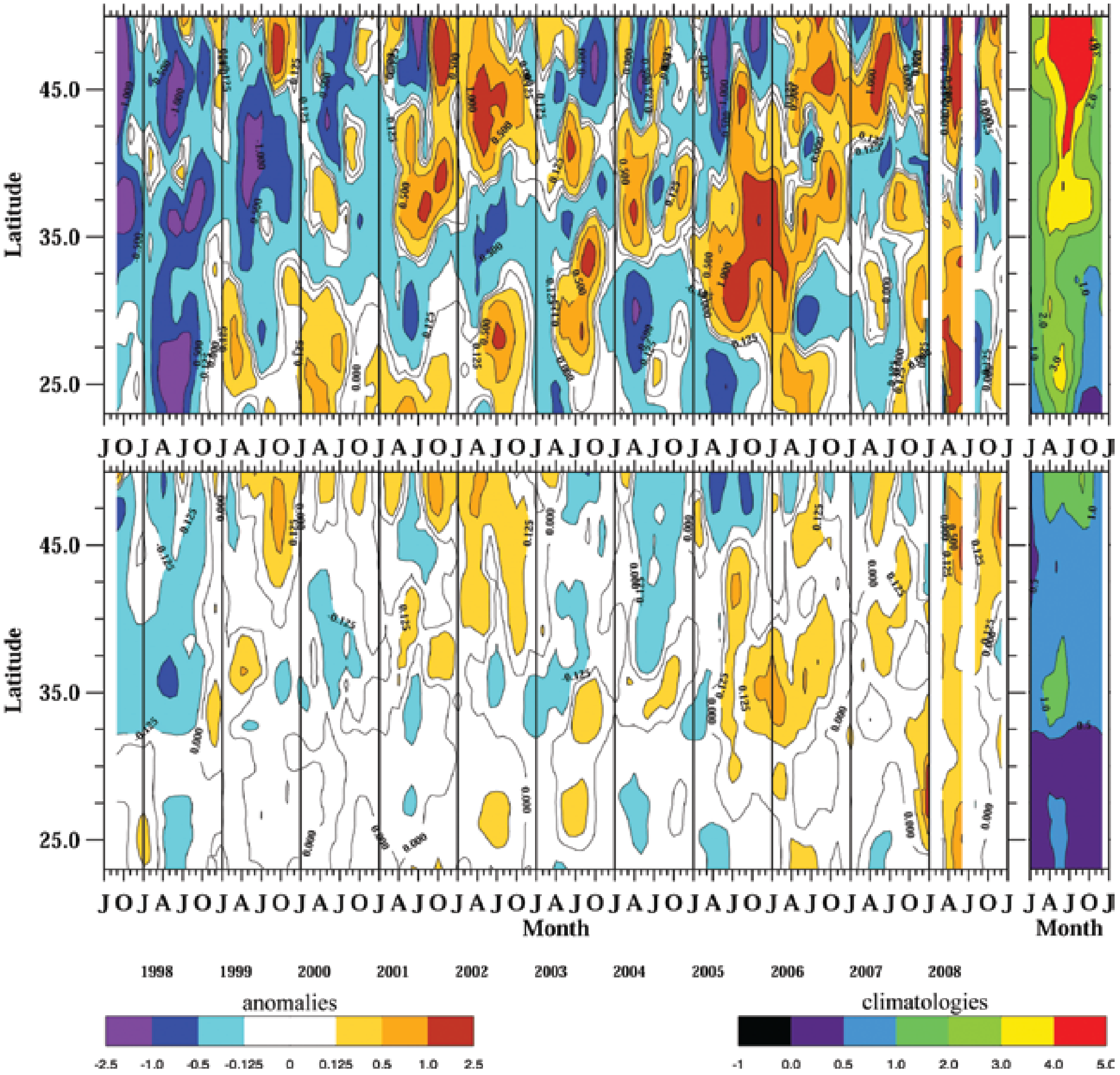
### 4.1.1 Surface chlorophyll interannual variability

The dominant spatial patterns of surface chlorophyll and their temporal variation can be identified by Empirical Orthogonal Function (EOF) decomposition of the non-seasonal time series (Fig. CC-11). The first mode (EOF1 = 13% of the non-seasonal variance) shows a strong coherence (higher values of EOF1 = higher chlorophyll concentrations) that extends 200-300 km offshore from the Vancouver Island to Cape Mendocino (40°N). South of this, the association with this pattern is weaker and constrained closer to shore with a narrow region of negative values off central California and Baja California. The time series of EOF1 was generally weak in 2003-2004, indicating that this spatial pattern (generally coast-wide chlorophyll concentrations) was not dominant. It was followed in early 2005 by a series of strong negative values that switched to strong positive values in mid-summer 2005 that lasted until fall. This period captures the change in upwelling phenology that occurred in 2005 when upwelling-favorable winds were delayed until mid-summer. The EOF1 pattern was weak through winter 2005-2006 but persistently positive through the rest of 2006, and again in summer 2007 and early 2008. The second mode (EOF2 = 7.6% of the non-seasonal variance) highlights out-of-phase variability in surface chlorophyll concentrations across the region. Negative values occur off British Columbia and Washington and positive values appear south of the Columbia River, strongest off central California. The strongest values of EOF2 were positive in 2005 extending into 2006, representing negative chlorophyll modal anomalies in the northern region and positive off central California.

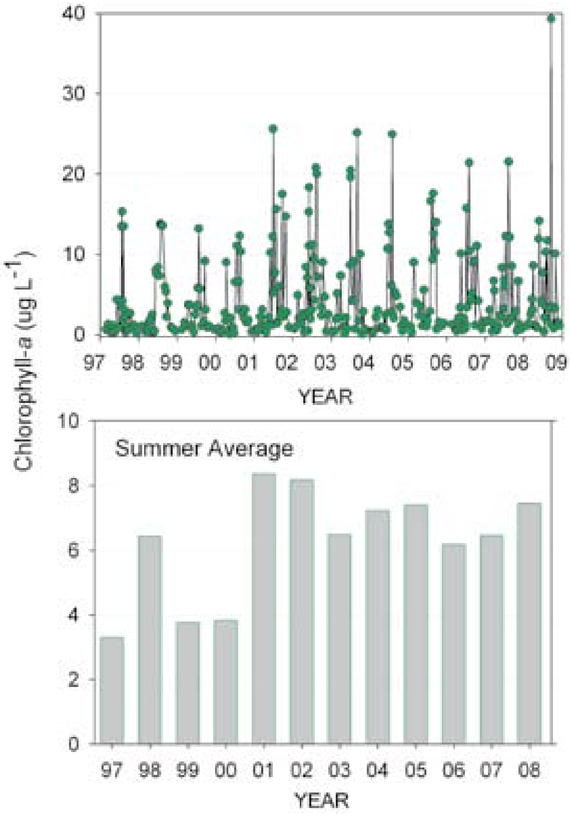
Mean surface chlorophyll concentration anomalies within two regions (0-50 km offshore, 100-200 km offshore; Fig. CC-12) describe variations within the coastal upwelling domain and the offshore region of enhanced upwelling-driven primary productivity, respectively. In the coastal upwelling domain, positive anomalies occurred from 30°-45°N in 2005, over much of the California Current region (except the Southern California Bight - northern Baja California region) in 2006, and remained strong north of 40°N in 2007, especially during early summer. Anomalies in 2008 were strongly positive from April-June throughout the region. These data reflect the latitudinal extent of anomalous upwelling in 2005, showing negative anomalies north of 40°N early in the year that remained negative throughout 2005 north of 48°N, but switched to strongly positive in July south of this. The strongest signals in the southern portion of the region were negative anomalies in 2004-2005 that switched to positive in the summer of 2006. In the offshore region,



[Figure CC-11] Dominant surface chlorophyll$_a$ spatial patterns and their temporal modulation in the California Current extracted by an EOF decomposition of the non-seasonal time series. Data are summarized from monthly composites of SeaWiFS satellite data, processed at 4 km resolution. Base period is 1998-2008.



[Figure CC-12] Surface chlorophyll$_a$ anomalies in the California Current as a function of time and latitude. Anomalies are averaged within two cross-shelf regions: 0-50 km offshore (top) and 100-200 km offshore (bottom). The monthly seasonal climatology for each cross-shelf region is shown at right.



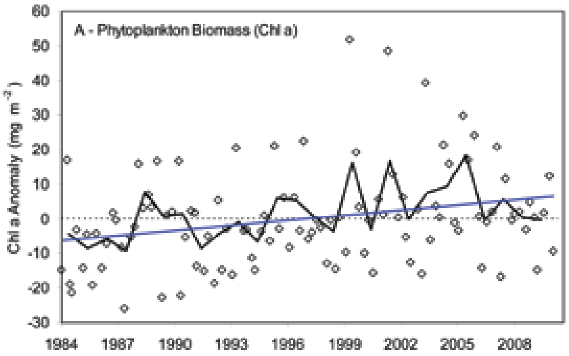
[Figure CC-13] Surface chlorophyll$_a$ time series (top) and summer average (bottom) at Newport Hydrographic Line station NH-05.

positive anomalies extended from 30-45°N in the summer of 2005 and persisted through winter and into summer 2006 in the region 30-40°N. Negative anomalies associated with the phenological shift in 2005 are evident north of 45°N, similar to those in the inshore region. Negative anomalies throughout summer 2004 in areas north of 35°N are less evident closer to shore, suggesting that the productive region was restricted to the coastal area that year. In 2008, anomalies in the offshore region were strongly positive and similar to those of the inshore region.

Surface chlorophyll concentrations in Monterey Bay have been anomalously high for several years (Kahru and Mitchell 2008; Kahru et al. 2009), consistent with the PDO shift that occurred in late 1998 (Peterson and Schwing 2003; Chavez et al. 2003; Fig. CC- 5b). Surface chlorophyll concentrations at a station on the Oregon continental shelf (NH-05, water depth 62 m) have also been high in recent years, with summer average values nearly double what they were in 1997-2000 (Fig. CC-13).

### 4.1.2 Chlorophyll at depth

Vertically-integrated chlorophyll$_a$ concentration in the mixed layer has an increasing trend and has been somewhat higher than average since 1999 (Fig. CC-14). This trend was observed at nearshore and offshore stations both north and south of Pt. Conception. The increasing trend in concentration of chlorophyll$_a$ is consistent with the long-term decline (since 1949) in Secchi depth in the coastal zone of the CalCOFI study region (Aksnes and Ohman 2009). Di Lorenzo et al. (2008) reported that the NPGO was correlated with salinity, nitrate concentration, and phytoplankton (chlorophyll concentration) within the CalCOFI domain.



[Figure CC-14] CalCOFI region averages for standing stocks of chlorophyll$_a$ integrated to the bottom of the euphotic zone, plotted against time. Data and symbol codes are the same as those in Fig. CC-4.

## 4.2 Zooplankton *(Peterson, Mackas, Durazo, Lavaniegos, Gaxiola-Castro, Goericke, Koslow, Suntsov)*

### 4.2.1 Regional time series

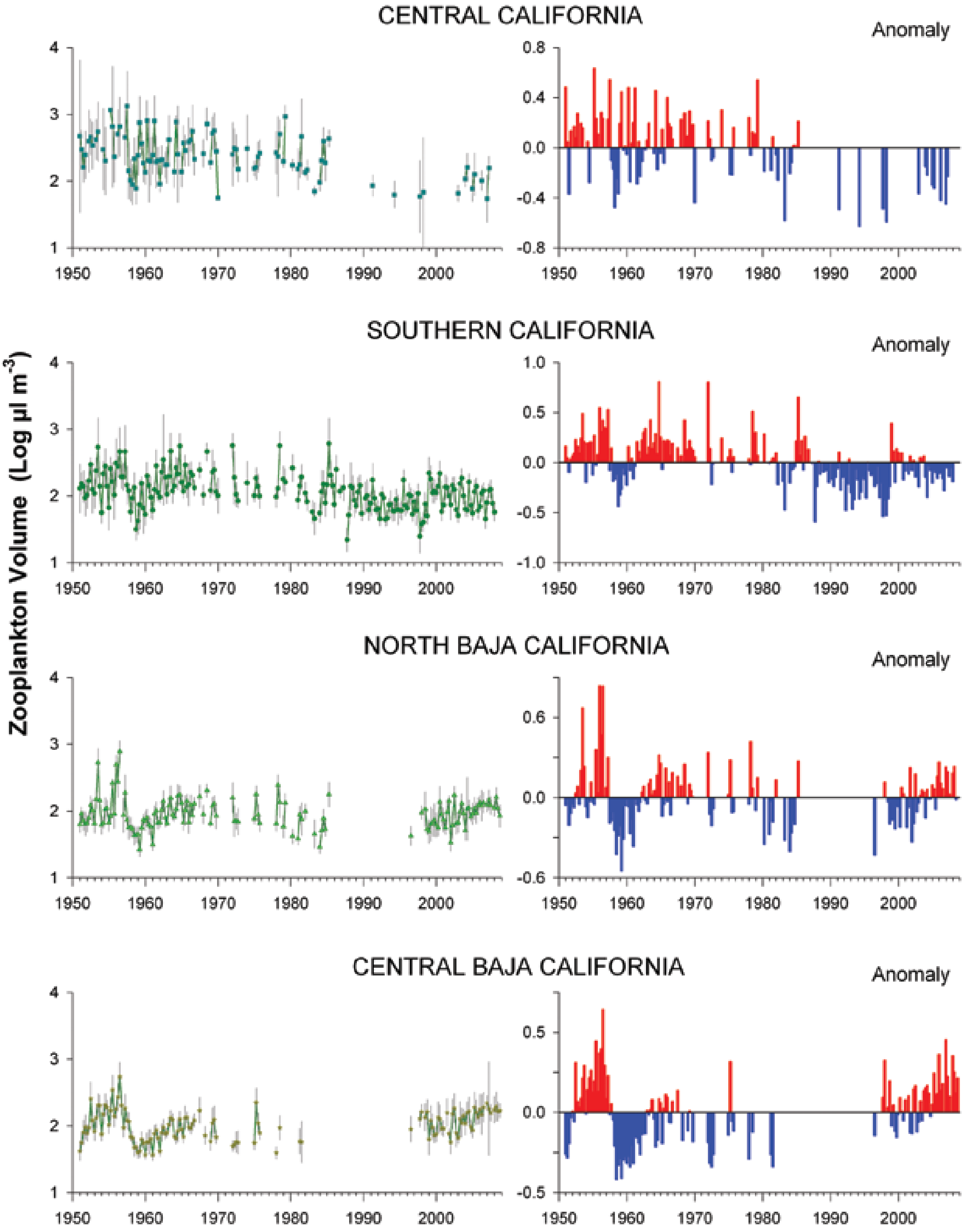
Off northern and central Baja California, zooplankton biovolume has an increasing trend from 2003-2008 (Fig. CC-3c,d). Zooplankton displacement volume off southern and central California has been low since about 1993; notably, the seasonal cycle of zooplankton biovolume, typical of earlier years in the time series, has been absent in recent years (Fig. CC-3a,b). Offshore curl-driven upwelling has apparently increased over time (Rykaczewski and Checkley 2008) and it promotes the production of relatively small zooplankton, which may not be sampled adequately by the coarse-meshed (505 µm) bongo nets used in the CalCOFI surveys. Nevertheless, the lack of a clear seasonal pulse in zooplankton biovolume in southern and central California in recent years is remarkable.

In the southern half of the CCS, the increasing trend in zooplankton appeared to be regional and more intense off central Baja California (Fig. CC-15; Baumgartner et al. 2008; Lavaniegos 2009). The increase was less intense in northern Baja California and was delayed after the recovery of low biomass during the 1999-2000 La Niña and the subarctic water intrusion (2002-2006). Unexpectedly, the trend was the opposite off southern California, which experienced a recovery in zooplankton biomass during La Niña only to diminish later with the freshening of the upper water column. The contrast is more remarkable considering that both northern Baja California and southern California regions are part of the recirculation that takes place in the Southern California Bight from summer to winter. The few data available from central California indicate negative anomalies in the last ten years.

Biomass anomalies of the northern copepods (*Calanus marshallae, Pseudocalanus mimus, Acartia longiremis*) on the Oregon shelf were low in the warm years of 1998 and 2005, near average in 1996, 1997, 2000, and 2003, and above average during the colder years of 2000-2002 and 2007-2008 (Fig. CC-16). Note that extremely low biomass was observed both during the 1998 El Niño and during the 2005 "warm event". Copepod biomass began to recover in 2007 and reached values in 2008 that were similar to those observed in 2002. An index of copepod community composition was computed, based on an ordination of all samples (n=435) collected at Station NH-05 off Newport, OR, from 1996-present. When the PDO is in positive phase, a "southern" or "warm water" copepod community predominates, whereas a "northern" or "cold water" copepod community prevails in a negative PDO phase. Since the 2007 phase shift of the PDO, the northern copepod community has shown a consistently strong presence.

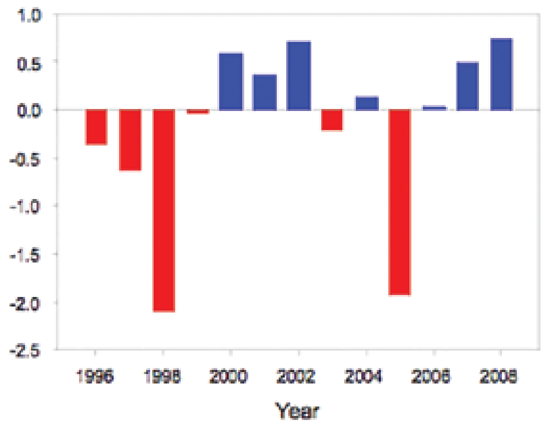
Zooplankton sampling off the southwestern coast of Vancouver Island has continued since 1979, and since 1990 (but with low sampling intensity and taxonomic resolution from 1991-1995) off northern Vancouver Island (Fig. CC-17). Sampling consists of vertical net hauls with black bongo nets (0.25 m² mouth area, 0.23 mm mesh aperture) from near-bottom to sea surface on the continental shelf and upper slope, and from 250 m to surface at deeper locations (Mackas et al. 2001). Abundance and biomass are routinely estimated for more than 50 zooplankton taxa. Seasonal variability is intense and somewhat repeatable from year to year (Fig. CC-18). Year to year differences in abundance and species composition are calculated by averaging log-transformed anomalies within groups of species sharing similar ecological niches and zoogeographic ranges (1979-2005 baseline for southern Vancouver Island; 1990-2005 baseline for northern Vancouver Island).

Sequences of warmer years were frequent during the past two decades. Warm ocean temperatures have direct effects on biota, but also cause changes in other important environmental factors such as increased vertical density stratification, resistance to wind-mixing and upwelling, reduced nutrient supply, reduced plankton productivity, and poleward shifts of anomalies in transport and migration. All of these push the zooplankton community toward reduced growth and survival of resident species, and increased abundance of their "warm-water" competitors and predators. These shifts in community composition are very evident in the southern Vancouver Island zooplankton anomaly time series (Fig. CC-19). Warm conditions prevailed in 2003-2005, leading to a higher abundance of "southern" origin copepod species and less abundant resident "northern" copepod species. Poleward/equatorward displacements were seen in other zooplankton groups, especially the chaetognaths. Cooler ocean conditions began to return in early 2006, but recovery of the boreal shelf copepods and northern chaetognaths and decline of the southern copepods and chaetognaths were delayed and more gradual. In 2007, the "cool ocean" community mix was confined primarily to the continental shelf. But in 2008, positive anomalies of cool-water (and negative anomalies of warm-water) zooplankton species groups were strong in all regions, leading to a zooplankton community similar in amount and composition to the beginning of our time series. The patterns of variation in the shorter northern Vancouver Island time series (Fig. CC-20) are qualitatively similar to those off southern Vancouver Island (bad for endemic species and good for southern species during warm years), but anomaly amplitudes off northern Vancouver Island are generally smaller. Zooplankton anomaly time series from further south in the CCS also show similar patterns of interannual-to-decadal variability (Mackas et al. 2006).

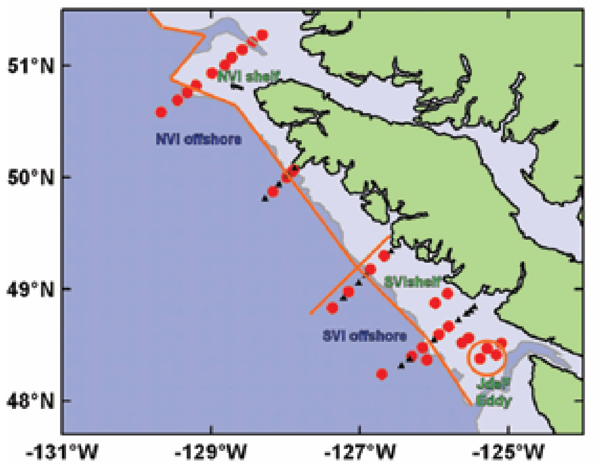


[Figure CC-15] Comparison of time series of zooplankton biomass in four regions of the CCS: central California (lines 60-70; 36°-38°N), southern California (lines 80-93; 32.5°-34.5°N), northern Baja California (lines 97-110; 30°-32°N), and central Baja California (lines 113-137, 25.5°-29.5°N). Left panels show the logarithm of quarterly values of mean biomass levels (with 95% confidence interval) over the corresponding lines. Right panels show the corresponding series of biomass anomalies obtained by removing the seasonal (quarterly) means from the values. All data are from nighttime samples. (CALCOFI data kindly provided by Mark Ohman and Paul Smith.)

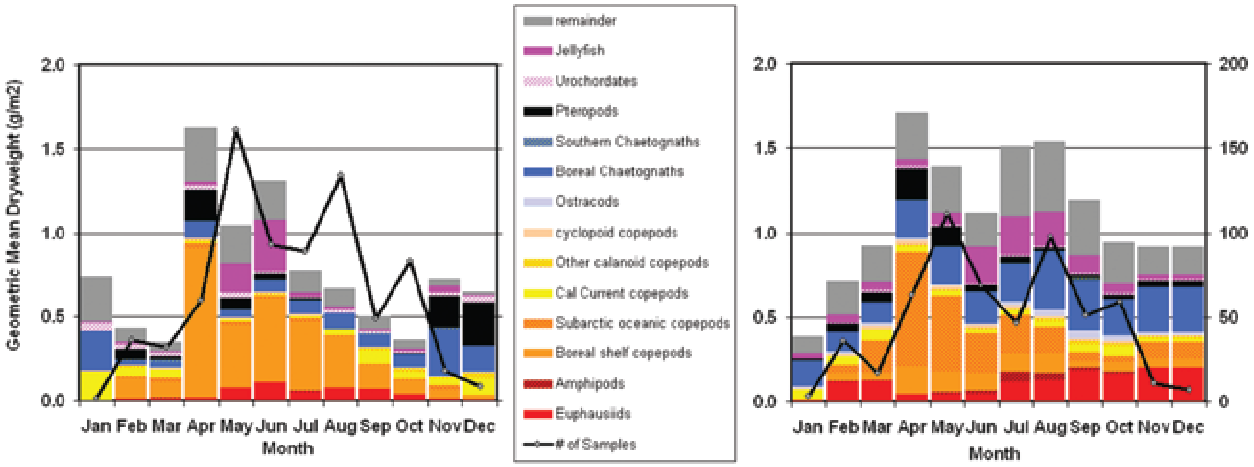
California Current



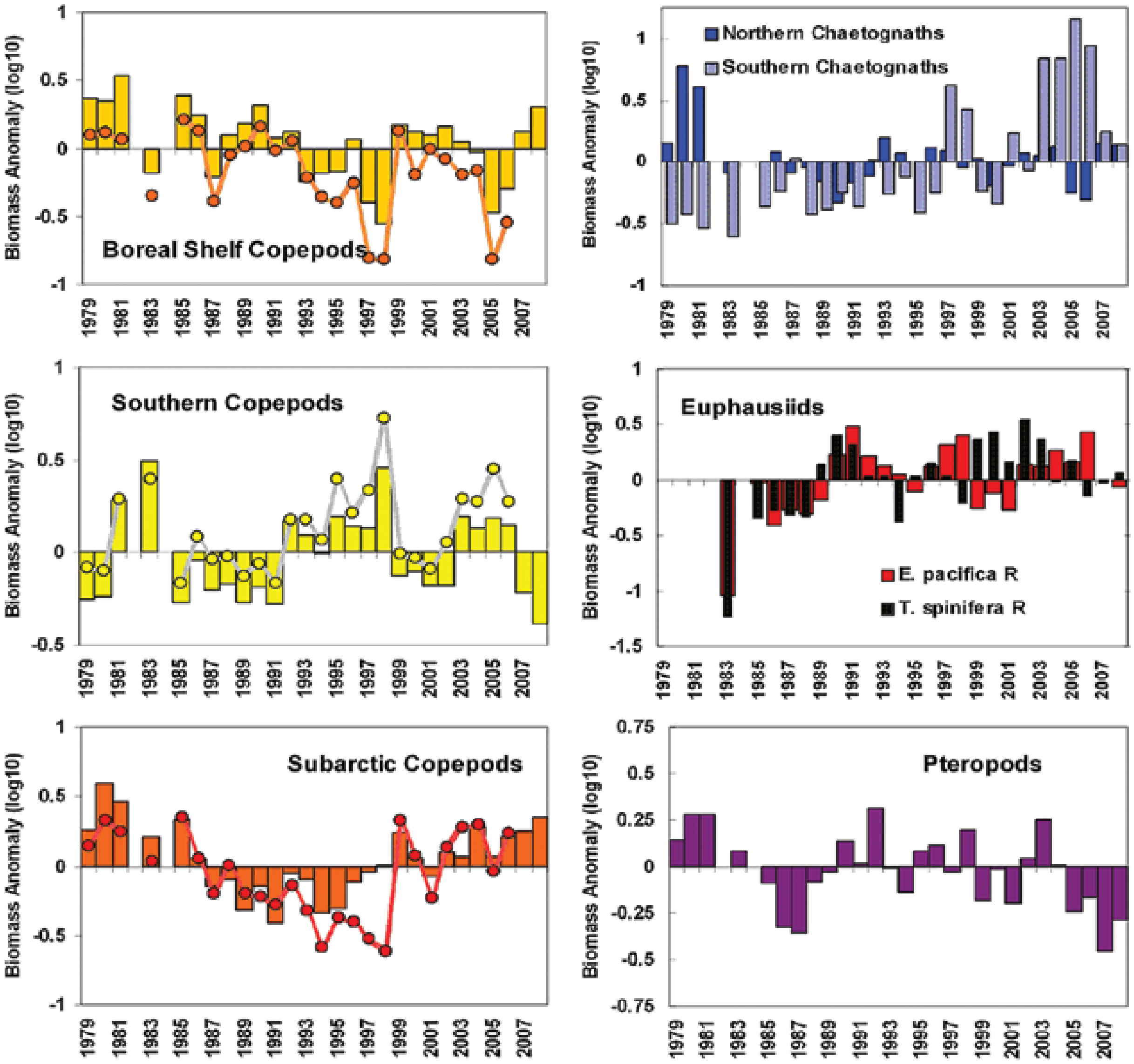
[Figure CC-16] Biomass anomalies of northern copepod species (*Calanus marshallae, Pseudocalanus mimus, Acartia longiremis*) based on bi-weekly sampling at Station NH-05 off Newport, OR (44.6°N). The anomalies are averaged monthly values for May through September for each year from 1996-2008.



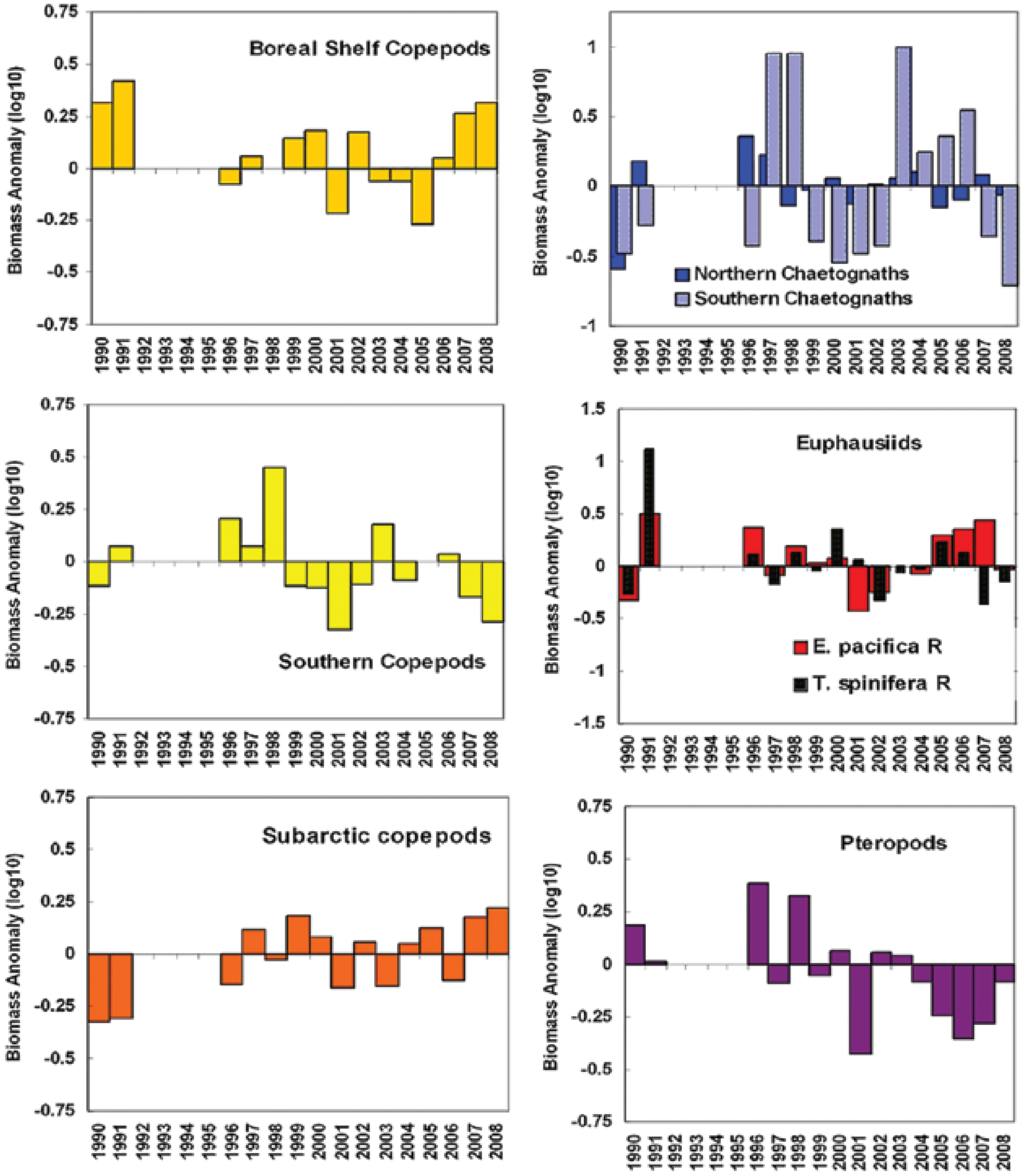
[Figure CC-17] Standard zooplankton sampling stations off the Vancouver Island continental margin (circles), and their spatial classification into statistical areas. Triangles show supplementary CTD stations.



[Figure CC-18] Average seasonal cycles (geometric mean of dry-weight biomass) for the southern Vancouver Island shelf and offshore regions shown in Fig. CC-17. Columns show cumulative amount within 14 summary taxonomic groups (1979-2005). Black lines show the number of samples included in each monthly and regional average.



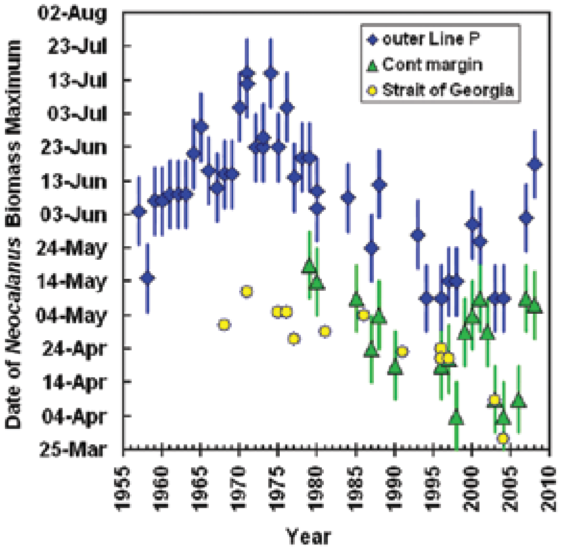
[Figure CC-19] Zooplankton anomaly time series for southern Vancouver Island. Column bars are species group anomalies referenced to the full 1979-2005 baseline period. The years 1982 and 1984 are omitted because there were too few samples. Circles and lines in the 3 left panels show for comparison the older anomalies (1979-1991 baseline). Euphausiid anomalies are reported only since 1983 (after a change in sampling method) and have been corrected for day vs. night effects on capture efficiency.



[Figure CC-20] Zooplankton anomaly time series for northern Vancouver Island. The years 1992-1995 are omitted because few samples were collected.

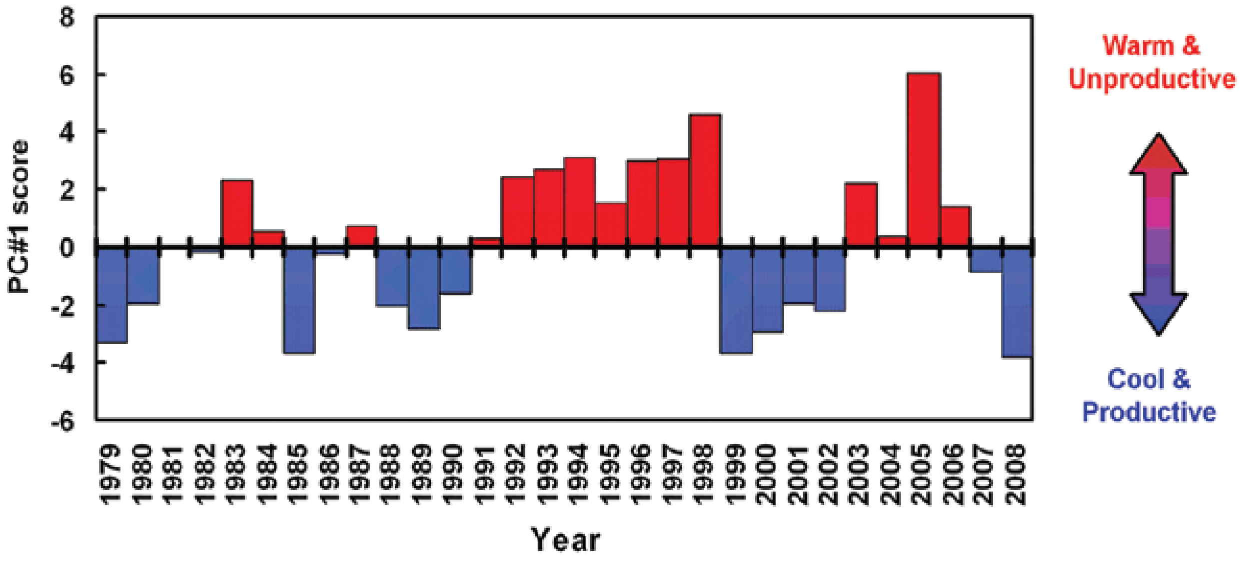
## 4.2.2 *Neocalanus* phenology off British Columbia

The biomass of the Subarctic oceanic copepods (*Neocalanus* spp.) has been increasing gradually off Vancouver Island since 1990. These large copepods make up most of the zooplankton biomass in the Alaska Gyre. They have an annual life cycle that includes a brief growing season from spring into early summer followed by emigration from the surface layer for a period of prolonged dormancy at depths from 400-1500 m. The annual biomass maximum, and maximum availability as food for upper ocean predators, is the 3-4 week period that precedes the start of this dormancy period. There is a very strong association between seasonal timing and ocean temperature (Mackas et al. 1998, 2007), with the annual biomass peak and onset of dormancy occurring early in the year if the upper ocean is warm in spring, and late if the water is cool. The years 2003-2006 were among the earliest recorded, both along the Vancouver Island continental margin, and in the Alaska Gyre (Fig. CC-21). Timing in 2007 was near the long-term average in both regions. Timing in 2008 was later than average (late June-early July) in the Alaska Gyre and near-average (mid-late May) along the continental margin.



[Figure CC-21] Time series of date of *Neocalanus plumchrus* biomass maximum for stations along Line-P.

The changes in zooplankton community composition in the past two decades appear to have had large effects on fish growth and survival (Mackas et al. 2007), probably because the "cool water" zooplankton are better fish food (larger individual body size and much higher energy content). Because much of the year to year variability of marine survival rate of harvested fish species occurs at early life stages (for salmon, in their first year after ocean entry), recent zooplankton anomalies provide a useful index of juvenile fish nutrition and a "leading indicator" for subsequent adult fish recruitment. Mackas et al. (2007) used multivariate ordination of the covariance among zooplankton composition and timing anomalies, local and large-scale indices of upper ocean temperature, and "success" of predator species (growth and marine survival of coho salmon on the west coast; sablefish recruitment; seabird reproductive success). They found that interannual variability of all of these series projected strongly onto a single component axis (loosely interpretable as a "cool-and-productive" to "warm-and-unproductive" gradient; Fig. CC-22). The years 1983, 1992-1998, and 2003-2006 all score as "warm and unproductive", however, data suggest that predator reproductive success and early marine survival of salmon may have been much better in 2008.



[Figure CC-22] Annual scores for zooplankton-temperature-predator Principal Component 1. Blue indicates cool temperature and favourable conditions for most of the endemic zooplankton and predators, red indicates warm and favourable for the southern zooplankton but unfavourable for endemic zooplankton and predators.

## 4.3 Fishes and Invertebrates

*(Brodeur, Emmett, Field, Irvine, McKinnell, Peterson, Ralston, Schweigert, Tanasichuk)*

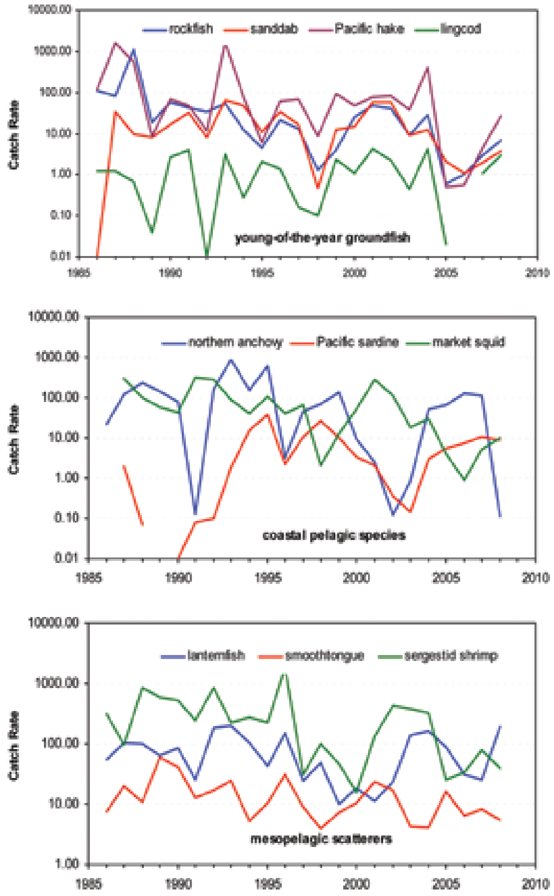
### 4.3.1 Larval fish abundance trends in the southern CCS

Based on CalCOFI data up to 2002, Hsieh et al. (2005, 2009) reported that the abundance of most oceanic fishes increased during warm phases of the PDO and declined during cool phases. These fishes are mostly mesopelagic and not commercially exploited making them a potential proxy for tracking environmental changes. Of the key coastal species, northern anchovy (*Engraulis mordax*) is often characterized as being favored during cool periods and Pacific sardine (*Sardinops sagax*) during warm periods (Chavez et al. 2003). However, for the past five years, a cool period, the abundance of sardine larvae has remained relatively high, but the abundance of anchovy and hake larvae has remained low (A. Koslow, Scripps Institution, pers. comm.), along with the larval abundance of jack mackerel (*Trachurus symmetricus*) and Pacific mackerel (*Scomber japonicus*). The larval abundance of *Leuroglossus stilbius, Stenobrachius leucopsarus, Tarletonbeania crenularis, Vinciguerra lucetia,* along with the coastal croakers, Sciaenidae spp. has also remained low during the past five years (Koslow and Suntsov, in prep.). The continuing recent declines in these oceanic species are inconsistent with the increased curl-driven upwelling offshore, which is hypothesized to lead to increased productivity (Rykaczewski and Checkley 2008). Their decline is, however, in agreement with the long-term decrease in zooplankton volume.

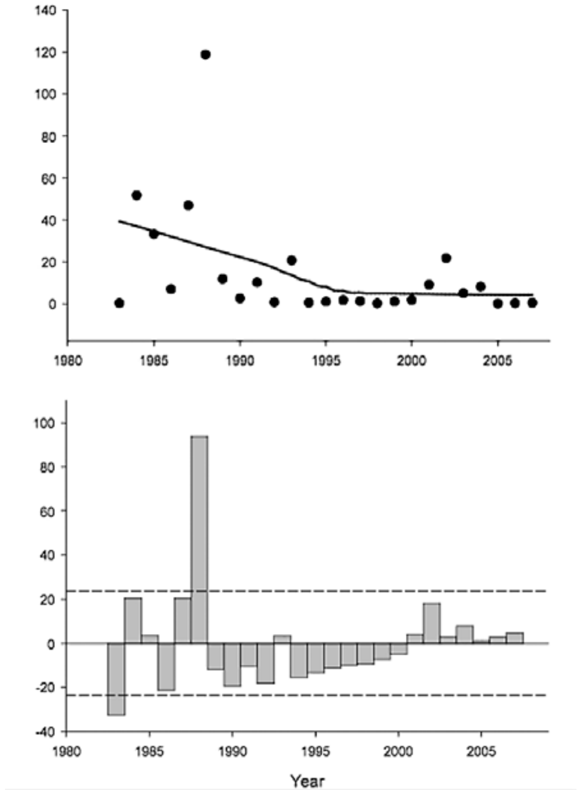
### 4.3.2 Forage fish and young of year predatory fish

The primary forage fishes in the CCS are Pacific sardine, northern anchovy, jack mackerel, chub (Pacific) mackerel, and Pacific herring (*Clupea pallasi*). Sardine, anchovy and mackerel are trans-boundary stocks, exploited primarily by U.S. and Mexican fleets. Sardines are taken for human consumption, bait, and aquaculture feed, while anchovy is generally reduced to fishmeal (Aquarone and Adams 2009). Market squid (*Loligo opalescens*) has become the most important fishery for the state of California in terms of revenue and landings. Landings of sardine and market squid to California ports have continued to increase, while those of Pacific herring, Pacific mackerel and jack mackerel have continued a dramatic decline in recent years (Sydeman and Thompson 2010). Primary groundfish resources in the CCS include sole, thornyheads, sablefish, rockfish, lingcod, flatfish, and Pacific hake.

A variety of epipelagic fish and invertebrate micronekton/nekton are sampled in the central CCS by a midwater trawl which is fished at a depth of 30 m with a 1-cm mesh cod-end.



[Figure CC-23] Long-term trends in abundance of 10 well-sampled taxa in NOAA's Southwest Fisheries Science Center (SWFSC) midwater trawl surveys, 1986-2008.



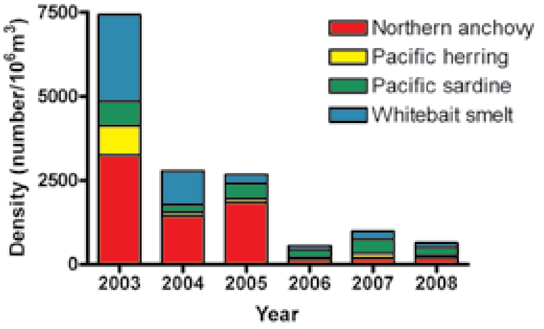
[Figure CC-24] Summed relative abundances (upper) and anomalies from long-term mean (lower) of 11 juvenile rockfish (*Sebastes* spp.) from the SWFSC midwater trawl surveys with a loess trend line indicated.

Catches of young of year (YOY) taken in replicate sweeps are available since 1986. Catches include rockfishes (*Sebastes* spp.), sanddabs (*Citharichthys* spp.), Pacific hake (*Merluccius productus*), and lingcod (*Ophiodon elongatus*). Likewise, catches of several important coastal pelagic species (northern anchovy, Pacific sardine, and market squid), as well as deep-scattering layer mesopelagic species (e.g., lanternfishes [*Myctophidae*], California smoothtongue [*Leuroglossus stilbius*], and sergestid shrimp) have been recorded routinely. Long-term trends in the average catch rates of 10 well-sampled taxa show significant interannual variability (Fig. CC-23). For example, YOY catch rates of Pacific hake have ranged over three orders of magnitude between 1986-2008. Among these taxa, lanternfish have been the least variable (CV = 0.76) and YOY rockfish have been the most variable (CV = 3.00). The composition of this forage fish community in 2005 and 2006 was most similar to that observed during the 1998 El Niño, with very low abundances of YOY groundfish and market squid, but with relatively high catch rates of anchovy and sardine. However, since 2006 the midwater trawl assemblage has trended back towards a species composition more characteristic of the cool, productive period of 2002. The relative abundance of juvenile rockfish (*Sebastes* spp.) observed in midwater trawl surveys varied among species but none increased over time (Sydeman and Thompson 2010). Abundances have been fairly stable since the mid-1990s, but have not reached the values observed in the mid-1980s (Fig. CC-24).

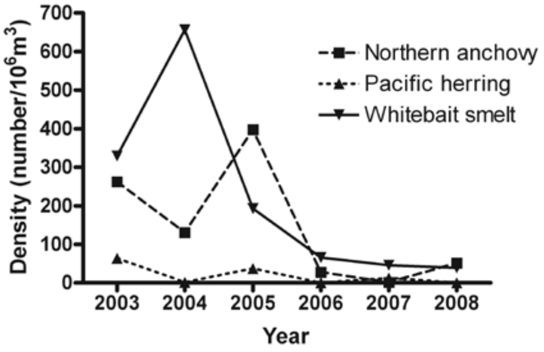
Surface trawls have been conducted bi-weekly from April-August off the mouth of the Columbia River at night since 1998 (Emmett et al. 2006). SST changed significantly over the recent time period with a cool, productive period from 1999-2002 changing to a warm, relatively unproductive period from 2003-2007. SST off the Columbia River was particularly warm during June-August of most years of the focus period. Temperatures were cooler in 2008, but since fish production lags ocean conditions by at least one year, the anticipated increase in productivity was not reflected in fish production.

Lower ocean productivity from 2003-2007 in the northern CCS was clearly reflected in the decreased abundance of forage fishes. Densities ranged from a high annual average of almost 7,500 per million m³ in 2003, to a low of only 554 per million m³ in 2006 (Fig. CC-25). The decline in forage fish densities appeared to be related to poor recruitment. The spring/summer sampling does not reflect the densities of larval or age-0 specimens of most forage fishes, however, the abundance of one-year-old or age-1 fishes is accurately reflected. Taking into consideration the one-year time lag, it appears that 2003, 2005-2007 were very poor spawning and recruitment years for Pacific herring and northern anchovy. The years 2004-2007 were also poor recruitment years for whitebait smelt (*Allosmerus elongatus*). Only 2003 was a good year for recruitment of whitebait smelt during the focus period (Fig. CC-26). Predatory fishes also showed a decline in densities, with highest annual average densities (200 per million m³) in 2004 and lowest densities in 2008 (<10 per million m³).

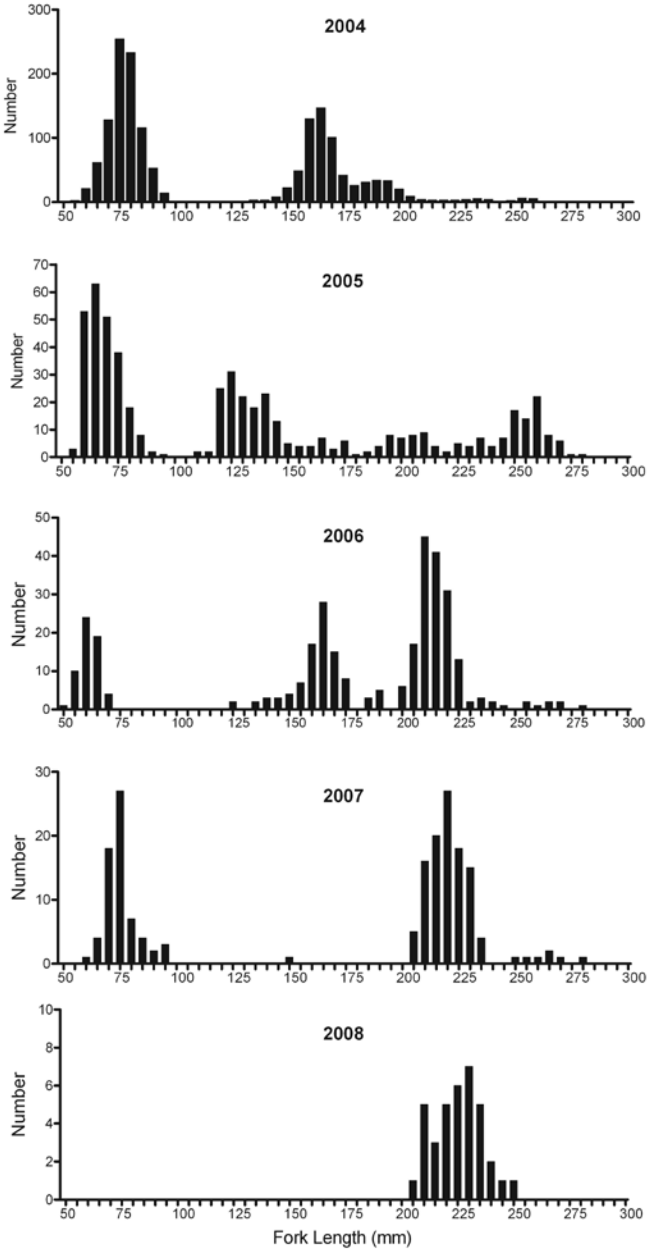
Pacific sardine had large changes in recruitment from 2004-2008 based on surface trawling for age-0 sardines off Oregon/Washington in September. The occurrence of a size mode of small individuals indicates that sardines spawned and recruited off Oregon in both 2004 and 2005, but poorly in 2006 and 2007, and not at all in 2008 (Fig. CC-27). Sardine biomass has continued to increase in British Columbia waters where the 2008 catch was the highest since the 1940s (Crawford and Irvine 2009). The return of sardines to Canadian waters over the past decade is likely due to the appearance of generally warmer waters.



[Figure CC-25] Average annual densities of key forage fishes caught off the Columbia River during bi-weekly night surface trawling during April-August.



[Figure CC-26] Average annual densities of one-year-old forage fishes caught off the Columbia River during bi-weekly night surface trawling during May-June.



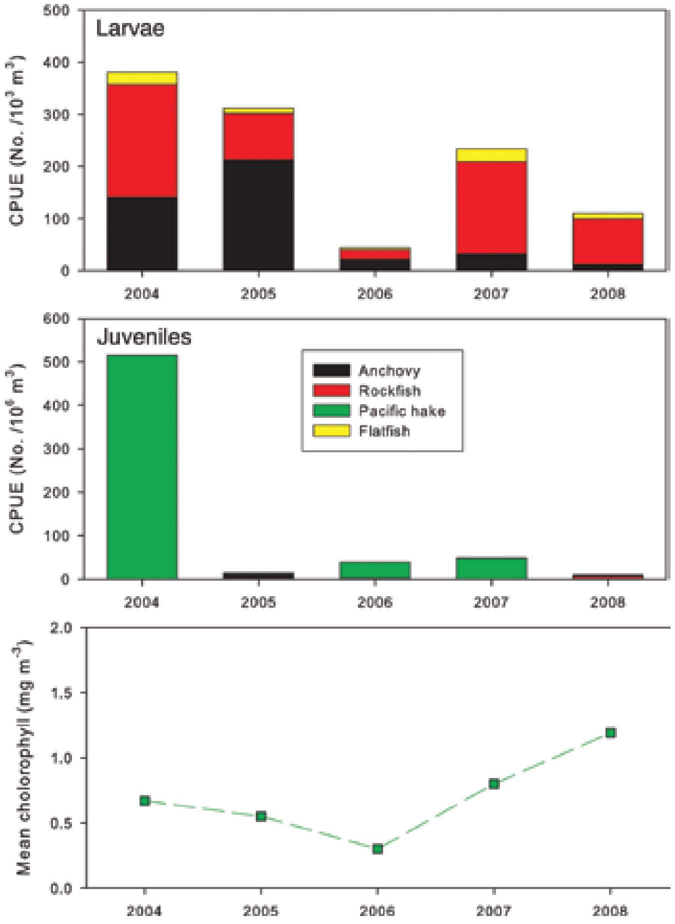
[Figure CC-27] Length frequency of Pacific sardine (*Sardinops sagax*) captured off northern Oregon/Washington in September.

Anchovy catches have been declining and rockfish catches have been increasing in the northern California Current surveys over the last 5 years (Fig. CC-28, Fig. CC-29). Many of these recruitment anomalies may have been triggered by unusual oceanographic events in 2004 and 2005 (Brodeur et al. 2006) coupled with a shift in the PDO that affected larval fish communities (Brodeur et al. 2008). Other ecosystem indicators such as jellyfish abundance in trawl surveys off Oregon and Washington do not show any consistent trends over the last 6 years, although jellyfish biomass was particularly high in June of 2004 and September of 2007 compared to the other cruises (Fig. CC-30).

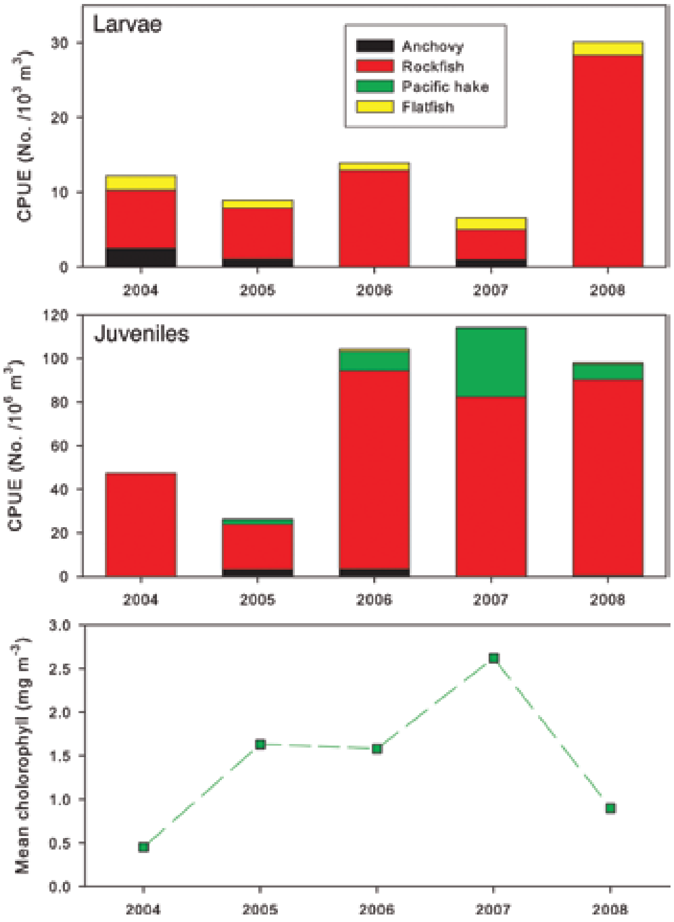
Herring abundance on the west coast of Vancouver Island is at an historically low level following a decade of poor recruitment (Crawford and Irvine 2009). Biomass has declined recently for all five major British Columbia stocks, with the Georgia Basin biomass declining nearly to the fishery-closure limit in 2008. Three other herring stocks in British Columbia were at or below the fishing limit, following weak recruitment of the 2003 and 2005 year-classes. Herring abundance in the Strait of Georgia has continued to decline since the near-historic high levels of 2002 (Fig. CC-31). Cooler ocean conditions since 2005, combined with a decrease in Pacific hake abundance, may result in improved herring recruitment and stock abundance over the short term (Crawford and Irvine 2009).

Euchalon (*Thaleichthys pacificus*) abundances off the west coast of Vancouver Island and in the Fraser River have declined since the mid-1990s. Anecdotal information suggests the decline has been coastwide throughout Washington and British Columbia (Crawford and Irvine 2009). Bottom trawl surveys off central Vancouver Island have found increasing biomass of smooth pink shrimp (*Pandalus jordani*) in 2008, up from very low levels found during the warmer period of 2004-2007 (Crawford and Irvine 2009). Biomass of British Columbia flatfish species also increased in 2008 after declines in 2006-2007 (Crawford and Irvine 2009).

Pacific hake showed unusual recruitment patterns off the northern California Current from 2003-2008. Pacific hake is not known to regularly spawn and recruit in the northern California Current off Oregon and Washington, however, relatively large densities of age-0 Pacific hake were first



[Figure CC-28] Annual average densities of dominant fish larvae (top) and pelagic juveniles (middle) from June Stock Assessment Improvement Plan (SAIP) surveys during 2004-2008. Also shown are the mean chlorophyll concentrations.

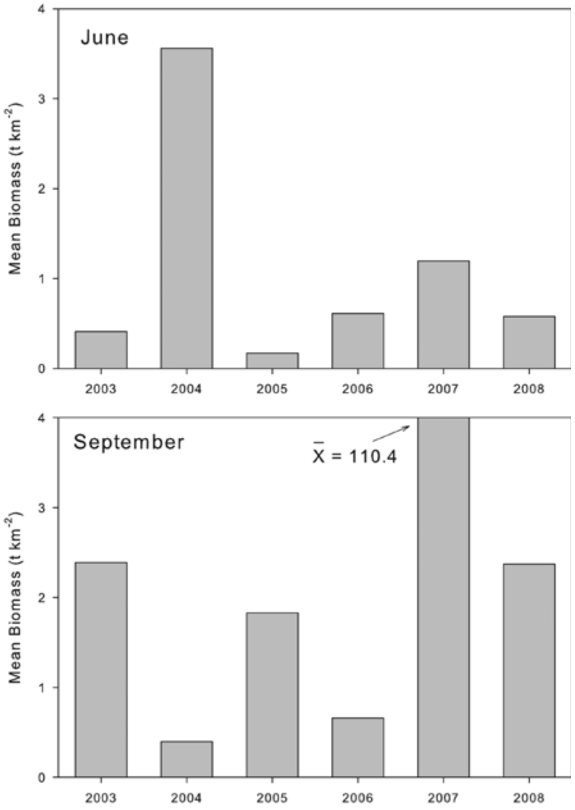


[Figure CC-29] Annual average densities of dominant fish larvae (top) and pelagic juveniles (middle) from September Stock Assessment Improvement Plan (SAIP) surveys during 2004-2008. Also shown are the mean chlorophyll concentrations.

observed in 2004 and very large numbers were observed in 2006. Pelagic juvenile hake appear in high concentrations in large-scale summer micronekton surveys off Oregon and Washington in June (Fig. CC-28) and September (Fig. CC-29) during most years. Pacific hake is generally the most abundant pelagic predatory fish in the northern California Current, but was found in very low abundances (2.6 per million m³) in 2008. These data and other information (Phillips et al. 2007) indicate that in recent years at least some Pacific hake do not appear to make their regular southerly spawning migrations to southern California, but perhaps spawn offshore off northern California or southern Oregon. Pacific hake numbers on the British Columbia continental shelf appeared to be low in 2008, continuing a trend that began developing around 2003-2004 (Crawford and Irvine 2009). On longer time scales, there has been a declining trend in pre-recruit (age-0) abundance and spawning biomass (Helser and Martell 2007; Sydeman and Elliott 2008; Sydeman and Thompson 2010).

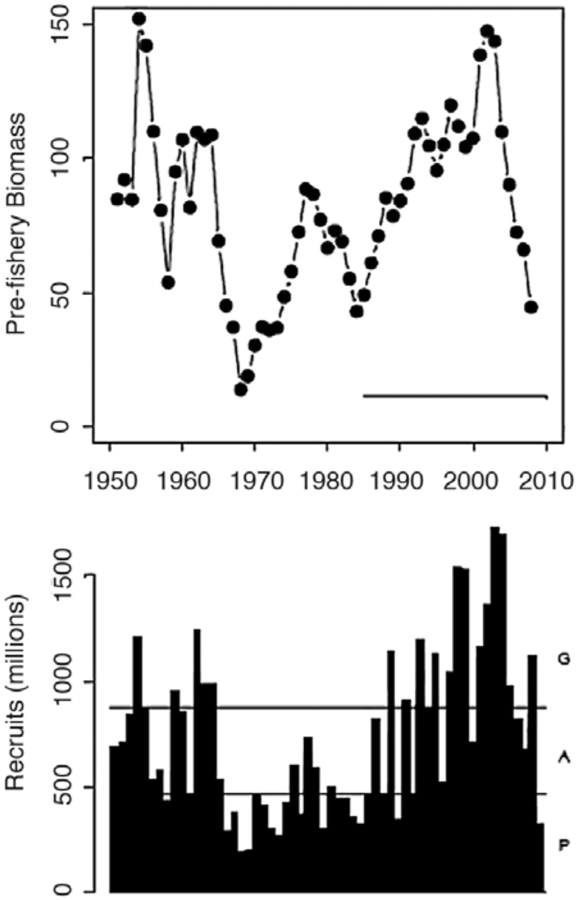
### 4.3.3 Pacific salmon

Pacific salmon (*Oncorhynchus* spp.) are among the most culturally important and economically valuable commercially fished species in the CCS. Significant fluctuations in salmon abundances and marine survival have occurred throughout the CCS during the focus period, leading to a number of dramatic management actions. Exceptionally low adult returns to California Central Valley occurred in 2007-2008 that was traced to poor survival of the 2005 and 2006 cohorts. The chinook (*O. tshawytcha*)



[Figure CC-30] Annual average biomass of large jellyfish in June (top) and September (bottom) from pelagic fish mesoscale surveys off Washington and Oregon during the 2003-2008.

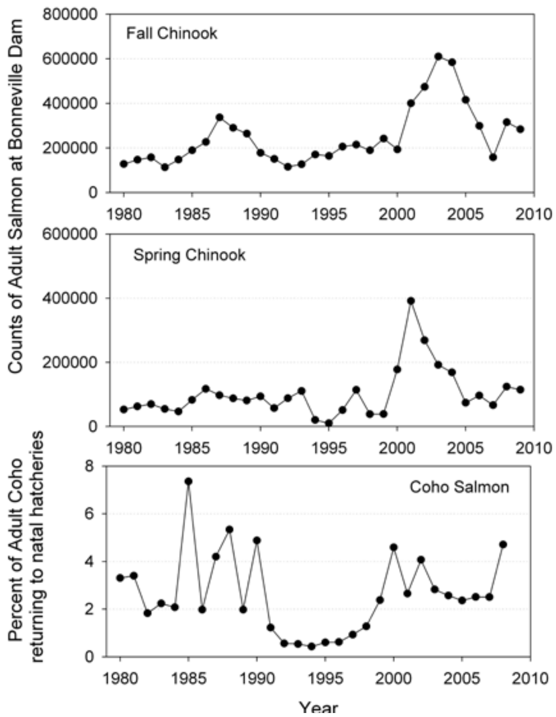
and coho (*O. kisutch*) salmon that emigrate from rivers from California to Oregon reside in coastal waters for a period of time before migrating up the coast. It is in these coastal waters that the greatest mortality occurs. A poor environment can lead to reduced early growth and ultimately poor survival and recruitment to the spawning stock (Beamish and Mahnken 2001; Beamish et al. 2004; Wells et al. 2008). Only 66,000 fall chinook returned to spawn in 2008, well below the minimum required to allow harvesting. The chinook salmon collapse may have been caused by climatic conditions that produced little food in the ocean (i.e., delayed upwelling in the ocean-entry year 2005) combined with a reliance on hatchery-reared salmon instead of wild salmon. The numbers of adult chinook salmon at Bonneville Dam, the lowest dam on the Columbia River, generally reflects the magnitude of salmon runs to this river. Fall Columbia River chinook salmon counts had a similar trend as fall Sacramento River chinook in California as well as forage fishes in the northern CCS,



[Figure CC-31] Pre-recruitment biomass and number of recruits of herring in Strait of Georgia stocks. The boundaries for poor (P), average (A), and good (G) recruitment are shown. (From Crawford and Irvine 2009).

with decreasing productivity from 2003-2007, particularly for fall chinook salmon (Fig. CC-32). The numbers of chinook salmon jacks (chinook males that spend two summers at sea before maturing) migrating past Bonneville Dam are good indicators of chinook salmon marine survival for Columbia River stocks. These clearly show declining marine survival from 2003-2005, then increasing since 2006 for most runs. Sockeye salmon returns to Bonneville Dam in 2008 (2006 ocean entry year) were the third highest since 1938, a rare example of a positive surprise for California Current salmon.

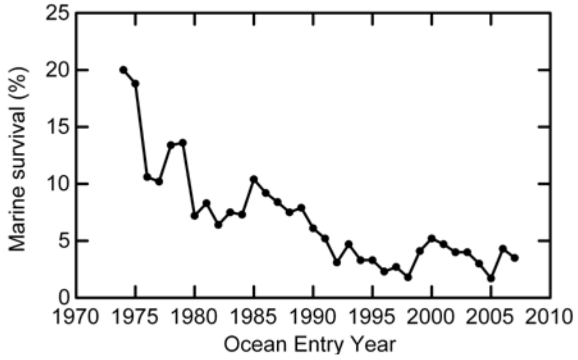
Estimates of coho salmon marine survival are made annually by the Pacific Fisheries Management Council (PFMC 2009). From 2003-2007 coho salmon marine survival was among the lowest on record, and similar to other salmon species (Fig. CC-33). There were regional differences, however, with Columbia River coho marine survival being higher



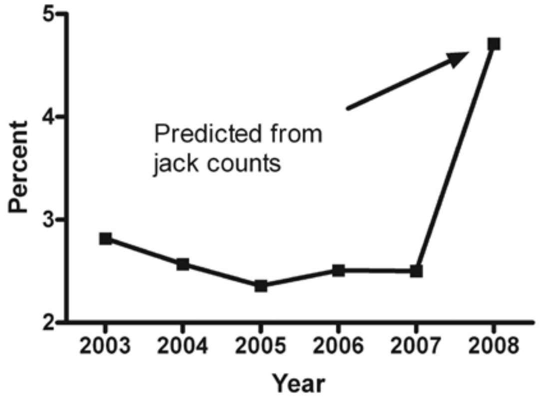
[Figure CC-32] Counts of adult spring and fall chinook salmon at Bonneville Dam, and survival of hatchery coho salmon returning to streams that enter the lower Columbia River. Note that the low returns in the 1990s was the period when coho salmon became listed as threatened under the U.S. Endangered Species Act.

than that observed in the mid-1990s. Predicted marine survival of coho salmon was higher for fish that migrated to sea in 2008 (Fig. CC-34). In 2008 and 2009, large numbers of sockeye salmon (*O. nerka*) returned to the Columbia River (Fig. CC-35). Preliminary analysis indicates that the large return in 2008 was due to good marine survival of fish migrating to sea in 2006.

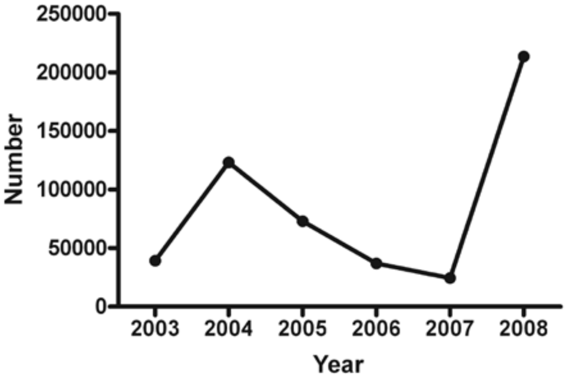
Although cooler oceans generally favour better survival for salmon, many British Columbia populations remain depressed because of low spawner numbers during 2003-2005 when conditions were less favorable (Crawford and Irvine 2009). Sockeye salmon returns were low coast-wide with the exception of Okanagan sockeye (Columbia River) that returned in record numbers in 2008 (Fig. CC-36). Coho salmon populations in southern British Columbia remain extremely depressed, while abundances of northern coho populations have improved. For chinook salmon, the situation is somewhat reversed. Northern populations continued to decline while the status of southern chinook is highly variable (Crawford and Irvine 2009).



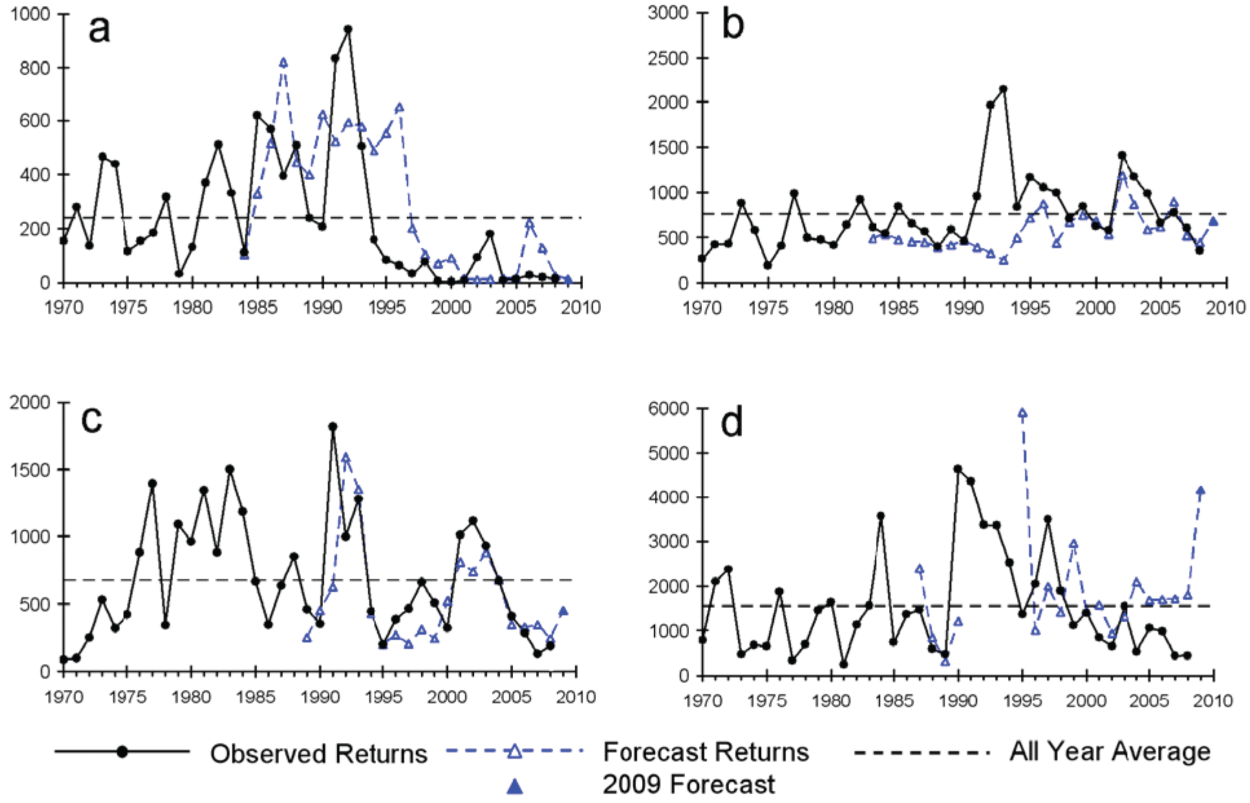
[Figure CC-33] Average marine survival of up to 45 coho salmon (*O. kisutch*) stocks in the northern California Current region by year of ocean entry. The lowest marine survival in the time series occurred when smolts went to sea in 2005.



[Figure CC-34] Oregon Production Index (OPI) for coho salmon (*O. kisutch*) marine survival during the focus period, 2003-2007 and a forecast for the 2008 release.

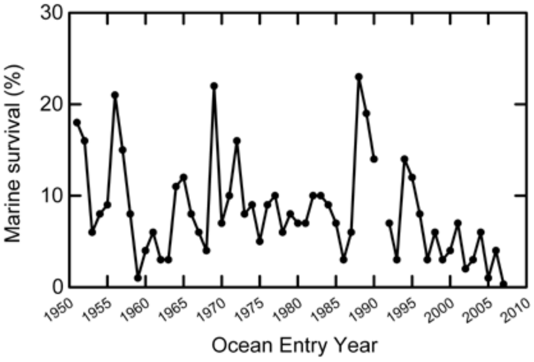


[Figure CC-35] Total numbers of sockeye salmon (*O.nerka*) migrating upstream past the Bonneville Dam on the Columbia River. (Data from Fish Passage Center website (http://www.fpc.org/fpc_homepage.html).



[Figure CC-36] Trends in the total returns (thousands of fish) and forecasts for British Columbia sockeye salmon index stocks: (a) Nass, (b) Rivers and Smith's Inlet, (c) Barkley Sound, (d) Fraser River (From Crawford and Irvine, 2009 – Fig. 14).

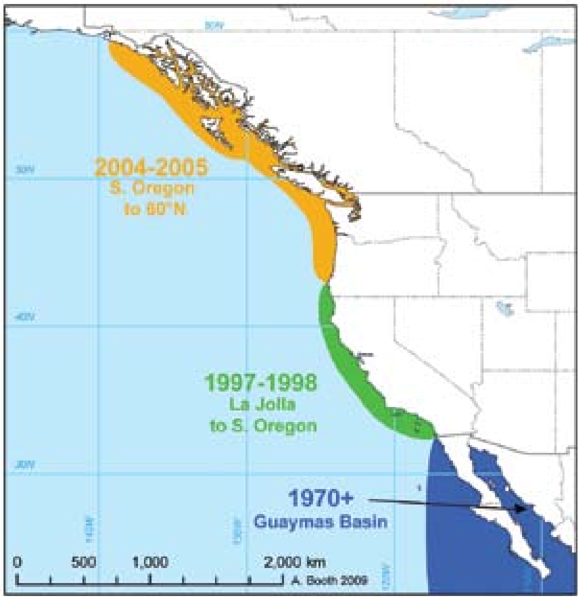
Sockeye salmon returns to the Fraser River in 2007 and 2008 (2005 and 2006 ocean entry years) were lower than expected and returns in 2009 were even worse. Marine survival of sockeye salmon from Chilko Lake (Fraser River drainage) was lower in 2003-2008 than during any equivalent period of this record (Fig. CC-37). The persistently low survivals in recent years resemble a shorter period of low survival that occurred in the late 1950s and early 1960s. These periods share a particularly disastrous ocean entry years for marine survival (1959 and 2005). The collapse of the Fraser River sockeye returns in 2009 was not a widespread event.



[Figure CC-37] Percentage of sockeye salmon smolts leaving Chilko Lake (Fraser River system) that return as adults, from 1951-2007. The worst survival on record occurred during the last year.

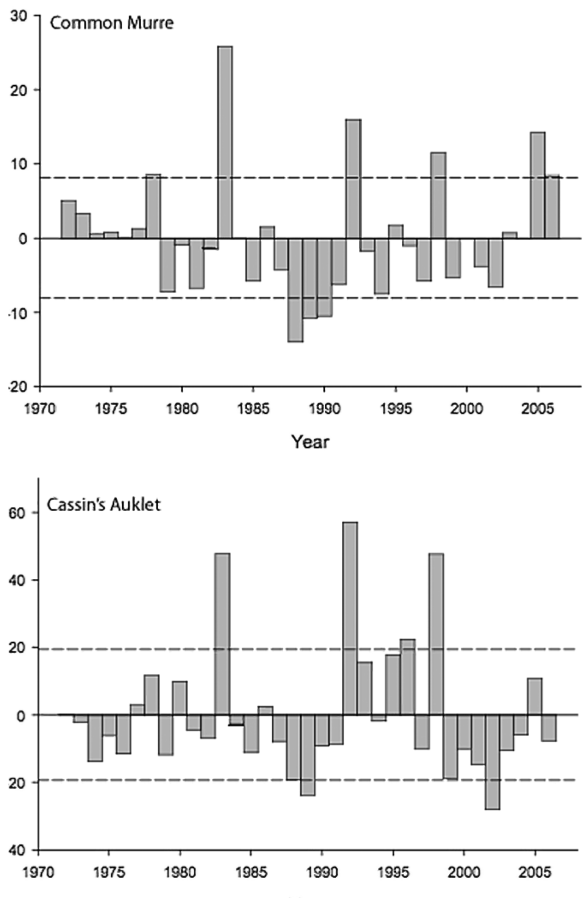
### 4.3.4 Humboldt squid

Prior to the 1997-98 El Niño, the Humboldt squid was an infrequent visitor to the U.S. waters of the CCS, yet since 2003 these animals have been regularly encountered in large numbers throughout the CCS in both the U.S. and Canada, and as far north as Southeast Alaska (Wing 2006; Zeidberg and Robison 2007; Field et al. 2007; Fig. CC-38). Although mature adults of both sexes have been encountered throughout the focus period, and demonstrated to have viable gametes as well as showing evidence of previous mating activity, zooplankton collections have provided no evidence that these squid are spawning in the northern waters of the CCS. Based on a qualitative interpretation of trends in catch rates from various fisheries and surveys throughout the CCS from 2003 to present, Humboldt squid appear to move north along southern and central California during late spring and early summer, showing up in surveys and commercial fisheries off Oregon, Washington and British Columbia during the late summer and early fall (particularly in the Pacific hake fishery, where Humboldt squid are frequently encountered as bycatch). They are then observed again off of California during late fall and early winter, suggesting a return migration of this population.



[Figure CC-38] Map showing the range expansion of Humboldt squid (*Dosidicus gigas*) in the eastern North Pacific.

The primary drivers of this apparent range expansion remain uncertain. It is possible that the large numbers of Humboldt squid observed since 2003, and particularly during 2005-2006, may have reflected changing ocean conditions (Gilly et al. 2006; Markaida 2006; Bograd et al. 2008). This period was characterized by unusually low upwelling, high stratification, and anomalous phenology, all of which contributed to the low productivity seen throughout many trophic levels (zooplankton, juvenile rockfish, salmon and seabird production) during those years. Although the impacts of the range expansion are not understood, a range of responses is plausible. Of some concern is the observation that many commercially important species, such as Pacific hake, Pacific sardine and several species of semi-pelagic rockfish are important prey of these animals (Field et al. 2007). Stock assessments for Pacific hake and sardine in particular have shown biomass declines over recent years. Although this could be a result of a wide range of factors, including non-causative covariation with the abundance of Humboldt squid, the poleward expansion of Humboldt squid has also been reported in the southern hemisphere where it appears to be affecting Chilean hake and other fisheries (Alarcón-Muñoz et al. 2008).



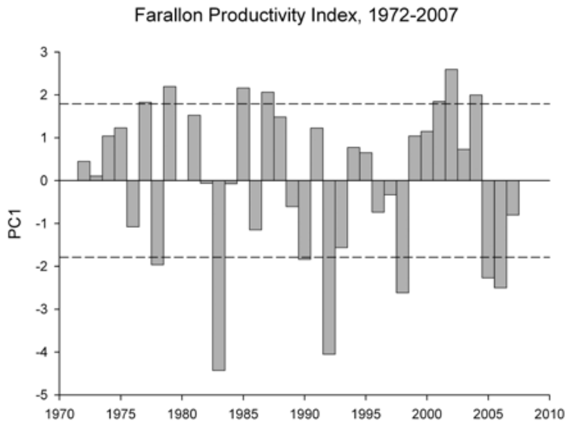
[Figure CC-39] Anomalies (day of year) of annual mean egg-laying dates for common murres (top) and Cassin's auklets (bottom) breeding on the Farallon Islands, California. Average day of year of egg-laying by murres is 134 (May 14) and by Cassin's auklet is 107 (17 April).

## 4.4 Marine birds and mammals

*(Sydeman, Munger, Barlow, Calambokidis, Hildebrand, Lowry, Manzano-Sarabia)*

### 4.4.1 Marine birds

There have been dramatic phenological changes in the reproductive cycles of CCS seabirds in recent years, presumably influenced by the changes in coastal upwelling (see section 2.2; Schroeder et al. 2009). Cassin's auklets did not show a change in their average annual egg laying date but the common murres were late laying eggs in 2005 and 2006 (Fig. CC-39; Sydeman and Thompson 2010). Trends and variability in reproductive success also varied by species. Reproductive success was substantially decreased for ashy storm-petrels and western gulls, while Brandt's cormorants had increasing reproductive success (Sydeman and Thompson 2010). Common murres, Cassin's auklets, rhinoceros auklets, pelagic cormorants, and pigeon guillemots have shown no overall change in reproductive success since the early 1970s. Common murres had somewhat consistent variation, with the exception of outliers, while Cassin's auklets had increasing variation in reproductive success measurements (Sydeman and Thompson 2010). Cassin's auklets were particularly affected by the unusually late upwelling in 2005, with nearly complete reproductive failure that year (Sydeman et al. 2006).

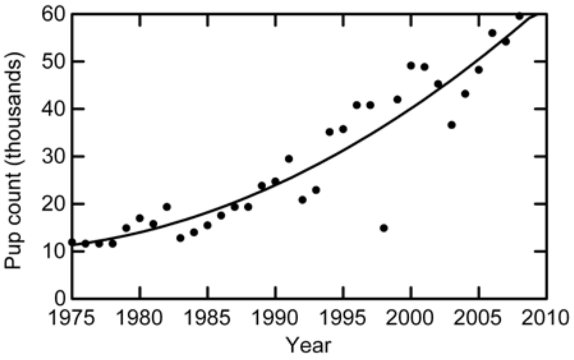


[Figure CC-40] The multivariate Farallon Productivity Index (Sydeman et al. 2001), based on the productivity of 6 seabird species: Cassin's auklet, common murre, Brandt's cormorant, pelagic cormorant, pigeon guillemot, and western gull.

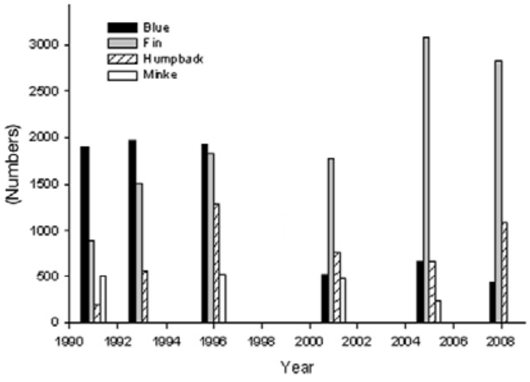
The multivariate *Farallon Productivity Index* (Fig. CC-40; Sydeman et al. 2001, Sydeman and Thompson 2010) reveals the same patterns of variability, with overall community failure during the El Niño years of 1983, 1992, and 1998 (all < -1 s.d.), a period of reasonably high productivity from 1999-2003 (> 1 s.d.), very poor productivity in 2005 and 2006 (< -1 s.d.), and poor productivity in 2007. The changes observed in seabird communities and population parameters in the CCS are consistent with predicted responses to climate change: (i) mean egg-laying dates for one species (murres) became earlier through time; (ii) species preferring colder waters (i.e., shearwaters and auklets) became less abundant; and (iii) productivity of some species declined and this was related to changes in the abundance/availability of their prey (zooplankton and forage fish). There was also an increase in variance in the productivity for one species (Cassin's auklet). The years 2005 and 2006 were particularly interesting with major declines in seabird productivity related to changes in their prey base (see Section 4.3.2). The years 2007 and especially 2008 (Warzybok and Bradley 2008) were more productive years, with recovery of seabird productivity to near average levels.

### 4.4.2 Pinnipeds

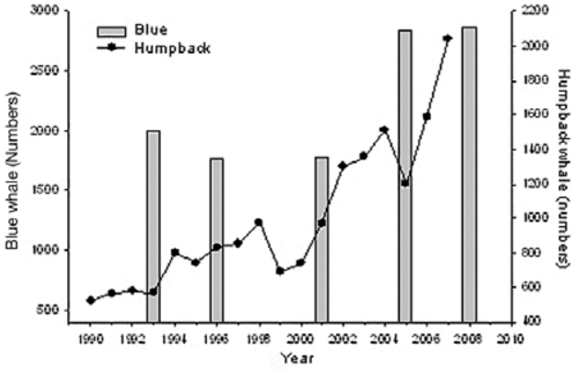
The breeding biology of California sea lion (*Zalophus californianus*) has been monitored on California's Channel Islands since the mid 1970s (Lowry and Maravilla-Chavez 2005). A trend for increasing numbers of pups counted during the 1970s, 1980s, 1990s, continued during the 2000s (Fig. CC-41). There was a substantial decline in pup counts during the weak El Niño of 2003, followed by increases in 2006 and 2008. The decline during this El Niño was similar to the drop-off during the 1992-1993 El Niño, but it was not as severe as the decline during the 1997-1998 El Niño.



[Figure CC-41] Counts of California sea lion pups (*Zalophus californianus*) on the Channel Islands, California, 1975-2008. The quadratic trend line was estimated from the data.



[Figure CC-42] Summer/fall baleen whale feeding populations in the California Current, 1991-2005. Data from Barlow and Forney (2007) and Barlow (in press).



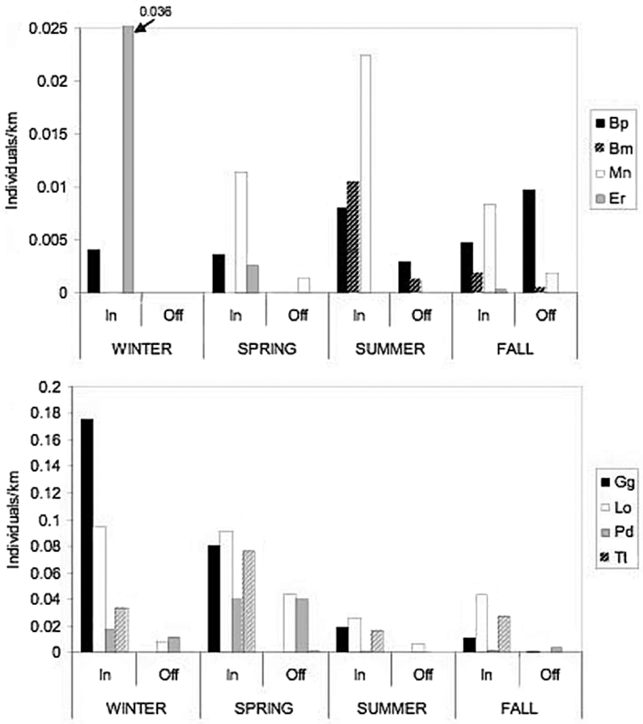
[Figure CC-43] Blue and humpback whale abundances in the California Current from sighting-resighting photo-identification surveys. Data from Calambokis et al. (2007) and Calambokidis (2009).

### 4.4.3 Cetaceans

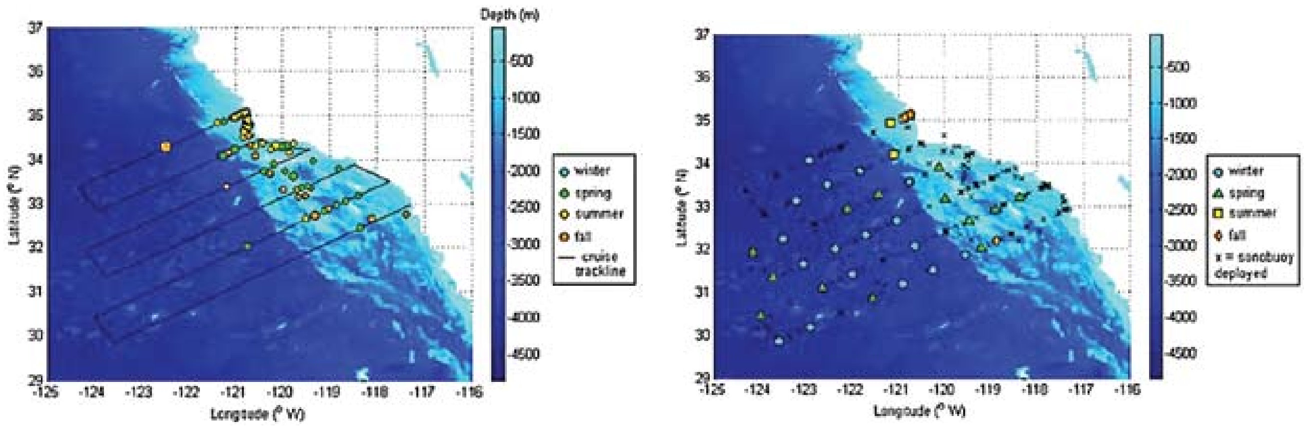
Systematic line transect surveys of cetaceans during the summer and fall throughout the California Current were conducted in 1991, 1993, 1996, 2001, and 2005 (Barlow and Forney 2007). These surveys provide information on the seasonal abundance of feeding whale populations. Ecosystem-scale feeding population surveys are supplemented with detailed photographic studies of individually identifiable whales (Calambokidis et al. 2007; Calambokidis 2009) to provide information on year-round whale abundance for humpback and blue whales.

Summer/fall feeding populations of fin whales have been increasing, with numbers exceeding 2800 individuals in 2008 (Fig. CC-42). Blue whales feeding in the California Current were much less abundant in 2001 and 2005 than during earlier survey years, but evidence suggest this reflects a re-distribution to more northerly feeding areas rather than a real decline in abundance (Calambokidis 2009). Estimated numbers of summer/fall feeding humpback and minke whales from line-transect surveys have been variable. Overall, the population of humpback whales in the California Current has been increasing at roughly 8% per year (Fig. CC-43; Calambokidis 2009). During 2005, there was an apparent decrease in abundance, but in 2006-2007 the population increases resumed. Blue whales have also increased in recent years, with approximately 2,800 estimated during the focus period.

The seasonal and spatial distribution patterns of cetaceans in the Southern California Bight were assessed using combined visual and acoustic surveys conducted during 18 quarterly CalCOFI cruises from summer 2004 through fall 2008 (Soldevilla et al. 2006). The most frequently sighted odontocete species were common dolphin (*Delphinus* spp.) (n=347 sightings), Dall's porpoise (*Phocoenoides dalli*) (n=58), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) (n=57), Risso's dolphin (*Grampus griseus*) (n=27), bottlenose dolphin (*Tursiops truncatus*) (n=23), and sperm whale (*Physeter macrocephalus*) (n=24). The most frequently sighted baleen whale species were humpback (*Megaptera novaeangliae*) (n=74 sightings), fin (*Balaenoptera physalus*) (n=69), gray (*Eschrichtius robustus*) (n=41), and blue whale (*Balaenoptera musculus*) (n=39). Some species distributions varied seasonally and spatially (Fig. CC-44). Gray whale and Dall's porpoise were sighted primarily in winter and spring, whereas blue whale was only detected in summer and fall. Species detected predominantly inshore (depth <2000 m) included gray whale, Risso's dolphin, bottlenose dolphin, and long-beaked common dolphin (*D. capensis*). Species detected both inshore and offshore included Dall's porpoise, Pacific white-sided dolphin, short-beaked common dolphin (*D. delphis*), and blue whale. Fin whales were only detected inshore in spring, whereas during other seasons they were detected both inshore and offshore.

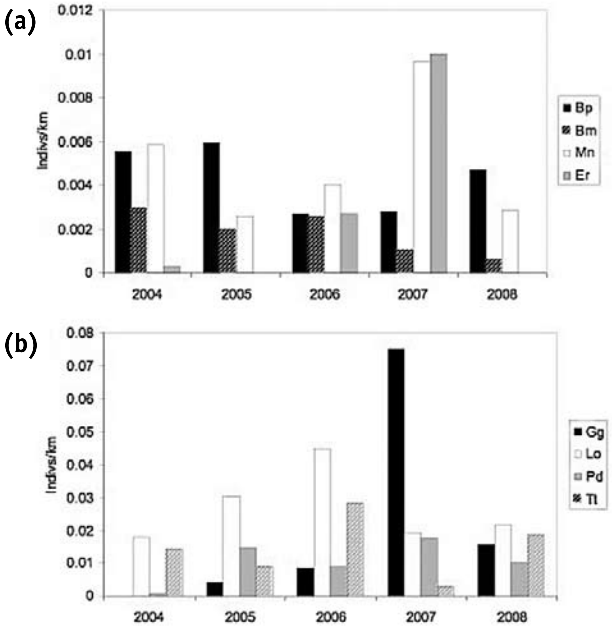


[Figure CC-44] Seasonal distribution of selected species from visual data in the Southern California Bight, 2004-2008. In = inshore of 2000 m, Off = offshore of 2000 m. (Top) Bp = fin whale, Bm = blue whale, Mn = humpback whale, Er = gray whale. (Bottom) Gg = Risso's dolphin, Lo = Pacific white-sided dolphin, Pd = Dall's porpoise, Tt = bottlenose dolphin.



[Figure CC-45] Humpback whale visual detections (left) and acoustic detections (right) from 2004-2008.

For some species the seasonal distribution of visual sightings varied markedly from acoustic detections. Humpback whales were visually detected in spring through fall primarily inshore, whereas they were acoustically detected offshore in winter and spring (Fig. CC-45). These contrasting patterns suggest that the probability of detecting animals visually or acoustically varies depending on their seasonal distribution and behavioural state, e.g. foraging, migrating, and social or reproductive interaction. In 2007 and 2008, the number of blue whale seen per km decreased from the number seen in 2004-2006 (Fig. CC-46). In 2007 there was also a slight decrease in Pacific white-sided dolphin per km and an increase in Risso's dolphin (Fig. CC-46b) and humpback whale (Fig. CC-46a).



[Figure CC-46] Annual number of individuals sighted per km of trackline in the Southern California Bight, 2004-2008. (a) Bp = fin whale, Bm = blue whale, Mn = humpback whale, Er = gray whale. (b) Gg = Risso's dolphin, Lo = Pacific white-sided dolphin, Pd = Dall's porpoise, Tt = bottlenose dolphin.

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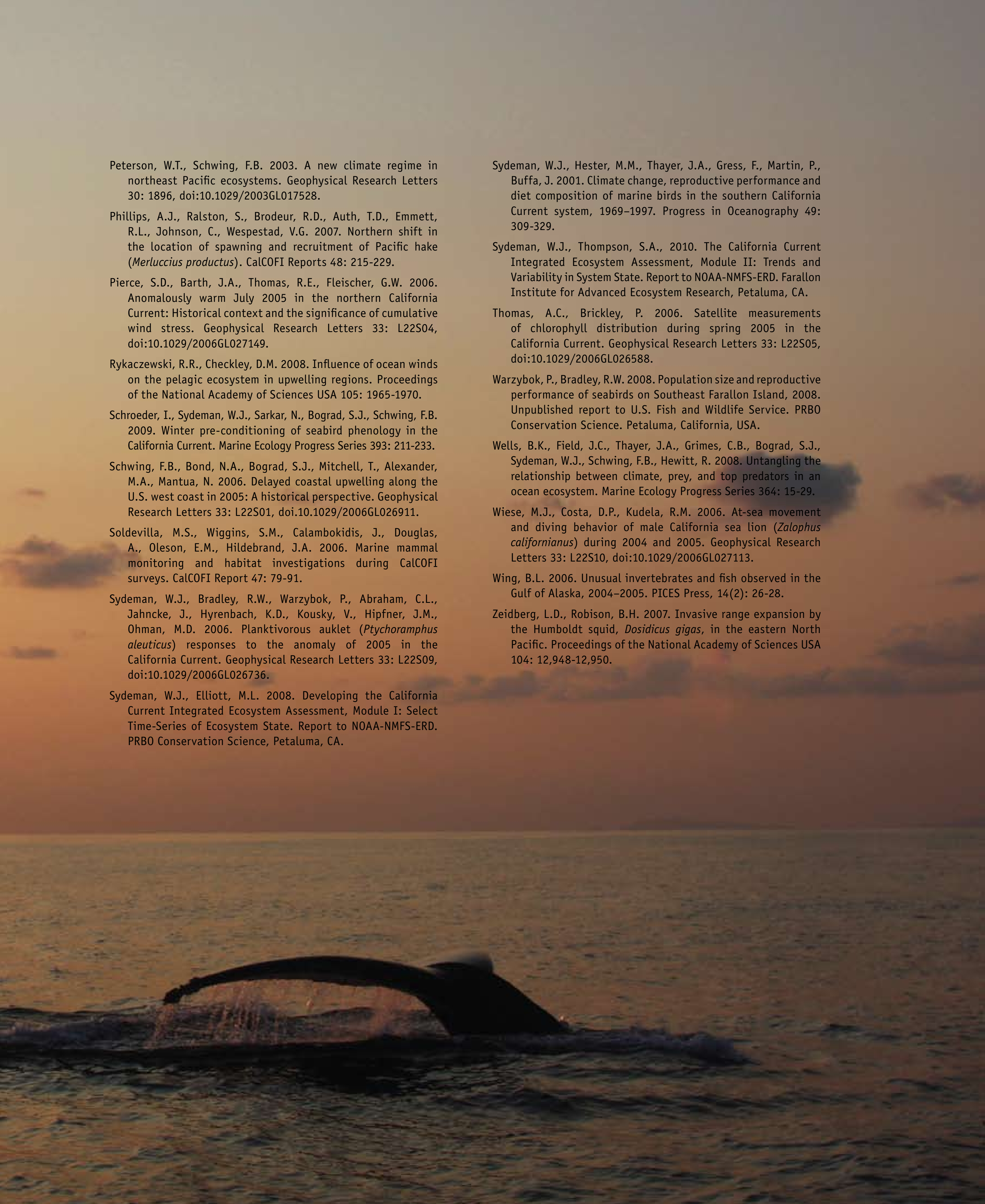

# Marine Ecosystems of the North Pacific Ocean 2003-2008

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# Alaska Current

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# highlights

- Despite some colder than average years, the overall effects of a preponderence of years of relatively warm surface temperatures during the last three decades were particularly apparent in coastal areas in the Gulf of Alaska during the *focus period*. Rapid recession of most glaciers, emergence of new coastal land and displacement of tide lands in response to the loss of glacial mass, larger than usual swings in precipitation, freshwater runoff, winds, and coastal storms in the last few years are all consistent with the effects of climate change anticipated in coastal Alaska.

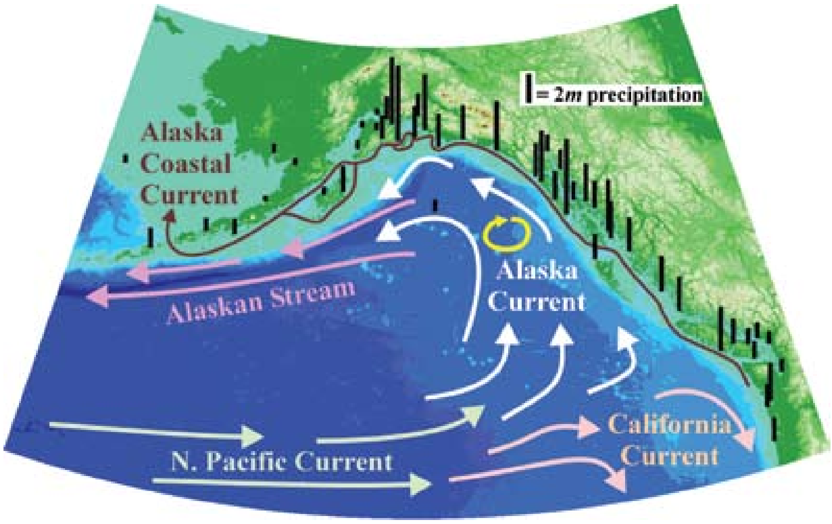
- Marine areas showed the effects of a move from very warm to very cold conditions. Pronounced annual changes in widely used indicators of climate and ocean conditions emphasized the instability of atmospheric and oceanographic conditions during the *focus period*. Warm years in 2003 – 2005 were followed by cold years in 2007 – 2008. Although sea surface temperatures in 2004 and 2005 were among the warmest on record, the water column in the north central Gulf (GAK 1) in 2007 and 2008 was colder than in the previous three decades.

- The timing and magnitude of primary and secondary productivity varied in concert with the shift from warm to cold conditions. The cross-shelf spatial extent of the spring phytoplankton bloom in the Gulf of Alaska was reduced in 2003 and the fall phytoplankton bloom was virtually non-existent in 2004 and relatively weak in 2006. In contrast, the spring bloom in 2007 was robust. During the relatively cold springs of 2006 – 2008, the spring bloom was delayed by several weeks, as was the development of the zooplankton community. Changes in zooplankton size and species composition occurred and the complex of southern species apparent in 2004-2005 became rare. Small copepods such as *Pseudocalanus* dominated the catch during warm years, whereas *Neocalanus plumchrus/flemingeri* was higher than average during cold years.

- Annual production of the key commercially exploited demersal species increased or remained stable from 2003-2008, even as production of crabs, shrimp and herring remained depressed outside of the southeastern Gulf of Alaska. No groundfish stock or stock complex is currently overfished and no groundfish stock or stock complex is being subjected to overfishing.
- A general depression in crab and shrimp production in the Gulf of Alaska has been apparent since the early 1980s. High catches of Tanner crab and flatfish, that were recorded in inshore net survey samples from 2003-2008, provide an indication of a possible recovery in these resources.
- Prominent piscivorous fish species were largely unchanged in biomass from 2003-2008 with one notable exception. While sablefish and rockfish remained stable, walleye pollock production reversed a long downward trend. Arrowtooth flounder continued to be one of the most abundant and widely distributed piscivorous fish species in the Gulf of Alaska.
- Some fish species appear to be changing geographic distribution from 2003-2008. The mean-weighted distribution of Gulf of Alaska rockfish (1990–2007), especially juvenile Pacific Ocean perch, appeared to be farther north and east and was more contracted in 2007, possibly indicating a change in rockfish distribution around. Further evidence of a change in the distributions of benthic fishes was the increase in lingcod bycatch in commercial fisheries in the northwestern Gulf of Alaska starting in 2005, increasing dramatically in 2008.
- Marine mammals showed overall growth and stability from 2003-2008 with the notable exceptions of beluga whales and the northern and western Steller sea lion. Populations of humpback whales in Gulf of Alaska were apparently at the highest recorded levels. Beluga whale is at extremely low abundance, making the extirpation of this species from the Gulf of Alaska a serious concern. Northern and western Steller sea lions remain at very low population levels, however those of southeastern Gulf of Alaska are at normal levels and continued to increase during the *focus period*.

# Introduction

The Gulf of Alaska (GoA) coastal area is comprised of the shoreward Alaska Coastal Current (ACC), the offshore Alaska Current (AC) and Alaskan Stream and the eddies and meanders that cross them (Fig. GA-1). The currents may extend along the continental shelf and shelf break as far south as the mouth of the Columbia River and as far west as the Aleutian Islands (Reed and Schumacher 1986; Thomson et al. 1989; Royer 1998). The GoA (Fig. GA-1) is bounded on the east and north by tall, rugged mountains that are separated by a continental shelf from abyssal depths in excess of 3000 m in the eastern Gulf of Alaska to more than 7000 m in the Aleutian Trench. The continental shelf has a total area of approximately 370,000 km² and ranges from 5 to 200 km in width. Islands, banks, ridges, and numerous troughs and gullies cut across the shelf, resulting in a complex bathymetry that promotes an exchange between shelf water and deeper waters. The coastal mountain range captures large amounts of precipitation from low pressure systems originating in the west, resulting in large volumes of nutrient-poor freshwater runoff into coastal areas (Weingartner et al. 2009). Freshwater buoyancy and local winds drive the nearshore ACC.



[Figure GA-1] Diagram of the predominant ocean currents and average annual precipitation at onshore stations (bars) from Danielson et al. (2000).

Situated on the inner third of the continental shelf, the ACC provides a sizeable and ecologically important transition zone between the shallow, nearshore communities and the outer-shelf and oceanic pelagic ecosystems. Fed by runoff from glaciers, snowmelt, and rainfall, the well-defined coastal current is marked by a freshwater output about one and a half times that of the Mississippi River (Weingartner et al. 2005). It flows consistently to the north and west around the northern GoA from British Columbia to Unimak Pass on the Aleutian archipelago. The ACC distributes subarctic plankton communities around the region and into protected inside waters such as Prince William Sound (Kline 2006). During the summer months, the ACC has local reversals and small eddies which can concentrate plankton and small fishes in convergence zones, for foraging fish, birds, and marine mammals.

Offshore of the ACC, the AC has its origins in the North Pacific Current (Fig. GA-1). The North Pacific Current flows eastward from Asia between about 30°N and 45°N and bifurcates as it approaches the west coast of North America (Reed and Schumacher 1986). The broad and sluggish (3-6 $m \cdot min^{-1}$) Alaska Current carries variable portions of the warm North Pacific Current northward along the coasts of northern British Columbia and Southeast Alaska into the northern GoA (Freeland 2006). The AC turns westward in the northern Gulf of Alaska where it is separated from the less nutrient rich ACC by a highly variable mid-shelf region enveloped in salinity fronts. The mid-shelf region of the northern GoA is characterized by pronounced changes in water properties, chemistry, and species compositions of phytoplankton, zooplankton, and fish along cross-shelf gradients. Superimposed on these cross-shelf gradients is considerable mesoscale variability resulting from eddies and meanders in the boundary currents (Weingartner et al. 2002; Stabeno et al. 2004; Crawford et al. 2006; Ladd 2007). Forced to the south by the Alaska Peninsula the AC continues as the much swifter (18-60 $m \cdot min^{-1}$) Alaskan Stream as it follows a southwestward course along the Alaska Peninsula and the Aleutian archipelago (Weingartner et al. 2009). A portion of the Alaskan Stream turns south and recirculates as part of the North Pacific Current, closing the loop to form the Alaska Gyre. The position of the North Pacific Current and the volume of water transported vary on interannual and decadal time scales, with associated variations in the Alaska Current (Parrish et al. 2000; Freeland 2006).

This chapter contains a review of the status and trends of the Alaska Current region from 2003-2008, hereafter the *focus period*.

## 2.0 Atmosphere *(Bond)*

The overall effects of a preponderance of years of relatively warm surface temperatures during the last three decades continued to be apparent in the Gulf of Alaska during the focus period. Rapid recession of most glaciers, emergence of new coastal land and displacement of tide lands in response to the loss of glacial mass, larger than usual swings in precipitation, freshwater runoff, winds, and coastal storms in the last few years are all consistent with the effects of climate change anticipated in coastal Alaska.

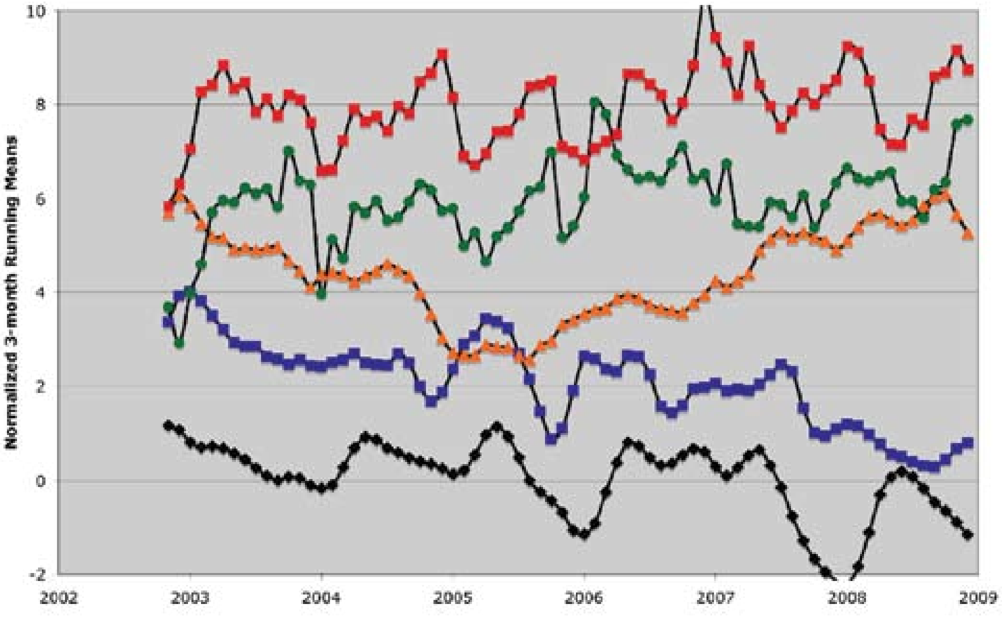
Sharp changes in short-term climate during the focus period preclude establishing a clear climate regime in the GoA. The very warm years of 2003-2005 were followed by very cold years in 2007 and 2008. Negative values of the Pacific Decadal Oscillation (PDO) developed in late 2007 and have persisted into 2008, but it remains highly uncertain whether the PDO will remain negative for an extended period. Summer temperatures from 2003 to 2005 in the GoA were among the warmest on record and coincided with a shift in forcing. The SST-based Victoria pattern, after being in its positive phase during 1999-2004, had a phase reversal in 2005. It was not consistent, however, with its atmospheric counterpart, a north-south dipole in sea level pressure (SLP). Instead, the anomalous SLP in 2005 featured an east-west dipole consisting of a negative anomaly centered along 170°W from 40°N into the Bering Sea, and a positive anomaly in the eastern Pacific from 40°N into the GoA. This combination brought about southerly wind anomalies and an enhancement of cyclonic activity for the Bering Sea shelf, and a suppression of storminess in the eastern North Pacific.

Significant anomalies in the forcing of the GoA occurred in the winter of 2006-2007 and the spring of 2007. The former featured anomalous southwesterly winds that combined with the prevailing seasonal winds to provide enhanced wind mixing and enhanced positive wind stress curl and hence upward Ekman pumping. The net effect, based on Project Argo data, was a relatively shallow mixed layer in the central GoA, and a deep mixed layer close to the coast at the end of winter of 2007, when compared with the previous year. During spring 2007, anomalously low SLP was present in the central GoA, which promotes anomalous downwelling in the coastal zone and a relatively strong ACC.

## 2.1 North Pacific climate and SST indices

The large-scale atmosphere-ocean climate system of the eastern North Pacific can be characterized in terms of five indices (Fig. GA-2). First, the NINO3.4 index represents the state of the El Niño/Southern Oscillation (ENSO), which is important because of its systematic impacts on higher latitudes. There appear to be two robust modes of eastern North Pacific oceanic variability, the Pacific Decadal Oscillation (PDO), which is the leading mode of North Pacific sea surface temperature (SST) variability, and the weaker but still biologically important, North Pacific Gyre Oscillation (NPGO) (DiLorenzo et al. 2008). The two principal atmospheric indices considered here are the North Pacific Index (NPI) and the Arctic Oscillation (AO). The NPI is one of several measures used to characterize the strength of the Aleutian Low. The AO signifies the strength of the polar vortex, with positive values signifying anomalously low pressure over the Arctic and high pressure over the Pacific and Atlantic at a latitude of roughly 45° N, and hence anomalously westerly winds across the northern portion of the Pacific and Alaska.

Time series of these five indices are shown in Fig. GA-2 for the period of winter the 2002-2003 through the winter of 2008-2009. The NINO3.4 index was positive early in the focus period (a moderate El Niño occurred during the winter of 2002-2003) and mostly negative late in the period in association with the moderate La Niña of the winter of 2007-2008 and the weaker La Niña during the following winter. The PDO tracked the NINO3.4 index quite closely but with a slightly more prominent decreasing trend. The decline in the PDO was accompanied by a concomitant decline in the SST along the western coast of North America from the Bering Sea to Baja California. The NPGO was positive at the start and end of the period and negative in the mid portion. A positive phase of the NPGO tends to be associated with anomalously strong equatorward flow in the California Current and relatively strong cyclonic flow along the periphery of the Gulf of Alaska. The NPI was negative at the very start of the period in association with an anomalously deep Aleutian Low, and then varied with season, with a tendency for positive values during the last half. The AO fluctuated around a neutral state on close to an annual basis. In summary, the eastern North Pacific Ocean experienced a full range of climate conditions during the focus period.

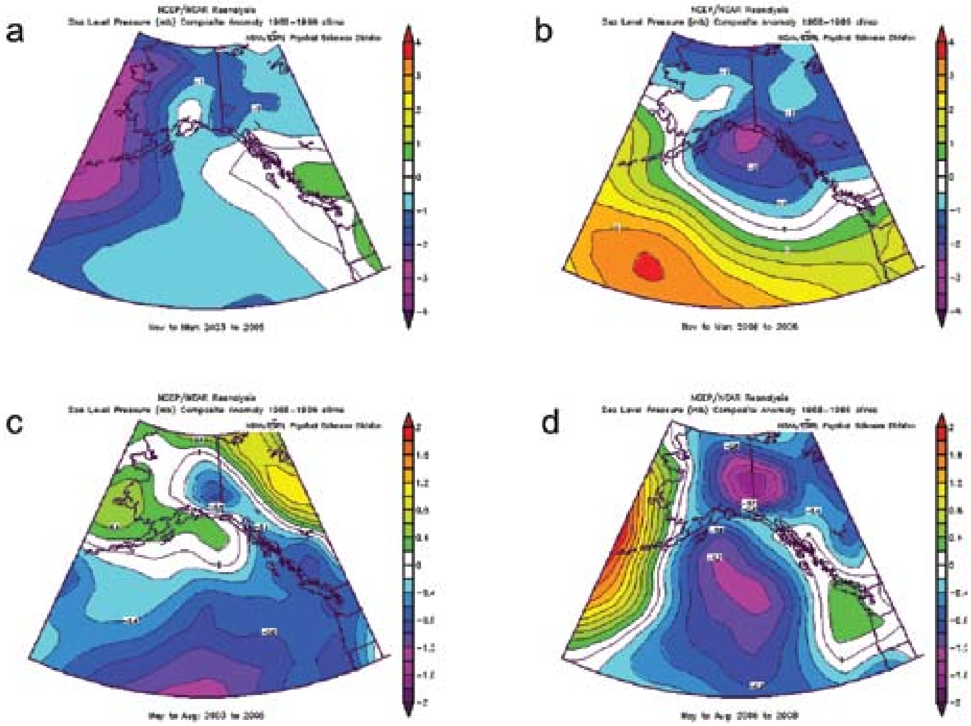


[Figure GA-2] Time series of 3-month running means of NINO3.4 (black), PDO (blue), NPGO (orange), NPI (green) and AO (red). All time series are normalized by their standard deviations, with offsets of 2 units between the individual series.

## 2.2 Regional circulation patterns

Regional-scale weather can be summarized with maps of seasonal mean SLP. These maps were examined for individual cool and warm seasons of the focus period. The cool (warm) season is defined as November-March (May-August) and represents the period when the net heat flux is consistently upward (downward) at the air-sea interface. This examination revealed that there was a marked shift at roughly the halfway point in the focus period with substantial commonality in the individual years comprising each half of the period. The state of the regional atmospheric circulation is therefore illustrated with composite maps of anomalous SLP for the cool seasons of 2003-2005 and 2006-2008, and for these groups of warm seasons separately (Fig. GA-3).

The cool seasons of 2003-2005 (Fig. GA-3a) featured relatively low SLP over the Bering Sea and high SLP over western North America from British Columbia to California. The consequence for the GoA was anomalous low-level winds from the south, which tend to be accompanied by relatively warm and wet conditions. A much different pattern prevailed in the cool seasons of 2006-2008 (Fig. GA-3b) which included anomalously high SLP extending from the Bering Sea towards the U.S. mainland, with a small but prominent area of low SLP in the GoA. This configuration implies an anomalously cold flow from the northwest for the western portion of the GoA and a relatively stormy environment for the central and eastern portions, including enhanced snowfall over the coastal terrain. The warm seasons of 2003-2005 (Fig. GA-3c) had relatively weak SLP anomalies with a tendency for higher (lower) SLP than normal in the western (eastern) half of the GoA, indicating generally weak wind anomalies from the north. The warm seasons of 2006-2008 on the other hand, had a mean pattern with high SLP over the Bering Sea and off the coast of the Pacific Northwest with low SLP over the GoA (GA-3d). This pattern indicates a modest enhancement in storminess and Ekman pumping in the central GoA. In an overall sense, the GoA was subject to regional forcing promoting relatively warm conditions early in the period with a shift to the opposite sense close to midway through the period.



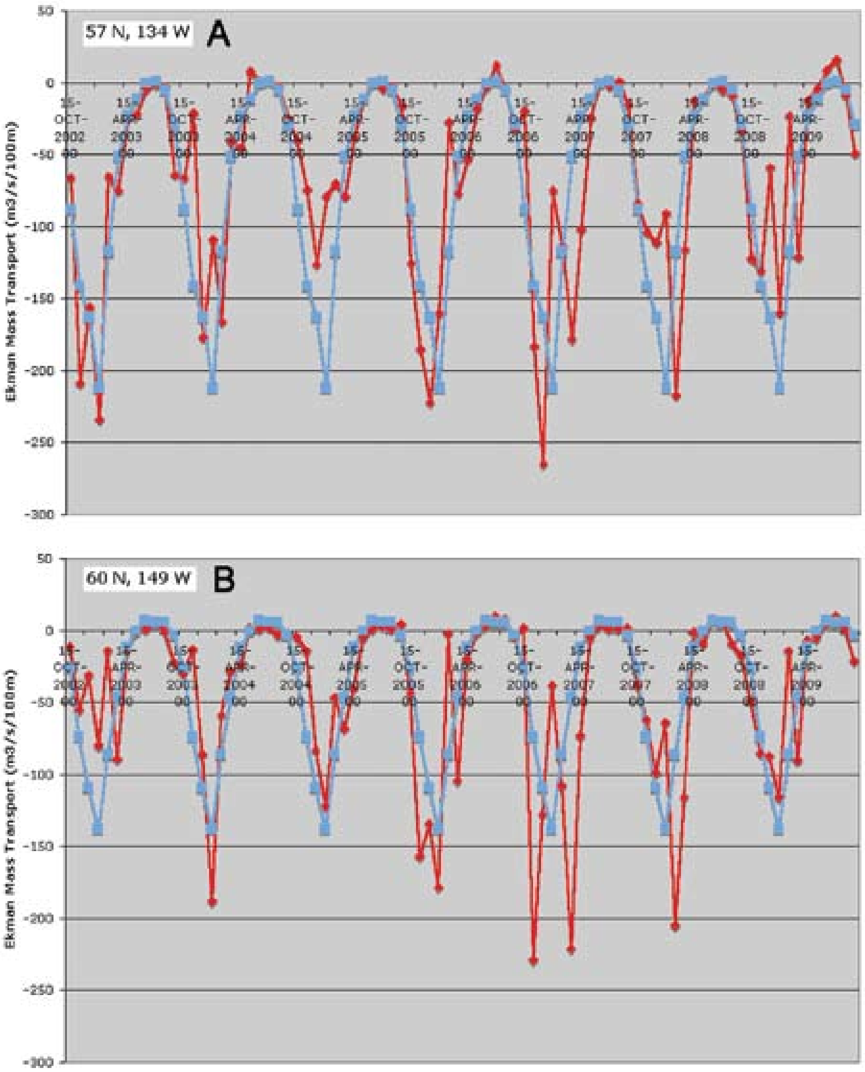
[Figure GA-3] Composite SLP anomalies for (a) the winters (November-March) of 2003-2005, (b), the winters of 2006-2008, (c), the summers (May-Sep) of 2003-2005, and (d) the summers of 2006-2008, from the NCEP/NCAR Reanalysis. The baseline period is 1968-1996. The contour intervals are 0.5 hPa and 0.25 hPa for the winter and summer SLP distributions, respectively.

## 2.3 Local atmospheric forcing

The local atmospheric forcing of the GoA is summarized here with regards to two variables important to the flow on the shelf, the upwelling component of the winds and freshwater runoff. The upwelling winds relate to cross-shelf flows in the ocean with implications for nutrient concentrations and along-shore mass transport on the shelf (Stabeno et al. 2004). The along-coast winds in the GoA help control the locations of boundaries between waters of different origin with different lower-trophic level communities. Freshwater runoff is a key aspect of the baroclinity that is prominent on the GoA shelf during the summer and fall seasons.

The upwelling winds that occurred along the GoA during the focus period are illustrated using monthly mean time series of upwelling indices at 57°N 134°W (near Sitka) and 60°N 149°W (near Seward) from NOAA's Pacific Fisheries Environmental Laboratory (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/PFELindices.html).

Upwelling along the GoA coast exhibits a clear annual cycle between strong downwelling in the cool season (peaking in January) and near-zero upwelling during the summer months (Fig. GA-4). The focus period included less downwelling than normal at Sitka (Fig. GA-4a), with the winters of 2004-2005 and 2008-2009 featuring especially weak downwelling. On the other hand, Seward (Fig. GA-4b) experienced substantially weaker than normal downwelling only during the winter of 2002-2003, and for the period as a whole, mean winds were near average. The summer months at both locations were characterized



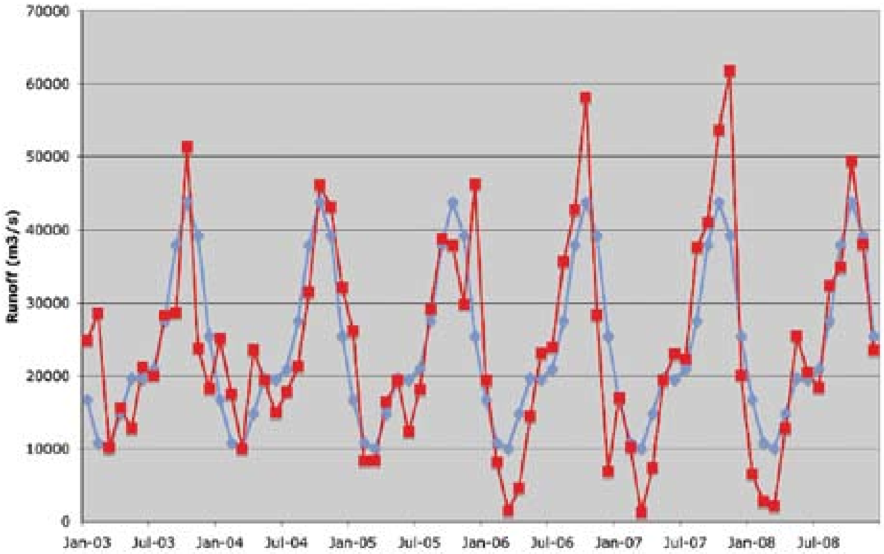
[Figure GA-4] Monthly mean upwelling (red line) near Sitka, Alaska (upper panel) and Seward, Alaska (lower panel) expressed in terms of total vertical mass transports per 100 m of coastline. The blue line indicates the climatological average.

not only by near zero winds (in the mean), but also very small month to month fluctuations. It is unknown whether these small fluctuations are sufficient to materially affect the physical and biochemical properties of the shelf waters during the summer. The timing of the cessation of the winter downwelling in spring, and its resumption in the fall varies considerably from year to year. In addition, there appears to be quite a bit of along-coast coherence in the variations in this timing. For example, both stations had weak downwelling in the spring of 2006 and relatively early onsets of strong downwelling late in 2006. The effects of anomalous upwelling/downwelling are expected to persist longer in the summer months when the flow is more sluggish, than during the cool season, especially in the near coastal region. As an aside, the Alaskan Stream is part of the deeper, gyre circulation and is impacted largely by basin-scale mechanisms on multi-year time scales.

Freshwater runoff during the focus period and its climatological mean were estimated using a simple hydrological model (Royer 1982) (Fig. GA-5). For the interval of 2003-2005, runoff was close to average, with minor month-to-month anomalies. The period from 2006-2008 features an enhanced seasonal cycle with anomalously low runoff in the spring and high runoff in the fall. This can be attributed to the relatively cold winters and cool and dry springs of 2006-2008, which resulted in a higher snow:rain ratio in coastal watersheds and a delayed snow melt. The relatively high estimated streamflows during recent autumns (especially 2006 and 2007) imply enhanced baroclinity for the ACC.

## 2.4 Sitka, Alaska *(Lam)*

The weather record for Sitka is the longest reliable regional climate record (mid-1800s to present) in the GoA. Atmospheric records at other localities in Alaska have only been kept for at most 60 years. Subsurface ocean temperature anomalies are correlated with air temperature anomalies at Sitka well enough for the air temperatures to have been used to infer ocean temperature near Seward (60°N 149°W) back to 1828 (Royer 1993). Nevertheless, the degree to which climate may be coherent throughout the GoA varies seasonally and interannually due to differences in coastal topographies and short term climate events such as ENSO (Royer 1989). For example, steep mountains on the GoA eastern boundary west of 150°W cause annual precipitation in the western coastal GoA to be substantially less than in the eastern coastal GoA (Fig. GA-1). Sitka precipitation is characteristic of the freshwater inputs from coastal mountain ranges on the eastern and northern boundaries of the Gulf and it is therefore a useful proxy for understanding the history of the oceanography of the coastal Gulf of Alaska. The precipitation captured by the coastal mountains of British Columbia and Alaska drives the Alaska Coastal Current (Royer 1981).



[Figure GA-5] Estimated monthly mean runoff ($m^3 \cdot sec^{-1}$; red line) for the entire Gulf of Alaska. The blue line indicates the climatological average.

The Sitka climate record was reconstructed from a combination of sites within the city. While under Russian control, precipitation was first recorded in 1842. Following the transfer of ownership to the United States, temperature was added in 1867. This record stopped in 1921. The Sitka Magnetic Observatory, located close to the coast, was established in 1899 to monitor magnetic deviations in the region and to continue the climate record. Due to the similarity between the Russian data and the Sitka Magnetic Observatory data, they were merged. On April 1, 1942, the Sitka Magnetic Observatory was moved 1 mile inland, and then in 1948, weather observations were started at the Sitka Airport near the coast. The climate record from the Sitka Airport was combined with the Sitka Magnetic Observatory dataset.

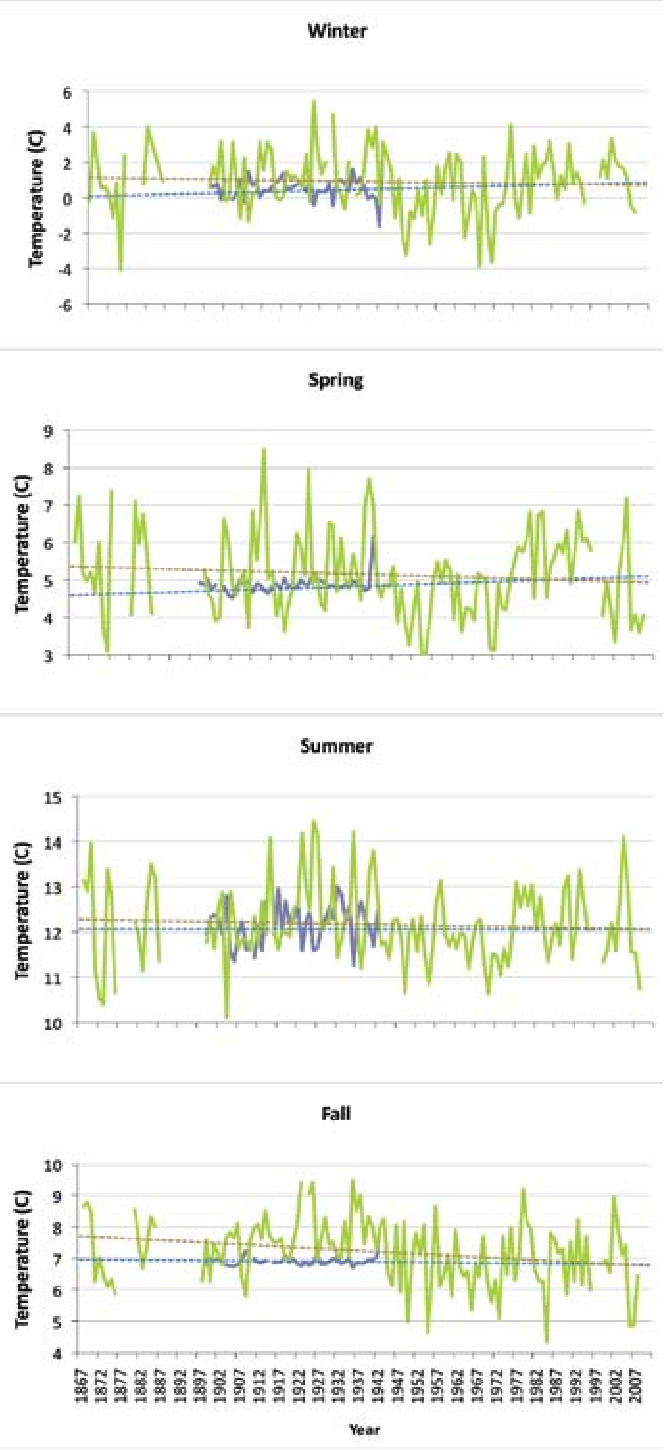
Trend analysis was performed on the temperature and precipitation datasets (Table GA-1). It should be noted that the focus period of 2003-2008 contained a distinctly warm interval (2003-2005), a distinctly cold interval (2007-2008), and a transitional year (2006). The temperature and precipitation trends per century are summarized by season (winter, spring, summer, and fall) (Figs. GA-6 and GA-7). For most periods except fall, these data indicate a warming trend in Sitka (Fig. GA-6). For most periods except summer, it is becoming increasingly wetter in Sitka (Fig. GA-7). From 2004 to 2008, Sitka experienced warmer than average summer and winter temperatures (+0.2°C warmer than the long-term averages), and wetter-than-average winter, summer, and fall. Fall temperatures in these years are much cooler, about -0.8°C below the long-term averages.

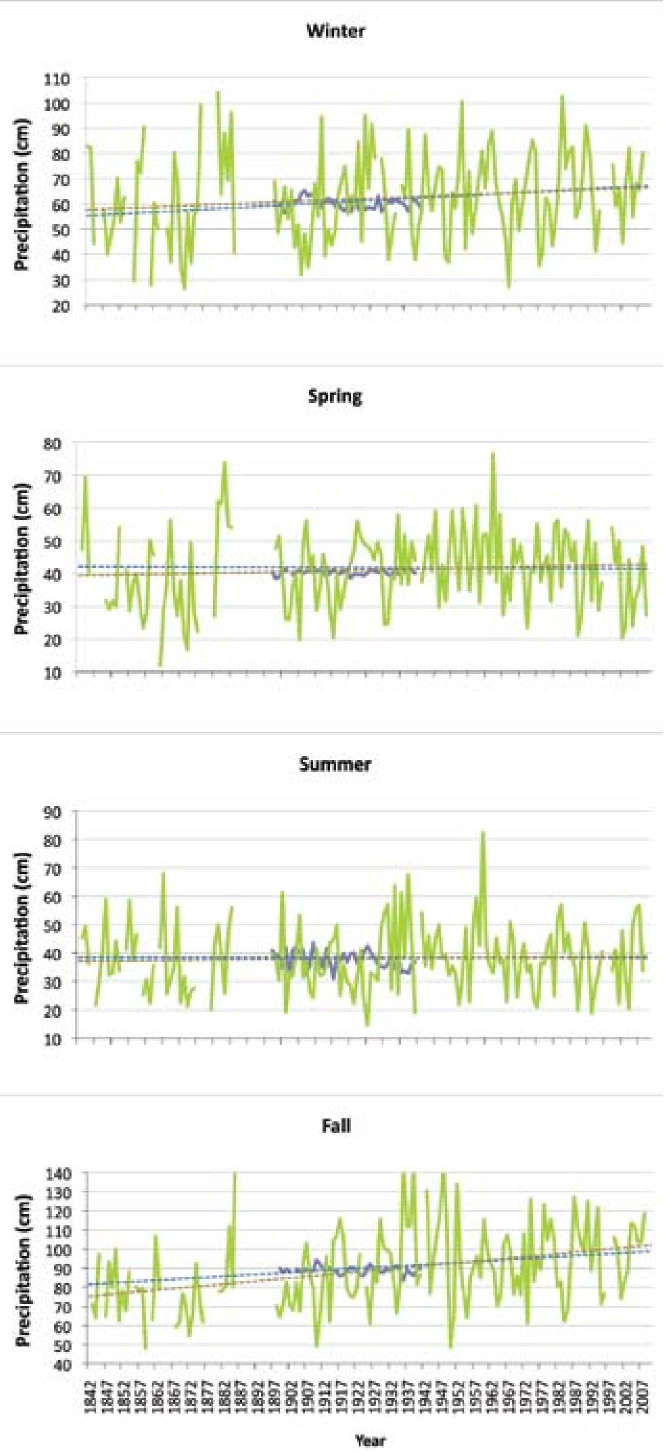
On an annual basis, air temperatures at Sitka changed on average about +0.28°C (ranges from -0.33 to +0.94°C) per century for the past 150 years. The dominant periodicity for the time series is about 55 years, and it can explain up to 28% of the variances in the time series. The 2004-2008 average annual temperature is about 0.05°C cooler than the long-term averages. Although the climate of Sitka is primarily maritime, it can occasionally be influenced by a more continental air mass from the east. The contrast between warm, wet maritime and cool, dry continental climate regimes is most significant in late fall and winter. Therefore, it is not surprising that a long-term warming trend in the winter is often accompanied by a long-term trend for increased precipitation (Schnetzler and Dierking 2008).

Annual precipitation from 2004 to 2008 is about 22.9 cm more than the long-term average. Winter, summer, and fall precipitation during 2004 to 2008 are greater than the long-term averages. From 2004 to 2008, winter precipitation is about 7.6 cm greater than the long-term average, summer precipitation is about 5 cm wetter than the long-term average, and fall precipitation is about 20 cm wetter than the long-term average. In contrast, spring precipitation from 2004 to 2008 is about 5 cm below the long-term average.

[Table GA-1] Summary showing long-term climate trend and recent climate in relationship to long-term averages.

| Period | Temperature trend (°C per century) | 2004-2008 temperature relative to long-term average (°C) | Precipitation trend (cm per century) | 2004-2008 precipitation relative to long-term average (cm) |
|---|---:|---:|---:|---:|
| Annual | +0.29 | -0.06 | +20.78 | +22.86 |
| Winter | +0.64 | +0.17 | +5.72 | +7.47 |
| Spring | +0.29 | +0.0 | +0.08 | -5.05 |
| Summer | +0.17 | +0.23 | -0.18 | +4.52 |
| Fall | -0.06 | -0.81 | +14.58 | +20.00 |





[Figure GA-6] Time series of average annual temperature in Sitka, AK from 1867 to 2008. Note that there are intermittent breaks in the data, especially before 1990. The green color is the location bias-corrected data (taking station move into account). The blue color is the dataset created by estimation using the average annual temperature time series from Juneau, Alaska.

[Figure GA-7] Time series of annual precipitation in Sitka, AK from 1867 to 2008. Note that there are intermittent breaks in the data, especially before 1990. The green color is the location bias-corrected data (taking station move into account). The blue color is the dataset created by estimation using the average annual precipitation time series from Juneau, Alaska.

# 3.0 Hydrography

The focus period includes significant transitions in ocean temperatures in the northern GoA upper (0-100 m) and lower (>100 m) layers. While conditions in 2003-2005 were characteristic of the continued warming of near-surface waters, northern GoA mean ocean temperatures decreased in the winter of 2006-2007 and remained below normal through 2008.

## 3.1 Hydrographic conditions at GAK1

*(Janout, Weingartner)*

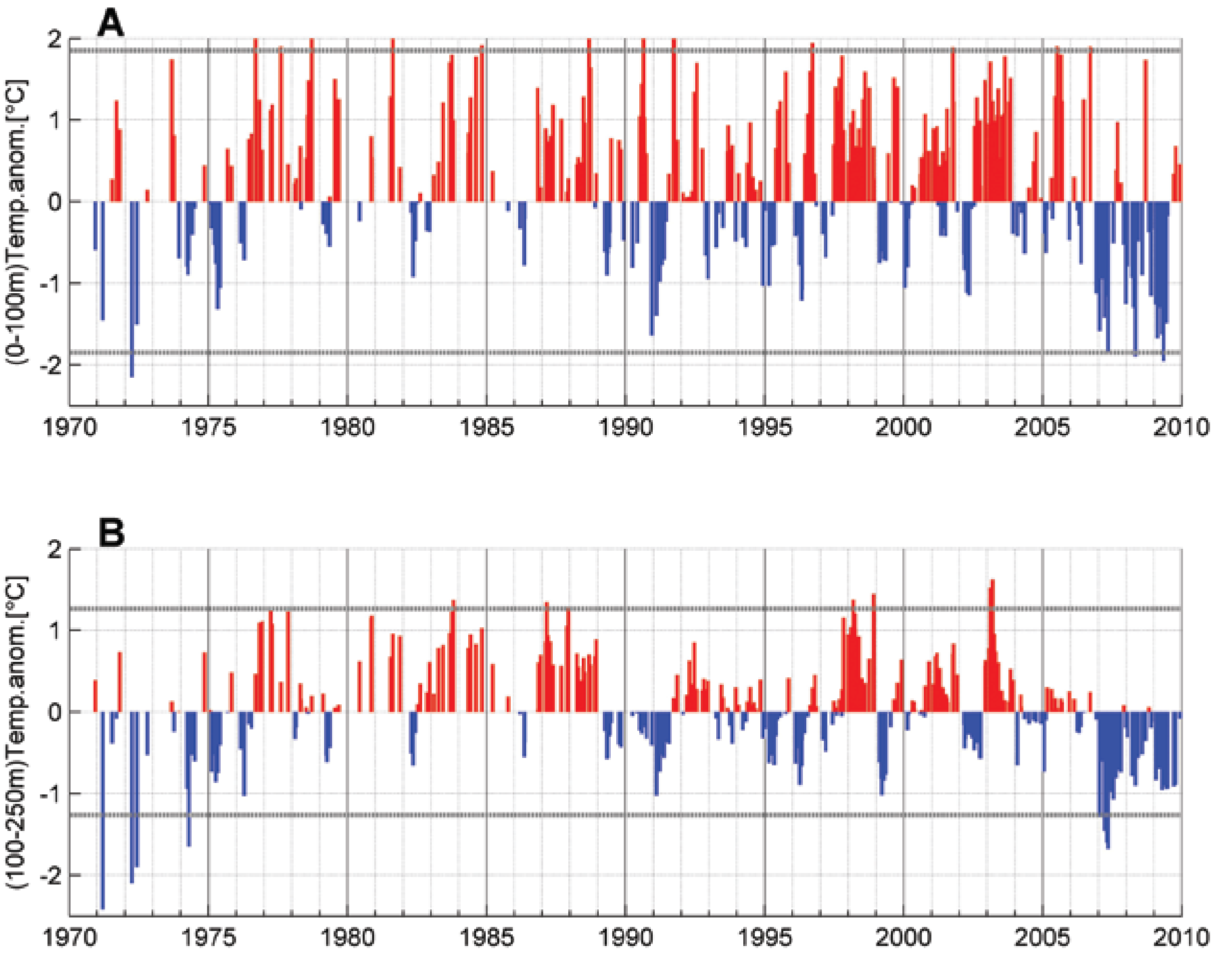
The coastal monitoring site, GAK1, is located at the mouth of Resurrection Bay (~59.8°N, ~149.5°W) where the water depth is 263 m. It is the longest hydrographic time series in the northern GoA with >450 CTD profiles collected during nearly 40 years of sampling. The CTD database is complemented by ~8 years of moored temperature and salinity records. GAK1 is the inshore station of the Seward Line, which was extensively sampled (6-7 surveys per year) during the Northeast Pacific GLOBEC program (1997-2004, Weingartner et al. 2002) and has been surveyed bi-annually since 2005 with support from the North Pacific Research Board.

The focus period includes significant transitions in ocean temperatures in the northern GoA upper (0-100 m) and lower (>100 m) layers (Fig. GA-8). While conditions in 2003-2005 were characteristic of the continued warming of near-surface waters (Royer and Grosch 2006) after the 1976-1977 regime shift (Mantua et al. 1997), northern GoA mean ocean temperatures decreased in the winter of 2006-2007 and remained below normal to present (Janout et al. accepted). The moored GAK1 temperature record suggests that the cooling began in November 2006 when strong northerly winds rapidly cooled the anomalously warm waters that were prevalent in summer 2006. Stratification was weakened by reduced coastal freshwater runoff (Royer 1982) and strong wind mixing. Near-normal atmospheric winter conditions from December-February were followed by anomalously strong heat loss in March 2007, which led to the lowest ocean temperatures since the early 1970s. The annual Seward Line monitoring in May 2007 recorded temperatures ~1.5°C lower than the May average throughout the water column, while salinity was higher (lower) than normal in the upper (lower) layer (Fig. GA-9). In May 2008 and 2009, upper layer temperatures were comparable to those of 2007 while the lower layer was slightly warmer than in 2007, although still colder than average. Seward Line temperature anomalies show that the recent cooling extended over much of the shelf in both the upper (0-100m) and lower (>100m) layers (Fig. GA-10).

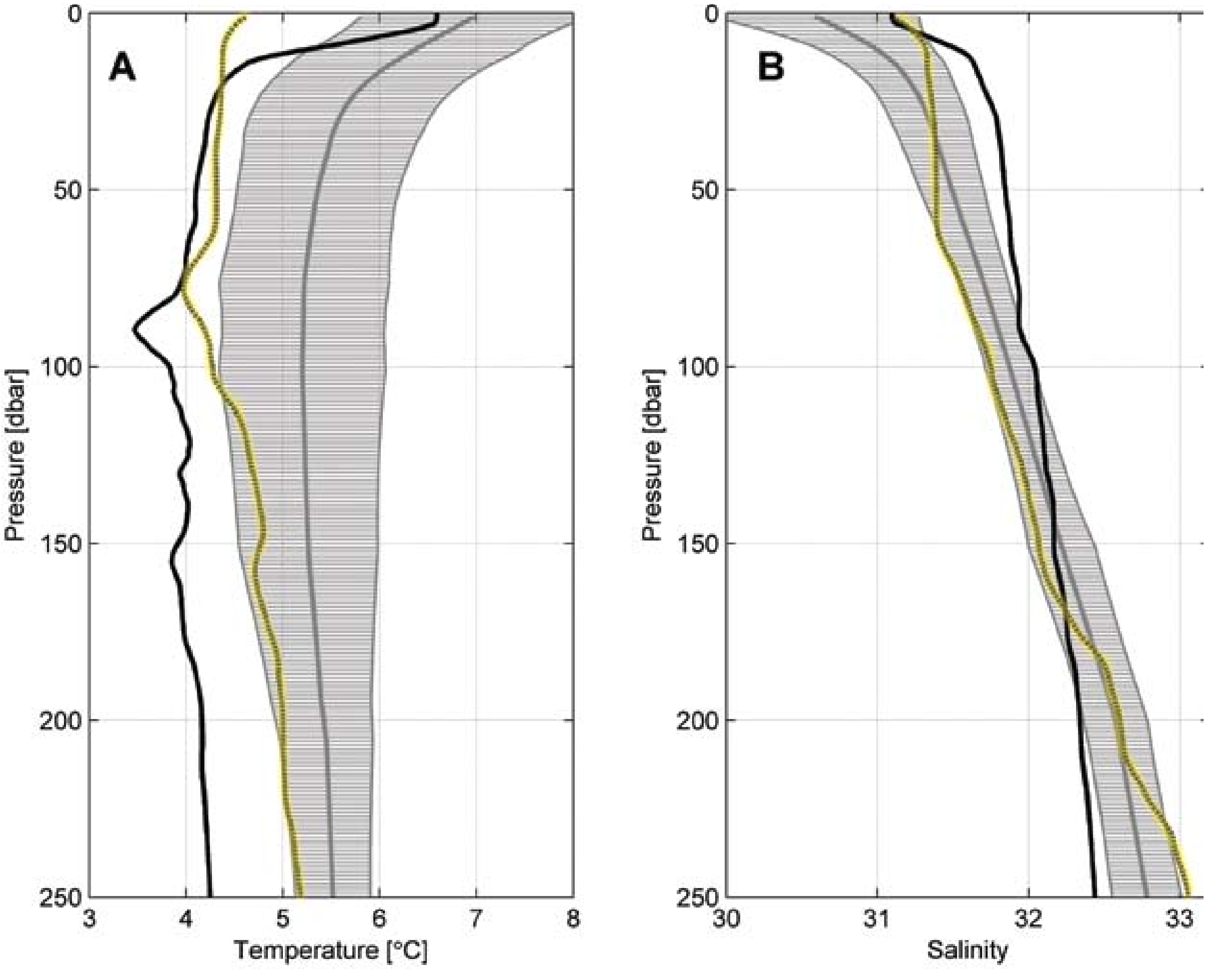
Salinity stratification, i.e. the difference between 20 m and 100 m salinities, appears to play a crucial role in shaping the lower layer temperatures at GAK1. In fact, stepwise regression analysis suggests that salinity stratification (governed by coastal freshwater runoff) and air-sea heat fluxes explain ~80% of the variability in deep temperatures (Janout et al. accepted). Therefore, the salinity stratification during the focus period followed the trend of the temperature anomalies, where 2003-2005 (2006-2008) showed anomalously strong (weak) salinity stratification. The weakest stratification, coincident with the lowest ocean temperatures since the early 1970s, was observed in spring 2007.

Besides its governing role on salinity stratification, coastal freshwater runoff is one of the forces behind the wind- and buoyancy-driven ACC (Weingartner et al. 2005). The baroclinic (i.e. freshwater–driven) portion of the ACC is estimated to be 70-90% (Williams et al. 2007), depending on the season, and therefore freshwater runoff significantly impacts the temperature variability in the northern GoA. Interestingly, geostrophic velocities in the ACC in May 2007, computed from the Seward Line density structure, were the lowest May values within the 1998-2009 record. This implies that the along-shore heat advection in the ACC was reduced and likely contributed to the anomalous cooling in spring 2007.

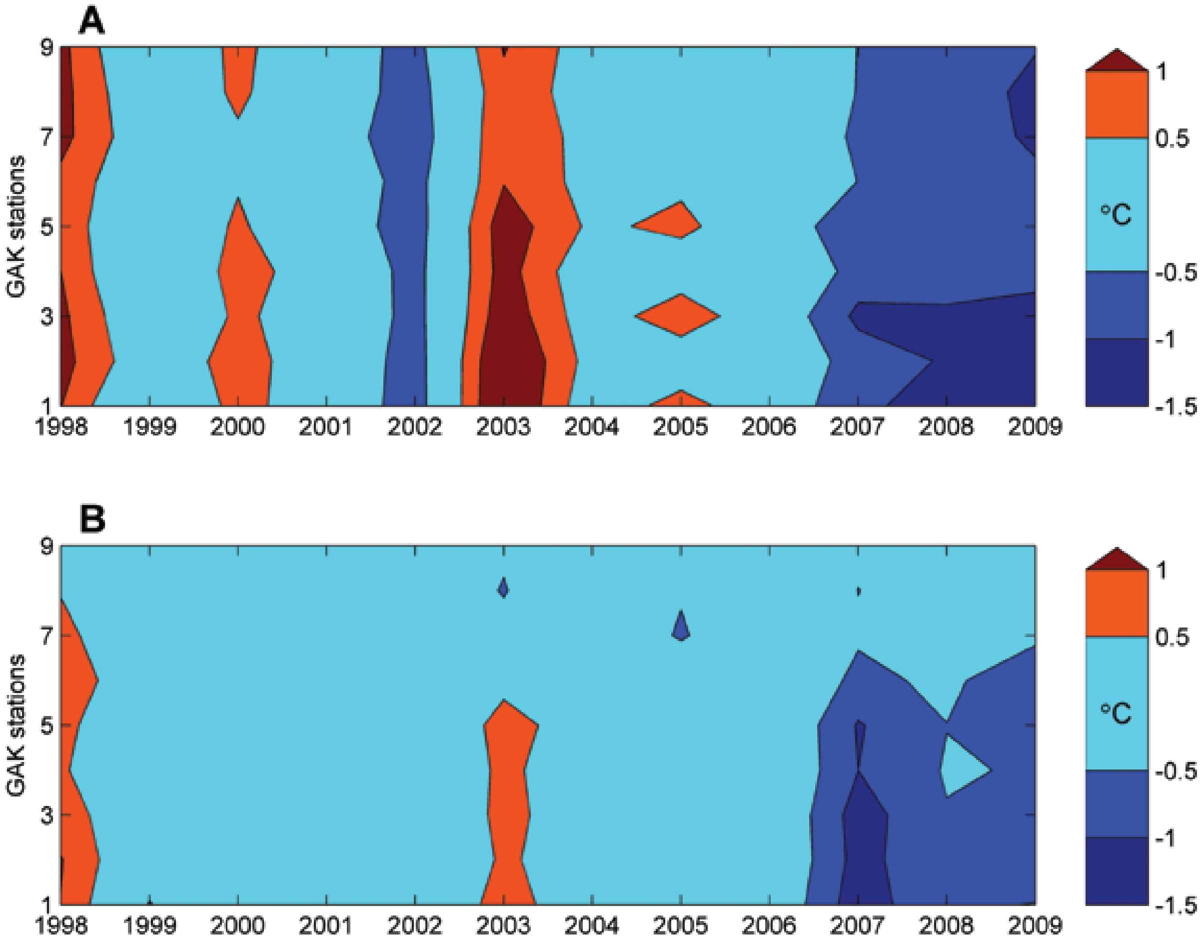
In summary, in late 2006, the northern GoA experienced a sudden shift in ocean temperatures, from warmer waters characteristic of the ocean climate after the 1977 regime shift, to colder conditions comparable to the early 1970s. This recent cooling coincided with enhanced northerly winds, which increased air-sea heat fluxes and reduced coastal runoff. The analysis of the GAK1 mooring and CTD record showed that the temperature variations in the upper layer are mainly the result of thermodynamic processes, while lower layer temperatures may in addition be regulated by salinity stratification, which is the result of three-dimensional processes affecting the freshwater dispersal on the northern GoA shelf.



[Figure GA-8] Upper layer (A) and lower layer (B) temperature anomalies at GAK1 from ~1970 to present.



[Figure GA-9] May 2007 (solid) and May 2008 (dashed-yellow) (A) temperature and (B) salinity profiles in comparison with the average May (~1970-2008 ) profiles (grey) including the range of ± 1 s.d.



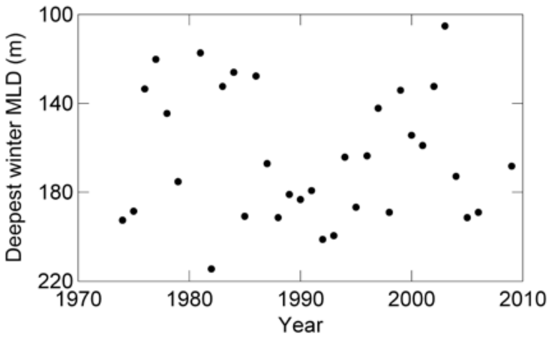
[Figure GA-10] Mean (A) upper (0-100 m) and (B) lower (>100 m) layer temperature anomalies along the Seward Line from coast (GAK1) to the shelfbreak (GAK9) during May surveys from 1998-2009.

## 3.2 Winter mixed layer at GAK1 *(Sarkar)*

Downwelling favourable winds predominate in the northern Gulf of Alaska coast yet the shelf is a region of high biological productivity. Various mechanisms have been suggested for the transport of nutrients across the shelf. One involves moving nutrient-rich water from the deep ocean to the shelf via cross-shelf transport along the shelf bottom, especially within submarine canyons during periods of relaxed downwelling. In this scenario, mixed layers at certain times of the year could be deep enough to mix nutrient-rich deep waters into the euphotic zone. In the northern Gulf of Alaska, mixed layers are deepest in the winter, when wind stress is high, air and water temperatures are low and salinity is high (freshwater is locked up as snow and ice; evaporation from the ocean surface is high due to low air relative humidity and strong winds sweeping the area).

The deepest winter mixed layer depths (MLD) at GAK1 were estimated using the Freeland et al. (1997) algorithm. This algorithm performs well at estimating winter MLDs (each winter is defined here as December of one year and January to May of the following year), but overestimates the summer and spring MLDs, but for our purposes, this method is adequate (Sarkar et al. 2005; Sarkar 2007). The deepest winter MLDs at GAK1 from 1974 to 2009 (Fig. GA-11) range from a minimum of 105 m in February 2003 to a maximum of 214 m in March 1987. The mean value is 164 m, with a standard deviation of 29 m. The record has only one missing value; that for the winter of 1979-1980. The MLD time series used here does not include values for the winters of 2006-2007 and 2007-2008 because of some anomalous conditions that changed the shape of the density profiles and the Freeland algorithm could not calculate meaningful MLDs. The deepest winter MLDs at GAK1 from 1974 to 2009 do not show any statistically significant linear trend. This is in contrast to studies by Freeland et al. (1997) who report a significant shoaling trend at Station Papa at the center of the Alaska gyre from 1956 to 1994.

The winters of 2006-2007 and 2007-2008 were unusual in the northern Gulf of Alaska (Janout et al. in press). Even though there were significant inter-annual differences within these years, the water column in the vicinity of GAK1 was colder than in the past three decades (mid-1970s to mid-2000s). In winter/spring 2006-2007, the anomalously low temperatures throughout the water column were accompanied by higher surface salinity, leading to lower water column stability. In winter/spring 2007-2008, the anomalously low temperatures were confined to the upper water column (0-100 m) as there was salinity stratification from large coastal freshwater runoff. The Freeland algorithm could not determine meaningful MLD values for these two years, but a visual examination showed that by late winter, both years had deeper than average MLDs. The water column appeared to be completely mixed to 263 m in March 2007, and in January 2008, the deepest mixed layer was 185 m. Both these values were determined by visual examination and have not been included in the Freeland MLD time series, as described above. Some of these anomalous temperature and salinity signals persisted up to mid-2009, though temperature and salinity values may have returned to within 1 standard deviation of the 1974-2006 values as of spring 2009 (www.ims.uaf.edu/gak1/). The Freeland algorithm returned an MLD value of 168 m for March 2009, which is close to the 35-year average for GAK1. Today, it is not possible to determine whether the events of the past few years signal a shift to another climatic state, perhaps a cold phase, as in the early 1970s (Royer 2005).



[Figure GA-11] Winter mixed layer depth (m) at GAK1 from 1974-2006.

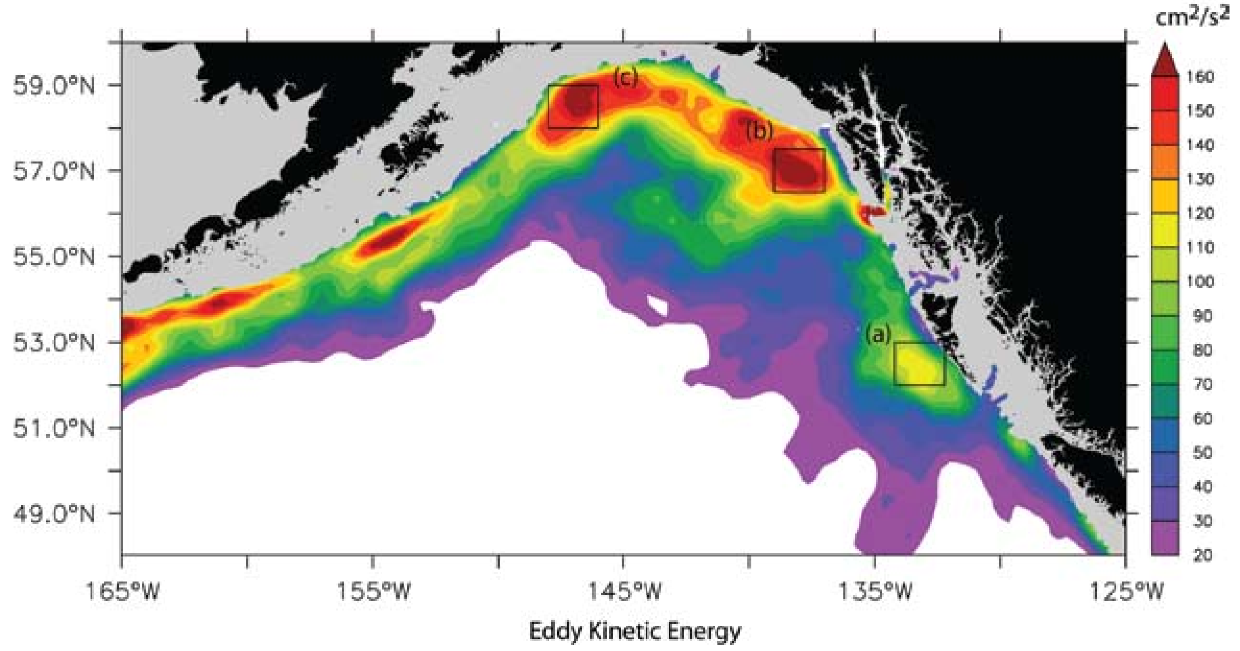
## 3.3 Eddies in the Gulf of Alaska *(Ladd)*

Eddies in the northern Gulf of Alaska influence the distributions of nutrients (Ladd et al. 2005; Ladd et al. 2007), phytoplankton (Brickley and Thomas 2004), ichthyoplankton (Atwood et al. submitted), and the foraging patterns of fur seals (Ream et al. 2005). Eddies propagating along the slope in the northern and western

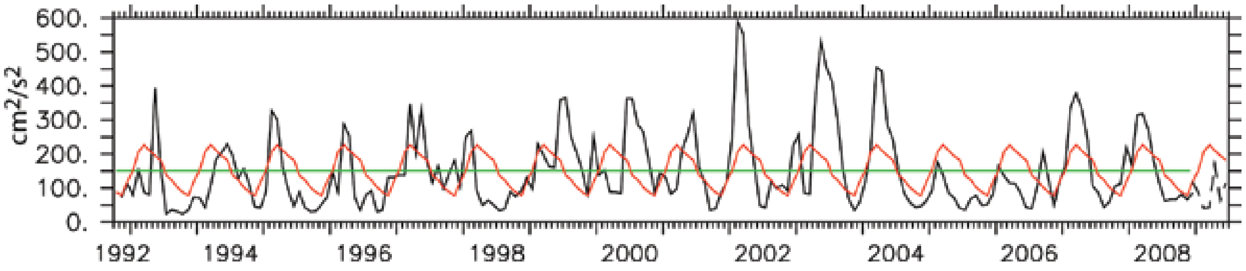
GoA are generally formed in the eastern GoA in autumn or early winter (Okkonen et al. 2001). In most years, these eddies impinge on the shelf east of Kodiak Island in the spring. Using altimetry data from 1993 to 2001, Okkonen et al. (2003) found an eddy in that location in the spring of every year except 1998. They found that strong, persistent eddies occur more often after 1997 than in the period from 1993 to 1997. Ladd (2007) extended that analysis and found that, in the region near Kodiak Island, eddy energy in the years 2002-2004 was the highest in the altimetry record (1993-2006).

Since 1992, the Topex/Poseidon/Jason/ERS satellite altimetry system has been monitoring sea surface height (SSH). Eddy kinetic energy (EKE) can be calculated from gridded altimetry data (merged TOPEX/Poseidon, ERS-1/2, Jason and Envisat) (Ducet et al. 2000). A map of eddy kinetic energy in the GoA averaged over the altimetry record (updated from Ladd 2007) shows three regions with local maxima (labeled a, b, and c in Fig. GA-12). The first two regions are associated with the formation of (a) Haida eddies and (b) Sitka eddies. Regions of enhanced EKE emanating from the local maxima illustrate the pathways of these eddies. Sitka eddies can move southwestward (directly into the basin) or northwestward (along the shelf-break). Eddies that move along the shelf-break often feed into the third high EKE region. By averaging EKE over region (c) (see box in Fig. GA-12), we obtain an index of energy associated with eddies in this region (Fig. GA-13).

Region (c) exhibits high EKE in the spring (March-May) with lower EKE in the autumn (September-November). EKE was particularly high in 2002-2004 when three large persistent eddies passed through the region. Prior to 1999, EKE was generally lower than the ~16-year average, although 1993 and 1997 both showed periods of high EKE. Low EKE values were observed for 2005-2006 indicating a reduced influence of eddies in the region. Higher EKE values were observed in the spring of 2007 and 2008 as eddies moved through the region. EKE levels were low in the spring of 2009. This may have implications for the ecosystem. Phytoplankton biomass was generally more tightly confined to the shelf during 2005-2006 due to the absence of eddies, while in 2007 and 2008 phytoplankton biomass extended farther off the shelf. In addition, cross-shelf transport of heat, salinity and nutrients were likely to be smaller in 2005-2006 and 2009 than in 2007 and 2008 (or other years with large persistent eddies). The altimeter products were produced by the CLS Space Oceanography Division (AVISO 2008).



[Figure GA-12] Eddy Kinetic Energy (cm²·s⁻² ) averaged over October 1993-October 2007 calculated from satellite altimetry. (c) denotes region over which EKE was averaged for Figure GA-13.



[Figure GA-13] Eddy kinetic energy ($cm^2 \cdot s^{-2}$) averaged over Region (c) shown in Figure GA-12. Black (line with highest variability): monthly EKE. Red: seasonal cycle. Green (straight line): mean over entire time series.

## 3.4 Chemical oceanography

### 3.4.1 Nutrients

Long term systematic observations of the chemical properties of GoA waters with which to evaluate the status and trends during the focus period are currently unavailable.

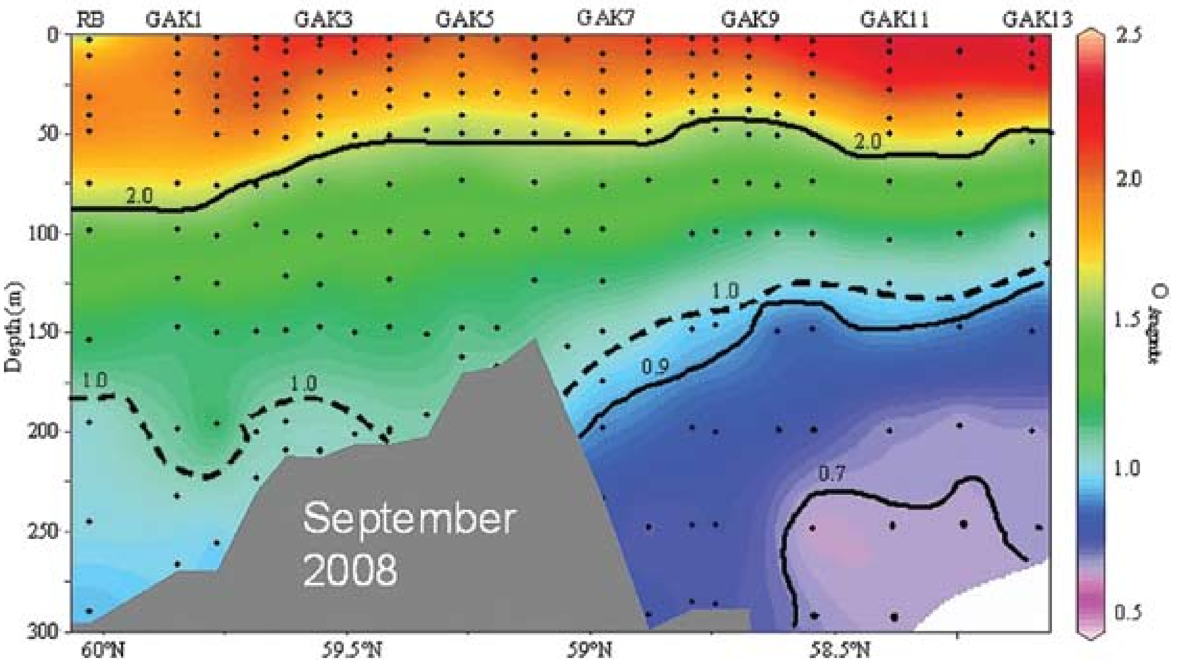
### 3.4.2 Ocean acidification *(Mathis)*

An extensive study measuring pH off the coast of Washington State from 2000-2008 demonstrated a clear decline in ocean pH of nearly 0.4 (Wootton et al. 2008). This was a much greater decline than most models predicted. The study also documented that the number of mussels and stalked barnacles declined as the acidity increased. Acidification will affect Alaskan waters earlier than more southerly latitudes due to a combination of the shallowness of the carbonate saturation depth and cold temperatures. The saturation horizon for calcium carbonate (aragonite) has become shallower in the North Pacific Ocean and is currently about 200 m. This contrasts with about 2000 m in the North Atlantic Ocean (Feely et al. 2004). Carbon dioxide is also more soluble in colder water so low pH water is available at shallower depths in the North Pacific than in other oceanic basins, and is becoming moreso with time.

Seasonal changes in saturation depth were observed during a transect line in May and September of 2009 that extended seaward from Resurrection Bay into the northern Gulf of Alaska. During these cruises, measurements were taken for dissolved inorganic carbon (DIC) and total alkalinity (TA) and when coupled with hydrographic and nutrient data allowed for the determination of the carbonate mineral saturation (i.e. $\Omega_{cal}$ and $\Omega_{arg}$) states. In May, the entire water column inside Resurrection Bay was supersaturated with respect to $\Omega_{arg}$, the more soluble of the carbonate minerals, with values ranging from ~1.8 at the surface to ~1.2 near to bottom (Mathis et al. unpublished). Over the inner and middle shelf, surface waters were also supersaturated with respect to aragonite with the saturation horizon (where $\Omega_{arg} = 1$) occurring at 150 m. However, by September several distinctive changes had occurred. The bottom waters both inside Resurrection Bay and on the inner shelf had become undersaturated with respect to $\Omega_{arg}$ (Fig. GA-14) likely due to the remineralization of organic matter exported from the upper mixed layer due to intense periods of late spring and summer primary production and from the relaxation of downwelling conditions which allowed deeper water, with lower $\Omega_{arg}$ to outcrop closer to the surface. The $\Omega_{arg}$ at the surface had increased to >2.0 in response to the drawdown of DIC from photosynthesis. This divergent trajectory between surface waters and bottom waters has been shown on other polar and sub-polar shelves (Bates and Mathis 2009; Bates et al. 2009; Fabry et al. in press) but this was the first time it had been observed in the Gulf of Alaska (Mathis et al., unpublished). The range of interannual variability in this seasonal cycle is not known, nor is it clear if there are any long term-trends in this biologically driven cycle.

### 3.4.3 Chemical contamination

Largely as a result of the Exxon Valdez oil spill and concern over mercury levels in seafood, the GoA has been a locus for contaminants work in the last two decades. Samples from locations in Alaska during the focus period have generally not detected concentrations of polychlorinated biphenyls (PCBs), pesticides, or mercury at levels of concern. In contrast, published GoA studies



[Figure GA-14] Oceanographic section taken in September 2008 in the northern Gulf of Alaska showing aragonite saturation state ($\Omega_{arg}$). Station numbers are shown at the top with RB indicating Resurrection Bay. Gulf of Alaska station 13 (GAK13) was the outermost station. The dashed line indicates the saturation horizon for aragonite (Adapted from Fabry et al., In Press).

during the same interval (Springman et al. 2008; Short et al. 2008) have concluded that petroleum hydrocarbons, so ubiquitous in the environment, are significantly more toxic, bioavailable, and persistent in the environment than previously thought. There are no trends suggesting an increase in any of these compounds in the GoA.

The Arctic and Subarctic are believed to be particularly at risk for PCB and pesticide accumulation in the tissues of marine organisms due to enhanced transport to these regions via the troposphere in gas phase, on particles, ocean currents, and in migrating fish. The cold temperatures of the north tend to cause precipitation, releasing the chemicals into the water, where they are absorbed by aquatic organisms (such as copepods) and sequestered in lipid, later to be consumed by higher predators such as fish and seals (AMAP 2009). However, a 2004 study (Alaska Department of Environmental Conservation 2004) concluded that total PCB levels in fish were below 10 ng·g$^{-1}$ and pesticide concentrations were largely below detection limits. Integrated samplers capable of detecting bioavailability of very low concentrations of these chemicals were deployed at 53 sites in Prince William Sound. The concentration of total PCBs and pesticides in the samplers rarely exceeded 1 ng·l$^{-1}$, far below the concentration likely to induce a biological response (Short et al. 2008). Concentrations of polychlorinated biphenyls and pesticides in ovaries or muscle tissue of chinook salmon returning to spawn in the Kenai River in 2004 were below 10 µg·g$^{-1}$, suggesting that remote delivery of these compounds was not occurring in that river (Rice and Moles 2006).

Mercury poses a high risk for pregnant women and the public remains concerned about mercury levels in fish. But a 2007 review of the extant data suggests that the levels in most commercially-harvested GoA fishes remain low. In a review of studies of mercury levels in fish species in Alaska, Jewett and Duffy (2007) concluded that concentrations of mercury were below the action levels of 1 mg·kg$^{-1}$ of fish weight, although mercury concentration in the muscle tissues of Pacific halibut (*Hippoglossus stenolepis*) and sablefish (*Anoplopoma fimbria*) are close to the critical value for human consumption set by the EPA.

Samples of Pacific cod (*Gadus macrocephalus*) have muscle mercury concentrations (0.17 mg·g$^{-1}$ wet weight) within the range known to cause adverse effects if consumed by sensitive birds and mammals (Burger and Gochfeld 2007). Similar values have been previously reported for a number of freshwater and marine fish species (Jewett and Duffy 2007). The FDA concludes that there is no evidence of an increase in mercury levels over the 30 years that the agency has maintained a database of methyl mercury levels in fish.

Polynuclear aromatic hydrocarbons (PAH), the primary toxic components in crude oil, have been monitored in the tissues of the mussel (*Mytilus trossulus)* at 12 locations in the Gulf of Alaska, including Prince William Sound, since 1993. Between 1999 and 2006, there was a decreasing trend in total hydrocarbons in the tissues of mussels at all sites. Levels in 2006 were below 100 ng·g$^{-1}$ dry weight. However, PAH could still be detected in 2004 at sites impacted by the Exxon Valdez oil spill in 1996, and these hydrocarbons were still capable of inducing a biological response (as measured by induction of the liver enzyme CYP1A) when injected into fish (Springman et al. 2008; Short et al. 2008).

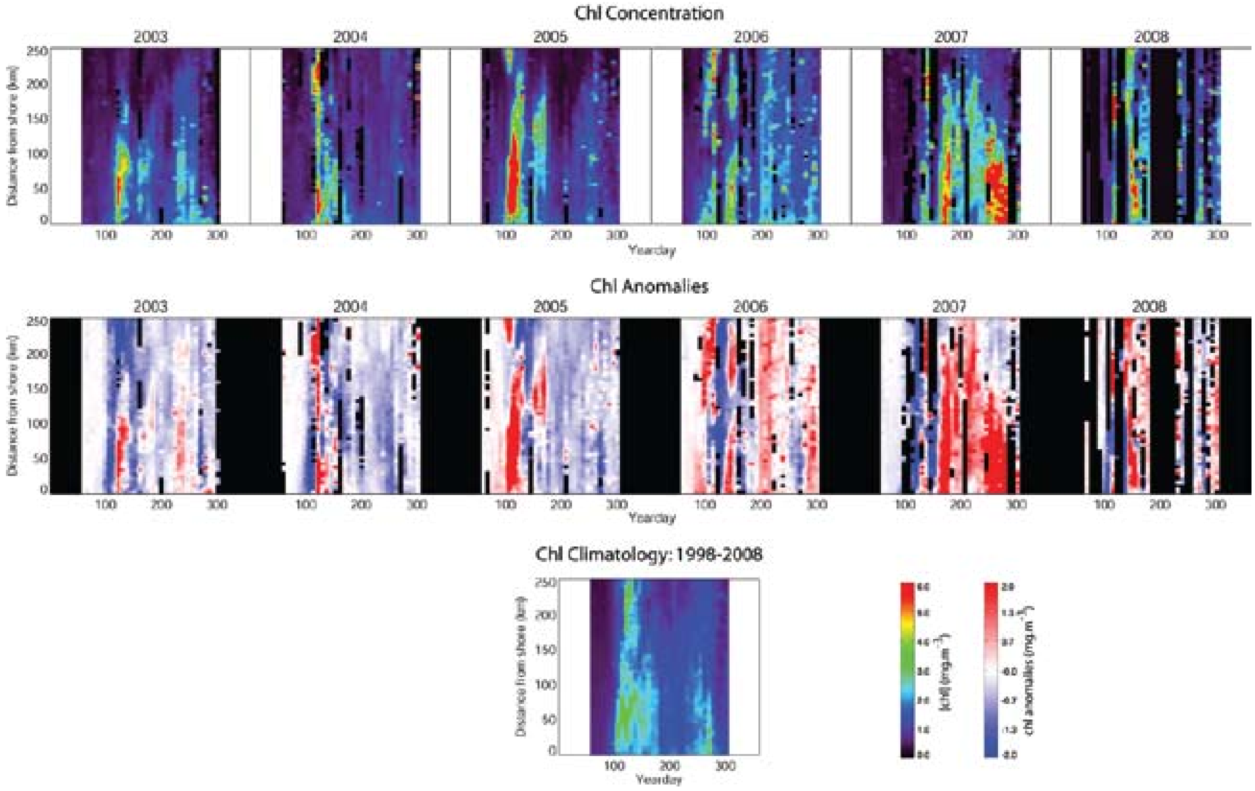
# 4.0 Biological Ocean

## 4.1 Phytoplankton *(Hopcroft, Thomas)*

Like most of the important physical processes in the coastal GoA, primary production varies on seasonal and interannual time scales, and exhibits pronounced cross-shelf and along-shelf gradients (Brickley and Thomas 2004). Nutrient re-supply to deep shelf waters occurs during summer relaxation of downwelling winds, and re-supply to surface waters occurs primarily during winter mixing (Childers et al. 2005; Hermann et al. 2009). Spring bloom onset is closely tied to increases in water column stability (Henson 2007) and solar irradiance (Dagg et al. unpublished). Ocean color images suggest that the bloom occurs in March in central Southeast Alaska offshore of Sitka, and in the inside waters near Wrangell, slightly later (early April) within Prince William Sound, and in late April or early May within the northern coastal Gulf of Alaska. Duration and intensity of the shelf spring bloom may be related to variations in bloom timing, with earlier blooms supporting higher chlorophyll concentrations (Henson 2007).

Macronutrient (N, Si) limitation of phytoplankton growth and production is evident during the latter part of the spring bloom as soon as biomass peaks (April or May), and continues throughout the summer months (Strom et al. 2006; Whitney et al. 2005). Episodic mixing due to tides and winds can stimulate summer production by delivering nutrients to surface waters, and primary production "hot spots" in the coastal GoA are typically associated with tidal mixing over banks and through channels (Stabeno et al. 2004; Hermann et al. 2009; Cheng et al. submitted). Study of the GoA during the U.S. GLOBEC Northeast Pacific program revealed strong cross-shelf gradients in plankton community composition, growth rates, and macronutrient distributions. These gradients are consistent with the hypothesis the iron may limit production at times on the mid and outer shelf (Strom et al. 2006). This is supported by dissolved Fe measurements from the same region (Wu et al. 2009) which show sharply decreasing surface Fe levels from the inner to mid and outer shelf, and a strong depth gradient on the outer shelf. The main sources of iron and macronutrients to the shelf are probably deep-water and freshwater runoff, with riverine inputs high in Fe and potentially, Si, and deep water enriched in N, Fe, and Si (Stabeno et al. 2004; Whitney et al. 2005). Light limitation clearly plays a role in spring bloom timing and magnitude (Napp et al. 1996) and light is sometimes considered the key limiting resource for this high-latitude ecosystem (Gargett 1997; but see above).

Temporal variability of satellite-measured chlorophyll concentrations along a transect across the Alaskan shelf at Seward (the GAK line), from the coast to 250 km offshore during the focus period is presented in Fig. GA-15. Data were measured by daily orbits of the SeaWiFS satellite and processed to chlorophyll using the standard NASA algorithm. The data shown are sub-sampled from 8-day composite images (the temporal resolution of the figure) that have 4 km spatial resolution (the cross-shelf resolution). Each cross-shelf value is the mean over ~50 km in space perpendicular to the transect. The top panel shows concentrations over the focus period. The middle panel shows anomalies, calculated by subtracting from each 8-day period the climatological annual seasonal cycle along the transect. The bottom panel shows this climatological annual cycle, calculated over the SeaWiFS mission period of (1998 – 2008). There are no data in the winter due to the low light conditions and data are



[Figure GA-15] Satellite-measured chlorophyll variability along the Seward (GAK) line extending from the coast to 250 km offshore as a colour contour map in time (2003-2008) and distance (0-250 km).

unavailable during cloudy periods. The SeaWiFS satellite had some data gaps in 2008 due to technical issues.

These data clearly capture the spring bloom in mid-late April, its duration and its cross-shelf structure. In many years, this event extends 250 km offshore (the 500 m isobath is approximately 150 km offshore). Concentrations are lower in summer across the entire shelf when the water column stratifies. *In situ* chlorophyll profiles show that this period is often characterized by a sub-surface chlorophyll maximum not visible to the satellite. Low summer surface concentrations are followed by a fall bloom in ~mid August of weaker intensity and less cross-shelf extent that the spring bloom. Interannual variability in both concentrations and spatial structure is strong. Prominent features in these data are the reduced cross-shelf extent of the spring bloom in 2003, the virtual absence of a fall bloom in 2004, relatively weak blooms in 2006, and a strong fall bloom in 2007.

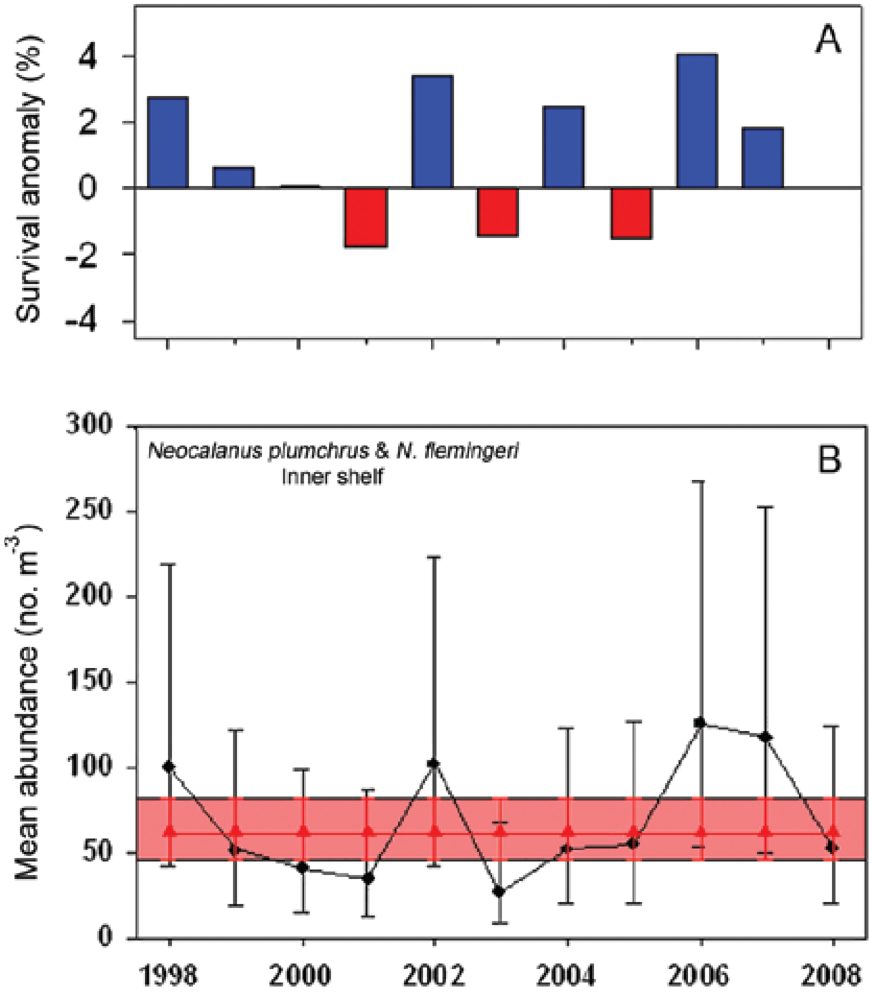
## 4.2 Meso- and macrozooplankton

*(Hopcroft, Sturdevant)*

Mesozooplankton on the GoA shelf are a mixture of two major species complexes, composed of neritic and oceanic taxa. During May and early June, the oceanic complex, consisting primarily of *Neocalanus flemingeri/plumchrus, N. cristatus, Metridia pacifica* and *Eucalanus bungii*, dominates the biomass. In July or August, abundances are dominated by smaller copepods, *Pseudocalanus* spp. and *Oithona similis*. Organisms of secondary importance in terms of abundance and biomass include the euphausiids (four *Thysanoessa* species plus *Euphausia pacifica*), the pteropod *Limacina helicina,* and larvaceans (*Oikopleura* spp.). All of these taxa contribute to the diets of various fishes during their early life-histories.

Prior to the GLOBEC program (1997-2004), little information was available on interannual variations in zooplankton stocks in the northern Gulf of Alaska and the physical mechanisms influencing those variations. Post-

GLOBEC sampling has continued along the Seward Line during 2005-2009, although confined to May and early September only. This sampling has revealed significant inter-annual differences in abundance, biomass and cross-shelf distribution of zooplankton over the past 12 years (http://www.ims.uaf.edu/GLOBEC/). For example, during May of 1998, 2002, 2006 and 2007, populations of *Neocalanus* were two to five times higher than populations during other years (Fig. GA-16b). These years coincided with years of high pink salmon (*Oncorhynchus gorbuscha*) survival (Fig. GA-16a). *Pseudocalanus* abundances in July 1998 and 2004 were about five times higher than in other years. Zooplankton abundance and biomass have been negatively correlated to salinity on the shelf, particularly in the region between the outer boundary of the ACC and the shelf break (Coyle and Pinchuk 2005). Examination of cross-shelf salinity-temperature profiles has further revealed that zooplankton abundance and biomass were depressed when oceanic water was pushed across the shelf, confining the mixing zone to a narrow band along the outer boundary of the ACC. High zooplankton abundance was observed when physical conditions created a middle shelf domain that extended from the outer boundary of the ACC to the shelf break. The exact cause of enhanced zooplankton abundance and biomass in the middle shelf mixing zone is uncertain, but release of iron limitation of primary production may play a role where low-nutrient high-iron ACC waters mix with high-nutrient low-iron oceanic waters. Interannual differences in zooplankton abundance and biomass within the ACC were much less pronounced. Thus, the abundance, biomass and productivity of zooplankton on the shelf are not simply determined by the magnitude of cross-shelf transport of dominant species such as *Neocalanus* and euphausiids, but are affected by the degree of mixing with shelf waters during along-shelf transport.



[Figure GA-16] The survival anomaly for Prince William Sound hatchery-released pink salmon tracks the abundance of *Neocalanus* copepods observed along the inner domain of the Seward Line. Red-band indicated long-term mean and 95% confidence interval.

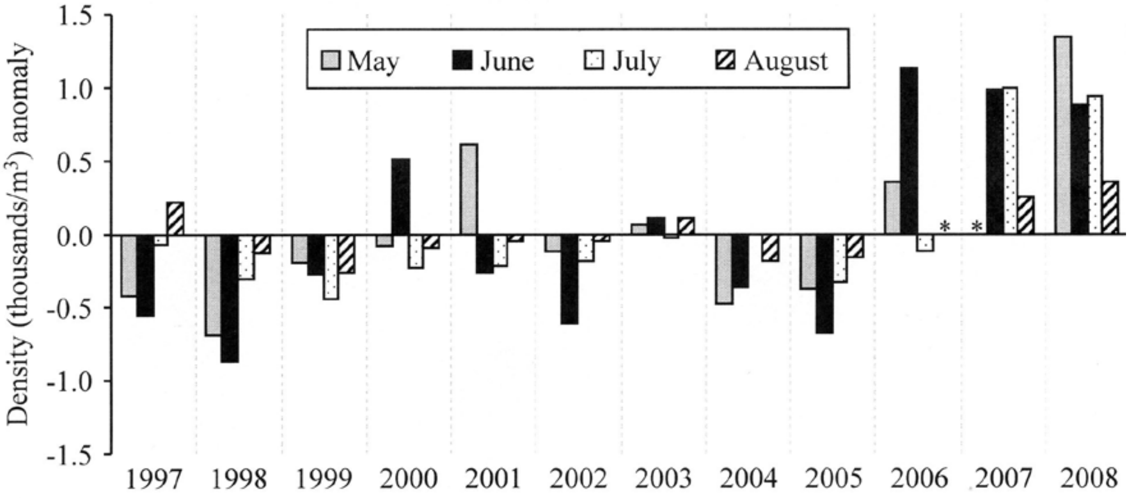
Significant variation has also been observed in the composition of the zooplankton community along the Seward Line. During cold springs such as 2002, and 2006-2009, the spring bloom was delayed, as was the development of the zooplankton community dependant upon it, by at least several weeks. Under these conditions some key zooplankton species have done better than average, while others have not. Specifically, abundance during May of the key copepod species *Neocalanus plumchrus/flemingeri* was higher than average during these cold years. Also notable has been the presence of "southern" species in warm years. During the 1997-1998 El Niño the copepods *Mesocalanus tenuicornis* and *Calanus pacificus* became more abundant (Coyle and Pinchuk 2003). During the warmer summer of 2003 the southern small copepod *Paracalanus parvus* began to appear in samples and it became unusually common during fall of 2005, persisted into 2006 concurrent with increases in *C. pacificus*, then disappeared from 2007 to the present. All of these southern species are smaller than corresponding resident species, and therefore replace larger prey items that may be more nutritious per individual for larval fish.

An unexpected revelation from the GLOBEC study was the importance of larvaceans and thecosome (shelled) pteropods in the diets of pink salmon, challenging the traditional view that *Neocalanus* and euphausiid species are the only key dietary elements (Boldt and Haldorson 2003; Armstrong et al. 2005; Cross et al. 2005). Years when juvenile pinks had high percentages of these species in the diet (2002 and 2004) were correlated with year classes of higher pink salmon growth and survival, albeit over a short (4 year) time frame (Malick et al. unpublished). The role of these under-studied taxa in the diets of other fish species may hold similar surprises.

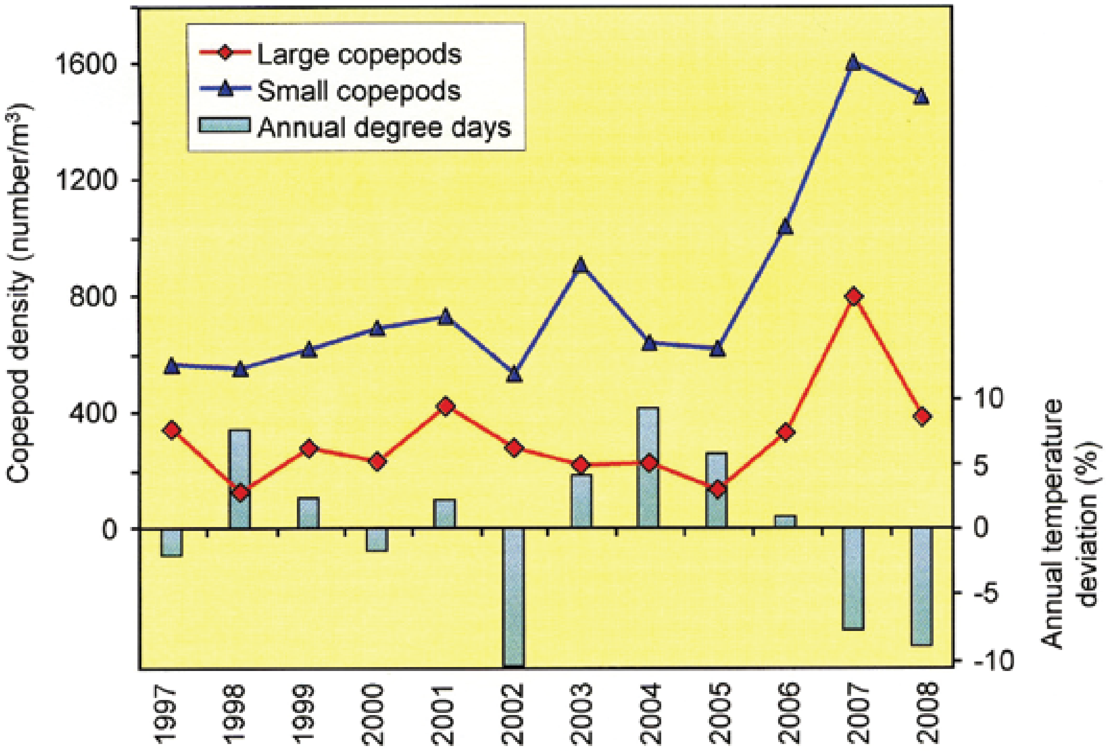
Similar to zooplankton communities along the Seward Line, patterns in zooplankton variability and trends were noted in studies using a continuous plankton recorder (CPR) across the North Pacific Ocean, which included sampling in the central and northern Gulf of Alaska (http://www.pices.int/projects/tcprsotnp/default.aspx). Mesozooplankton abundance tended to peak later in the year and was longer in duration in cool, PDO-negative years (2007, 2008) compared to warmer, PDO-positive years (2003, 2004, 2005), when the peak abundance was earlier in the year and of shorter duration. The 9 years of CPR data show an ~6 week range in the timing of peak *Neocalanus* biomass in offshore waters. Data from both the CPR survey and the Line P surveys carried out by DFO Canada (http://www.pac.dfo-mpo.gc.ca/SCI/osap/projects/linepdata/default_e.htm) show the same signal, likely caused by warmer surface conditions since they are correlated with sea surface temperature anomalies (Mackas et al. 2007). During the warmer years development is faster (although this does not account for all of the time difference) than in the cool years. The estimated timing in 2008 was later than in 2004-2006 and similar to the earlier cool period. 2007 was intermediate between the two groupings of years.

In Southeast Alaska, NOAA personnel have also assessed status and trends in zooplankton from 1997-2009 in the upper water column of the neritic waters of the ACC up to ~65 km offshore (http://www.afsc.noaa.gov/ABL/MSI/msi_secm.htm). Both standing stock ($ml \cdot m^{-3}$) and abundance ($number \cdot m^{-3}$) of total zooplankton show strong seasonal patterns, peaking in May or June and declining over the summer. Standing stock was highest in the strait habitat (Icy Strait 58.25° N 137.5°W) in summer and lowest in the coastal habitat (Icy Point 58° N 137.5°W) throughout the 12-y sampling period. These habitat comparisons suggest that the June arrival of juvenile salmon in Icy Strait coincides with an abundant food supply. During 2006-2008, zooplankton abundances were anomalously high in every month (Fig. GA-17), principally due to abundant copepods. In contrast, integrated (0-20 m) temperatures and salinities were anomalously low in 2008; the temperatures were low in all four months, while salinity and MLD varied in May and June, then were anomalously low in late summer (Orsi et al. 2009).

As with the northern and central Gulf of Alaska, the abundance of the dominant copepods of the zooplankton community varied from year-to-year in coastal Southeast Alaska, at least partially in response to climate. The 12 year time series of large (e.g., *Metridia* spp., *Calanus marshallae, Neocalanus* spp.) and small (e.g., *Pseudocalanus* spp., *Acartia* spp., and *Centropages abdominalis*) calanoid abundances showed different responses to annual temperature signals (Fig. GA-18) (Park et al. 2004). Abundance of large calanoids most often increased during cooler years and decreased during warmer years. Small calanoids may be more responsive to short term, within-season, temperature fluctuations because they can produce multiple generations per year, while many of the larger GoA copepods have life-history strategies that constrain them to a single generation per year.



[Figure GA-17] Zooplankton concentration (thousands·m$^{-3}$) across a 12 year time series from Icy Strait in the northern region of southeastern Alaska, 1997-2008. Data are monthly anomalies by year (deviation from mean monthly density, patterned bars). Samples represent “deep” (≤200 m depth; *n* = 4 stations) 333-μm mesh bongo net towed in double oblique fashion during daylight. Asterisk indicates no samples collected.



[Figure GA-18] Trends in average summer abundance of large and small calanoid copepods in Icy Strait, Southeast Alaska. Data are average concentration (number·m$^{-3}$ in 333-μm mesh bongo nets) for May-August compared to annual percent deviation of average sea surface temperature (cumulative degree days from prior September-August, in °C, at 0 m) in Auke Bay, 1997-2008.

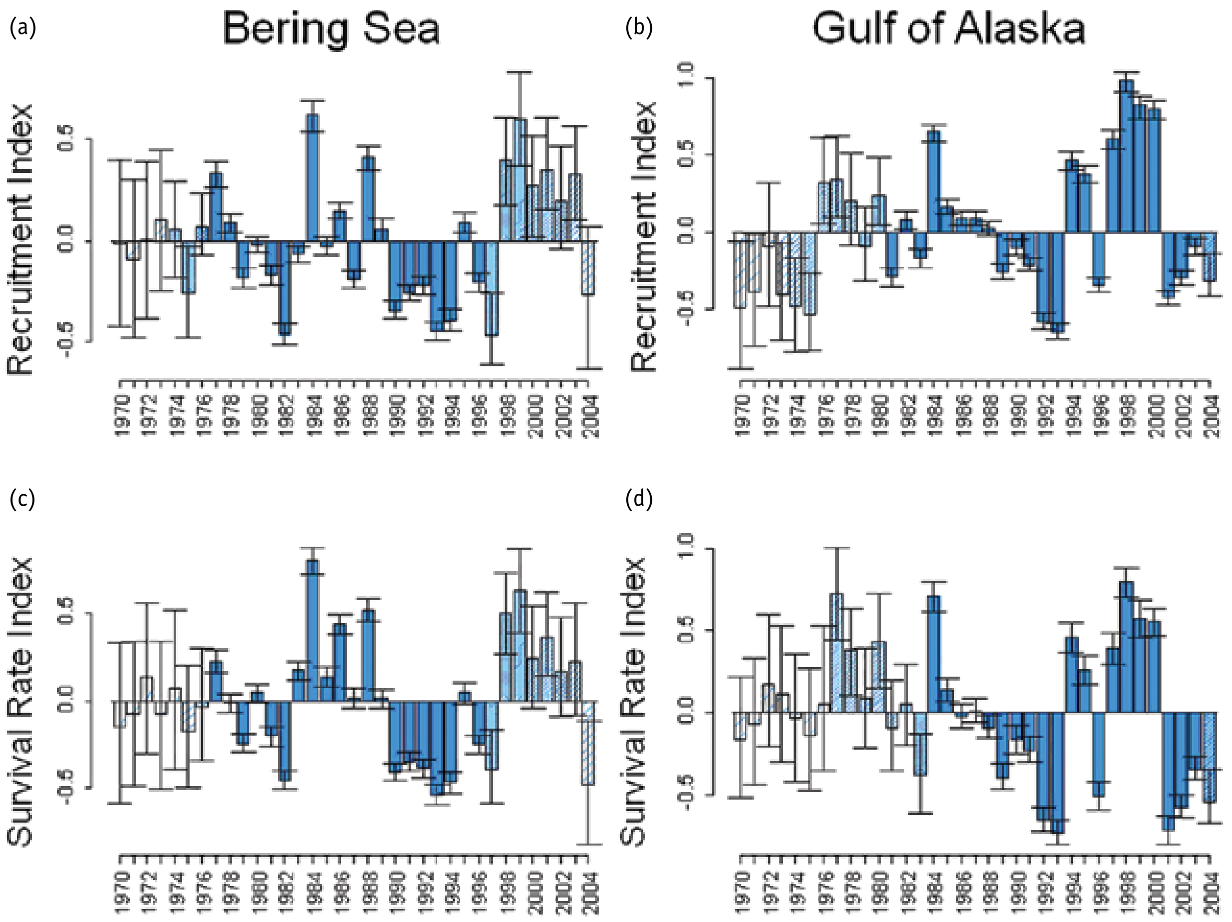
# 5.0 Fishes and Invertebrates

## 5.1 Groundfish recruitment and survival

*(Mueter)*

Decadal-scale variability in climate may affect groundfish survival and recruitment (Hollowed et al. 2001). Indices of recruitment and survival rate (adjusted for spawner abundance) across the major commercial groundfish species in the Gulf of Alaska (GoA, 11 stocks) provide an index of interannual and decadal-scale variability. Time series of recruitment and spawning biomass for demersal fish stocks were obtained from the 2007 SAFE reports to update results of Mueter et al. (2007). Only recruitment estimates for age classes that are largely or fully recruited to the fishery were included. Survival rate (SR) indices for each stock were computed as residuals from a spawner-recruit model. Each time series of log-transformed recruitment (logR) 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). A combined standardized index of recruitment (CSIR) and survival (CSISR) was computed by simply averaging indices within a given year across stocks. Stock-specific estimates of logR and SR indices were not taken into account; therefore the most recent estimates of the combined indices should be interpreted with caution.

The CSIR and CSISR suggest that survival and recruitment of demersal species in the GoA were below average during the early 1990s and above average across stocks in the late 1990s / early 2000s. Because estimates at the end of the series were based on only a few stocks and are highly uncertain, the index is shown through 2004 only, the last year for which data for at least 6 stocks was available in each region (Fig. GA-19). There is strong indication for



[Figure GA-19] Recruitment (a), (b) and survival (c), (d) indices for groundfish in the Gulf of Alaska and Bering Sea (1970-2004).

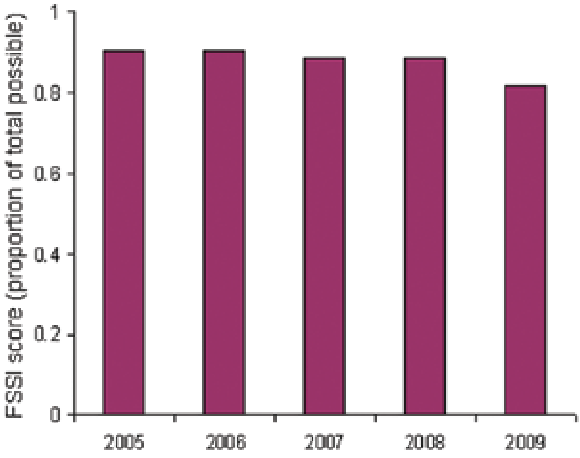
above-average survival and recruitment in the GoA from 1994-2000 (with the exception of 1996, which had very low indices) and below-average survival / recruitment since 2001. From 2001 to 2004, 9 out of 11 or 8 out of 10 stocks have had below average CSISR and CSIR indices. More recent years can not be estimated because there is no survey or catch data for most species for these years. Gadid estimates are available through 2007, but are highly unreliable.

Trends in recruitment are a function of both spawner biomass and environmental variability. Trends in survival rate indices, which are adjusted for differences in spawner biomass, are presumably driven by environmental variability but are even more uncertain than recruitment trends. Typically, spawner biomass accounted for only a small proportion of the overall variability in estimated recruitment. The observed patterns in recruitment and survival suggest decadal-scale variations in overall groundfish productivity in the Gulf of Alaska and are moderately correlated with similar indices for the Bering Sea (CSIR: r = 0.42; CSISR: r = 0.47) (Fig GA-19). These variations in productivity are correlated with, and may in part be driven by, variations in large-scale climate patterns such as the PDO or more regional measures such as ocean temperatures. The November-March PDO index for the preceding winter was positively correlated with both indices, but the correlations were not significant at the 95% level.

## 5.2 Fish Stock Sustainability Index *(Boldt)*

The Fish Stock Sustainability Index (FSSI) is a performance measure of the sustainability of fish stocks selected for their importance to commercial and recreational fisheries (http://www.nmfs.noaa.gov/sfa/statusoffisheries/SOSmain.htm). The FSSI will increase as overfishing is ended and stocks rebuild to the level that provides maximum sustainable yield. The maximum score for each stock is 4. The value of the FSSI is the sum of the individual stock scores. In the Gulf of Alaska, there are 13 FSSI stocks and an overall FSSI of 52 would be achieved if every stock scored the maximum value (Tables GA-2 and GA-3). There are also 18 non-FSSI stocks in Gulf of Alaska (Tables GA-2 and GA-4). There are 230 FSSI stocks in the U.S., with a maximum possible score of 920.

The current overall Gulf of Alaska FSSI is 39.5 of a maximum possible 48 (Fig. GA-20). The sablefish, which are managed as an Alaskan complex, score is 4. For the entire U.S., the score is 557.5 of a possible maximum score of 920. From 2004-2009, no Gulf of Alaska groundfish stock or stock complex was overfished and no groundfish stock or stock complex was being subjected to overfishing (Tables GA-2 and GA-3). The stocks that had low FSSI scores (1.5) in the GoA are shortspine thornyhead rockfish (an indicator species for thornyhead rockfish complex), yelloweye rockfish (an indicator species for demersal shelf rockfish complex), and rex sole. These scores were low because it is undefined whether these species are overfished and unknown if they are approaching an overfished condition. Additionally, Pacific halibut is a non-FSSI stock that is now undefined in terms of its overfishing status because there is no overfishing definition contained in the FMP (only an overfishing target).



[Figure GA-20] Fish Stock Sustainability Index Score as a proportion of the total possible score.

[Table GA-2] Description of FSSI and non-FSSI stocks managed under federal fishery management plans off Alaska, March 2009.

| **Jurisdiction** | **Stock Group** | **Number of Stocks** | **Overfishing** | | | | | **Overfished** | | | | | **Approaching Overfished Condition** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Yes | No | Not Known | Not Defined | N/A | Yes | No | Not Known | Not Defined | N/A | |
| NPFMC | FSSI | 13 | 0 | 13 | 0 | 0 | 0 | 0 | 10 | 0 | 3 | 0 | 0 |
| NPFMC and IPHC | Non FSSI | 18 | 0 | 11 | 0 | 7 | 0 | 0 | 3 | 0 | 15 | 0 | 0 |
| | Total | 31 | 0 | 24 | 0 | 7 | 0 | 0 | 13 | 0 | 18 | 0 | 0 |

[Table GA-3] This table was adapted from the Status of U.S. Fisheries website, which is updated quarterly: http://www.nmfs.noaa.gov/sfa/statusoffisheries/SOSmain.htm. Information presented in this table is for FSSI stocks and was updated July 2009 (note that these are updated through March 2009 and posted online in July 2009).

| **Stock** | **Overfishing? Is Fishing Morality above Threshold** | **Overfished? Is biomass below threshold** | **Approaching Overfished Condition?** | **Management Action Required** | **Rebuilding Program Progress** | **B/Bmsy or B/Bmsy Proxy** | **FSSI score** |
|---|---|---|---|---|---|---|---|
| Sablefish | No | No | No | N/A | N/A | 1.05 | 4 |
| Arrowtooth flounder | No | No | No | N/A | N/A | 2.98 | 4 |
| Flathead sole | No | No | No | N/A | N/A | 2.69 | 4 |
| Deepwater flatfishes | No | No | No | N/A | N/A | 2.35 | 4 |
| Demersal shelf rockfish | No | Undefined | Unknown | N/A | N/A | Not est. | 1.5 |
| Pelagic shelf rockfish | No | No | No | N/A | N/A | 1.51 | 4 |
| Thornyhead rockfish | No | Undefined | Unknown | N/A | N/A | Not est. | 1.5 |
| Northern rockfish | No | No | No | N/A | N/A | 1.49 | 4 |
| Pacific cod | No | No | No | N/A | N/A | 0.91 | 4 |
| Pacific Ocean perch | No | No | No | N/A | N/A | 1.16 | 4 |
| Rex sole | No | Undefined | Unknown | N/A | N/A | Not est. | 1.5 |
| Blackspotted and rougheye rockfish | No | No | No | N/A | N/A | 1.6 | 4 |
| Walleye pollock | No | No | No | N/A | N/A | 0.79 | 3 |

[Table GA-4] This table was adapted from the Status of U.S. Fisheries website, which is updated quarterly: http://www.nmfs.noaa.gov/sfa/statusoffisheries/SOSmain.htm. Information presented in this table is for non-FSSI stocks and was updated July 2009 (note that these are updated through March 2009 and posted online in July 2009). Area abbreviations: BS (Bering Sea), AI (Aleutian Islands), GoA (Gulf of Alaska).

| Stock | Area | Overfishing? Is Fishing Morality above Threshold | Overfished? Is biomass below threshold | Approaching Overfished Condition? |
|---|---|---|---|---|
| Atka mackerel | GoA | No | Undefined | Unknown |
| Big skate | GoA | No | Undefined | Unknown |
| Other skates | GoA | No | Undefined | Unknown |
| Other slope rockfish | GoA | No | Undefined | Unknown |
| Other species complex | GoA | Undefined | Undefined | Unknown |
| Shallow water flatfish | GoA | No | Undefined | Unknown |
| Longnose skate | GoA | No | Undefined | Unknown |
| Shortraker rockfish | GoA | No | Undefined | Unknown |
| Walleye pollock | Eastern GoA | No | Undefined | Unknown |
| Coho salmon Assemblages | Alaska | No | No | No |
| Chinook salmon | Eastern North Pacific Far North Migrating | No | No | No |
| Bering scallop | Alaska | Undefined | Undefined | N/A |
| Giant rock scallop | Alaska | Undefined | Undefined | N/A |
| Reddish scallop | Alaska | Undefined | Undefined | N/A |
| Spiny scallop | Alaska | Undefined | Undefined | N/A |
| Weathervane scallop | Alaska | No | Undefined | N/A |
| White scallop | Alaska | Undefined | Undefined | N/A |
| Pacific halibut | Pacific coast and Alaska | Undefined | No | No |

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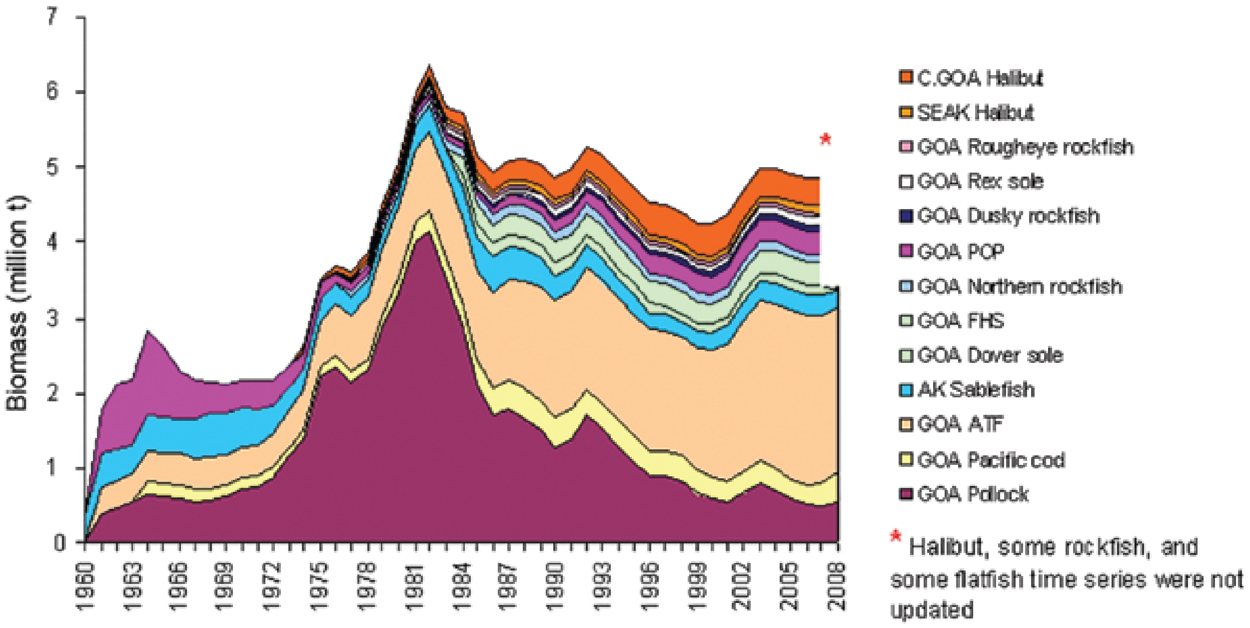
### 5.3 Trophic level of the catch *(Livingston)*

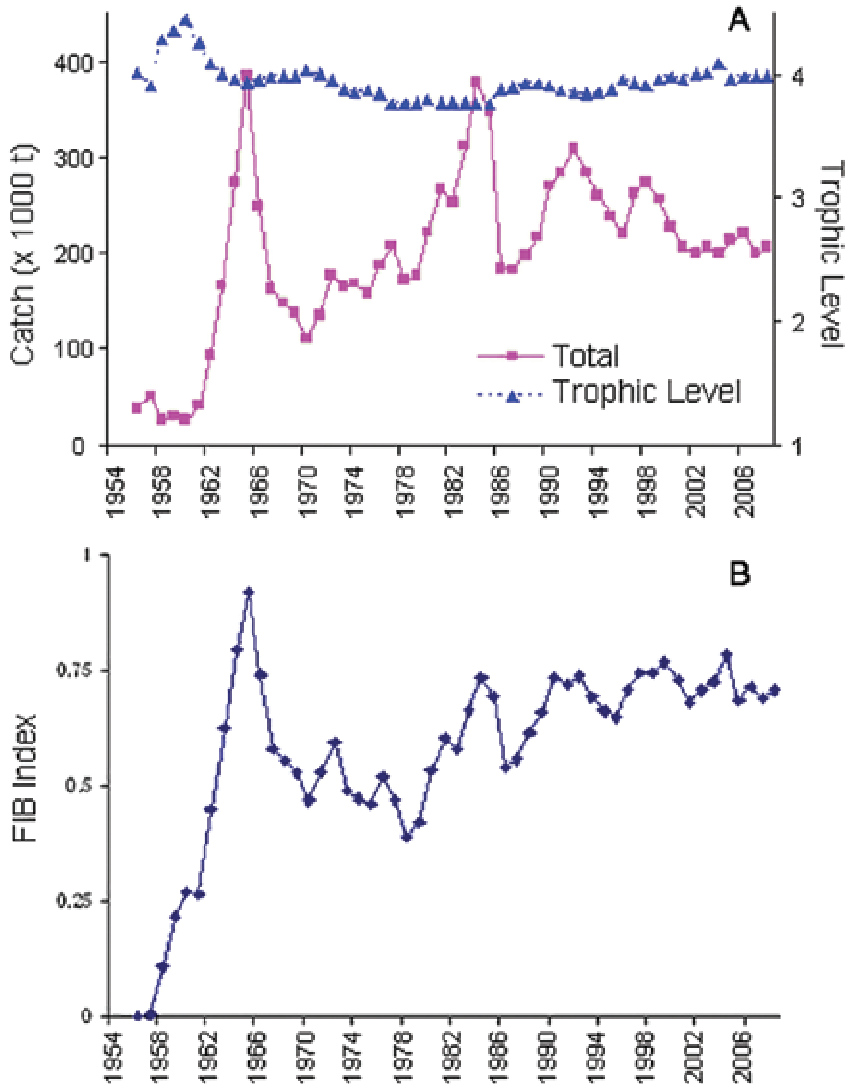
To determine whether North Pacific fisheries were "fishing-down" the food web, the total catch, trophic level of the catch (Pauly et al. 1998), and the Fishery In Balance (FIB) Index (Pauly et al. 2000) in the Gulf of Alaska were determined. Total groundfish and invertebrate composition was dominated by walleye pollock from the 1970s to at least the early 1990s (Fig. GA-21). Rockfish dominated catch prior to the 1970s. Stability in the trophic level of the total fish and invertebrate catches (Fig. GA-22) indicate that "fishing-down" the food web is not occurring in the GoA. Although there has been a general increase in the amount of catch since the late 1960s, the trophic level of the catch has been high and stable over the last 25 years.

The Fishery in Balance Index of Pauly et al. (2000) was developed to ascertain whether trophic level catch trends are a reflection of deliberate choice or of a “fishing down the food web” effect. This index declines only when catches do not increase as expected when moving down the food web, relative to an initial baseline year. The FIB index (Fig. GA-22) allows an assessment of the ecological balance of the fisheries. Unlike other regions for which the FIB index has been calculated, such as the Northwest Atlantic, catches and trophic level of the catch in the GoA has been relatively constant and suggest an ecological balance in the catch patterns. Another species of interest is arrowtooth flounder because of recent abundance increases. Since this species comprises a small proportion of the catch, it has virtually no effect on the trophic level of the catch or the FIB index in the GoA, and fishing-down the food web is not occurring in the GoA.



* Halibut, some rockfish, and some flatfish time series were not updated

[Figure GA-21] Groundfish biomass trends (t) in the Gulf of Alaska (1960-2008) as determined from age-structured models of the Alaska Fishery Science Center reported by the North Pacific Fishery Management Council (2008). Halibut data were provided by the International Pacific Halibut Commission (S. Hare, pers. comm.) but not updated for 2008 for this graph. Some rockfish and flatfish species in the Gulf of Alaska were also not updated in this graph.



[Figure GA-22] (a) Total catch (groundfish, herring, shellfish, and halibut) and trophic level of total catch in the Gulf of Alaska, 1954-2008; (b) Fishery in Balance (FIB) index for the Gulf of Alaska, 1954-2008.

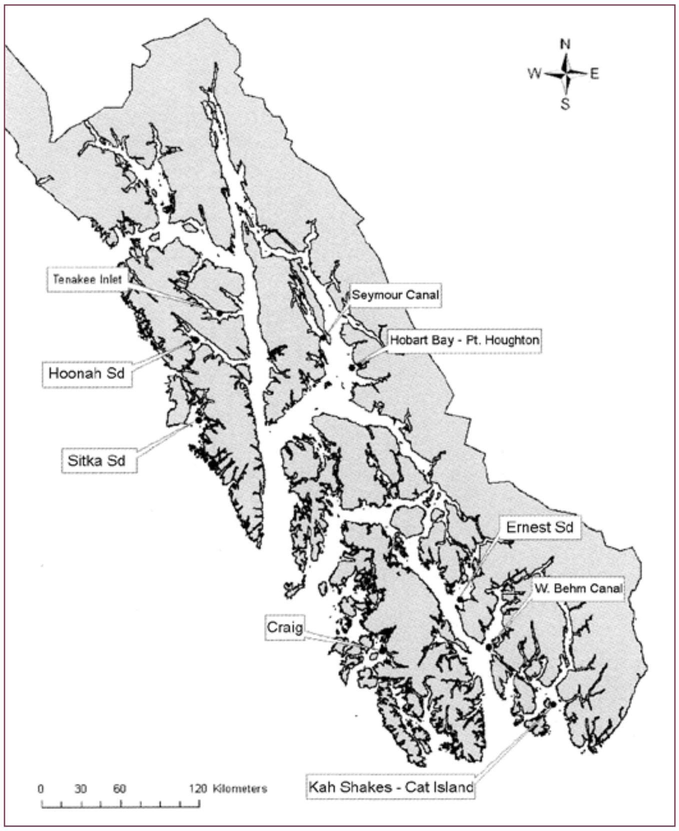
## 5.4 Fish species

### 5.4.1 Southeast Alaska Pacific herring *(Dressel)*

Southeast Alaska waters are comprised of a web of interconnected canals, inlets, sounds, and bays. Currently, there are nine major stocks of herring that reside in southeast Alaska waters, each defined on a spawning area basis: Sitka Sound, Craig, Seymour Canal, Hoonah Sound, Hobart Bay-Port Houghton, Tenakee Inlet, Ernest Sound, West Behm Canal, and Kah Shakes-Cat Island (Fig. GA-23). More limited spawning occurs at other locales throughout southeastern Alaska. Spawning at the nine primary sites for which regular assessments are conducted has probably accounted for 95-98% of the spawning biomass in southeastern Alaska in any given year. The herring that spawn in all areas of Southeast Alaska are believed to be affected by the physical and chemical characteristics of Gulf of Alaska waters, though the spawning areas on the open coast (Sitka Sound, Craig, Kah Shakes-Cat Island) may be affected the greatest or the most immediately.

Although the biomass of Southeast Alaska herring may have been greater prior to the reduction fishery and foreign fisheries that peaked around 1935 and 1970, respectively, the most reliable estimates of biomass are those from data collected since 1980, discussed here. For all stocks combined, the biomass of Southeast Alaska herring has increased since 1980 (Fig. GA-24). The combined biomass level remained relatively consistent until the late 1990s, at which time it began to increase. Age-structured assessment (ASA) modeling for the Sitka Sound, Craig, and Seymour Canal herring stocks indicated a change in herring survival in the late 1990s, which coincided with a period of climate change as described by a shift in the Pacific Decadal Oscillation index (http://jisao.washington.edu/pdo/).

For all stocks combined, five of the six highest annual biomasses since 1980 occurred during the focus period. When viewed separately by stock, the biomass of five southeast herring stocks were at high levels (Sitka Sound, Craig, Hoonah Sound, Seymour Canal, and Ernest Sound), three stocks were at intermediate levels (Hobart Bay-Port Houghton, Tenakee Inlet, and West Behm), and one stock was at a low level (Kah Shakes-Cat Island) in the focus period, compared to previous years. The low level in the Kah Shakes-Cat Island spawning area is at least in part due to a shift in spawning location to the Annette Island Reserve, which is outside the State's management authority. Levels were defined as "high" if all biomass estimates in the focus period were greater than the historical (1980-2002) average, "intermediate" if some biomass estimates in the focus period were above the historical average and some below, and "low" if all biomass estimates during the focus period were below the historical average (Table GA-5).



[Figure GA-23] Location of major Pacific herring stocks in southeast Alaska.

[Table GA-5] Estimates of mature herring biomass (t) for nine primary spawning areas in southeastern Alaska, 1980-2008, and "historical" (1980-2002) average. Values indicate either spawn deposition survey estimates plus catch (regular font), hydro-acoustic estimates (italics), or age-structured model estimates (regular font with footnote).

[a] Estimates include commercial sac roe harvest only.

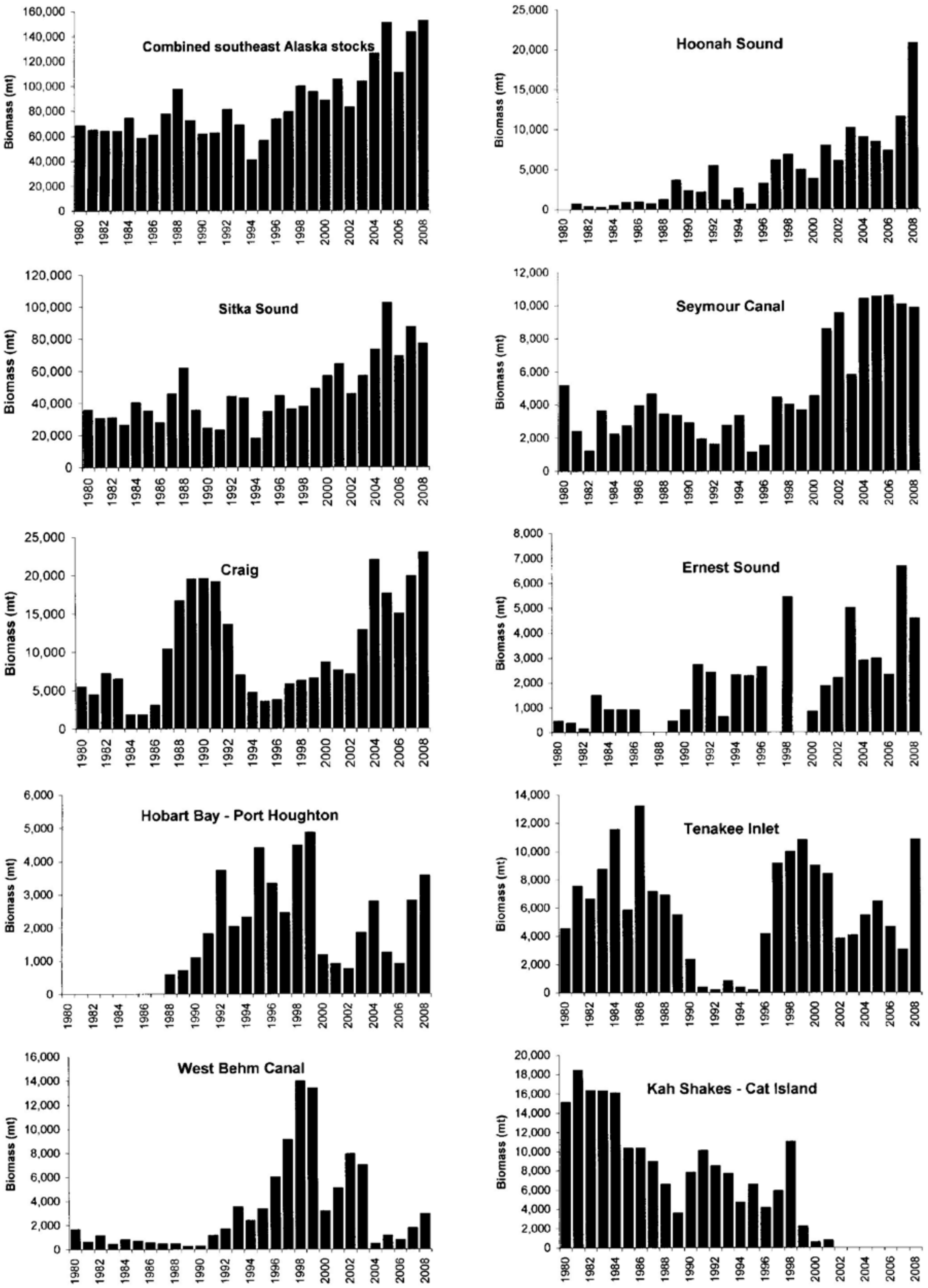
[b] Estimate based on 2008 ASA estimate because of large variability in survey estimate.

[c] Estimates are approximated because they include harvest estimates that are based on a conversion of spawn-on-kelp product to tons of herring (assumes 100% mortality of pounded herring).

[d] Unavailable due to low spawn and therefore no sampling.

[e] Unavailable due to no sampling.

| | Spawning Area | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | Kah Shakes - Cat Island | W. Behm Canal | Craig | Ernest Sound | Hobart Bay-Port Houghton | Seymour Canal | Sitka[a] | Hoonah Sound [c] | Tenakee Inlet | Combined southeast Alaska stocks |
| 1980 | 15,096 | *1,654* | 5,453 | *454* | d | 5,166 | 35,729 | d | *4,526* | 68,078 |
| 1981 | 18,407 | *635* | 4,415 | *372* | d | 2,389 | 30,396 | 680 | *7,539* | 64,833 |
| 1982 | 16,310 | *1,134* | 7,219 | *145* | d | 1,216 | 30,720 | 361 | *6,626* | 63,731 |
| 1983 | 16,274 | *454* | 6,476 | *1,488* | d | 3,642 | 26,263 | 240 | *8,743* | 63,581 |
| 1984 | 16,086 | 794 | 1,814 | *907* | d | 2,239 | 40,215 | 490 | *11,538* | 74,084 |
| 1985 | 10,338 | 680 | 1,814 | *907* | d | 2,722 | 34,904 | 841 | 5,834 | 58,041 |
| 1986 | 10,331 | 567 | 3,041 | *907* | d | 3,939 | 27,617 | 902 | *13,190* | 60,494 |
| 1987 | 8,926 | *454* | 10,415 | e | d | 4,628 | 45,555 | 671 | 7,144 | 77,794 |
| 1988 | 6,565 | *454* | 16,659 | e | 576 | 3,435 | 61,756 | 1,202 | 6,874 | 97,521 |
| 1989 | 3,549 | *227* | 19,497 | *454* | 697 | 3,322 | 35,502 | 3,629 | 5,488 | 72,364 |
| 1990 | 7,824 | 257 | 19,569 | *907* | 1,091 | 2,913 | 24,316 | 2,267 | 2,354 | 61,497 |
| 1991 | 10,079 | 1,155 | 19,117 | *2,722* | 1,814 | 1,905 | 23,050 | 2,123 | 363 | 62,327 |
| 1992 | 8,488 | 1,694 | 13,577 | 2,404 | 3,719 | 1,615 | 44,197 | 5,446 | 181 | 81,322 |
| 1993 | 7,691 | 3,496 | 6,946 | 628 | 2,030 | 2,726 | 42,970 | 1,119 | 820 | 68,426 |
| 1994 | 4,683 | 2,378 | 4,688 | 2,308 | 2,317 | 3,334 | 17,866 | 2,593 | 363 | 40,530 |
| 1995 | 6,584 | 3,320 | 3,499 | 2,269 | 4,400 | 1,136 | 34,380 | 577 | 181 | 56,346 |
| 1996 | 4,113 | 5,993 | 3,738 | 2,617 | 3,334 | 1,545 | 44,425 | 3,187 | 4,145 | 73,097 |
| 1997 | 5,901 | 9,091 | 5,779 | d | 2,444 | 4,457 | 36,068 | 6,148 | 9,160 | 79,049 |
| 1998 | 11,029 | 13,922 | 6,241 | 5,442 | 4,480 | 3,983 | 37,759 | 6,846 | 9,984 | 99,684 |
| 1999 | 2,184 | 13,355 | 6,513 | d | 4,853 | 3,669 | 48,690 | 4,964 | 10,781 | 95,008 |
| 2000 | 582 | 3,155 | 8,627 | 834 | 1,173 | 4,522 | 56,796 | 3,799 | 8,998 | 88,486 |
| 2001 | 743 | 5,057 | 7,570 | 1,861 | 901 | 8,549 | 64,163 | 7,960 | 8,417 | 105,220 |
| 2002 | d | 7,898 | 7,004 | 2,182 | 750 | 9,515 | 45,499 | 6,027 | 3,828 | 82,702 |
| 2003 | d | 6,968 | 12,768 | 4,997 | 1,834 | 5,771 | 56,879 | 10,182 | 4,056[c] | 103,457 |
| 2004 | d | 402 | 21,943 | 2,868[c] | 2,778 | 10,373 | 72,937 | 8,976 | 5,443[c] | 125,719 |
| 2005 | d | 1,116 | 17,583 | 2,965 | 1,244 | 10,524 | 102,213 | 8,431 | 6,434[c] | 150,464 |
| 2006 | d | 739 | 14,967 | 2,302 | 895 | 10,559 | 69,017 | 7,307 | 4,636 | 110,423 |
| 2007 | d | 1,733 | 19,822 | 6,671 | 2,802 | 10,050 | 87,155 | 11,560 | 3,035 | 142,827 |
| 2008 | d | 2,883 | 22,946 | 4,573[c] | 3,557 | 9,832 | 76,719 | 20,760 | 10,848 | 152,118 |
| Historical (1980-2002) average | 8,717 | 3,384 | 8,247 | 1,569 | 2,305 | 3,590 | 38,645 | 2,822 | 5,960 | 73,661 |

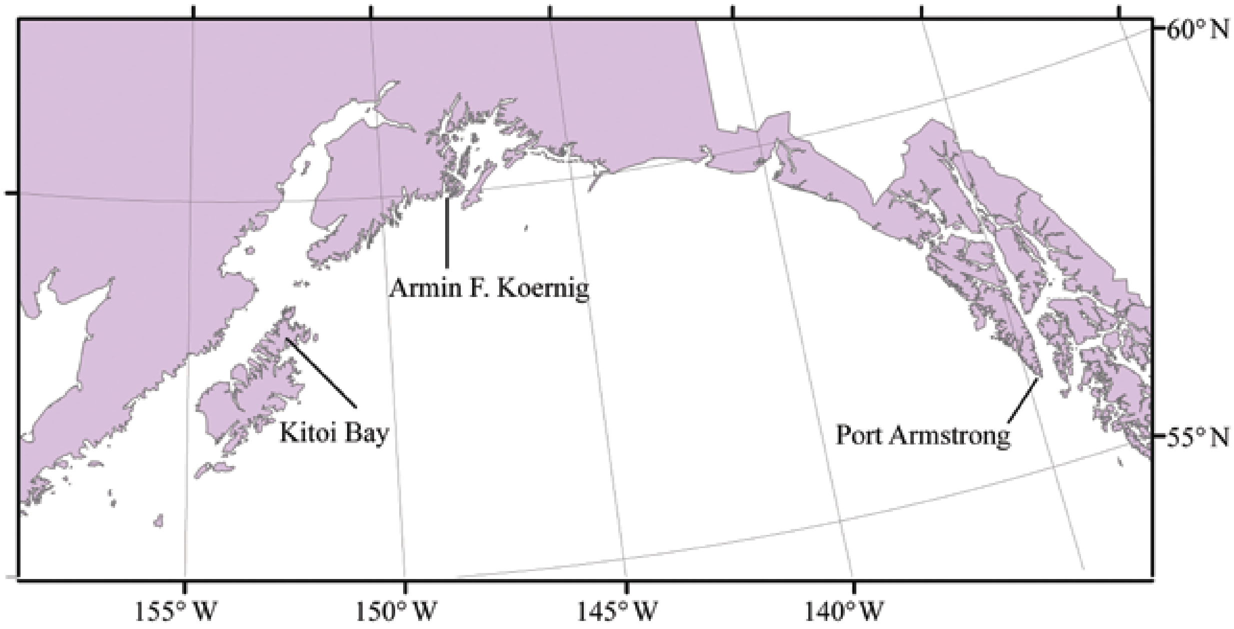


[Figure GA-24] Mature herring biomass prior to spring fishery for nine southeast Alaska stocks and all stocks combined.

### 5.4.2 Hatchery pink salmon *(Farley)*

Decadal-scale and interannual variability in climate and ocean productivity are known to affect total harvest of Pacific salmon (Hare and Francis 1995; Mantua et al. 1997; Francis et al. 1998; Hare et al. 1999; Downton and Miller 1998). More recent papers utilized a large pool (n >100) of salmon return and spawner (R/S) data to develop survival indices for Pacific salmon. These studies found environmental processes affecting temporal variation in salmon survival rates operated at regional scales rather than larger oceanic basin scales (Pyper et al. 2001), and that local ocean conditions (sea surface temperature, sea surface salinity, and coastal upwelling) had little to no impact on regional salmon survival rates (Mueter et al. 2005). In contrast, there was evidence that salmon survival indices positively responded to the 1976-1977 regime shift but both negative and positive responses were found for the proposed climatic regime shift of 1988-1989 (Mueter et al. 2007). Climate regime shifts are believed to have occurred during 1988-1989 (Hare and Mantua 2000) and 1998-1999 (Chavez et al. 2003; Peterson and Schwing 2003) within the GoA. Impacts of the 1976-1977 regime shift on salmon catches are well documented (e.g., Mantua et al. 1997) but further examination of this issue is warranted.

The best time series available to test for possible effects of climate regimes on hatchery pink salmon marine survival are from three hatcheries located at three representative locations in the eastern, central and western coastal Gulf of Alaska. The metric used was the ratio of the annual pink salmon fry released into marine waters to the annual number of adults returning the following year for three hatcheries, Port Armstrong (eastern), Armin F. Koernig, and Kitoi Bay hatcheries located within Southeast Alaska, Prince William Sound, and Kodiak Island along coastal waters of the Gulf of Alaska (Fig. GA-25). These hatcheries are likely representative of survival in the Gulf of Alaska since their locations minimize the effect of conditions in inside waters of Southeast Alaska and Price William Sound on early marine survival of juveniles. Hatchery data are well suited for comparisons of marine survival and climate variability because marine survival is estimated from a known number of fry released and the number of returning adults (catch + spawners), providing more accurate marine survival estimates over R/S indices used in the above papers. In addition, pink salmon only spend approximately 1 year at sea before returning to their natal streams/hatcheries to spawn.



[Figure GA-25] Pink salmon hatchery locations in Southeast Alaska (Port Armstrong), Prince William Sound (Armin F. Koernig), and Kodiak Island (Kitoi Bay).

Marine survival (1971-2007) in year t for each pink salmon cohort (eggs fertilized in year t-1) was determined by dividing the number of pink salmon fry released to marine waters of the GoA (now considered juvenile salmon) during year t by the number of returning adult pink salmon during year t+1. Pink salmon catch data (1971-2007) were assembled from Alaska Department of Fish and Game, Fishery Management Reports for Southeast Alaska (Davidson et al. 2008), Prince William Sound (Lewis et al. 2008), and Kodiak (Wadle 2007). Marine survival and pink salmon catch data were normalized and the time period of 2002 to 2007 was compared to the previous five years.

Pairwise correlations among pink salmon marine survival and catch data (regional covariation) were tested using a standard significance test, where statistical significance was determined using a two-tailed test with $\alpha = 0.05$. Positive correlation among these regionally spaced hatcheries may imply a common basin scale atmospheric/oceanic condition equally affecting hatchery pink salmon marine survival in the Gulf of Alaska.

Alaska hatcheries thermally mark otoliths of pink salmon during the egg stage. These unique thermal marks on otoliths can then be used to identify hatchery pink salmon captured during ocean surveys (Carlson et al. 2000). Otoliths were removed from juvenile pink salmon captured during the surveys and hatchery origin was determined by examining the otoliths for unique thermal marks.

Survival anomalies were negative beginning in 2002 for Port Armstrong, oscillated between positive and negative for Armin F. Koernig, and were generally positive for Kitoi Bay (Fig. GA-26). Comparing hatchery pink salmon survival anomalies from the last five years with the previous five years indicated survival anomalies generally switched from positive to negative for Port Armstrong, but no real detectible shift could be seen for either Armin F. Koernig or Kitoi Bay.

Pink salmon catch anomalies were generally positive for Southeast Alaska, with the exception of 2006, oscillating between being highly positive to near 0 for Prince William Sound, and were positive for Kodiak Island (Fig. GA-27). In Kodiak and Southeast Alaska, pink salmon catch remained positive during the last five years in all areas when compared to the previous five years.

Marine survival estimates and catch data for hatchery pink salmon were not significantly correlated ($p > 0.5$) among hatcheries and regions located around the GoA (Tables GA-6 and GA-7). Correlation coefficients were positive among hatcheries that were nearest each other and negative among hatcheries that were furthest apart. Correlation coefficients were positive among Southeast Alaska, Prince William Sound, and Kodiak pink salmon catch data but negative between Prince William Sound and Kodiak pink salmon catch data.

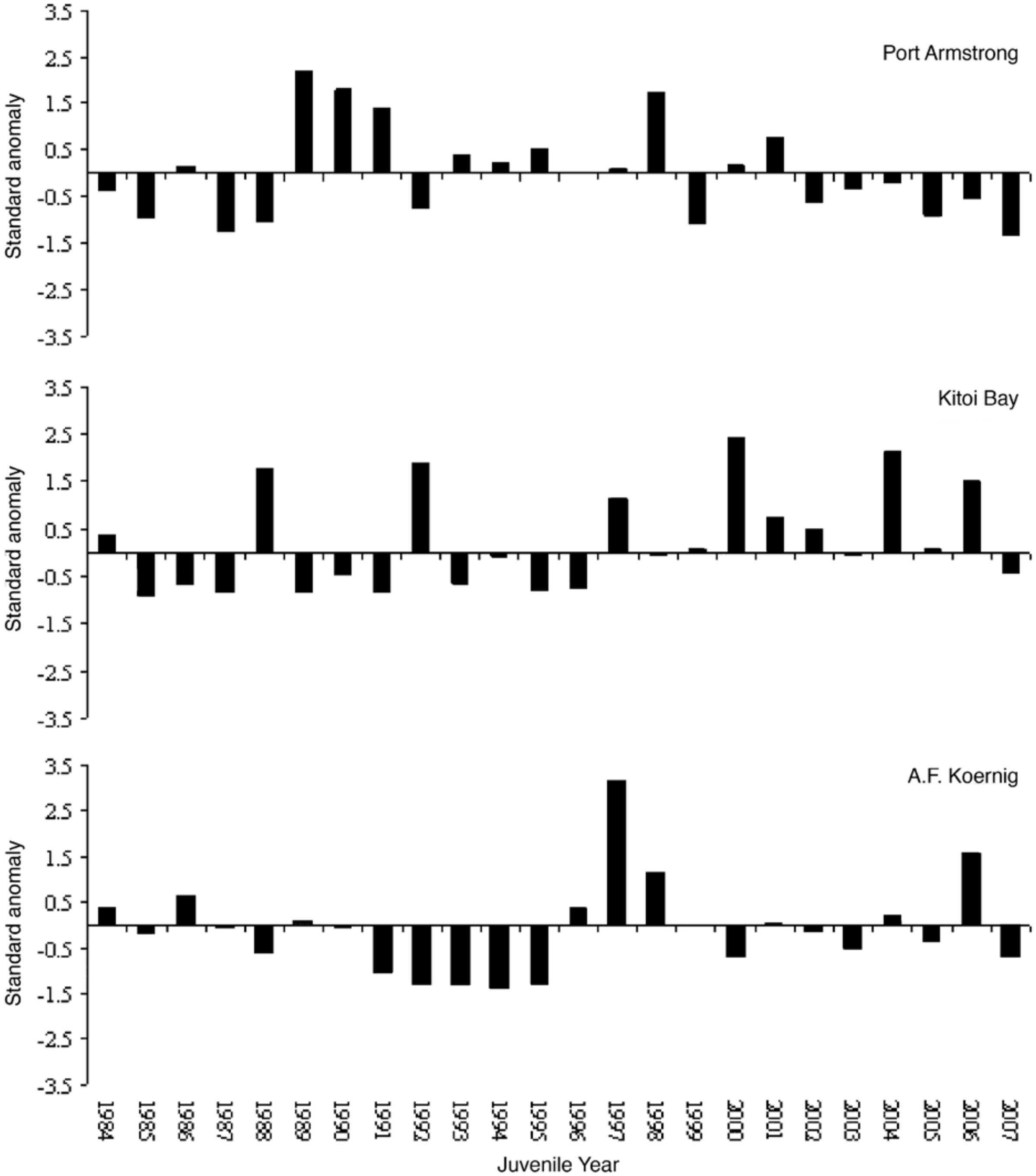
In conclusion, hatchery pink salmon survival and catch were not correlated at the regional scales examined across the GoA, further indicating that survival is likely linked to regional oceanic conditions and not basin scale conditions (Mueter et al. 2007).

[Table GA-6] Summary of pairwise correlations among pink salmon marine survival estimates (1984 – 2007) from Port Armstrong, Armin F. Koernig, and Kitoi Bay hatcheries.

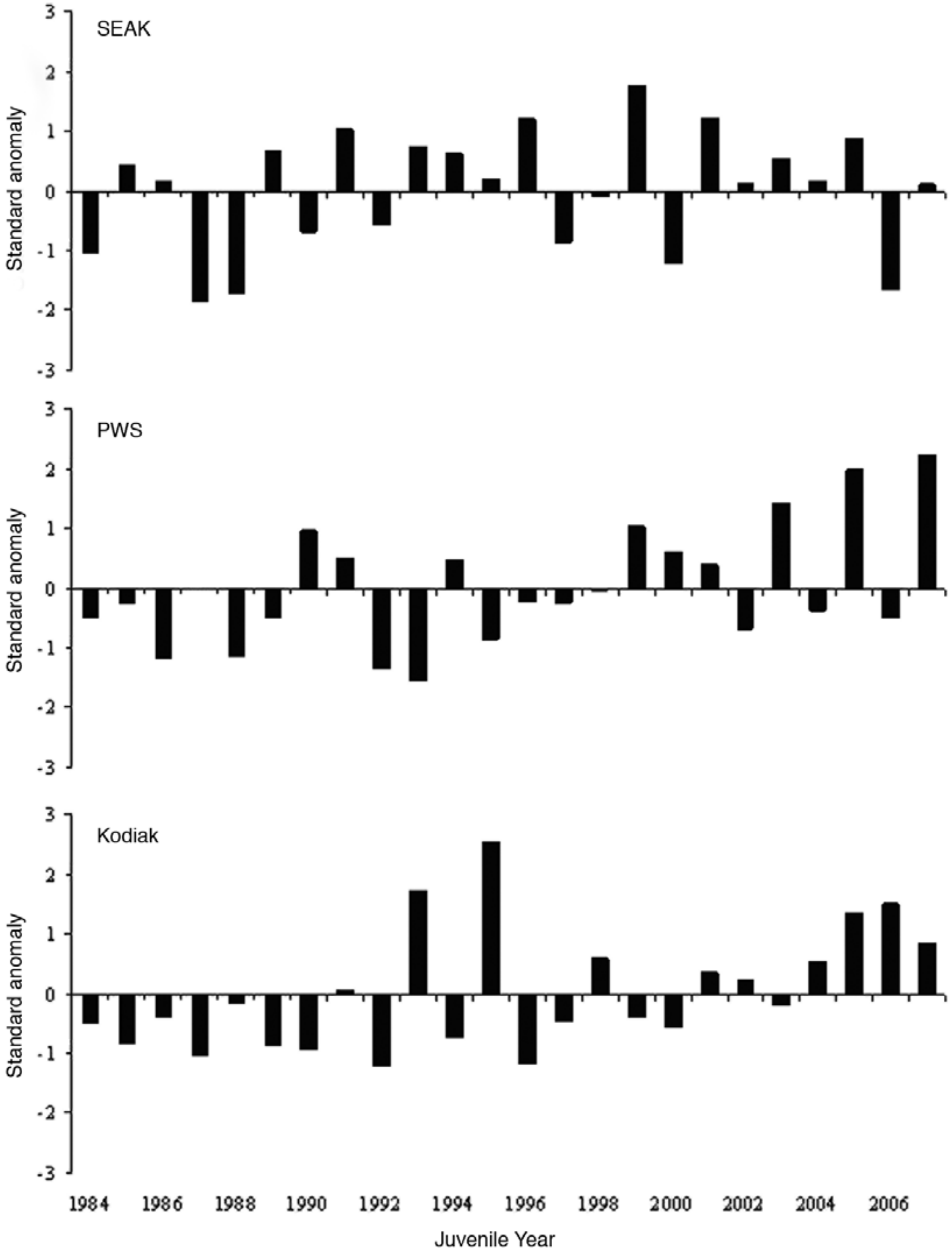
| Hatchery | Port Armstrong | Armin F. Koernig |
|---|---|---|
| Port Armstrong | | |
| Armin F. Koernig | 0.071 | |
| Kitoi Bay | -0.250 | 0.14 |

[Table GA-7] Summary of pairwise correlations among pink salmon catch (1984 – 2007) for Southeast Alaska (SEAK), Prince William Sound (PWS), and Kodiak.

| Region | SEAK | PWS |
|---|---|---|
| PWS | 0.28 | |
| Kodiak | 0.11 | -0.00 |



[Figure GA-26] Standard anomalies of hatchery pink salmon survival, 1984 to 2007.

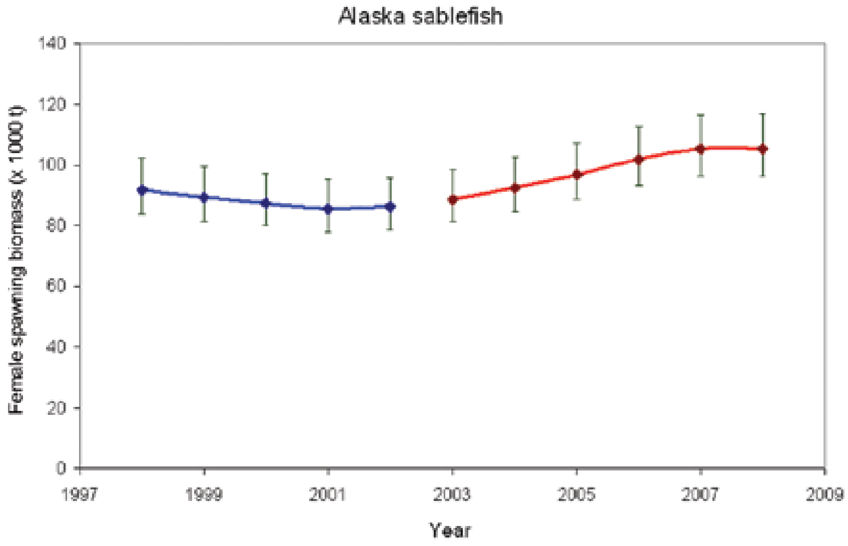


[Figure GA-27] Standard anomalies of pink salmon catch data from southeast Alaska (SEAK), Prince William Sound (PWS), and Kodiak Island, (1984 to 2007).

### 5.4.3 Sablefish

*(Hanselman, Shotwell, Lunsford, Heifetz)*

Sablefish (*Anoplopoma fimbria*) in Alaska are managed as a single stock so all data presented here reflect the Gulf of Alaska, Bering Sea, and Aleutian Islands regions. Sablefish abundance decreased slightly during the time period 1998-2003 reaching an all-time low in 2001 (Fig. GA-28). Since 2003, abundance has increased slightly. Sablefish abundance is highly dependent on successful recruitment. Recruitment for sablefish is defined as abundance of age-2 fish. During 1998-2002, recruitment was above average in 1999 (1997 year class) and 2002 (2000 year class) (Fig. GA-29). Annual recruitment during the focus period appears to have been below average but because it takes several years of data to accurately determine recruitment, estimates since 2002 are highly uncertain and should be considered preliminary. In general, detecting statistically significant recent trends for long-lived, late-selected groundfish is unlikely.



[Figure GA-28] Estimated female sablefish spawning biomass, 1998-2008. Error bars are ±2 times the standard deviation estimates from the stock assessment model. Blue line and markers represent the first period 1998-2002, red line and markers represent the second period 2003-2008.

[Figure GA-29] Estimated recruitment (age-2) anomalies of Gulf of Alaska sablefish, 1998-2008. Blue bars represent the first period 1998-2002, red bars represent the second period 2003-2008.

### 5.4.4 Rockfish species *(Rooper)*

In an analysis of Alaska rockfish (*Sebastes* spp.), five species assemblages were defined based on similarities in their distributions along environmental gradients: central GoA shelf, southeastern Alaska break, Aleutian Islands shelf, Aleutian Islands break, and Aleutian Islands slope (Rooper 2008). Data from 14 bottom trawl surveys of the GoA and Aleutian Islands (n = 6,767) were used. The distinct assemblages of rockfish were defined by geographical position, depth, and temperature (Rooper 2008). The 180 m and 275 m depth contours were major divisions between assemblages inhabiting the shelf, shelf break, and lower continental slope. Another noticeable division was between species centered in southeastern Alaska and those found in the northern GoA and Aleutian Islands. In this time-series, the mean-weighted distribution of six rockfish species along the three environmental gradients (depth, temperature, and position) was calculated for the Gulf of Alaska and Aleutian Islands. Position is the distance of each trawl from Hinchinbrook Island (60.2°N 146.6°W), Alaska. A-CPUE weighted mean value and standard deviation for each environmental variable was computed (Rooper 2008). There were no trends in distribution over the time series for depth or temperature, although the distributions of rockfish species across temperatures were more contracted in 2007 than in previous years (Fig. GA-30). However, there did appear to be a continued movement of the mean-weighted distribution towards the north and east (as indicated by the position variable). This may indicate a change in rockfish distribution around the Gulf of Alaska and is especially apparent in the distribution of juvenile Pacific Ocean perch.

### 5.4.5 Pacific Ocean perch

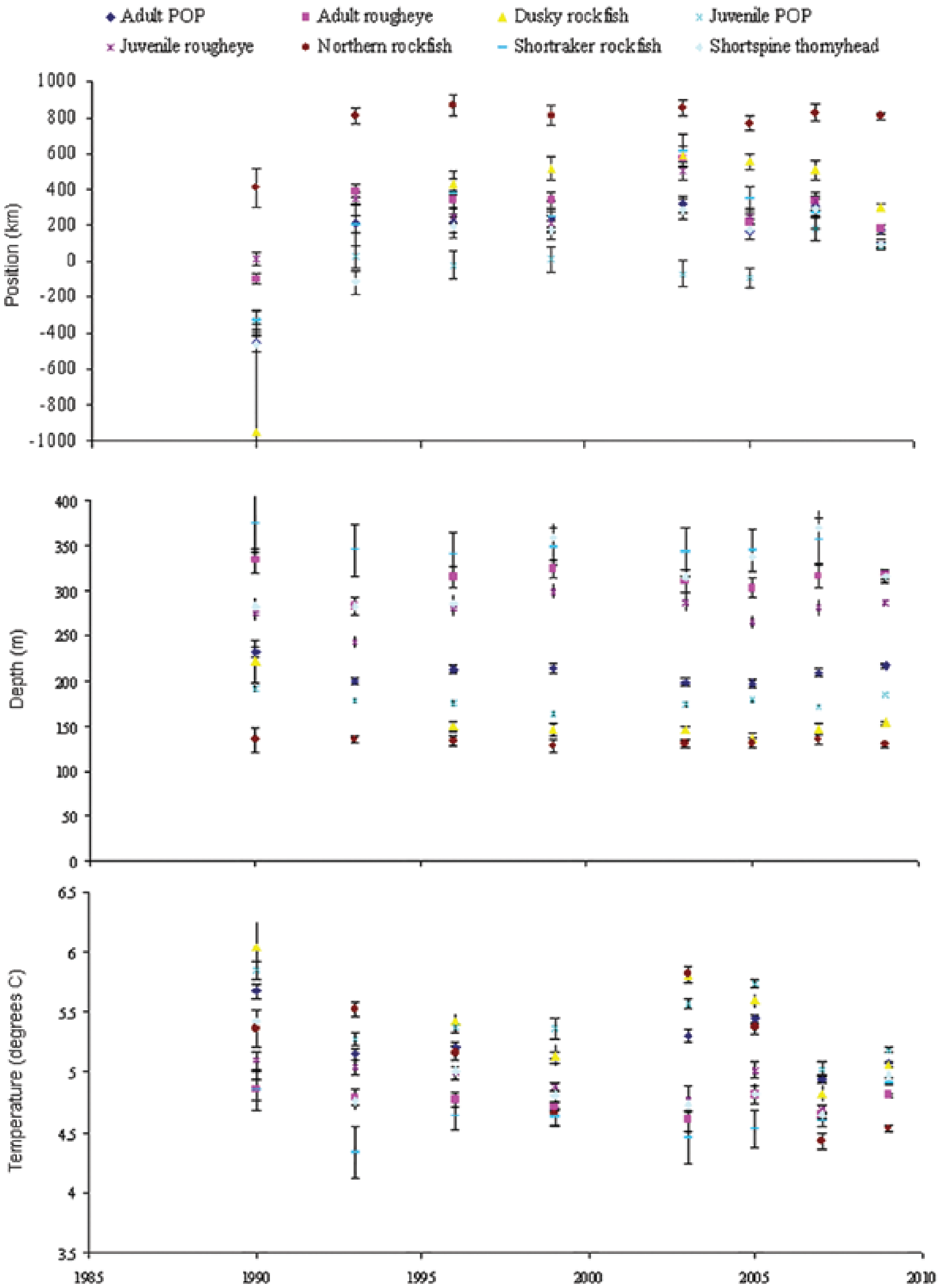
*(Hanselman, Shotwell, Lunsford, Heifetz)*

Pacific ocean perch (POP) (*Sebastes alutus*) is the most abundant species of rockfish in the GoA. POP abundance increased slightly during 1998-2002 and continued to increase during the focus period (Fig. GA-31). Female spawning biomass in 2008 was 29% higher than in 1998. POP abundance is highly dependent on successful recruitment, which varies widely (Fig. GA-32). Recruitment for POP is defined as age-2 fish. From 1998-2002 recruitment was near average in 1999 and 2002 (1997 and 2000 year classes), above average in 1998 and 2000 (1996 and 1998 year classes), and substantially above average during 2001 (1999 year class). Annual recruitment during the focus period appears to have been below average but, because it takes several years to accurately predict recruitment, estimates since 2002 include a high degree of uncertainty and should be considered preliminary.

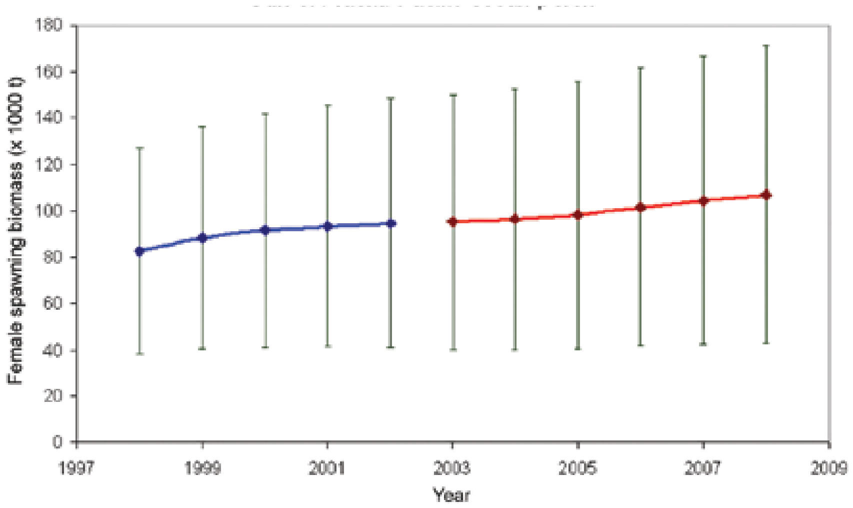
### 5.4.6 Northern rockfish

*(Hanselman, Shotwell, Lunsford, Heifetz)*

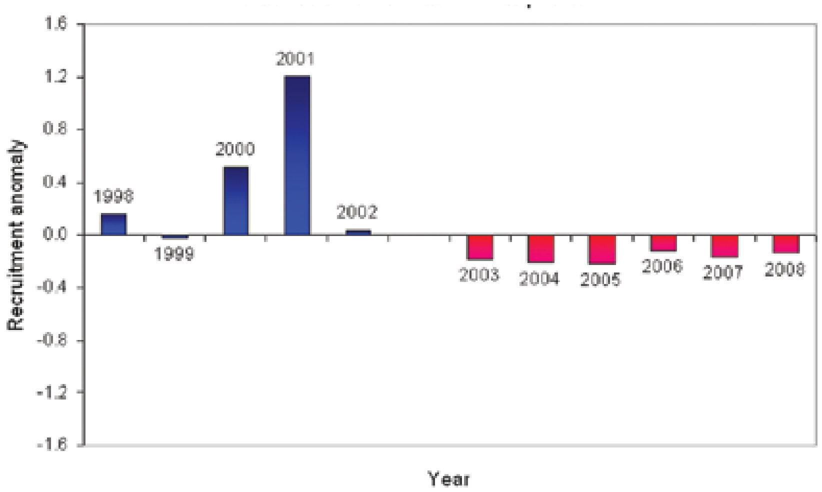
Northern rockfish (*Sebastes polyspinus*) are the second most abundant rockfish species in the Gulf of Alaska. Their abundance decreased during 1998-2002 and continued to decrease during the focus period (Fig. GA-33). Female spawning biomass in 2008 was 18% lower than in 1998. Northern rockfish abundance is highly dependent on successful recruitment which varies widely (Fig. GA-34). Recruitment for northern rockfish is defined as age-2 fish. From 1998-2002 recruitment was below average in 1998 (1996 year class), average in 1999 (1997 year class), above average in 2000 (1998 year class), and below average during 2001 and 2002 (1999 and 2000 year classes). Annual recruitment during the focus period appears to have been below average but because it takes several years to accurately predict recruitment, estimates since 2002 include a high degree of uncertainty and should be considered preliminary.



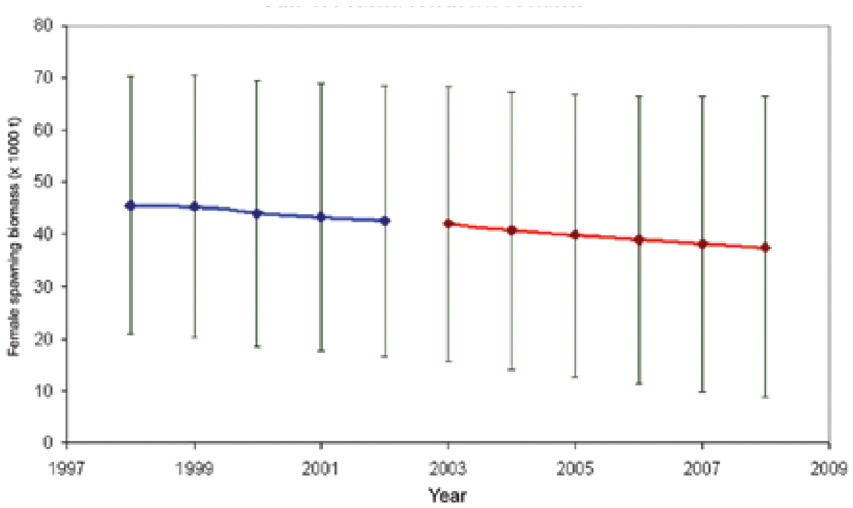
[Figure GA-30] Plots of mean-weighted (by catch per unit effort) distributions (and standard errors) of seven rockfish species groups by position in the Gulf of Alaska. Position is the distance from Hinchinbrook Island, Alaska, with positive values west of this central point in the trawl surveys and negative values in the southeastward.



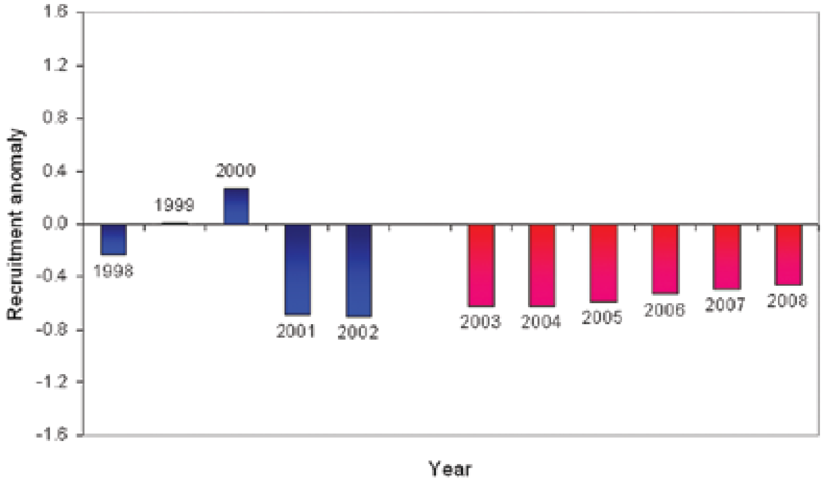
[Figure GA-31] Estimated Gulf of Alaska female Pacific Ocean perch spawning biomass, 1998-2008. Error bars are ±2 times the standard deviation estimates from the stock assessment model. Blue line and markers represent the first period 1998-2002, red line and markers represent the second period 2003-2008.



[Figure GA-32] Estimated recruitment (age-2) anomalies of Gulf of Alaska Pacific Ocean perch, 1998-2008. Blue bars represent the first period 1998-2002, red bars represent the second period 2003-2008.



[Figure GA-33] Estimated Gulf of Alaska female northern rockfish spawning biomass, 1998-2008. Error bars are ±2 times the standard deviation estimates from the stock assessment model. Blue line and markers represent the first period 1998-2002, red line and markers represent the second period 2003-2008.



[Figure GA-34] Estimated recruitment (age-2) anomalies of Gulf of Alaska northern rockfish, 1998-2008. Blue bars represent the first period 1998-2002, red bars represent the second period 2003-2008.

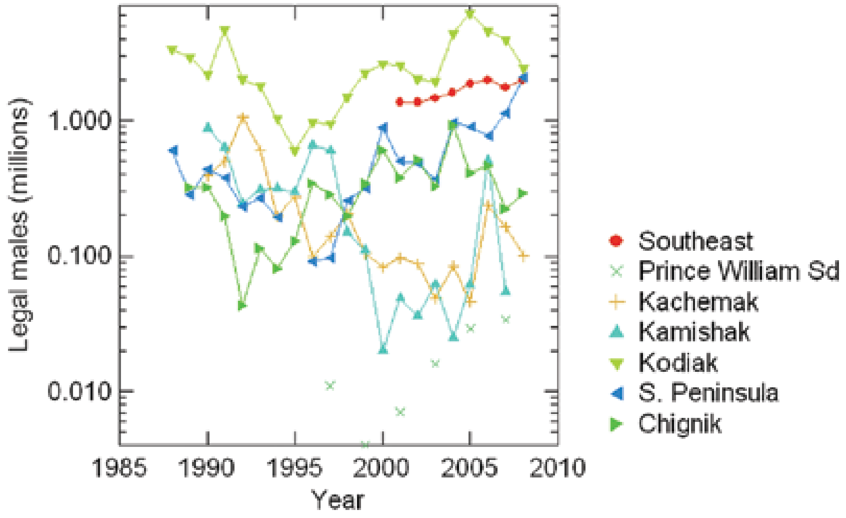
## 5.5 Invertebrates *(Woodby)*

### 5.5.1 Tanner crab

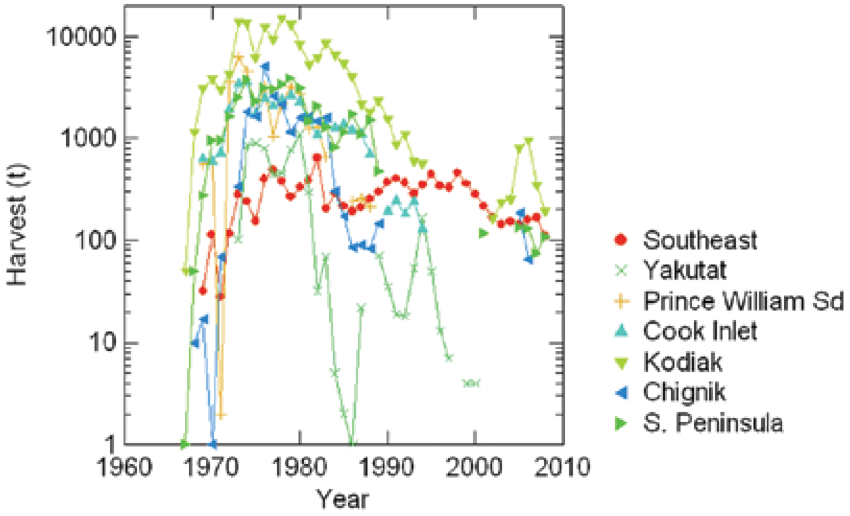
Surveys by the Alaska Department of Fish and Game indicate that Tanner crab (*Chionoecetes bairdi*) abundances have been slowly increasing during the focus period in the central and western Gulf of Alaska in waters off Kodiak (57°N, 153°W), Chignik (56.5°N, 158°W), and the Alaska Peninsula (55°N, 161°W) relative to lows in the 1990s (Fig. GA-35). The Tanner crab population in Prince William Sound (60.5°N, 147°W) has been on an increasing trend as well, however, there are no trawl survey data for comparison there prior to 1997. Populations in lower Cook Inlet at Kachemak and Kamishak Bays (59.6°N, 151.7°W and 59.2°N, 153.8°W, respectively) have continued to be depressed relative to the prior decade, with some weak signs of recovery, particularly in 2006. The Southeast Alaska (55-59°N, 131-137°W) population has been relatively stable since 2001 when Tanner crab pot surveys began there.

Commercial fisheries for Tanner crab developed in the late 1960s and 1970s in the Gulf of Alaska, with large harvests taken from Kodiak area waters, as well as from Prince William Sound and Cook Inlet (60° N, 152° W), and smaller fisheries at Yakutat (59.5° N, 140° W) and in Southeast Alaska (Fig. GA-36). Peak Gulf-wide harvests were as high as 28,500 mt in the 1973/74 season, representing about 27 million legal males (approximately 1.07 kg each). With the exception of Southeast Alaska, each of the major fisheries declined and was closed for conservation purposes, first in Prince William Sound, Chignik, and the South Peninsula fisheries in the late 1980s, followed by Cook Inlet, Kodiak, and Yakutat in the 1990s.

In the recent 5 years, commercial Tanner crab fisheries have been open only in Southeast Alaska and in the central Gulf of Alaska at Kodiak, with only a few annual openings at Chignik and the South Peninsula areas. The Southeast Alaska fishery has been relatively stable but at levels one-half or less than in prior decades. The Kodiak fishery reopened in the 2001-2002 season with recent peak harvests in the 2004-2005 and 2005-2006 seasons, followed by declines due to management decisions based on declining abundance estimates (Sagalkin 2008). Harvests in this decade in the central and western Gulf have been minor compared to peak harvests in the 1970s and 1980s, reflecting a lack of significant recruitment despite little or no directed commercial fishing from 1990 through 2001. Hypothesized explanations for the decline in abundance include a reorganization of the benthic community following a climate regime shift in 1977 (Anderson and Piatt 1999) as well as overfishing and serial depletion (Orensanz et al. 1998).



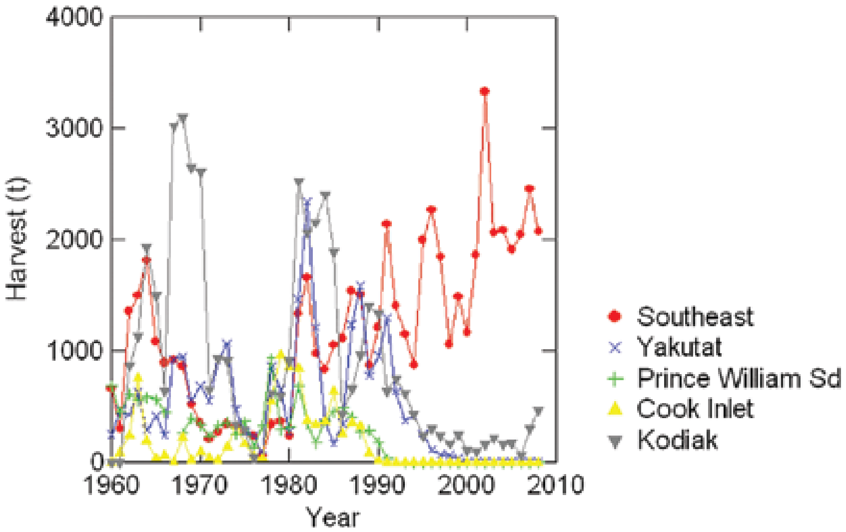
[Figure GA-35] Tanner crab survey abundance indices for Gulf of Alaska sites. All data are for legal males (at least 140 mm carapace width Gulf-wide except 135 mm in Prince William Sound) estimated by area-swept methods from trawl surveys, except in Southeast Alaska where surveys have been conducted by pots and estimates are based on catch survey analysis.



[Figure GA-36] Tanner crab commercial harvests in Gulf of Alaska fisheries. Data are confidential or missing for Chignik in 1971-1972 and for Yakutat for 1987-1988 and 1997-1998. Source: Alaska Department of Fish and Game fish ticket system, except data for Kodiak, Chignik, and South Peninsula are from Sagalkin (2008).

### 5.5.2 Dungeness crab

Harvests of Dungeness crab (*Metacarcinus magister*) in Alaska's extant fisheries are generally indicative of recruitment and abundance. This is because intensive fishing, since at least the 1980s, harvests the majority of the legal population each year, with the result that annual production is highly dependent on recruitment to legal size classes. Alaska's largest Dungeness crab fishery in Southeast Alaska has been at record high levels in the focus period compared to prior years (Fig. GA-37). Fisheries elsewhere in the GoA have been closed due to low stock abundance, as in Yakutat, Prince William Sound, and Cook Inlet, or are prosecuted at reduced levels, as in Kodiak. Strong annual recruitment in the inside marine waters of Southeast Alaska is in contrast to cyclical recruitment in outer coastal regions in other jurisdictions, such as Washington, Oregon, and California, where environmental forcing, including ENSO, and density-dependent mechanisms have been hypothesized to affect recruitment through larval transport or feeding (Botsford 2001; Botsford and Hobbs 1995). The physical oceanographic connections between the inside waters of Southeast Alaska and the coastal currents of the GoA are not well understood (Weingartner et al. 2009) but the productivities of the inside waters are substantially lower than those of the outer coast.



[Figure GA-37] Dungeness crab commercial harvests in five Gulf of Alaska fisheries, 1960 to 2008. Data are confidential for Kodiak in 1977 and Prince William Sound in 1992. Data are missing for Prince William Sound in 1967. Source: Alaska Department of Fish and Game fish tickets.

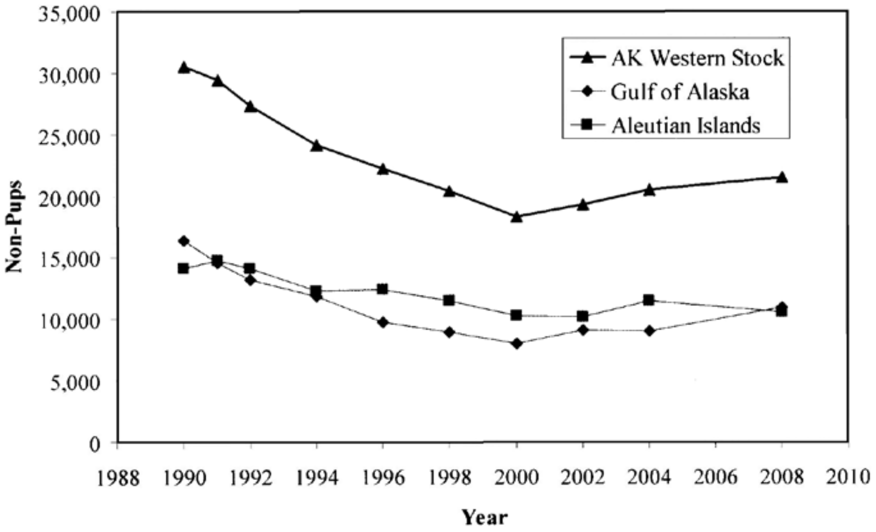
## 6.0 Marine Mammals *(Allen)*

Trends in marine mammal populations require extensive surveys that must often target the most vulnerable species. During the focus period in the Gulf of Alaska, the Cook Inlet beluga whale stock (2008), transient and resident killer whales (2009), northern fur seal (2008), and western (2009) and eastern (2009) stocks of Steller sea lion were assessed. In addition, new information is available for some sea otter populations.

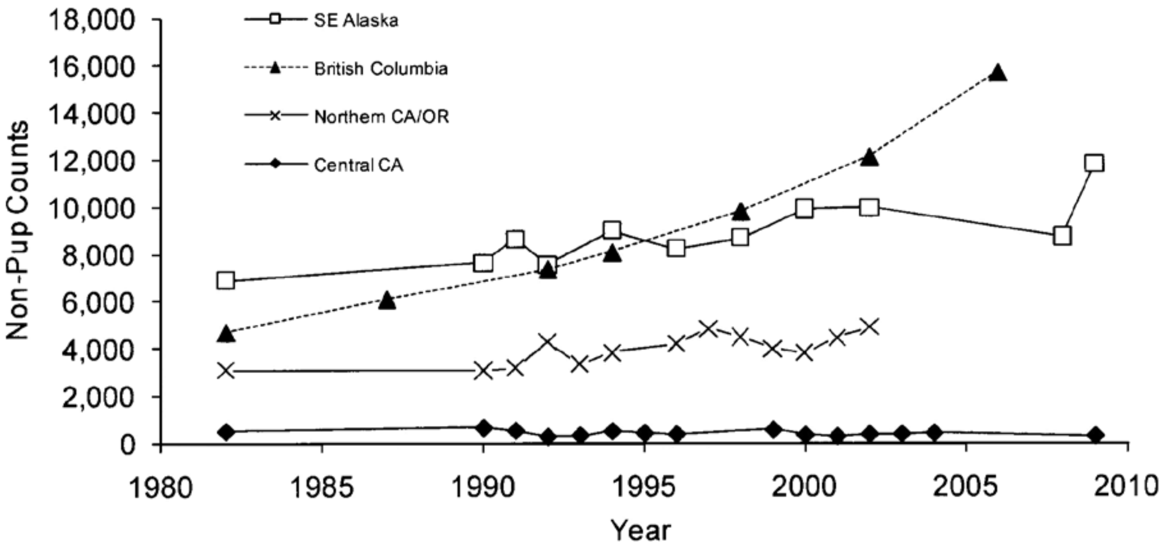
### 6.1 Steller sea lion

Two stocks of Steller sea lion occur in the Gulf of Alaska: the western U.S. stock, which includes animals at and west of Cape Suckling (144°W), and the eastern stock, which is comprised of animals east of Cape Suckling. The minimum population estimate for the western stock is 42,366, which is based on the 2008 counts of non-pups (31,246) and counts of pups (11,120) from 2005-2009 (Fritz et al. 2008a; DeMaster 2009). Counts of Steller sea lion at trend sites for the western U.S. stock decreased 40% from 1991 to 2000, an average annual decline of 5.4% (Loughlin and York 2000). Counts of non-pup Steller sea lion at trend sites for the western U.S. stock increased 5.5% from 2000 to 2002, and at a similar rate between 2002 and 2004 (Allen and Angliss 2010). These were the first region-wide increases for the western stock since standardized surveys began in the 1970s.

Although counts at some trend sites are missing for both 2006 and 2007, available data indicate that the size of the adult and juvenile portion of the western Steller sea lion population throughout much of its range in Alaska has remained largely unchanged between 2004 (N=23,107) and 2007 (N=23,118) (Fritz et al. 2008a). Results of the aerial survey conducted in 2008 (Fritz et al. 2008b) confirmed that the recent (2004-2008) overall trend in the western population of adult and juvenile Steller sea lion in Alaska is stable. However, there are significant regional differences in recent (2004-2008) trends. A consistent increase (7%) was observed between 2004 and 2008 in the eastern Aleutians Islands population whereas the central and western Aleutian Island populations declined 30% and 16%, respectively. An increase was seen in the populations in the central and western Gulf of Alaska between 2004 and 2007 but a decline was noted between 2007 and 2008. Non-pup counts in the eastern GoA increased 35%; however, this may be in part a reflection of a slight change in the timing of the 2008 survey and seasonal movements of animals into this area from the central Gulf of Alaska and Southeast Alaska (eastern stock). Survey results from 2009 are consistent with the hypothesis that seasonal movements into the eastern Gulf of Alaska may have affected non-pup trend analyses, and these results support the conclusion that the increase observed between 2000 and 2004 did not continue, with the population remaining stable between 2004 and 2008 (Fig. GA-38).



[Figure GA-38] Counts of adult and juvenile Steller sea lion at rookery and haulout trend sites throughout the range of the western U.S. stock in Alaska, 1990-2008. Correction factor applied to 2004 and 2008 counts for film format differences (Modified from Fritz and Stinchcomb 2005).



[Figure GA-39] Counts of adult and juvenile Steller sea lion at rookery and haulout trend sites throughout the range of the eastern U.S. stock, 1982-2009. Data from British Columbia include all sites. (Modified from Allen and Angliss 2010).

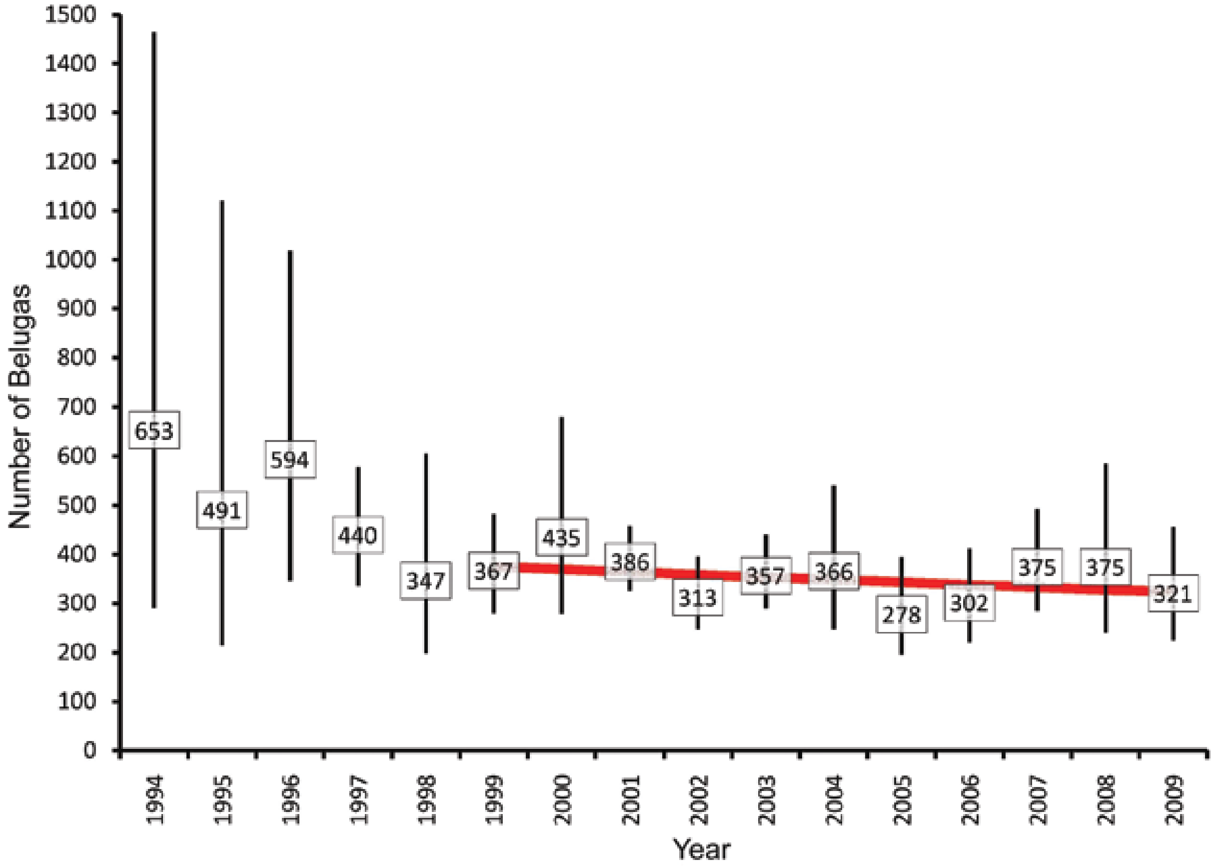
The eastern U. S. Steller sea lion stock has traditionally been stable or increasing throughout its range in the GoA. Declines in populations have been observed historically in southern and central California but overall, counts of non-pups at trend sites in California and Oregon have been relatively stable or slowly increasing since the 1980s (Allen and Angliss 2010). In Southeast Alaska, counts of non-pups at trend sites increased by 56% from 1979 to 2002 from 6,376 to 9,951 (Merrick et al. 1992; Sease et al. 2001; NMFS 2008). Between 1979-2009, counts of pups on the three largest rookeries in Southeast Alaska (Forrester Complex 54.9°N 133.5°W, Hazy Island 55.9°N 134.5°W, and White Sisters 57.6°N 136.3°W) more than tripled (from 2,219 to 6,859). In British Columbia, counts of non-pups throughout the Province increased at a rate of 3.9% annually from 1971 through 2006 (Olesiuk and Trites 2003; Olesiuk 2008). Counts of non-pups at trend sites throughout the range of the eastern Steller sea lion stock are shown in Figure GA-39. Between the 1970s and 2002, the average annual population growth rate of eastern Steller sea lion was 3.1% throughout most of their range (Pitcher et al. 2007). The minimum population estimate for the eastern Steller sea lion stock is 52,847 based on counts of pups and non-pups as old as 2001 (Washington) to as recent as 2009 (all trend sites in Southeast Alaska and California, and rookeries in Oregon) (Allen and Angliss 2010; DeMaster 2009).

## 6.2 Beluga whale

The abundance of the Cook Inlet stock of beluga whales (*Delhinapterus leucas*) was estimated to be 321 individuals in 2009. A statistically significant declining trend in abundance was detected between 1994 and 1998 (Hobbs et al. 2000), although the power was low due to the short duration of the time series. A Bayesian inference on the population size estimates for 1994-2005 gave a modal estimate of the current trend of -1.2% per year, with a 71% probability that the population is declining (Lowry et al. 2006). The rate of decline since a hunting quota was in place (1999-2009) has been 1.49% per year (Fig. GA-40). A recent review of the status of the population indicated that there is an 80% chance that the population will decline further (Hobbs and Shelden 2008).

## 6.3 Killer whale

Recent data from Matkin et al. (2008) indicate that the component of the Alaska resident stock of killer whale (*Orcinus orca*) that spends its summers in the Prince William Sound and Kenai Fjords area is increasing. With the exception of the AB pod, which declined drastically after the *Exxon Valdez* oil spill in 1989 and has not yet recovered, the component of the Alaska resident stock in the Prince William Sound and Kenai Fjords (59.9° N 149.6°W) area has increased 3.2% per year from 1990 to 2005 (Matkin



[Figure GA-40] Abundance of beluga whales in Cook Inlet, Alaska 1994-2009 (Rugh et al. 2005, Hobbs and Shelden 2008). Error bars depict 95% confidence intervals. In the years since a hunting quota was in place (1999-2009), the rate of decline (red trend line) has been -1.49% per year.

et al. 2008). Although the current minimum population count from the 2000-2009 period of 2,084 is higher than the last population count of 1,123, examination of only count data does not provide a direct indication of the net recruitment into the population, and the increase is primarily attributed to the identification of new uniquely identifiable individuals based on increased survey effort and coverage (Matkin, pers. comm. 8 February 2010). At present, reliable data on trends in population abundance for the entire Alaska resident stock of killer whales are unavailable.

In Prince William Sound, one resident pod, (AB Pod) and one transient population (AT1 Group) suffered losses of 33 and 41%, respectively, in the year following the spill (Matkin et al. 2008). Sixteen years later, AB Pod had not recovered to pre-spill numbers, and the rate of increase was significantly less than that of other resident pods that did not decline at the time of the spill. The AT1 Group, which lost 9 of its 22 members during the winter following the 1989 spill, is currently estimated to consist of seven whales (Matkin et al. 2008; Allen and Angliss 2010). Based on the continued decline of the AT1 Group, this group is now listed as depleted under the Marine Mammal Protection Act. The loss of individuals, particularly of reproductive-age females, from these two ecologically and genetically separate groups, and a declining trend in group size post-spill, suggest killer whales are highly vulnerable to environmental disasters such as oil spills. It is highly likely that the AT1 group will not recover (Matkin et al. 2008).

## 6.4 Humpback whale

Two stocks of humpback whale (*Megaptera noraengeliae*) occur in the Gulf of Alaska: the western North Pacific and the central North Pacific stocks (Allen and Angliss 2010). During 2004-2006, a large-scale study of humpback whales throughout the North Pacific was conducted, referred to as the Structure of Populations, Levels of Abundance, and Status of Humpbacks (SPLASH) project (Calambokidis et al. 2008). Based on SPLASH results, it is apparent that humpback whales from these two Alaska stocks mix to a limited extent on summer feeding grounds ranging from British Columbia through the central Gulf of Alaska and up to the Bering Sea. Population structure in the North Pacific based on samples collected from this study is currently being analyzed. Point estimates of abundance for Asia (Philippines, Okinawa, and the Ogasawara Islands), the wintering grounds for much of the western North Pacific stock, range from 938 to 1,107. These estimates of abundance for Asia from SPLASH represent a 6.7% annual rate of increase over the 1991-1993 abundance estimate for this stock. However, the 1991-1993 estimate did not include estimates from waters near the Philippines. SPLASH results showed point estimates of abundance for Hawaii, the wintering grounds for much of the central North Pacific stock, ranging from 7,469 to 10,103. Comparisons of SPLASH abundance estimates for Hawaii with estimates from 1991-1993 gave estimates of annual increase that ranged from 5.5 to 6.0% (Calambokidis et al. 2008). Abundance estimates from SPLASH on the summer feeding grounds for the central North Pacific stock ranged from 2,889 to 13,594 for the Aleutian Islands and Bering Sea, from 2,845 to 5,122 for the Gulf of Alaska, and 2,883 to 6,414 for Southeast Alaska/northern British Columbia (Calambokidis et al. 2008). Zerbini et al. (2006) estimated and annual rate of increase of 6.6% (95% C.I. of 5.2-8.6%) from 1987-2003 for humpback whales from the shelf waters of the northern Gulf of Alaska.

## 6.5 Sea otter

Estimates of sea otter (*Enhydra lutris*) abundance in Glacier Bay (58.4°N 136.0°W) in Southeast Alaska increased between 2002 and 2006 to 2,785 individuals (Bodkin and Esslinger 2006). This increase cannot be explained by reproduction alone, indicating that there has been a substantial redistribution of sea otters in the past several years with immigration into Glacier Bay in the past decade. Sea otter abundance in Yakutat Bay (59.7°N 140.0°W) has also increased over the last decade, likely through reproduction, although some amount of immigration cannot be ruled out (Gill and Burn 2007). During this process, sea otters appear to have expanded their range to include the western shores of Yakutat Bay. The current population trend for the southeast Alaska stock is believed to be stable.

With the exception of the Kodiak archipelago, there have been no new large-scale abundance surveys for sea otters in Southwest Alaska since 2002, however, additional skiff and aerial surveys conducted from 2003 to 2005 show that sea otter abundance has continued to decline in the western and central Aleutians (63%) and the eastern Aleutians (48%) (Estes et al. 2005). Aerial surveys in other portions of Southwest Alaska show further evidence of population declines. Sea otter counts in the Shumagin Islands (55°N 159°W) area south of the Alaska Peninsula showed a 33% decline between 2001 and 2004, and counts at Sutwik Island (56.5°N 157.2°W) declined by 68% over the same time period (USFWS unpublished data). Unlike the Aleutian Islands and portions of the Alaska Peninsula, the population trend in the Kodiak archipelago does not appear to have undergone a significant population decline over the past 20 years (Doroff et al. unpublished). Other portions of the southwest Alaska stock, such as the Alaska Peninsula coast from Castle Cape (56.2°N 158.3°W) to Cape Douglas (58.9°N 153.3°W) and Kamishak Bay (58.3°N 153.8°W) in lower western Cook Inlet, also show no signs of declining abundance. The estimated population size for the Southwest Alaska stock increased slightly since 2002, primarily due to a higher population estimate for the Kodiak archipelago in 2004. However, the overall sea otter population in southwest Alaska has declined by more than 50% since the mid-1980s. Thus, the overall population trend for the southwest Alaska stock is believed to be declining.

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# Bering Sea

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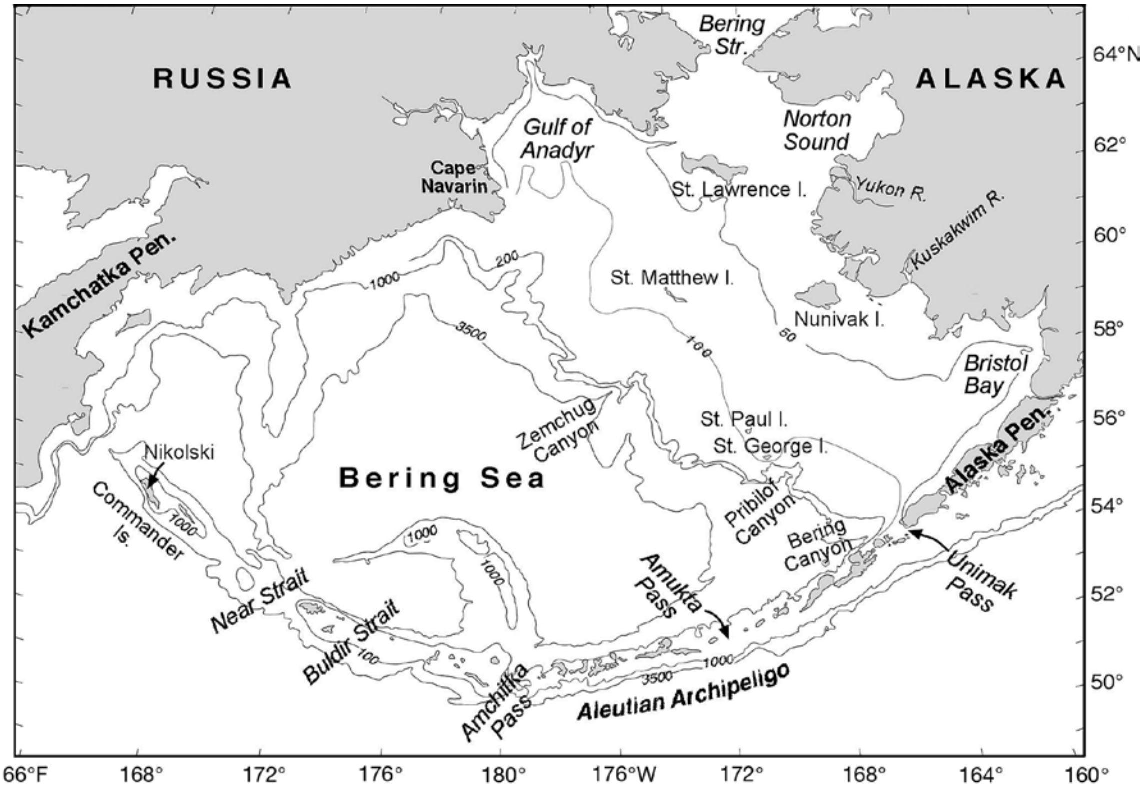
# highlights

- The Bering Sea experienced four years with low sea ice cover and extraordinarily warm summers (2002-2005), followed by four years with some of the heaviest sea ice cover since the early 1970s and cold summers (2006-2009). During the warm period, integrated water column temperatures were elevated, bottom temperatures were higher, and the cold pool over the southeastern shelf was small and not as cold as in the cold period. During the cold period, integrated water column temperatures were anomalously low, bottom temperatures were below the long term mean, and the cold pool consisted of cold, -1.7 °C water that extended across most of the Middle Shelf Domain with cool waters extending to Bristol Bay and the Alaska Peninsula.
- Water column stratification varied spatially, and was sometimes stronger in the warm years and sometimes stronger in the cold years, depending upon location.
- Net primary production and surface chlorophyll$_a$ were positively affected by temperature. The size distribution of crustacean zooplankton became smaller in years of warmer temperature.
- In the warm years of 2002-2005, small neritic species of crustacean zooplankton thrived whereas the medium-large copepod, *Calanus marshallae*, and the shelf euphausiid, *Thysanoessa raschii*, were scarce. In the cold years of 1999 and 2006-2008, both *C. marshallae* and *T. raschii* were abundant.
- Catches of both eastern and western Bering Sea groundfish stocks declined in recent years. In the eastern Bering Sea and Aleutian Islands, Pacific cod, yellowfin sole, flathead sole and Greenland turbot, and particularly walleye pollock, have shown declines while Pacific ocean perch, northern rockfish, rock sole, Alaska plaice, and especially arrowtooth flounder (whose biomass has quadrupled since the late 1970s) have increasing biomass trends.

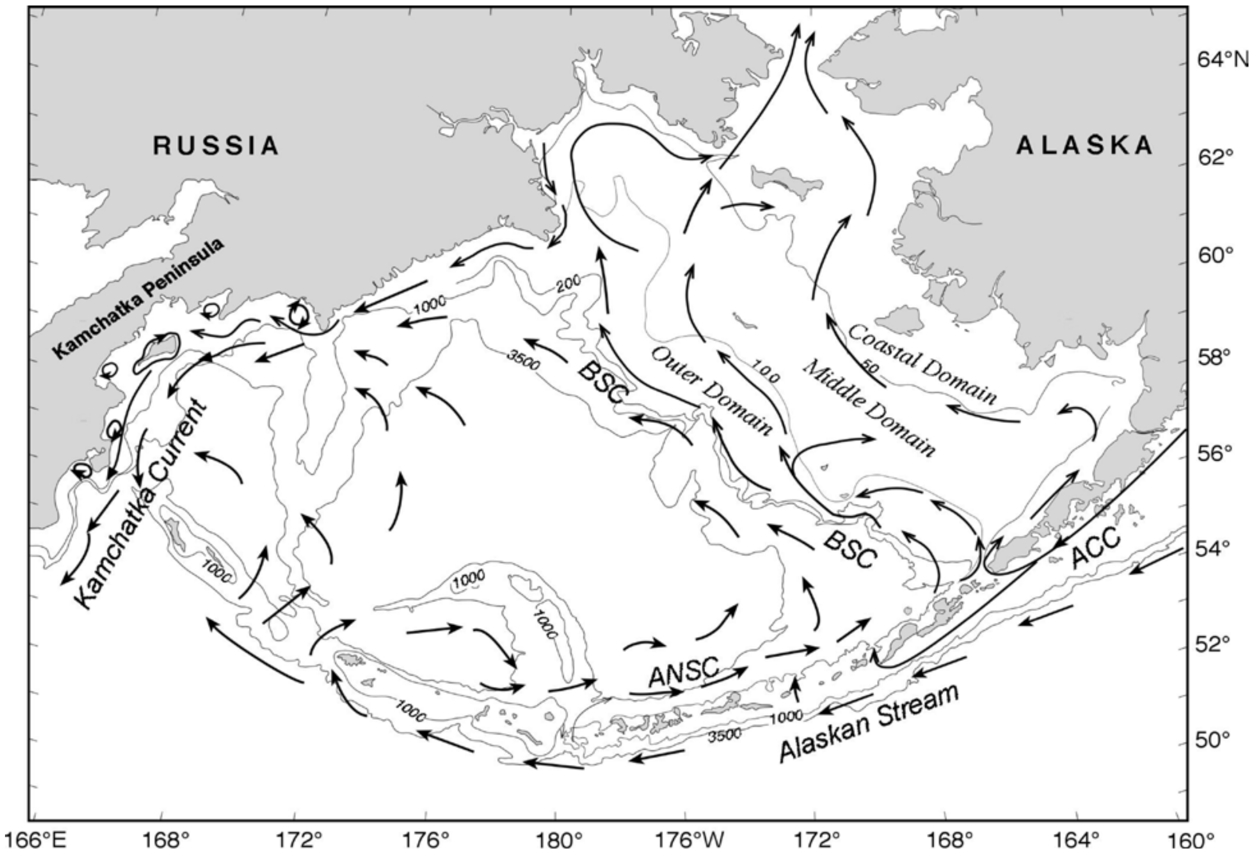
- Walleye pollock recruitment may be adversely affected by unusually warm conditions; strong year-classes failed to emerge in the warm years of 2002-2005 despite a declining biomass of pollock. Possibly, there were strong year-classes in the cold years of 2006 and 2008. In the cold years of 2006-2008, age-0 pollock were in good condition and energy-rich, though not as abundant as they were in the warmer years, when they were less energy-rich.
- Age-0 pollock consumed mostly small crustacean zooplankton and smaller pollock in the warmer years, and neither *C. marshallae* nor *T. raschii* were important dietary components. In the cold years, their diets were dominated by *C. marshallae* and euphausiids, and there was less cannibalism.
- Comparison of fisheries statistics between the eastern and western Bering Sea showed that, overall, the aggregated catches of all major fisheries tended to be positive, suggesting that the two sides of the Bering Sea were responding similarly to shared climate forcing.
- Both size-at-age and weight-at-length of groundfish tended to be above the long term mean in the warmer years, and below the mean in the cold years.
- Catches of crabs in the eastern and western Bering Sea declined after the early 1990s (eastern Bering Sea) or the late 1990s (western Bering Sea), but catches began to increase on both sides of the Bering Sea after 2004. The biomass of both red king crab and snow crab have increased in the eastern Bering Sea, although snow crab catches remain low due to conservative catch limits.
- Catches of Pacific herring on both sides of the Bering Sea have been stable since 2001, whereas the Togiak stock in the eastern Bering Sea has declined.
- Catches of salmon in both the eastern and western Bering Sea were above average and dominated by pink and chum salmon in the western Bering Sea and sockeye salmon in the eastern Bering Sea. In both the eastern and western Bering Sea, the catches of chinook salmon are in decline when compared to catches from the mid-1960s to the early 1990s.

# Introduction

The Bering Sea is a semi-enclosed Subarctic sea that connects the North Pacific and Arctic Oceans. It is bounded by Bering Strait to the north and the Aleutian archipelago to the south, and lies between 52° and 66°N, and 162°E and 157°W. The Bering Sea consists of a deep central basin, a northwestern shelf in the Gulf of Anadyr that reaches south along the Kamchatka Peninsula, and a broad eastern shelf that stretches from the Alaska Peninsula to Russia and the Bering Strait (Fig. BS-1). The Bering Sea area covers almost $3\times10^6$ km$^2$ and is divided almost equally between waters >200 m deep and shelf waters <200 m in depth (ACIA 2005). The 500 km-wide eastern continental shelf is about 1,200 km from north to south, and encompasses about 40% of the Bering Sea.



[Figure BS-1] The Bering Sea region, showing major Aleutian Island passes, depth contours, and geographic sites referred to in this chapter. Map courtesy of N. Kachel, NOAA Pacific Marine Environmental Laboratory, Seattle, WA.



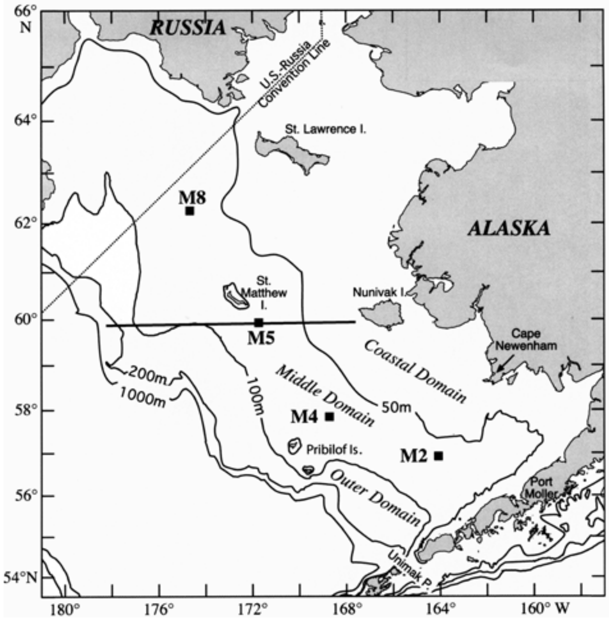
[Figure BS-2] Schematic diagram of the major currents in the Bering Sea. BSC – Bering Slope Current; ACC- Alaska Coastal Current; ANSC- Aleutian North Slope Current. Modified from Stabeno et al. 1999a, courtesy of N. Kachel, NOAA Pacific Marine Environmental Laboratory, Seattle, WA.

Water enters the Bering Sea through the passes of the Aleutian Islands and from the rivers of Siberia and Alaska (Fig. BS-1). Water from the Alaska Coastal Current, a shelf current that originates in the Gulf of Alaska, enters the Bering Sea primarily through Unimak Pass and Samalga Pass (Fig. BS-2) (Reed and Stabeno 2002; Ladd et al. 2005; Stabeno et al. 2005). Water from the Alaskan Stream, a shelf-edge current that is part of the North Pacific Subarctic gyre, enters the Bering Sea through a series of deep passes from Samalga Pass westward to Amchitka Pass and beyond (Stabeno et al. 1999, 2005). Water leaves the Bering Sea primarily through Bering Strait and through Kamchatka Strait. Flow through Bering Strait is important for the northern shelf of the Bering Sea and for the Arctic Ocean but it has virtually no effect on circulation in the Bering Sea basin.

The Bering Sea basin is dominated by a cyclonic gyre with the north-flowing Bering Slope Current forming the eastern boundary current and the south-flowing East Kamchatka Current forming the western boundary current (Fig. BS-2). The East Kamchatka Current originates near Shirshov Ridge (about 175°E) (Fig. BS-2), flows southward until it splits to form a portion that enters the Sea of Okhotsk or continues along the Kuril Islands to contribute to the Oyashio. Its source is a combination of the westward continuation of the Bering Slope Current and water flowing northward through Near Strait (Stabeno and Reed 1994; Khen 1989). The oceanic portion of the basin is influenced by Alaskan Stream water that enters the Bering Sea through many passes. That portion of the current that enters through Amchitka and Amukta Passes turns eastward to form the Aleutian North Slope Current (Reed and Stabeno 1999; Stabeno et al. 2009) (Fig. BS-2). This current, in turn, provides the major source of water for the Bering Slope Current (Stabeno et al. 1999).

The eastern Bering Sea shelf has been sub-divided into the southeastern, central, and northeastern shelf (Schumacher and Stabeno 1998). The northeastern region of the shelf is dominated by advective processes and has relatively weak tides whereas the southeastern region generally has relatively weak cross-shelf transport and strong tides. The southeastern Bering Sea shelf is differentiated into three bathymetrically-fixed domains which include the Coastal Domain that extends from the shore to about the 50m isobath, the Middle Domain, between the 50 m and 100 m isobaths, and the Outer Domain which ranges from 100 m to 200 m in depth (Fig. BS-3) (Iverson et al. 1979; Coachman 1986; Schumacher and Stabeno 1998; Stabeno et al. 2001). In summer, the Coastal Domain is well mixed to weakly stratified, the Middle Domain is strongly stratified, and the Outer Domain has well mixed upper and lower layers with a zone of gradually increasing density between (Schumacher et al. 2003). During summer in the southern Middle Domain, the temperature difference between the upper and lower layers can be greater than 8°C, and changes in density are dominated by temperature rather than salinity (Hunt et al. 2002).

A number of sources of information on the Bering Sea have become available in recent years. These include: a review of recent research on the southeastern shelf (Macklin and Hunt 2004), and three dedicated journal volumes of recent research (Dagg and Royer 2002; Macklin et al. 2002, 2008). In addition, the North Pacific Fisheries Management Council, as part of its annual Stock Assessment and Fisheries Evaluation Report for the eastern Bering Sea fisheries, attaches an Ecosystem Considerations analysis that provides annual updates on ecological change in the eastern Bering Sea (http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm). This chapter contains a review of the status and trends of the Bering Sea region from 2003-2008, hereafter the *focus period*.

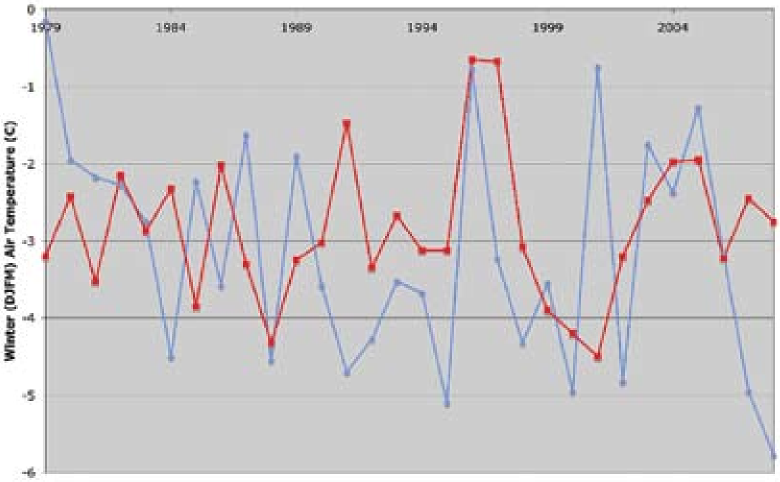


[Figure BS-3] Southeastern Bering Sea shelf showing isobaths, domains and the location of NOAA's biophysical Moorings M2, M4, M5, and M8. Horizontal line through M5 is the MN line of the BEST / BSIERP Program. Map courtesy of N. Kachel, NOAA Pacific Marine Environmental Laboratory, Seattle, WA.

## 2.0 Atmosphere *(Bond)*

### 2.1 Temperature

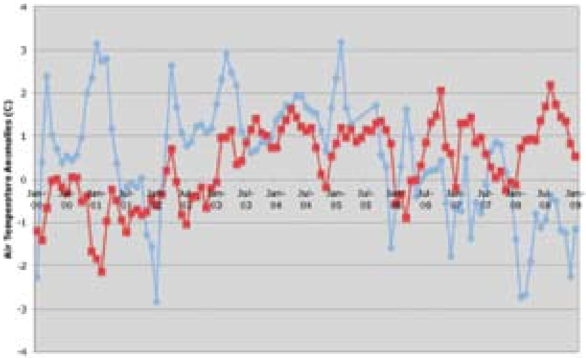
Context for the recent weather of the Bering Sea is provided by Figure BS-4, which portrays seasonal mean winter (December-March) air temperatures observed along the western Bering Sea coast at Nikolski (55.2°N 166.0°E) and on the eastern Bering Sea shelf at St. Paul Island (57.2°N 170.2°W) for the period of 1979-2008 (data from NOAA's National Climatic Data Center; http://www.ncdc.noaa.gov/oa/ncdc.html). Nikolski experiences about 50% less year-to-year variability in winter air temperature than St. Paul and this difference can probably be attributed to the effects of regional sea ice. In winters with extensive sea ice, the prevailing low-level air flow from the northeast is modified less by the underlying surface than during winters with more open water. This source of variability is absent for Nikolski because of the lack of sea ice in the deep waters off the east coast of the Kamchatka Peninsula, even during cold winters. Instead, the variations in seasonal air temperatures at Nikolski reflect the relative prevalence of cold air masses originating in eastern Siberia versus more maritime air



[Figure BS-4] Winter (DJFM) mean air temperatures (°C) at Nikolski (red) and St. Paul (blue).

masses from the North Pacific. Fig. BS-4 also illustrates that there is only a weak correspondence between winter air temperatures in the western and eastern portions of the Bering Sea. The early part of these time series was interpreted as being out of phase but since 1992, the two time series have often been in phase. Most recently, they are again out of phase. The overall correlation coefficient between the air temperatures at the two stations for the period of 1950-present is only 0.17. The temperature record over the last 30 years at Nikolski indicates a relatively cold period near the turn of the century and a warm period during 2003-2005 but little overall trend. The corresponding record at St. Paul features a very warm temperature in 1979 (in association with the especially mild conditions occurring in the eastern Bering Sea for a few years after the 1976-1977 climate regime shift), and decidedly cold temperatures in 2006-2009, but little trend over the vast majority of the 30-y period. The St. Paul temperatures show that 2003-2005 was also warm on the eastern Bering Sea shelf.

A more detailed perspective on the weather of the Bering Sea over the last few years is offered by the 3-month running mean temperature anomalies (referenced to means for 1971-2000) at Nikolski and St. Paul (Fig. BS-5). Note that Nikolski tends to experience considerably greater season-to-season persistence in its temperatures as compared with St. Paul; the standard deviation in the high-pass filtered temperature record at Nikolski is less than one-half that at St. Paul. Both locations were relatively warm during the summers of 2003-2005 as well as during the winters. This warming occurred a year later at Nikolski than at St. Paul, which experienced a high rate of anomalous warming during early 2002. During summer, air temperatures at Nikolski have been mostly high relative to the long-term mean, and during winter, they have been near the mean. The temperatures at St. Paul have undergone an overall decline since the summer of 2005, with temporary periods of relative warmth in early 2006, and in the autumns of 2007 and 2008.

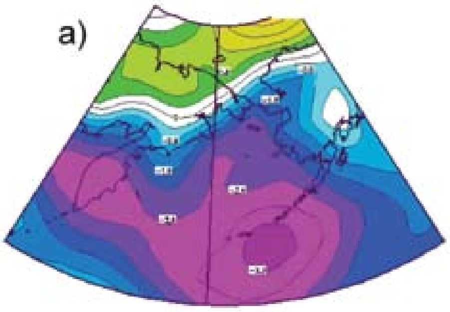


[Figure BS-5] Air temperature anomalies (°C) at Nikolski (red) and St. Paul (blue). Values are three-month running means referenced to a base period of 1971-2000.

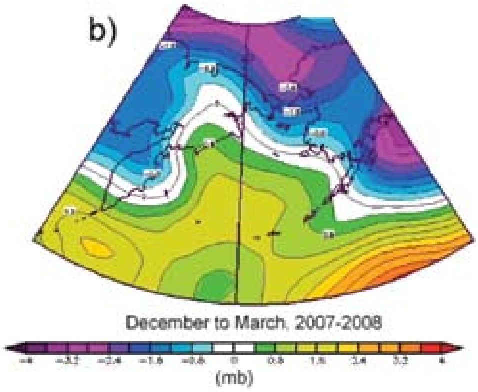
## 2.2 Sea level pressure

Maps of sea level pressure (SLP) anomalies are an effective means of illustrating the regional atmospheric circulation corresponding with the periods of anomalous weather noted above. Towards that purpose, the warm period of 2003-2005 for the entire Bering Sea is compared with the cold period of 2006-2008 for the eastern Bering Sea, with separate consideration of cool and warm seasons using data from the NCEP/NCAR Reanalysis available at http://www.cdc.noaa.gov/cgi-bin/data/composites/printpage.pl. The cool season is defined as the period from November through March, during which the ocean is being consistently cooled by the atmosphere, and the warm season as May through August, during which the ocean systematically warms. The cool seasons of 2003-2005 (Fig. BS-6a) featured a deeper than average Aleutian Low and anomalously high pressure over the Chukchi Sea. This is a warm pattern for the Bering Sea because it yields anomalous warm, southerly winds in the eastern Bering Sea. For the western Bering Sea, the lobe of low pressure extending westward over the southern portion of the Kamchatka Peninsula indicates anomalous easterly flow, and hence air of more maritime and less continental origin, and poleward Ekman transports. The distribution of anomalous SLP for the cool seasons of 2006-2008 (Fig. BS-6b) is almost the mirror image of that for the former set. The weaker Aleutian Low of the latter years signifies less air of maritime origin over the Bering Sea, and enhanced flow off Siberia. The relationships between the temperatures and SLP found for these two sets of cool seasons are consistent with the climatological analysis of Rodionov et al. (2007).

The mean anomalies in SLP for the warm seasons (May-August) of 2003-2005 (Fig. BS-7a) are quite weak. This result suggests that the relatively warm ocean temperatures during these years, as documented in the following section and as reflected in the air temperatures shown in Figure BS-4, can be attributed largely to the effects of the suppressed cool-season of this period persisting into the following warm seasons. In contrast, the pattern of anomalous SLP for the warm seasons of 2006-2008 (Fig. BS-7b) includes a relatively prominent ridge of high pressure extending from south of the Aleutians into the northwestern portion of the Bering Sea, with relatively low pressure over Siberia and Alaska. This distribution favoured an anomalous flow of cool air from the northwest over the eastern Bering Sea and warm air from the southwest over the western Bering Sea. This configuration therefore acted to reinforce the cool season forcing in the east and counteract it in the west.



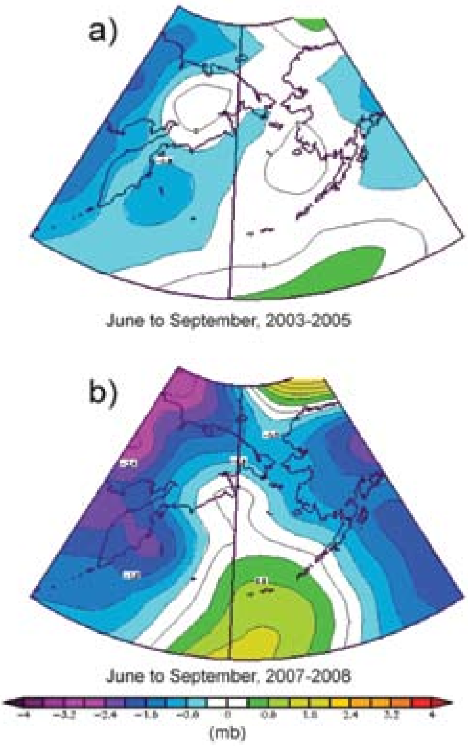
December to March, 2003-2005



December to March, 2007-2008

[Figure BS-6] (a) Mean anomalous sea level pressure (mb) for the cold seasons of 2003-2005, and (b) for the cold seasons of 2007-2008. Anomalies are determined from 1968-1996 mean values for these months using data from the NCAR/NCEP Reanalysis. The figures were generated by the NOAA/ESRL Physical Sciences Division website.

The atmospheric forcing of the Bering Sea during the warm season is strongly related to the insolation (surface flux of shortwave radiation) and wind mixing (e.g. Bond and Overland 2005). As a measure of the former, we have compiled the average cloudiness for the months of June through September for a western region (55-60°N, 165-175°E) and an eastern region (55-60°N, 170-160°W) based on the NCEP real-time marine data set (http://www.cdc.noaa.gov/data/gridded/data.ncep.marine.html). For the latter, we use an index of wind mixing on the eastern Bering Sea shelf for the months of June and July based on daily winds from the NCEP Reanalysis. Annual values for the cloudiness and wind mixing are itemized in Table BS-1. The seasonal mean cloudiness was remarkably constant on the eastern Bering Sea shelf for the summers during the focus period. More variability occurred



[Figure BS-7] (a) Mean anomalous sea level pressure (mb) for the warm seasons of 2003-2005, and (b) for the warm seasons of 2007-2008. Anomalies are determined from 1968-1996 mean values for these months using data from the NCAR/NCEP Reanalysis. The figures were generated by the NOAA/ESRL Physical Sciences Division website.

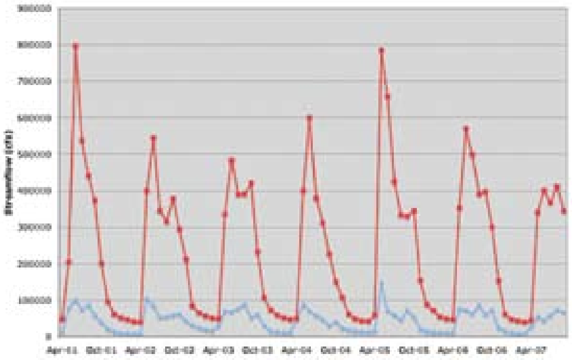
[Table BS-1] Summer cloudiness and wind mixing. The cloud fractions are averages for June through September of each year, and for a western region of 55-60°N, 165-175°E, and an eastern region of 55-60°N, 170-160°W. The source of these data is the NCEP Real-time Marine Data. The wind mixing index is for the months of June-July and pertains to a region in the vicinity of St. Paul Island in the eastern Bering Sea; it is presented in units of standard deviations from the climatology - 1950-2008. The source of these data is the NCEP/NCAR Reanalysis.

| Year | Cloud Fraction (West) | Cloud Fraction (East) | Wind Mixing (East) |
|---|---|---|---|
| 2003 | 0.81 | 0.86 | 0.3 |
| 2004 | 0.85 | 0.86 | -0.9 |
| 2005 | 0.80 | 0.88 | -1.1 |
| 2006 | 0.73 | 0.86 | 0.5 |
| 2007 | 0.87 | 0.88 | -1.4 |
| 2008 | 0.76 | 0.85 | 0.3 |

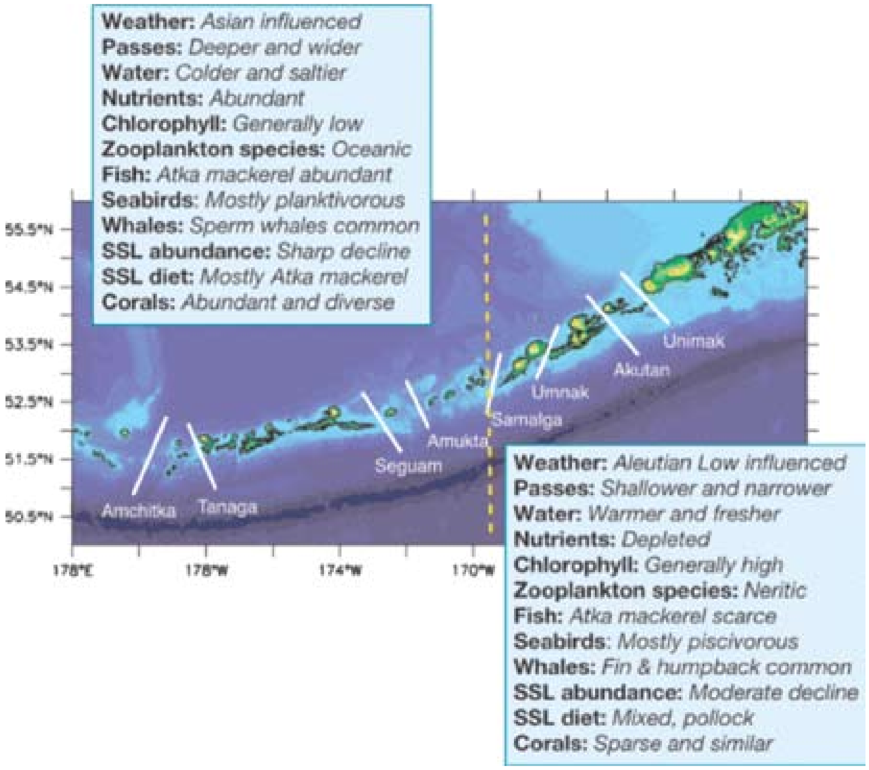
in the western region, with relatively cloudy conditions tending to coincide with the relatively calm (reduced wind mixing) warm seasons of 2004, 2005 and 2007 for the eastern Bering Sea.

## 2.3 River inputs

Time series of monthly stream flow for the Kuskokwim and Yukon Rivers, the two primary sources of runoff for the eastern Bering Sea, are available through the summer of 2007, and are plotted in Figure BS-8. The interannual differences in these stream flows reflect variations in precipitation for their watersheds, with considerable lags (especially for the Yukon River), and differences in temperature and consequent timing in seasonal snowmelt. The time series show that the discharge of freshwater into the eastern Bering Sea was particularly large in 2005 and peaked in May, which is about a month earlier than typical. The discharge in 2007, on the other hand, was reduced early in the warm season. Because the stream flows for the Yukon are generally much greater than those for the Kuskokwim, variations in salinity and hydrographic structure due to runoff tend to be more pronounced on the portion of the eastern shelf north of Nunivak Island. Stream flow records were not found for the rivers emptying into the western portion of the Bering Sea. Based on the precipitation and temperature in far eastern Siberia, it is expected that the western Bering Sea also experienced relatively great and seasonally early freshwater runoff during the period of 2003-2005.



[Figure BS-8] Monthly mean stream flows measured for the Yukon River (red) at Pilot Station, and for the Kuskokwim River (blue) at Crooked Creek. Data are from the US Geological Service (http://waterdata.usgs.gov/ak/nwis/monthly/?referred_module=sw).



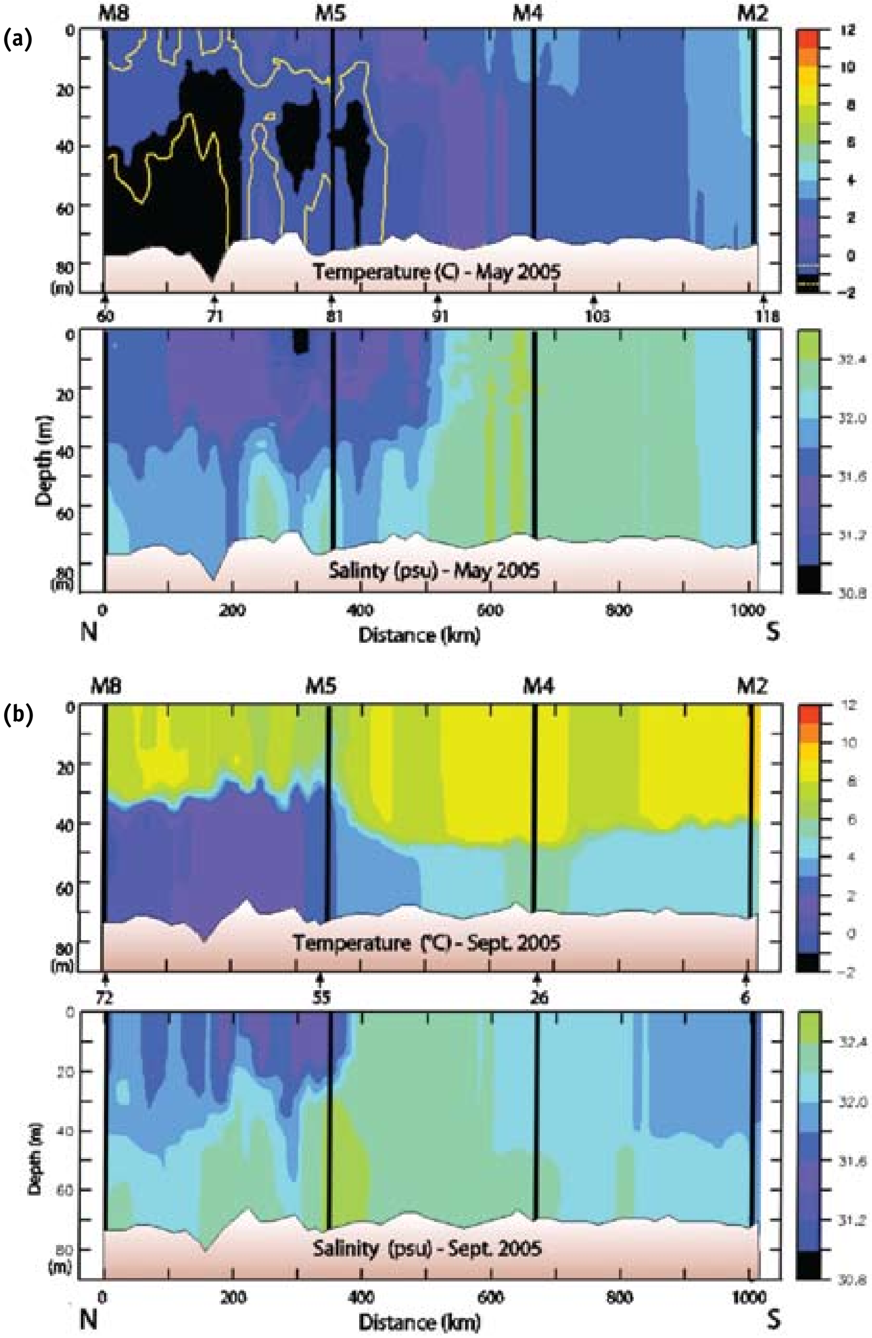
[Figure BS-9] Many Aleutian marine environmental attributes change in the vicinity of Samalga Pass, suggesting that the marine ecosystem of the archipelago may be differentiated into multiple, ecologically distinct regions. Future examination of status and trends in the Aleutians may require separate examination of these marine eco-regions. (From Hunt and Stabeno 2005).

## 3.0 Physical Ocean *(Stabeno, Ladd, Hunt)*

### 3.1 Fluxes and currents

Marine connections between the North Pacific and the Bering Sea occur via passes between the Aleutian Islands. While the temperature on the eastern Bering Sea shelf is largely controlled by local forcing (atmospheric and sea-ice), variability in the basin is controlled by a combination of local forcing and flow through the Aleutian passes. The passes east of Near Strait are the source water for the transport in the Bering Sea gyre (Stabeno et al. 2009). Few measurements have been made in the last 5 years in any of the passes except for Amukta Pass. Transport through Amukta Pass is approximately $5\times10^6$ $m^3\cdot s^{-1}$ which is the majority of transport in the Aleutian North Slope Current (Fig. BS-2). Significant spatial variation has been observed along the Aleutian Island chain with an abrupt shift of ecosystem and physical properties at Samalga Pass near 170°W (Hunt and Stabeno 2005) (Fig. BS-9). This pass is the farthest west that the Alaska Coastal Current flows before entering the Bering Sea (Ladd et al. 2005). Transports from the Pacific to the Bering Sea are typically strongest during the winter months when along-shore winds are the strongest (Stabeno et al. 2002; Ladd et al. 2009). Transports in Amukta Pass, one of the primary transport pathways in the central Aleutians, were lower by approximately 10 percent in spring and summer of 2008 than the climatological average calculated since 2001. Data from Argo floats show that, from 2001 to 2005, there was warming and freshening of the surface mixed layer in the basin (Wirt and Johnson 2005). This warming was a result of atmospheric forcing and perhaps of transport through Amukta Pass. During the cooler years (2006-2008), there also appears to be some cooling in the basin.

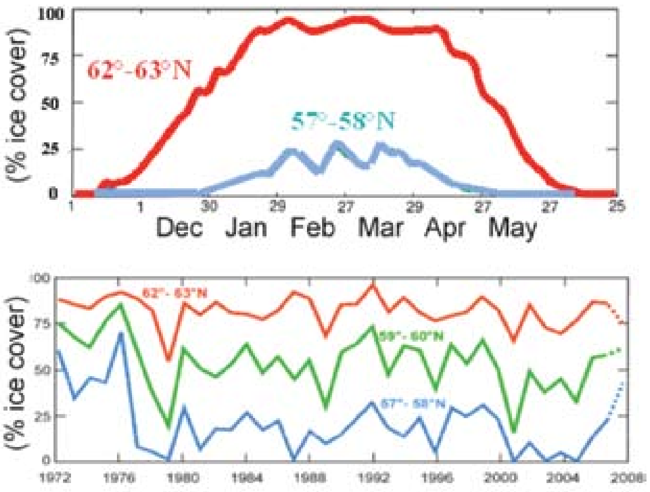
Just as transport through the Aleutian passes influences the water properties in the Bering Sea, northward flow through Bering Strait influences the Arctic (Woodgate 2006 et al.). There was an increase of northward transport during 2001-2005, likely a result of the weaker southward winds that occurred during this five year period (Woodgate et al. 2006). The heat flux through Bering Strait increased during the same period, reaching a maximum in 2004. While the increase in transport through Bering Strait accounted for about half the increased heat flux, the remainder was a result of the unusually warm water found over the eastern Bering Sea shelf in 2001-2005 (Stabeno et al. 2010).



[Figure BS-10] Temperature and salinity along the 70 m isobath in the eastern Bering Sea in a) May, and b) September, 2005.

## 3.2 Hydrography and structure

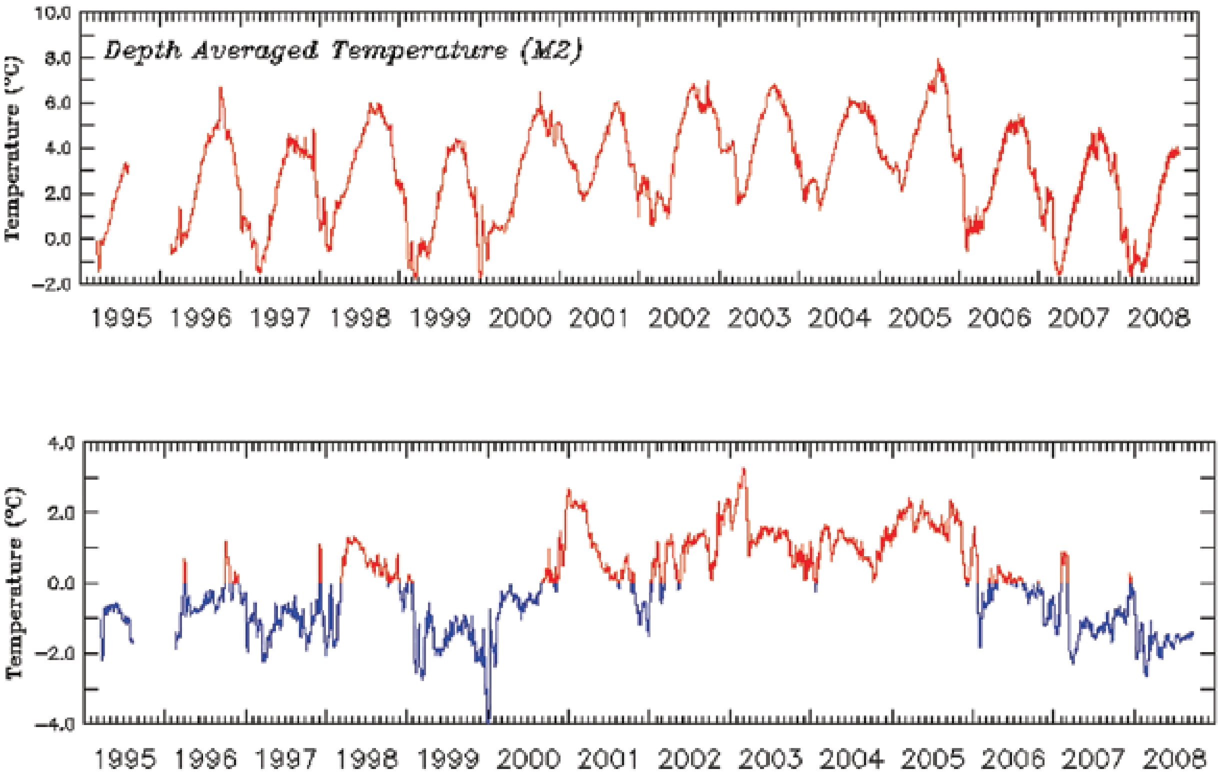
The cross-shelf variability on the eastern Bering Sea shelf has been noted by many scientists (e.g., Schumacher et al. 1979; Kinder and Schumacher 1981; Kachel et al. 2002). Described more recently is the frontal structure that forms south of St. Matthew Island during the summer (Stabeno et al. 2010). It divides the colder, fresher northern shelf from warmer, saltier southern shelf (Fig. BS-10). Since its identification, this frontal structure has been observed each summer (2005-2008). That it has been observed in both cold and warm years indicates it is not solely dependent upon the extent of sea ice. While its cause is not completely understood, it appears to be related to weaker tidal energy north of St. Matthew Island and perhaps to on-shelf advection of water from the Outer Domain into the region (Stabeno et al. 2010). There was no comparable data set provided from the western Bering Sea.



[Figure BS-11] Top panel: The average percent of ice cover in a 1° band of latitude that stretches from the Alaskan coast to the shelf break. The weekly averages were calculated over the period 1972-2008. Bottom panel: The yearly (December – May) average of ice cover in 1° latitude bands. Weekly data on ice extent and concentration were obtained from the National Ice Center.

## 3.3 Seasonal sea ice

The Bering Sea, especially the broad, eastern shelf, is strongly influenced by seasonal sea ice. Ice typically arrives over the northeastern shelf in November and persists into June, while over the southeastern shelf, sea ice arrives a month or more later and retreats a month earlier (Fig. BS-11). Ice extent and concentration vary on decadal scales over the southern part of the eastern shelf (south of 58°N), but over the northern shelf, variability appears to be dominated by year-to-year fluctuations (Fig. BS-11). Sea ice is an important regulator of the timing of the spring bloom and of determining the extent of the cold pool (Stabeno and Hunt 2002; Stabeno et al. 2007). During periods of extensive ice over the southern shelf, the temperature at M2 (56.9°N 164°W) on the southern shelf is closely related to the extent of the sea ice. The integrated temperature at M2 (water depth 70 m) shows a strong annual signal, with temperatures varying from -1.7°C in the winter when ice is over the mooring to 4-8°C in late September at the end of the warm season (Fig. BS-12). The ocean temperature reflects the persistence of ice over



[Figure BS-12] Top panel: Depth averaged temperature at M2 (56.9°N 164°W). Bottom panel: The depth averaged temperature anomaly at M2. The mean was obtained using data from 1995-2008.

the shelf, with 2005 having the highest depth integrated temperatures on record (8°C). With the increase of sea ice over the southern shelf, the southern shelf cooled in 2006, with the coldest temperatures occurring in 2008 (Fig. BS-12). As with the sea ice concentration over the southern shelf, the temperature appears to vary on time scales of several years.

The period 2001-2008 saw sharp swings in the temperature over the eastern Bering Sea shelf and basin. The years 2001-2005 were characterized by low ice extent and warm conditions, while 2006-2008 saw a marked cooling of the eastern Bering Sea and extensive ice over the southeastern shelf. This occurred despite the very low ice extent in the summers of 2007 and 2008 in the Arctic Ocean, showing that variations in the extent of seasonal sea ice in the Bering Sea during winter and spring are largely uncoupled from the changes occurring in the Arctic Ocean during the previous summer (Stabeno et al. 2008). There was no comparable data set provided from the western Bering Sea.

## 3.4 Variability in the cold pool

The bottom waters over the Bering Sea shelves show considerable interannual variation in temperature. Over the northern parts of the shelf, cold, salty brine is rejected as sea ice forms, and this dense water sinks to the bottom. Density flows to the north carry much of this salty bottom water through Bering Strait to the Arctic Ocean where it contributes to the halocline (Cavalieri and Martin 1994; Schumacher and Stabeno 1998). Over the central and southeastern Bering Sea shelf, cold bottom waters are formed when sea ice melts, and the cold, fresh melt water is mixed throughout the water column by storms (Stabeno et al. 1998). This melt water cools the entire water column to approximately –1.7°C. When the surface waters are warmed by solar radiation in spring, a thermocline forms, and the cold bottom waters are insulated from further heating (Coachman et al. 1980; Ohtani and Azumaya 1995; Wyllie-Echeverria 1995). Bottom temperatures in this “cold pool” warm slightly over the summer, but often remain below 2°C until storm-induced mixing occurs in fall. The extent and temperature of the southern cold pool is dependent on the amount of ice melt that occurs.

With the low ice extents in 2001-2005, the bottom water over the southern shelf did not cool to -1.7°C, and the cold pool was largely limited to the northern shelf (Fig. BS-13). With the return of extensive ice in 2006, the cold pool (which is a summer feature) became larger. In 2008, the cold pool stretched the entire north-south length of the eastern Bering Sea shelf.

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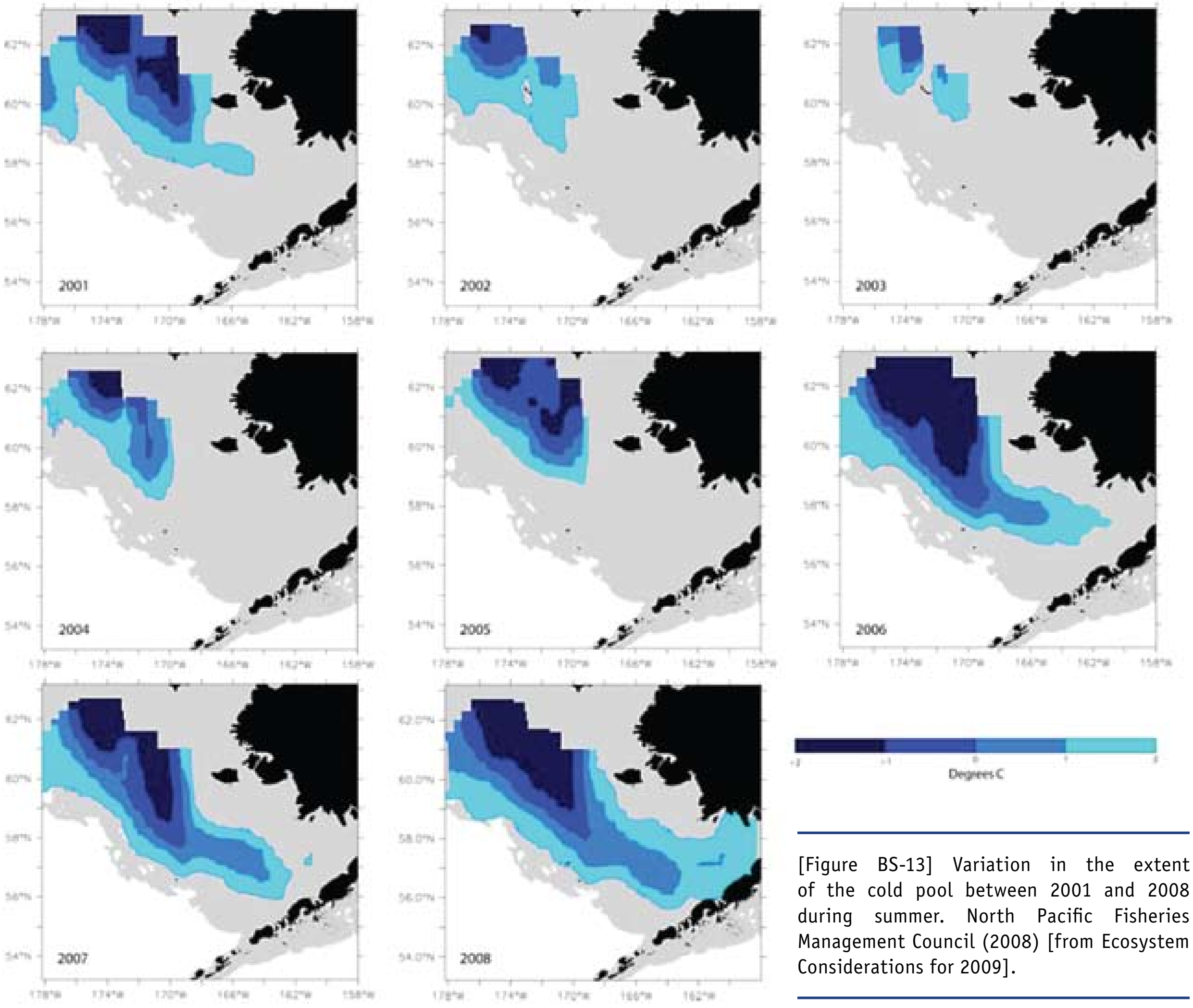
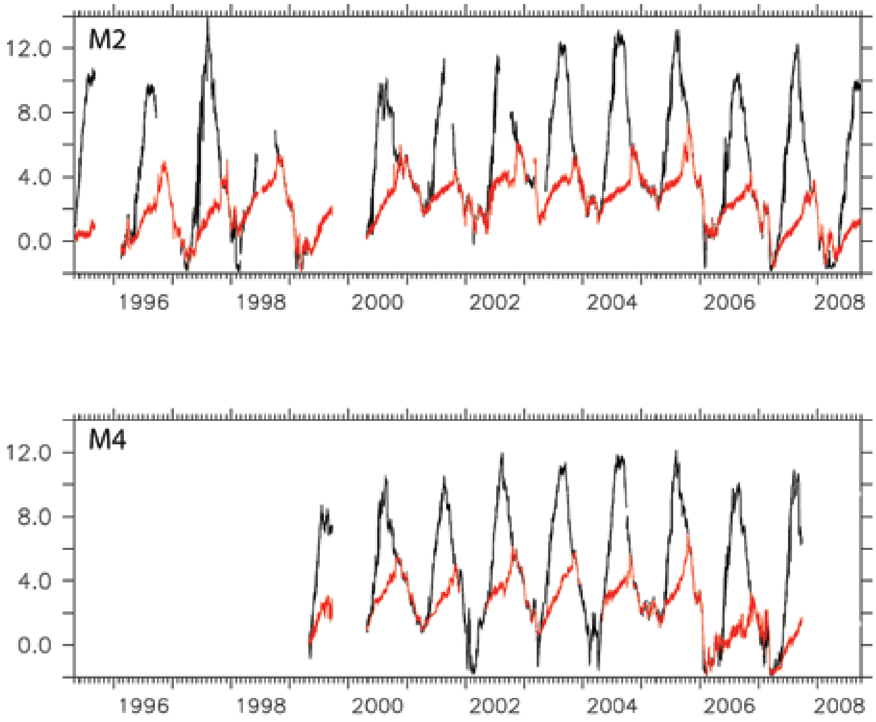


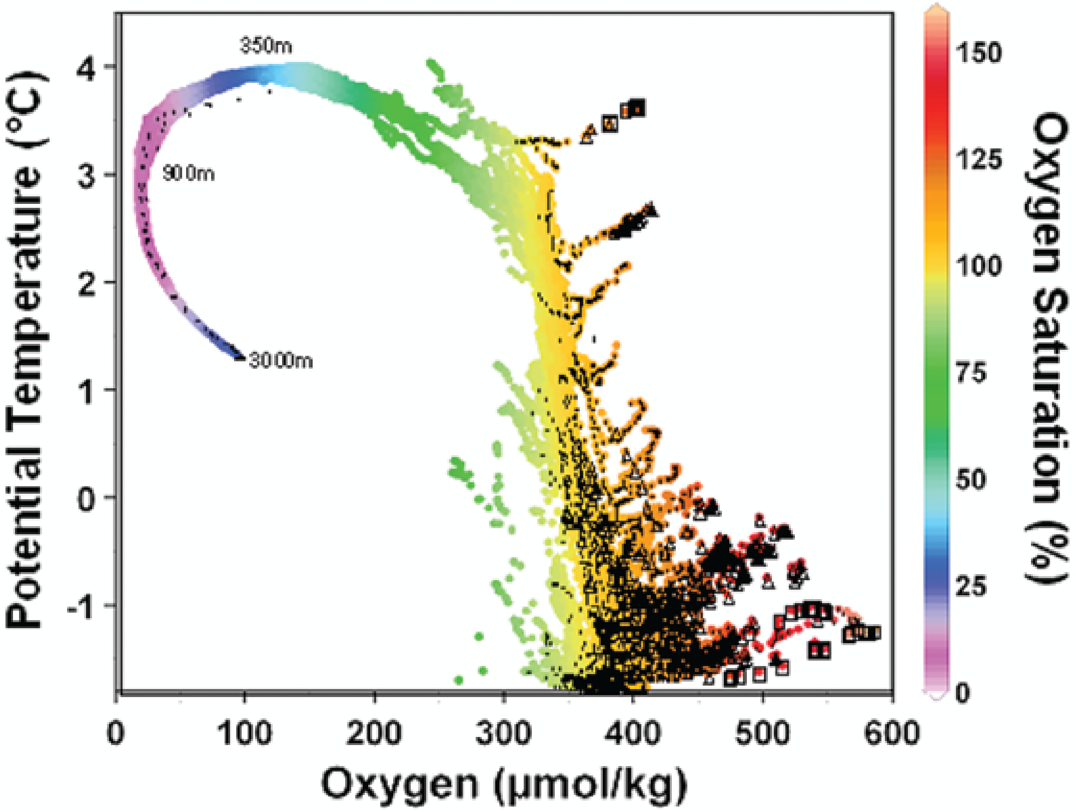
[Figure BS-13] Variation in the extent of the cold pool between 2001 and 2008 during summer. North Pacific Fisheries Management Council (2008) [from Ecosystem Considerations for 2009].

## 3.5 Eastern Bering Sea stratification

The timing and magnitude of stratification on the middle shelf of the eastern Bering Sea can be examined using temperature data from two moorings (M2 and M4) (Fig. BS-14). In the southern location (M2: 57°N 164°W), the average date that stratification begins to set up is 12 May. The earliest set up in the 14-year record at M2 was 28 April in 2003 (a warm year), while the latest was 26 May in 2006 (a cold year). Warm years tend to have an earlier stratification setup and stronger maximum summer stratification. However, the differences are not statistically significant. At M4, farther north (58°N 169°W), the average date of stratification initiation is about 2 weeks later (26 May). The earliest setup was 28 April, 2003 (as at M2), while the latest was 8 June 2002. The shorter record at M4 (9 years) makes it more difficult to see differences between warm and cold periods. However, it appears that the strongest stratification at M4 occurred in the summer of 2006 (a cold year) due to the very cold bottom temperatures, while the weakest stratification at M4 occurred in 2001 (a warm year). These data indicate that the strength and timing of stratification and relationships with surface temperatures and sea ice vary spatially.



[Figure BS-14] Temperatures (°C) at 10 m (black) and 60 m (red) at two moorings on the eastern Bering Sea shelf.



[Figure BS-15] Concentration and % saturation of oxygen over the eastern Bering Sea in early spring 2007. Black dots (from depths >350m) are from the WOCE P14 stations obtained in 1993. In surface waters, black symbols represent chlorophyll concentrations of 0.5-4 µg·l⁻¹ (dots), 4-6 µg·l⁻¹ (triangles), and >6 µg·l⁻¹ (squares). Data were obtained from the WOCE hydrographic office, and the Bering Ecosystem Study (BEST) archive at the Earth Observing Laboratory at http://www.eol.ucar.edu/projects/best/.

## 4.0 Chemical Ocean

*(Mordy, Whitledge, Feely, Mathis, Shull, Devol)*

### 4.1 Oxygen saturation

There are no large regions of anoxia in the Bering Sea. Vertical profiles of oxygen have a minimum of ~17 µmol·kg⁻¹ (5% saturation), and this minimum is found between 600-1000 m depending on regional circulation patterns. There has not been a measurable change in subsurface oxygen concentrations since the July 1993 P14 WOCE expedition (Fig. BS-15). This observation is consistent with the interpretation that the overall biological production in the central Bering Sea has not dramatically changed in the past 15 years, as the extent of remineralized organic material at depth remains relatively unchanged. Differences in $T_{max}$ between 2007 and 1993 (0.1-0.2°C in Fig. BS-15) are well within the range of observed seasonal and interannual variability (Reed 1995; Wirts and Johnson 2005).

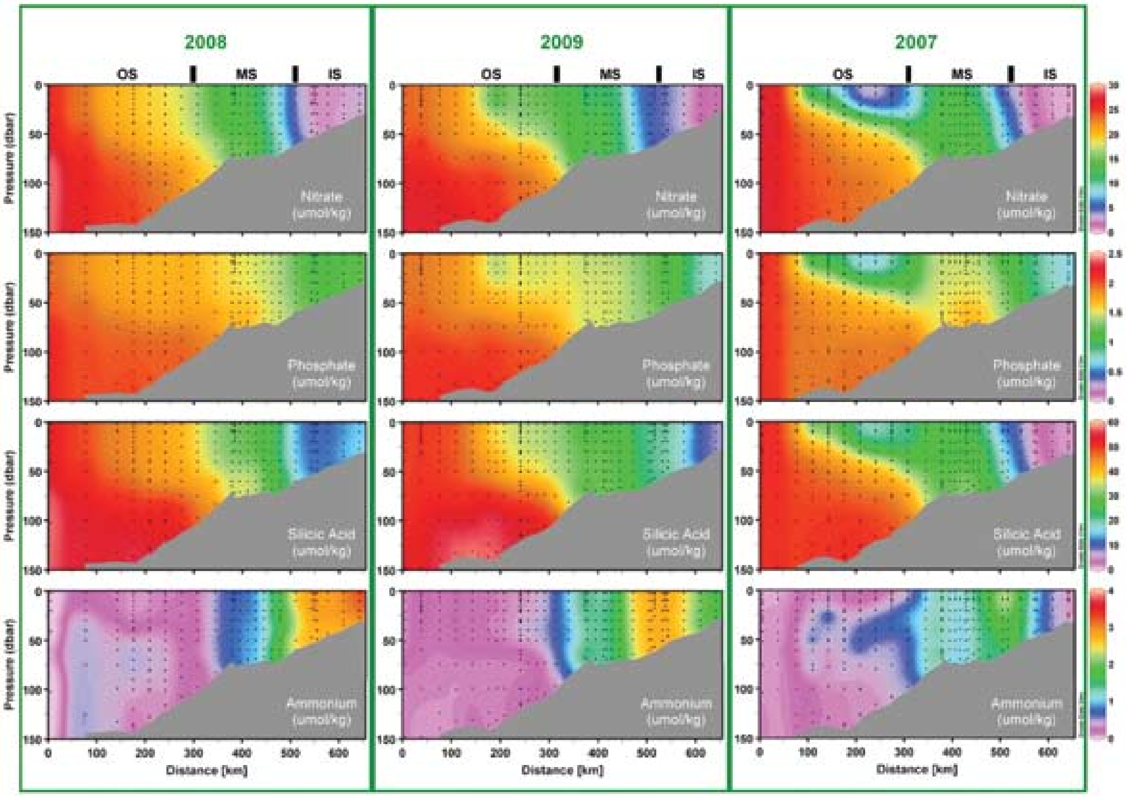
### 4.2 Interannual variation in seasonal nutrient dynamics on the Bering Sea Shelf

Spring (April-May) conditions were measured across the shelf on the MN line (Fig. BS-3) in 2007-2009 (Fig. BS-16). In general, ice was more prevalent over the middle shelf each spring, was less concentrated on the inner shelf, and there was a gradient of decreasing ice cover over the outer shelf. Over the middle shelf, the water column was well mixed, and there was little interannual variability in nutrient concentrations. However, winter nitrate concentrations at M5 were lower than winter concentrations farther south at M2 (~18 µmol·kg⁻¹ measured from moored nitrate sensors, not shown), suggesting dilution of nutrient concentrations by admixture of nutrient-depleted Alaska coastal water.

The MN transects over the outer shelf captured a series of snapshots of nutrient concentrations during different stages of the spring bloom (Fig. BS-16). In 2008, the outer shelf was in pre-bloom conditions with an intrusion of nutrient-rich water beneath a mixed layer of ~75 m. Nutrient concentrations were lower in 2009 and 2007 either because cruises occurred at different parts of the bloom cycle, or because winter pre-bloom concentrations were lower. In 2007, a region of low nitrate concentration was beginning to occur in surface waters, and increased ammonium underneath the area of depressed nitrate concentration was consistent with rapid remineralization of organic nitrogen (Fig. BS-16).

Over the inner shelf, pre-bloom conditions (i.e., the extent of nutrient re-supply in winter) are not well known. In each year, the inner shelf of the MN-line had low concentrations of nitrate by the time of the Bering Ecosystem Study (BEST) spring cruise (Fig. BS-16). The abundance of ammonium in 2008 and 2009 suggested that significant production had already occurred. In 2007, dissolved inorganic nitrogen and silicic acid were absent from the inner shelf, and these conditions persisted into the summer (not shown).

Due to sluggish flow over the middle shelf in spring and summer, seasonal changes in nutrient concentrations can be used to infer variability in nutrient uptake over the shelf. A 5-year time series of nitrate at mooring M2 showed little interannual variability in pre-bloom nitrate concentrations (~18 μM). Likewise, integrated nitrate from hydrocasts along the 70 m isobath in spring 2007 and 2008 were similar in the south. To the north, winter replenishment was more variable, with spring concentrations in 2008 lower by about 25% compared to 2007. Fall concentrations of nitrate in the south were similar in 2005 (warm year), and 2007 and 2008 (cold years). In the north, concentrations in fall and summer were higher and more variable than in the south. The implication is that the seasonal drawdown of nitrate (and phosphate) was greater and less variable in the south than in the north in both cold and warm years.



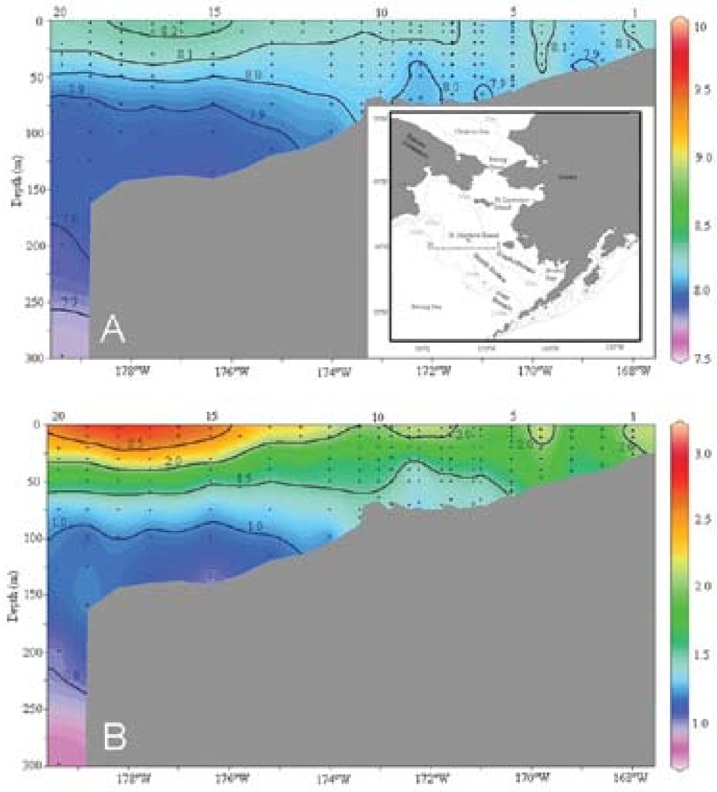
[Figure BS-16] Vertical sections of nutrients in April-May 2007-2009 along the MN line (See Fig. BS-3) in the eastern Bering Sea. Years are presented in order of decreasing nitrate. The Outer, Middle and Inner domains are indicated on the top figure for each year (OS, MS, and IS respectively). Data were obtained from the BEST archive at the Earth Observing Laboratory.

## 4.3 Dissolved iron

In the absence of sea-ice, the outer shelf contains insufficient dissolved iron (DFe) for the complete assimilation of the available nitrate by diatoms (Aguilar-Islas et al. 2008). However, they found that melting sea ice contained sufficient DFe to support biological depletion of nitrate. Their conclusion was that "variability in sea ice extent is likely to translate into a varying supply of DFe to the Bering Sea outer shelf and shelf break in early spring, and thereby contribute to the observed changes in the timing and community composition of the spring phytoplankton bloom." One also expects that blooms in the outer shelf and shelf edge would be reduced in light ice years, such as 2001-2005, and greater in heavy ice years such as 2006-2007, though such patterns do not appear in the satellite record (see Section 5.1.1).

## 4.4 Ocean acidification

There are insufficient data to show a long term trend in ocean acidification in the Bering Sea, although one would be expected given patterns in other parts of the globe, including the Gulf of Alaska. Seasonality, however, is strong. In the Bering Sea, enhanced export production of organic matter during the spring bloom leads to high rates of remineralization in the bottom waters and sediments on the shelf. Because the eastern shelf of the Bering Sea is broad and relatively shallow (<150 m), the organic matter has a longer residence during which remineralization can occur. This process adds $CO_2$ back into the water column in the form of DIC, thus lowering the pH and carbonate mineral saturation states. Observations during the summer of 2008 showed that pH values ranged from approximately 7.7 to 8.2 and that the aragonite saturation state, $\Omega_{arg}$, was >1.0 above a depth of 80 m (Fig BS-17). Corrosive under-saturated ($\Omega_{arg}$ range 0.5 - 1.0) waters occurred over a depth range from 80 m to 300 m. On highly productive arctic and Subarctic shelves like the southeastern Bering Sea, seasonal cycles of ocean acidification and carbonate mineral saturation are coupled with surface biological production. In the Gulf of Alaska north of 50°N near the Alaskan coast, the aragonite saturation depth shoals to a minimum of approximately 100 m (Feely et al. 2008; Mathis unpublished). A summary of other chemical distributions and dynamics in the Bering Sea can be found in Whitledge and Luchin (1999).



[Figure BS-17] Distribution of: A) pH and B) aragonite saturation (Ω) in the Bering Sea in summer of 2008. The map inset in (A) shows the location (dotted line) of the transect (from Mathis, unpublished).

# 5.0 Phytoplankton Biomass and Primary Production *(Eisner)*

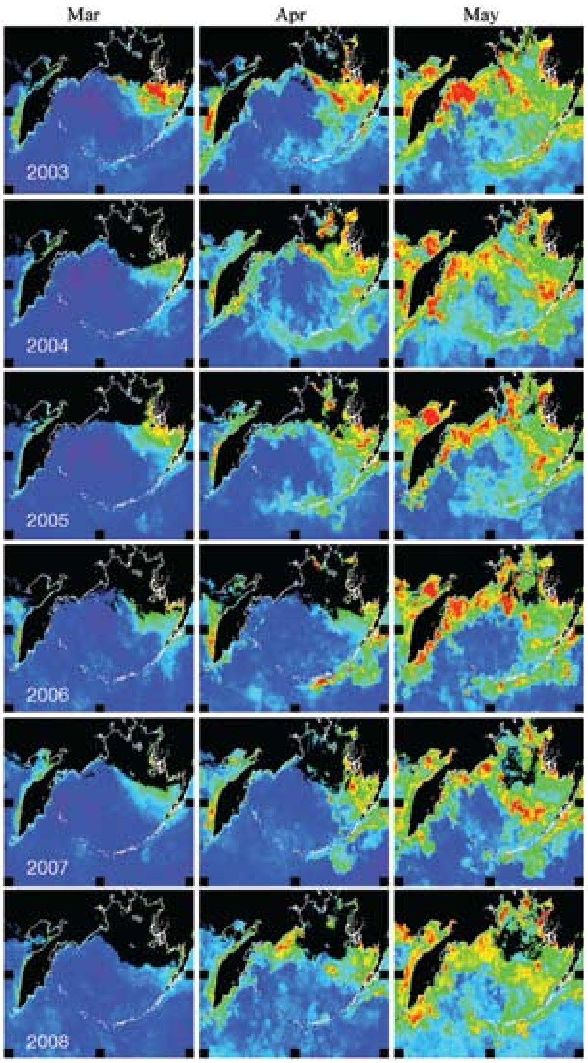
## 5.1 Spatial and temporal distribution of chlorophyll

### 5.1.1 Satellite ocean colour data

Chlorophyll$_a$ data for March, April and May show considerable spatial variation (e.g. between the shelf and deep basin and from west to east) and temporal variation (e.g. timing of spring bloom development) (Figs. BS-18 and BS-19). Blooms in the eastern Bering Sea (EBS) began in March in 2003 and in April in the remaining years. Blooms in the western Bering Sea (WBS) generally occurred in May, although a high biomass was seen southwest of Cape Navarin and along the Kamchatka Peninsula in April of some years (2004 and 2008 in particular, Fig. BS-18). Increases in biomass near the ice edge can be seen at various locations in March, April or May during all years (Fig. BS-18).

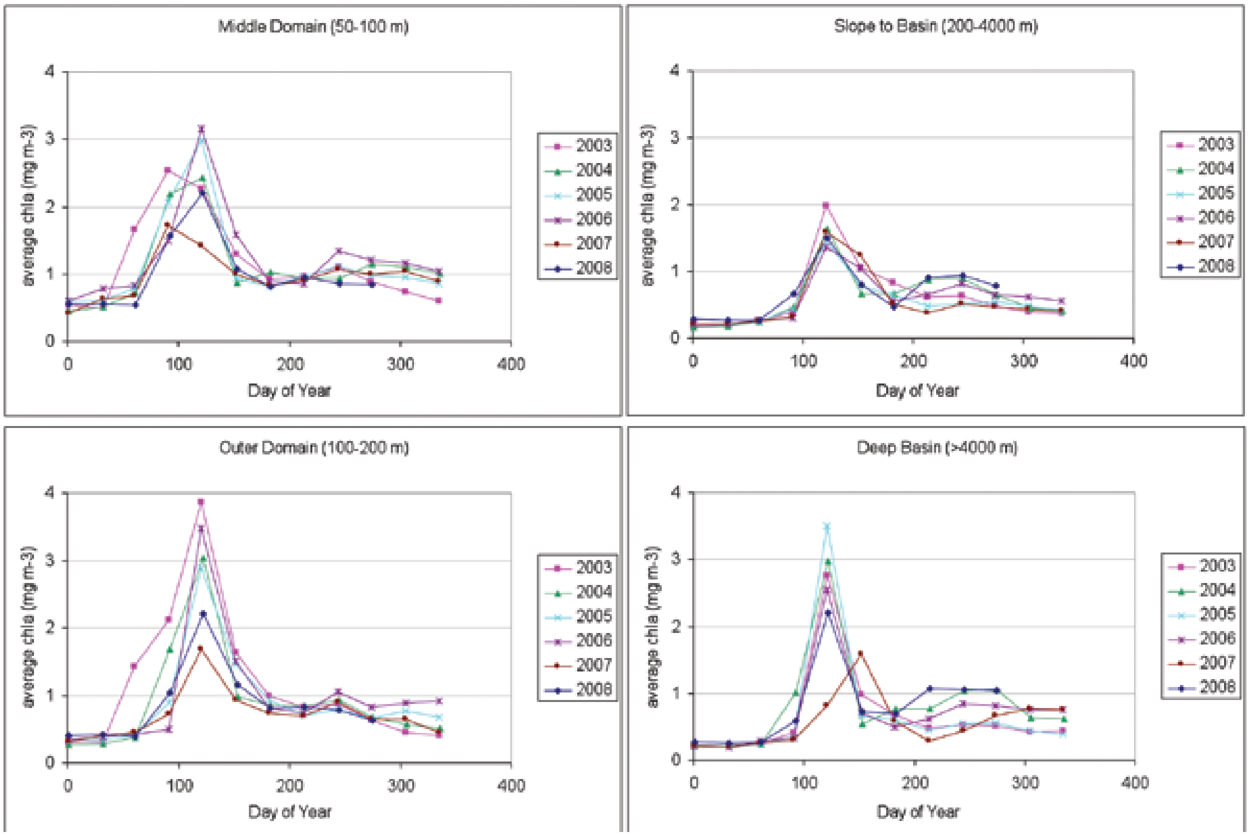
Monthly average chlorophyll$_a$ data indicate that the peak biomass was observed in May for the Middle Domain, Outer Domain, slope to basin and deep basin, with exceptions in April 2003 and 2007 for the Middle Domain, when April and May biomass was comparable, and in June 2007 for the deep basin (Fig. BS-19). Smaller, fall blooms were observed in September and October, with exceptions seen in August in slope to basin (2004 and 2008) and deep basin (2008) regions. The highest average spring chlorophyll$_a$ was observed in the Outer Domain and lowest in slope to basin waters. The highest average fall chlorophyll$_a$ was observed in the Middle Domain (Fig. BS-19). For the 50-200 m depth intervals (shelf regions), higher spring chlorophyll$_a$ was seen in 2003-2006 and than in 2007-2008 (Fig. BS-19).

Ocean colour data from earlier time periods can be used to help extend the time series. SeaWIFS chlorophyll$_a$ data for 1998 to 2002 showed that the spring bloom occurred in June 1998 and in May in 1999-2002 for the EBS (Iida and Saitoh 2007). In the southeastern Bering Sea, May SSTs were below average in 1998-2000, average in 2001, and above average in 2002 (http://www.beringclimate.noaa.gov). In the EBS, the peak chlorophyll biomass in recent years occurred in May in all years except 2006 (a cold year), when the peak was in late June. Thus, the two years when late spring blooms were observed, 1998 and 2006, were both cold years, although not the coldest of this 11-y data set. In the coastal WBS, the bloom started in April in 1998 and 2001, and in May in 1999, 2000 and 2002 (Iida and Saitoh 2007). In recent years, blooms in the WBS started in April in 2004 and 2008 and in May in 2003, 2005-2007.



[Figure BS-18] Satellite chlorophyll$_a$ for 2003-2008 for March, April and May. Log colour scale range 0.08 to 8.0 mg·m$^{-3}$. Land is shown in black outlined in white and ice is shown in black. Data courtesy of Robert O'Malley at Oregon State University: http://www.science.oregonstate.edu/ocean.productivity/standard

The location and strength of the Aleutian Low can affect the timing of the spring bloom in the EBS and WBS. For example, the Aleutian Low was centered over the EBS in early spring of 1998 and 2001, and stronger winds and weaker solar radiation led to reduced stratification and a late spring bloom (May to June) in the EBS. In contrast,



[Figure BS-19] Average chlorophyll$_a$ (mg·m$^{-3}$) estimated from ocean colour data (http://www.science.oregonstate.edu/ocean.productivity/standard) for a) Middle Domain, b) Outer Domain, c) slope to basin, and d) deep basin regions of the Bering Sea (eastern and western) during 2003-2008.

the WBS had early spring blooms (April) due to weaker winds and stronger irradiance in these years (Iida and Saitoh 2007). Similar comparisons to the Aleutian Low and other climatic factors may provide an understanding of the east-west variations in the recent (2002-2008) data.

Comparisons across regions were also described by Yoo et al. (2008) using SeaWIFS data for 1998-2005 from the EBS shelf, slope to basin (termed MSB), East Kamchatka Current (EKC) and Bering Sea Basin (BSB). Spring peaks in chlorophyll$_a$ were seen in mid-April to mid-May in the EBS, May in MSB and EKC and in May-June in the BSB (Yoo et al. 2008). Fall peaks were seen in mid- to late-September (EBS and EKC), August in MSB, and in mid-August to October in the BSB. Bloom concentrations were generally higher in spring than fall, with the exception of the BSB. The deep BSB had longer peak periods than the shallower coastal regions. The growing season, based on the timing of the spring and fall peaks, may be longer in the EBS and EKC than in the MSB region.

### 5.1.2 Mooring fluorometer data

The relative timing of the phytoplankton bloom, as indicated by an increase in chlorophyll$_a$ fluorescence measured at the mooring sites M2 and M4, was evaluated for spring and fall periods (Table BS-2, Fig. BS-20). At M2, the spring blooms typically began in mid-May in the warm years and varied in the cold years from mid-March to early June, with fall blooms ending in October for both warm and cold years.

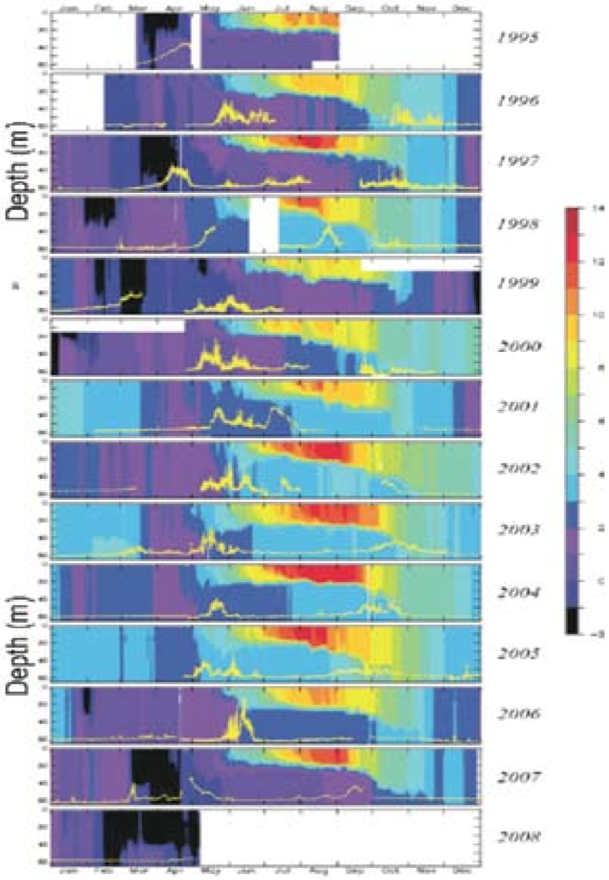
At M4, spring blooms were observed earlier than at M2 (March and April) for both warm and cold years, but peaked in May, as typically seen at M2. The sea surface temperature (SST) was often ~ 4°C when the spring bloom peak was observed at M2 (e.g. 2003-2006) (Fig. BS-20). These were all years in which the ice retreated early at M2, and the bloom did not begin until the water was stratified by insolation (Hunt et al. 2002).

[Table BS-2] Timing of the start and peak of spring (and fall for M2) blooms indicated by increases in chlorophyll$_a$ surface fluorescence at 70 m EBS moorings M2, M4 and M5. NA indicates data not available. Data courtesy of EcoFOCI/PMEL: http://www.pmel.noaa.gov/foci/foci_moorings/moorings/bering_sea_frames.html

| Year | Spring Start M2 | Spring Start M4 | Spring Start M5 | Spring Peak M2 | Fall Start M2 | Fall Peak M2 |
|---|---|---|---|---|---|---|
| 2003 | early May | early March | NA | mid May | early October | early to late October |
| 2004 | mid May | early April | NA | mid May | mid September | late September to late October |
| 2005 | NA | late March to early April | NA | mid May and early June | late August | September to late October |
| 2006 | early June | NA | early May | late June | mid Sept | late September to mid October |
| 2007 | mid March | late April | April | late April to early May | late August | September to early October |
| 2008 | mid April | late April | May | early May | late July? | NA |

### 5.1.3 Comparisons of ocean colour and mooring data

Mooring data from the 70 m isobath (Middle Domain) generally support the conclusions from ocean colour chlorophyll$_a$ data. For example, in 2003, mooring data substantiated satellite chlorophyll$_a$ data with earlier spring blooms observed at M4. Therefore, these data suggest the growing season was longer in 2003 than in other years (given that the spring bloom was earlier in 2003 and end of the fall bloom occurred within the same month each year). The higher annual net primary production in 2003, estimated from satellite observations (Table BS-3), supports this conclusion. In general, spring blooms were not earlier in cold years than in warm years based on satellite data and mooring data from M4. M2 data indicate that in warm years, spring blooms occurred in May, but bloom timing varied in cold years with a late bloom in 2006 (June), and early blooms in 2007 and 2008.



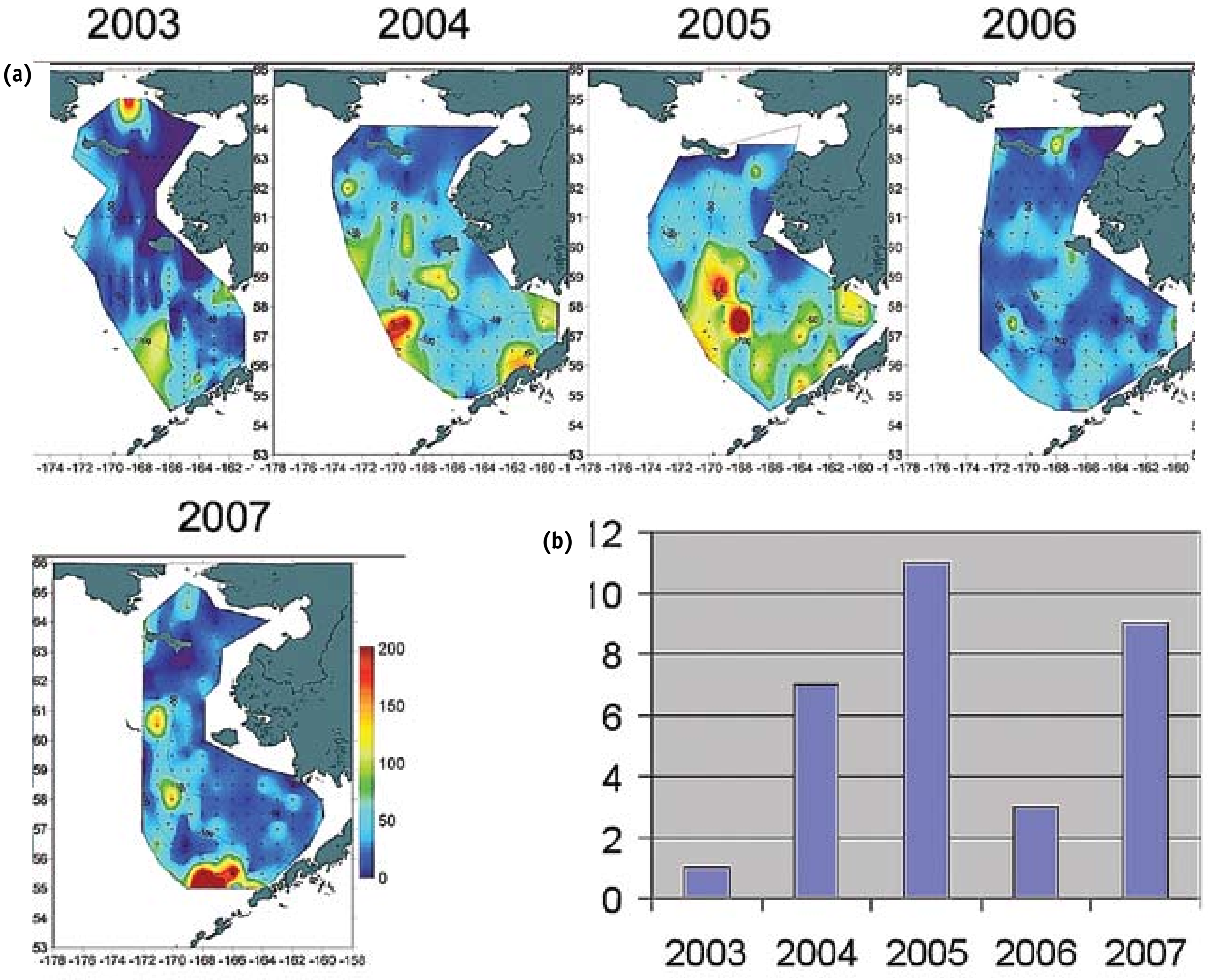
[Figure BS-20] Temperature contours overlaid with surface chlorophyll$_a$ fluorescence trace (yellow line) from mooring M2 for 1995-2008. Data courtesy of Phyllis Stabeno, EcoFOCI / PMEL/NOAA.

[Table BS-3] Mean water column integrated chlorophyll$_a$ ($\text{mg}\cdot\text{m}^{-2}$) from discrete chlorophyll$_a$ samples collected mid-August – September by BASIS. *$p<0.05$, ANOM for ln transformed data with ↑ or ↓ indicating significantly above or below mean, respectively.

| Year | Mean | SE | Min | Max | N |
|---|---|---|---|---|---|
| 2003 | 40.0 | 2.3 | 2.6 | 103.7 | 90 |
| 2004 | 56.0*↑ | 3.2 | 2.5 | 227.2 | 132 |
| 2005 | 66.3*↑ | 4.3 | 11.1 | 386.2 | 114 |
| 2006 | 32.0*↓ | 1.5 | 8.2 | 113.8 | 132 |
| 2007 | 42.0*↓ | 3.8 | 4.0 | 281.9 | 126 |

### 5.1.4 Fall chlorophyll data

Late summer/early fall integrated chlorophyll$_a$ were patchy during all years with more "hot spots" (i.e. high values) seen in 2004, 2005 and 2007, coinciding with an increase in wind events (wind speed cubed > $0.4\times10^4 \text{m}^3\cdot\text{s}^{-3}$) during August and September (Fig. BS-21). Mean integrated chlorophyll$_a$ values were high in 2004 and 2005 (warm years), low in 2006 and 2007 (cold years) and average in 2003 (warm year) (ANOM for ln transformed data, $p < 0.05$, Table BS-4). The low chlorophyll$_a$ seen in 2003 during the late summer (August to September) surveys supports the idea of a late fall bloom (started in October at M2) due to the reduced number of late summer wind events (Fig. BS-21b).



[Figure BS-21] a) Integrated water column chlorophyll$_a$ ($\text{mg}\cdot\text{m}^{-2}$) from discrete chlorophyll$_a$ samples collected mid-August to early October for 2003-2007 (BASIS/ABL/AFSC/NOAA), and b) Number of wind events, defined as wind speed cubed greater than $0.4 \times 10^4\ \text{m}^3\cdot\text{s}^{-1}$, during August and September in SE Bering Sea (near M2).

### 5.1.5 Surface chlorophyll

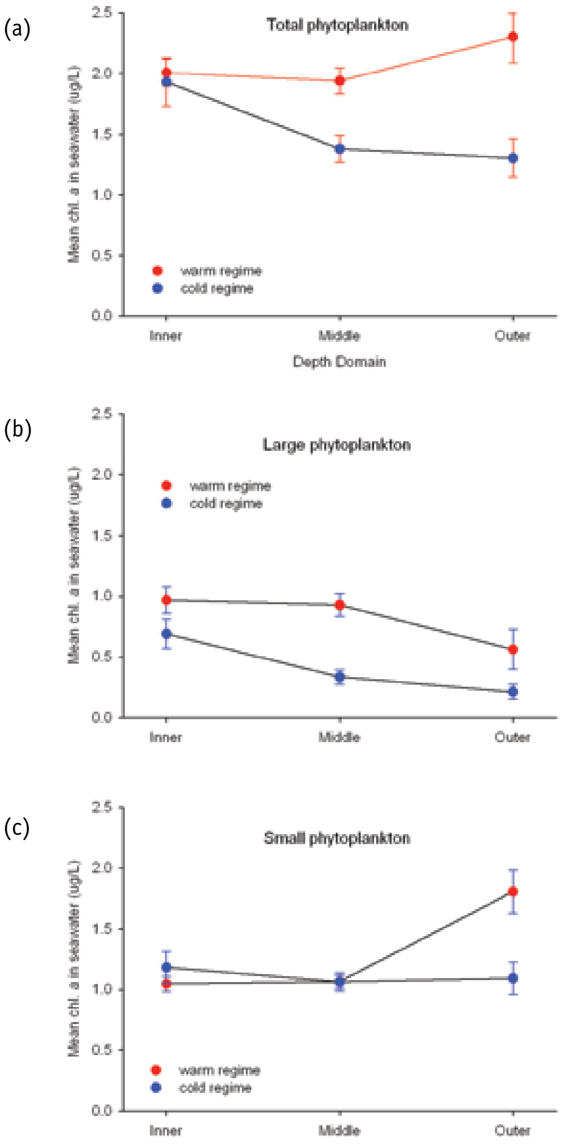
Surface chlorophyll$_a$ showed trends similar to integrated chlorophyll$_a$, with higher surface (5m) concentrations observed in 2004 and 2005 than in 2006, 2007 and 2003. Concentrations were significantly higher in 2005 and lower in 2007, $p<0.01$ (Table BS-4). Interannual differences in surface chlorophyll$_a$ reflect warm-cold regime shifts, with significantly higher total biomass in warm (2004-2005) vs. cold (2006-2007) years ($p< 0.001$). Phytoplankton biomass was higher south compared to north of 60°N ($p<0.001$) and mesoscale patchiness in surface chlorophyll$_a$ was apparent in both areas. In general, late summer/fall surface blooms were observed in nearshore waters near the Pribilof Islands, Nunivak Island and the Alaska Peninsula. In spring, the largest surface phytoplankton blooms appear to occur along the shelf-break region, as suggested by May ocean colour data.

[Table BS-4] Surface (5 m) chlorophyll$_a$ ($mg \cdot m^{-3}$) from discrete chlorophyll$_a$ samples collected mid-August – early October by BASIS. *$p<0.05$, anomalies for ln transformed data with ↑ or ↓ indicating significantly above or below the mean, respectively.

| Year | Mean | SE | Min | Max | N |
|---|---|---|---|---|---|
| 2003 | 1.69 | 0.10 | 0.20 | 5.56 | 117 |
| 2004 | 1.85 | 0.10 | 0.47 | 6.21 | 127 |
| 2005 | 2.23*↑ | 0.11 | 0.28 | 7.54 | 111 |
| 2006 | 1.63 | 0.11 | 0.20 | 7.89 | 118 |
| 2007 | 1.22*↓ | 0.08 | 0.16 | 4.75 | 113 |

### 5.1.6 Surface size-fractionated chlorophyll

Within the southeastern Bering Sea, phytoplankton biomass and taxonomic assemblage structure may vary on both spatial (Inner, Middle, Outer Domains) and temporal (warm or cold regime) scales (Stockwell et al. 2001; Hare et al. 2007). During mid-August to early October, the highest biomass of small cells in surface waters was seen in the Outer Domain in warm years ($p<0.001$) (Fig. BS-22). Large cell biomass decreased from Inner to Middle to Outer Domains in the cold regime ($p<0.001$), but Inner and Middle Domain biomass was similar in the warm regime. There was a striking increase in large cell biomass in the Middle Domain in the warm regime (Fig. BS-22). The increase in total phytoplankton biomass in warm compared to cold regimes ($p<0.001$) was driven by increases in small cells in the Outer Domain and large cells in all domains (particularly evident in the Middle Domain).



[Figure BS-22] Surface chlorophyll$_a$ ($mg \cdot m^{-3}$) for: a) total, b) large fraction (> 10 µm) and c) small fraction (< 10 µm) in warm (2004-2005) and cold (2006-2007) years from Inner (> 50 m), Middle (50-100 m) and Outer (100-200 m) Domains in the EBS for samples collected mid-August to early October. Data from BASIS/ABL/AFSC/NOAA.

Preliminary analysis of these data indicates that cell size was larger at the subsurface maximum than at the surface in the Middle Domain. Additionally, Strom and Frederickson (2008) found that during August 2004 at the M2 mooring, large cells dominated the subsurface community compared to small cells at the surface.

In summary, large cell biomass is higher in nearshore environments and decreases with distance from shore, especially in cold years (Fig. BS-22). Overall surface phytoplankton biomass is higher during warm years, with dramatic increases in small particle biomass in the Outer Domain, and large particle biomass in the Middle Domain during late summer and early fall (Fig. BS-22).

### 5.1.7 Net primary production

Yearly NPP on the EBS shelf (excluding the Inner Domain) was significantly higher in warm years (2003-2005) than in cold years (2006-2007), with 2003 higher than all other years (Table BS-5). Interestingly, NPP appears consistently higher per unit area in the Middle Domain than in the Outer Domain. Note that these NPP values may be overestimates, since nutrient limitation is not directly considered in this global estimation of NPP.

[Table BS-5] Yearly averaged results of a Vertically Generalized Production Model for net primary production (NPP) in the eastern Bering Sea (EBS). Courtesy of Mizobata, Iida, Saitoh and Hirawake using data from Oregon State University: http://www.science.oregonstate.edu/ocean.productivity.

| | **Middle Domain (50m-100m)** | | **Outer Domain (100m-200m)** | |
|---|---|---|---|---|
| Year | Ave. NPP (mgC·m$^{-2}$·d$^{-1}$) | 95% CI | Ave. NPP (mgC·m$^{-2}$·d$^{-1}$) | 95% CI |
| 2003 | 705 | 697 - 713 | 618 | 606-630 |
| 2004 | 673 | 665 - 681 | 568 | 560-576 |
| 2005 | 668 | 660 - 676 | 556 | 543-569 |
| 2006 | 643 | 635 - 651 | 518 | 508-529 |
| 2007 | 647 | 637 - 657 | 460 | 447-473 |

Phytoplankton taxonomic data were not available to evaluate interannual differences during 2003-2008. However, coccolithophore blooms comprised of *Emiliania huxleyi* were not observed or covered much smaller areas relative to the large blooms observed during 1998-2001 (Iida et al. 2002). Small blooms were documented in 2003, 2004, and 2007 during September BASIS cruises, and were generally located in the Middle Domain north of 57°N (Eisner, unpublished data).

### 5.1.8 Conclusions

Based on ocean colour data, phytoplankton biomass appears to have been highest in 2003 for the Bering Sea shelf (Middle and Outer Domains) and higher in warm than cold years. The spring blooms started in March (2003) or May (2004-2005) in warm years and varied from April (2007 and 2008) to June (2006) in cold years based on mooring chlorophyll$_a$ fluorescence and satellite ocean colour observations. The fall blooms began in August to September with the exception of 2003 when blooms began later (in October). Late summer/fall data indicate that phytoplankton blooms are patchy and that “hot spots” increase during periods of high winds when deep nutrients may be vertically mixed up into depleted surface waters to fuel this fall production, as seen in 2005, 2007 and 2004. The waters surrounding Nunivak Island have increased concentrations of large cells that may be sustained by mixing of nutrients across the Inner Front (Rho and Whitledge 2007). Size fractionation data for late summer/early fall surface waters indicate that in warm years, small phytoplankton were in higher concentration in the Outer Domain. Additionally, in all domains, large cells were in higher concentration in warm versus cold years with the most apparent differences seen in the Middle Domain. These recent data suggest that phytoplankton biomass and possibly production was higher in warm than in cold years. In addition, the spring blooms did not occur consistently earlier in cold than in warm years, although, as predicted by Stabeno et al. (1999) and Hunt et al. (2008), early blooms were associated with late ice retreat from the area of Mooring M2. These results suggest that water temperatures and the timing of ice retreat may influence primary production in different ways. The extreme cold of 2006 to 2009 may have additional effects that were not anticipated in the original Oscillating Control Hypothesis (OCH) (Hunt et al. 2002).

## 6.0 Microzooplankton *(Sherr, Strom)*

Although there is less information on microzooplankton compared to other components of marine food webs in the eastern Bering Sea, results of previous studies have found that heterotrophic protists are abundant and important herbivores during summer in this region (Olson and Strom 2002; Strom and Frederickson 2008). Recent field work during spring in the presence of sea ice is expanding our view of microzooplankton in eastern Bering Sea waters, as well as our understanding of heterotrophic protists associated with sea ice algae. To our knowledge, there is no information available on microzooplankton in western Bering Sea waters.

The Bering Sea has a diverse community of heterotrophic protists both in the water column and in sea ice. Protists in the microzooplankton size fraction include morphological types and genera of ciliates and heterotrophic dinoflagellates commonly found in other regions of the sea. Ice algal protists include ciliate morphotypes typical of benthic habitats, heterotrophic euglenae, and amoebae. In addition, heterotrophic flagellates are abundant in the water column and sea ice communities. To date, there is little information about protists <~15 µm in size in the Bering Sea, and data on nanoplankton-sized heterotrophic protists are not reported here.

### 6.1 Biomass and seasonal cycles

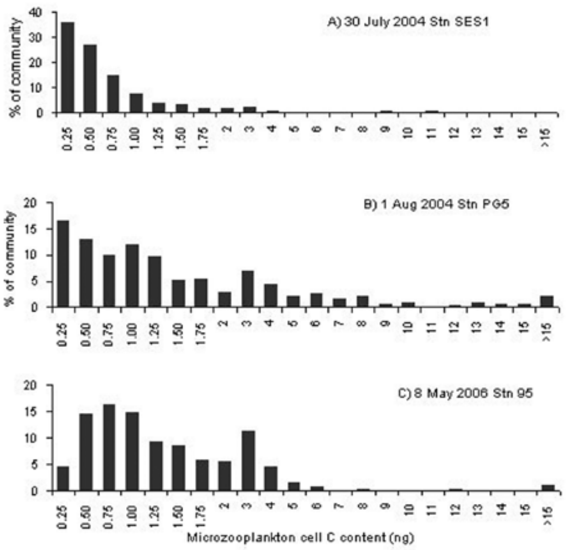
To date, data on the biomass of microzooplankton in the Bering Sea, mainly ciliates and heterotrophic dinoflagellates, are limited to early spring and mid-summer and have all been collected in the eastern Bering Sea. Overall biomass levels ranged from 2 to 178 µgC·l$^{-1}$ (Table BS-6). Two early spring cruises (2006 and 2008) collected samples from the ice edge, in ice edge blooms, and in adjacent open water. Winters in both 2006 and 2008 had below-average temperatures and relatively late ice retreat. Conditions in 2008 were more extreme, with heavy ice cover and January-April SSTs in the southeastern Bering Sea approximately 5°C below the long-term average.

Microzooplankton biomass during the two early spring cruises was similar whereas biomass levels were much higher, on average, during the summers of 1999 and 2004 (Table BS-6), even though both average and maximum chlorophyll concentrations were lower than in spring. The lower microzooplankton biomass in summer 2004 has been related to the greater degree of water column stratification and nutrient limitation of phytoplankton growth in that year (Strom and Fredrickson 2008). Large microzooplankton (cells >40 µm in length) appear to be especially important in early spring, comprising an average of 53 - 71% of the community (Table BS-6).

[Table BS-6] Total microzooplankton (MZP) biomass, percent of total biomass composed of >40 µm sized cells, and percent of total biomass composed of heterotrophic dinoflagellates (Hdinos) in the Bering Sea. All samples are from the upper 35m. Values are means ±1 SD, with range in parentheses. N: number of stations sampled.

| Region | Months/Year | Chl$_a$ µg·l$^{-1}$ | Total MZP µgC·l$^{-1}$ | >40 µm MZP as % of total | Hdinos as % of Total MZP | n |
|---|---|---|---|---|---|---|
| SE Bering Sea[1] | July /Aug 1999 | 1.5 ± 1.1<br>(0.4 – 4.5) | 62.3 ± 45.8<br>(18.4 – 178) | nd | 51 ± 14<br>(16 – 75) | 18 |
| SE Bering Sea[2] | July /Aug 2004 | 1.4 ± 1.0<br>(0.2 – 3.3) | 35.0 ± 25.8<br>(9.2 – 116) | 45 ± 19<br>(13 – 77) | 65 ± 11<br>(49 – 81) | 19 |
| SE Bering Sea[3] | April/May 2006 | 2.9 ± 1.8<br>(0.6 – 6.7) | 14.6 ± 10.6<br>(1.9 – 34.6) | 53 ± 13<br>(35 – 80) | 26 ± 11<br>(4 – 40) | 11 |
| Eastern Bering Sea[4] | April 2008 | 7.8 ± 8.0<br>(0.2 – 28) | 15.8 ± 12.0<br>(4.2 – 40.5) | 67 ± 11<br>(31 – 91) | 72 ± 13<br>(49 – 88) | 9 |
| Eastern Bering Sea[4] | July 2008 | nd | 19 ± 16.9<br>(1.7 – 52.5) | 58 ± 19<br>(42 – 88) | 51 ± 14<br>(16 – 75) | 9 |

[1]Olson and Strom 2002; [2]Strom and Frederickson 2008; [3]Strom and Napp Unpublished; [4]Sherr and Sherr Unpublished



[Figure BS-23] Size frequency distributions of microzooplankton from the SE Bering Sea. A) Summer 2004, station in the productive "green belt"; B) Summer 2004, station from a diatom bloom between the Pribilof Islands; C) Early spring 2006, station in heavy sea ice. Microzooplankton cells are binned by C content (0.00-0.25 ng; 0.26-0.50 ng; etc.).

While large microzooplankton can be abundant in summer, for example, at a high-chlorophyll station near the Pribilof Islands, many summer stations were dominated by small cells (Fig. BS-23). These smallest cells were scarce during early spring 2006 (Fig. BS-23c). Dinoflagellates were a major component of the microzooplankton community during early spring 2008, as well during early summer cruises (Table BS-6). However, ciliates dominated the microzooplankton community at all stations during early spring 2006, and at stations with low chlorophyll in summer 2008. The source of these differences is uncertain.

## 6.2 Growth rates

During spring 2008, net protist community growth rates were variable and in some cases a decline of protist biomass occurred (Table BS-7). However, positive growth rates of up to 0.3 to 0.4 $d^{-1}$ were observed in samples with high $chlorophyll_a$ concentrations or when incubations were made at temperatures of 5-6°C. An abundance-based growth rate of 0.36 $d^{-1}$ was found for a species of testate amoeba parasitizing centric diatoms at -1°C, and of 0.32 $d^{-1}$ for a *Ptychocylis* sp. tintinnid ciliate in samples incubated at 5-6°C (Table BS-7). These higher rates of growth

[Table BS-7] Growth rates of various size classes and groups of microzooplankton during spring sea ice conditions in the eastern Bering Sea, April, 2008. Negative growth rates indicate a decrease in biomass during the incubation period. Growth rates were determined via sampling experiments over periods of 1 to 2 weeks. Data from Sherr and Sherr, unpublished. P. sp. Tin = *Ptychocyclis* sp. Tintinnid.

| **Growth experiment conditions** | | | **Biomass-based growth rates** | | | | **Abundance-based growth rates** | |
|---|---|---|---|---|---|---|---|---|
| Incubation condition | inc. temp °C | initial $Chl_a$ $\mu\cdot gl^{-1}$ | ‹40 µm ciliates $d^{-1}$ | ‹40 µm Hdinos $d^{-1}$ | ›40 µm ciliates $d^{-1}$ | ›40 µm Hdinos $d^{-1}$ | Testate amoeba $d^{-1}$ | P. sp. Tin. $d^{-1}$ |
| Deck Incubator ambient Light | -1 to +2 | 0.4 | -0.121 | 0.039 | 0.019 | 0.014 | | |
| Environ chamber, dark | -1 | 20.4 | 0.025 | 0.263 | -0.312 | 0.131 | 0.362 | |
| Environ chamber, dark | -1 | 7.3 | -0.018 | -0.079 | -0.152 | -0.071 | | |
| Environ chamber, dark | +5 to +6 | 7.3 | -0.097 | -0.083 | 0.440 | 0.288 | | |
| Environ chamber, dark | -1 | 27.9 | 0.017 | 0.091 | 0.197 | -0.072 | | |
| Environ chamber, dark | +5 to +6 | 27.9 | -0.140 | -0.014 | 0.429 | 0.158 | | 0.325 |

were comparable to maximum growth rates observed for phytoplankton at 0-2°C during deck incubation experiments in the spring 2008 Bering Ecosystem Study (BEST) cruise (Campbell and Sherr unpublished).

### 6.3 Microzooplankton as grazers of phytoplankton

Microzooplankton are known to be major consumers of phytoplankton production in both coastal and open ocean regions of the world's oceans (Calbet and Landry 2004; Calbet 2008). Data from the southeastern Bering Sea demonstrate that microzooplankton grazing is typically the major process removing phytoplankton from the ecosystem. Published data so far are confined to summer months, although microzooplankton grazing impact experiments are being conducted during spring and summer cruises in the eastern Bering Sea in the current BEST research program.

During summer 1999, microzooplankton grazing on phytoplankton averaged 0.26 $d^{-1}$ (range 0.08-0.57 $d^{-1}$) (Olson and Strom 2002). Rates during 2004 tended to be lower, averaging 0.13 $d^{-1}$ (range 0.00-0.27 $d^{-1}$) (Strom and Fredrickson 2008). The fraction of primary production consumed per day by microzooplankton was strikingly lower in 2004 than in 1999 (average 0.49 versus 0.88). This difference was attributed to the stronger stratification in 2004, inducing phytoplankton nutrient limitation and poor food quality (Strom and Fredrickson 2008). Results for spring 2008 and 2009 cruises in the eastern Bering Sea showed average microzooplankton grazing rates of 0.085 $d^{-1}$ (range 0.0-0.55 $d^{-1}$), with an average fraction of phytoplankton production consumed of 0.41 (range 0-2.9) (Sherr and Sherr unpublished). Given that much of phytoplankton production in the Bering Sea is consumed by microzooplankton, the response of these grazers to environmental conditions is important in dictating transfer of production to organisms at higher trophic levels.

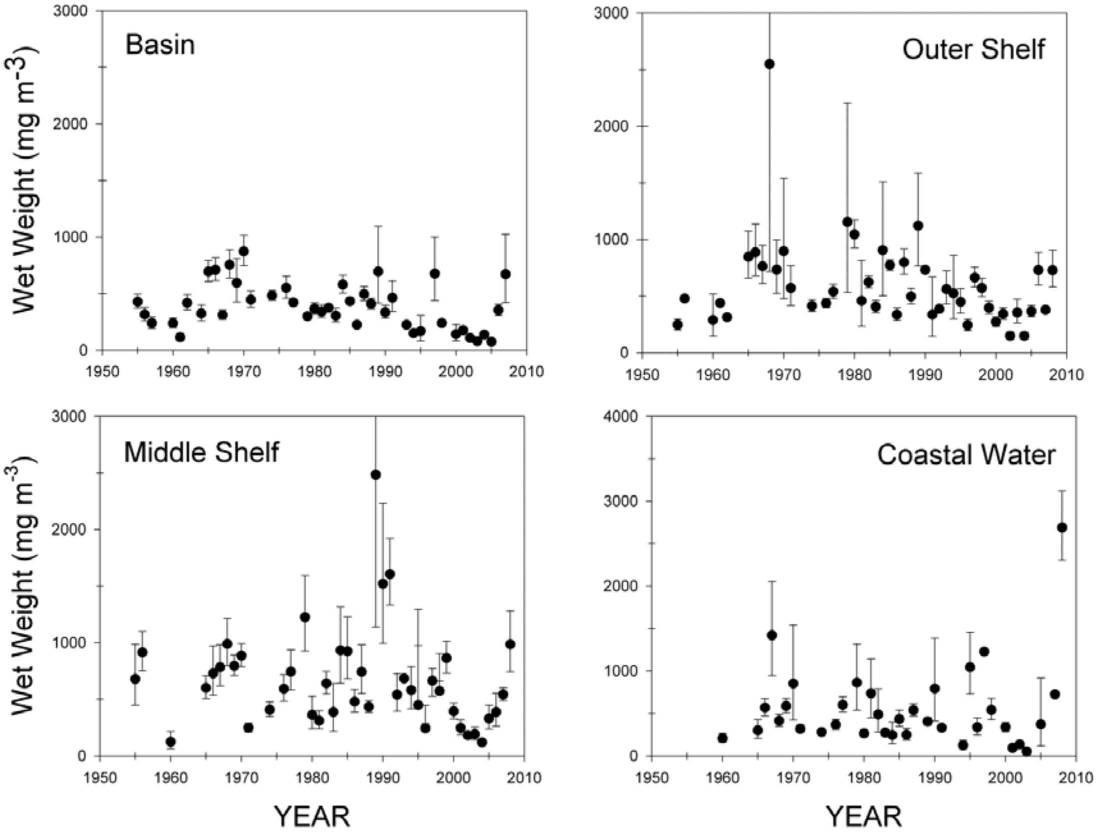
## 7.0 Mesozooplankton *(Napp, Coyle, Eisner)*

### 7.1 Total mesozooplankton biomass

The T/S *Oshoro Maru* zooplankton time series from Hokkaido University is the best record available for examining recent changes in the biomass of mesozooplankton in the eastern portion of the basin and on the eastern Bering Sea shelf. Each year since the mid-1950s, samples have been obtained during a single summer cruise using a vertically hauled net. The T/S *Oshoro Maru* data best represents the biomass of crustacean mesozooplankton such as copepods and soft-bodied organisms such as chaetognaths. Larger, faster-moving zooplankters such as euphausiids are probably under-represented in these collections. Station locations and timing have varied over the course of the time- series, although since 1995 a fixed grid of stations has been sampled (Napp et al. 2002). The time series has been examined by many to show the characteristic modes of variability in the eastern Bering Sea (e.g., Sugimoto and Tadokoro 1997; Hunt et al. 2002; Napp et al. 2002; Hunt et al. 2008). There have been declines in summer zooplankton biomass starting in the early 1980s and ending in 2005, depending on the region, with increases in more recent years (Fig. BS-24), possibly as a response to cooling and an increase in the maximum extension of sea ice relative to the previous period (1980s to 2005). In particular, in 2006-2008, the summer wet weight biomass of zooplankton in the eastern Bering Sea increased or remained at high levels relative to the minimum observed during the warm period of 2000 to 2005 (Fig. BS-24). In 2008, the biomasses in the Outer and Middle Domains were significantly higher or the same as in 2007, although it is important to note that the cruise timing was earlier in 2008 than the rest of period from 1995 to 2007. Data from the Middle Domain show a continual increase from the low of 2005 to 2008. Note that there were no 2008 samples for the basin and only two samples from the Coastal Water. Data from the late summer and fall, collected over the eastern Bering Sea shelf since 2002 show a similar pattern of low zooplankton biomass in the warm years of 2002-2005, with marked increases in zooplankton biomass over the Middle Domain in 2006, 2007 and particularly 2008 (Figs. BS-24, BS-25).

### 7.2 Species composition

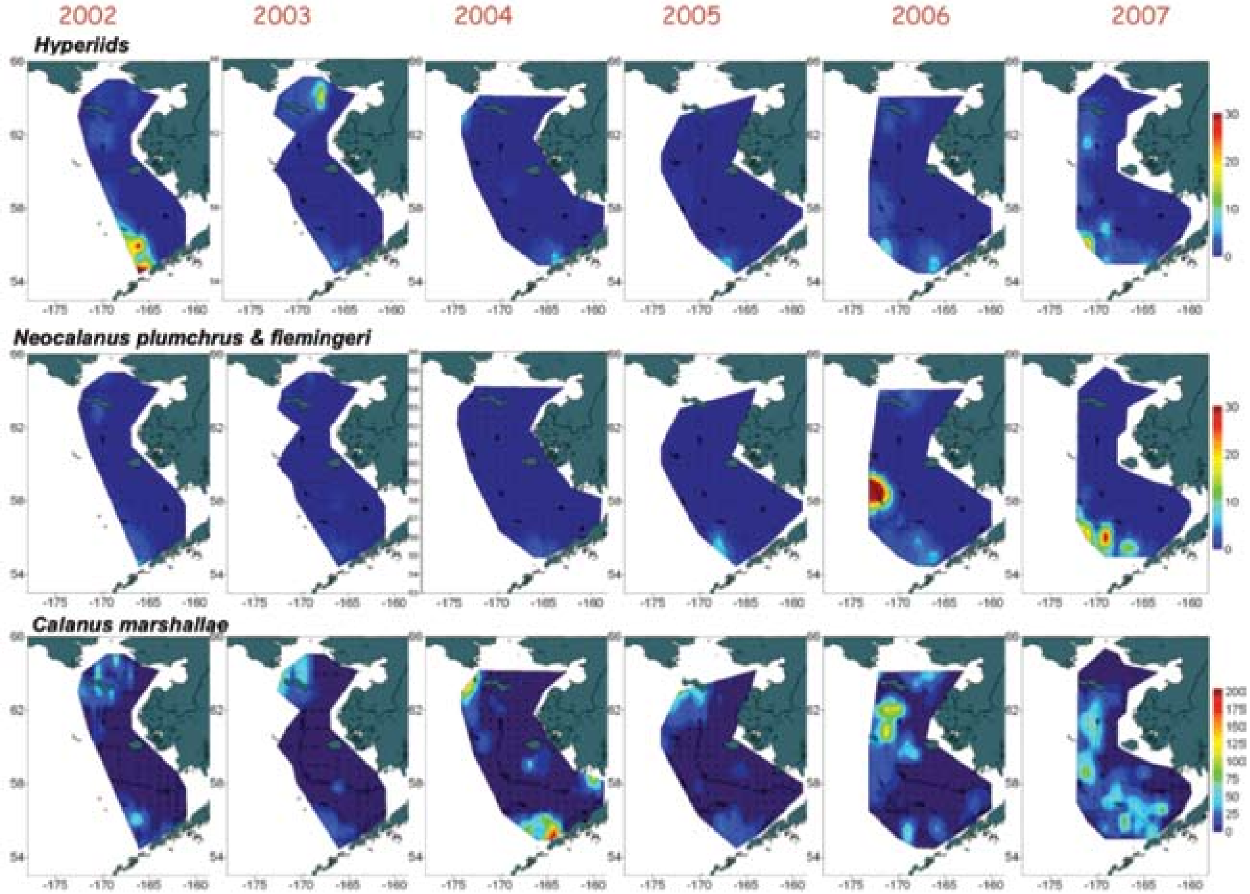
The species composition of the zooplankton community is important to the transfer of energy to higher trophic levels because of the sensitivity of predators to prey size and the timing of prey availability. The recent alternation of warm and cold years has given us limited insight into how temperature (and those factors that co-vary with it) affects the species composition. Collections made by the U.S. NOAA from the T/S *Oshoro Maru* form a short time series of fluctuations for



[Figure BS- 24] T/S *Oshoro Maru* summer zooplankton biomass time series. Preserved wet weight biomass of zooplankton collected with a metered 0.333 mm mesh NORPAC net towed vertically from near bottom to the surface. Tows were assigned to an oceanographic domain based on the station water depth (>200m, basin; 100<X≤200, Outer Shelf; 50<X≤100, Middle Shelf; X≤50, Coastal Water). Shown are the means and standard errors calculated from 4th root transformed raw data. The measurements were made by the Marine Biology Laboratory, and the data were provided by Atsushi Yamaguchi, both from Hokkaido University. Data analyses and interpretation were done by J. Napp (NOAA – Fisheries) and A. Yamaguchi. Inconsistencies in sampling dates and stations occupied before 1995 are discussed in Napp et al. (2002).

selected taxa (Fig. BS-26). For example, subsequent to the strong depression in the concentration of *Calanus,* during the warm period 2000-2005, there has been a “recovery” in *Calanus* coincident with the cooling and southerly extension of sea ice in 2006. The summer concentrations of *Calanus* have increased since 2005, both in the Middle and Outer Domains (although there was only a single station for the Outer Domain in 2008). Similarly, *Neocalanus* spp. (*N. plumchru*s + *N. flemingeri*) appear to be somewhat more abundant in the Outer Domain beginning in 2005. The increases in these two larger mesozooplankton may be responsible for part of the increases seen in the wet weight biomass observed in the T/S *Oshoro Maru* biomass data.

Interannual patterns in the concentrations of the two smaller copepods, *Pseudocalanus* (all developmental stages) and *Acartia* (C6 only) are less clear (Fig BS-26). The data from the latter two taxa do not support a simplified paradigm that the smaller copepods do better in warm than in cold years. The concentrations of *Pseudocalanus* in the Middle Domain are somewhat higher during the cool to cold period 2006-2008 than in the warm period 2000-2005. It is difficult to discern a pattern in the *Acartia* data, particularly with the high variability. As with the biomass samples, the 2008 community composition data were also collected earlier than the rest of the time series (ca. June 18 - July 7).

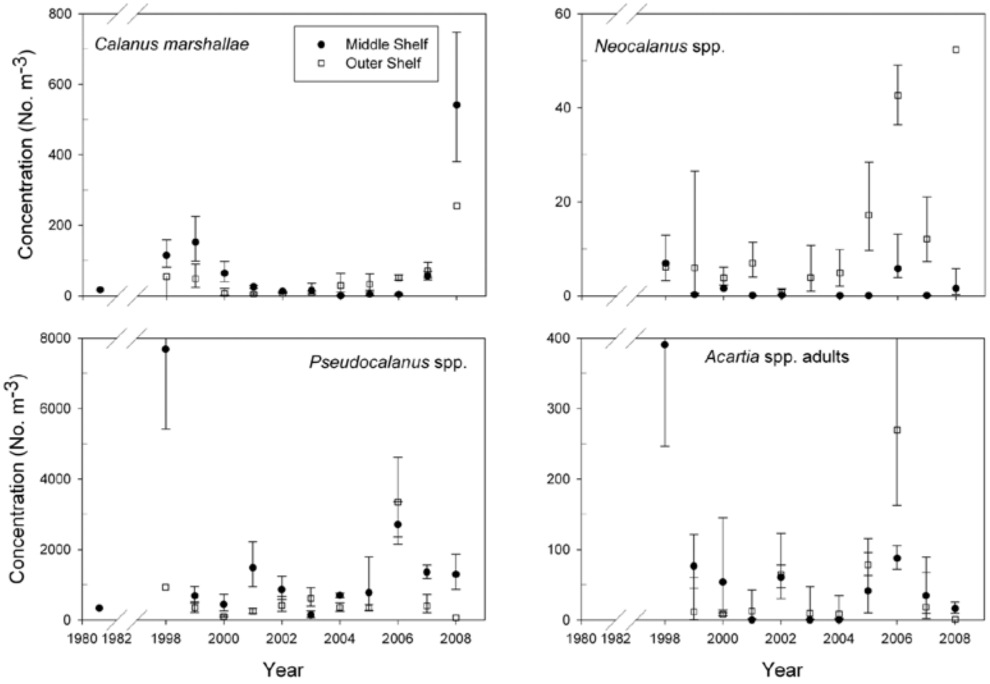


[Figure BS-25] Distribution and abundance (#·m$^{-3}$) of large zooplankton sampled by a 505 μm mesh Bongo net in the BASIS program, 2002-2007. Figure courtesy of Lisa Eisner.

Collections made during the Bering Sea and Aleutian Salmon International Survey (BASIS) reveal a similar temperature-related pattern (Fig. BS-25). These samples, taken in the late summer and early fall, showed that the large zooplankton fraction remained low through 2003-2005, then began to show signs of recovery in 2006 (Volkov et al. 2007). Fall biomass estimates for *Calanus* on the eastern Bering Sea shelf averaged 3.2, 8.2, 9.3 and 30.5 mg·m$^{-3}$ for 2003-2006 respectively (Volkov et al. 2007).

## 7.3 Interannual variations in seasonal patterns of zooplankton species abundance

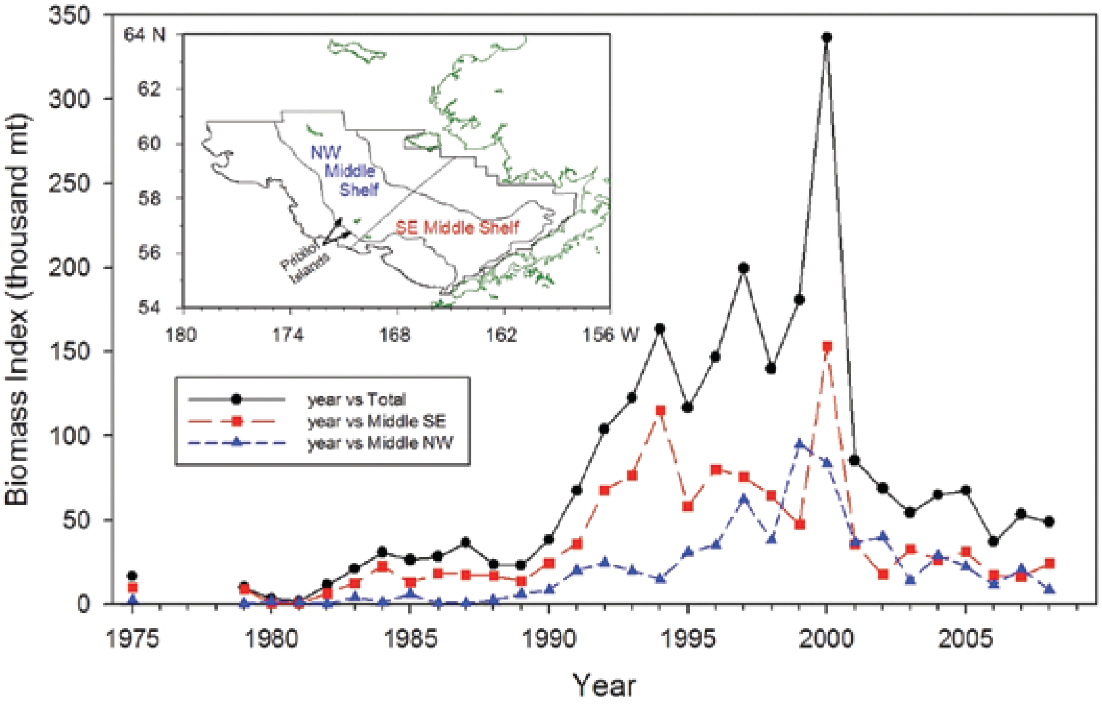
Insight has also been gained into fluctuations in species composition by comparing the results from process studies that occurred under different conditions. For example, comparison of plankton abundance and biomass between a cold year in the Inner Front Study (1999) and a warm year during the Pribilof Island Study (2004) showed strong differences (Table BS-8). While the biomass and abundance of small copepods were higher or not different in 2004 relative to 1999, *Calanus marshallae* and other large zooplankton had virtually disappeared from the shelf in 2004, the fifth warm year in a row; euphausiids and chaetognaths also showed dramatic declines in biomass that year (Coyle et al. 2008).



[Figure BS-26] Concentrations of selected copepod species from the eastern Bering Sea shelf. Data from 1998 to 2007 were collected from the T/S *Oshoro Maru* using paired 20 cm and 60 cm bongo frames (0.150 and 0.333 mm mesh, respectively) towed obliquely. Data from 2008 were collected with the same sampling gear but from the NMFS annual bottom trawl survey using a chartered fishing vessel. Shown are the means and standard errors calculated from 4th root transformed raw data. Data were analyzed and interpreted by J. Napp (NOAA – Fisheries).

Likewise, the large scyphozoan *Chrysaora melanaster*, which overwhelmingly dominates zooplankton wet-weight biomass during summer of most years on the southeastern Bering Sea shelf, showed a steep decline between 1999 and 2006 (Fig. BS-27). Hydromedusae were the only large zooplankton having significantly higher biomass in 2004 relative to 1999, probably due to a relaxation of predation by scyphozoans. The cause of the decline in *Chrysaora* is not known, though it may have been related to the scarcity of large prey (copepods and euphausiids) over the shelf (Brodeur et al. 2002).

Insight can also be gained by comparing the adjacent years of warm and cold conditions at various time points in the year. During June of the cold year (1999), the abundance and biomass of all copepods was depressed relative to the warm year (1998), particularly the small taxa, *Pseudocalanus* and *Oithona*. During June of the cold year, the spring zooplankton community was dominated by euphausiid larvae and meroplankton, but during June of the warm years, the plankton was dominated by copepods (copepod nauplii, *Pseudocalanus*, *Calanus marshallae* and *Oithona similis*). By August zooplankton abundance and biomass during both years were not significantly different (Coyle and Pinchuck 2002). Although cold conditions during June of 1999 depressed initial zooplankton abundance, biomass and production, substantial warming of the water column during subsequent months elevated copepod production, so that conditions in August were comparable to conditions during the other two years. *Pseudocalanus* and *Acartia* were positively correlated to temperature (all years pooled) during June and August; *Calanus marshallae* was positively correlated during June, but negatively correlated with temperature during fall (Coyle and Pinchuk 2002, Table BS-8), indicating that elevated summer temperatures may depress *Calanus* populations.



[Figure BS-27] Trends in relative jellyfish biomass in the southeastern Bering Sea. Data from Alaska Fisheries Science Center, bottom trawl surveys. Figure courtesy of M.B. Decker, Yale University.

| Data Type | 1999 | 2004 | Change | P |
|---|---|---|---|---|
| Physical Properties | | | | |
| Upper Mixed Temperature (°C) | 7.0 | 12.6 | +5.6 | <0.001 |
| Lower Mixed Temperature (°C) | 2.0 | 3.2 | +1.2 | <0.001 |
| Stability Parameter (J·m$^{-3}$) | 34.9 | 98.4 | +63.5 | <0.001 |
| Upper Mixed Salinity (PSU) | 31.6 | 31.8 | +0.2 | <0.001 |
| Lower Mixed Salinity (PSU) | 31.7 | 32.0 | +0.3 | <0.001 |
| Zooplanton abundance (No·m$^{-3}$) | | | | |
| *Oithona similis* | 348 | 1633 | +1295 | <0.001 |
| *Pseudocalanus* spp. | 404 | 1211 | +807 | <0.001 |
| *Calanoid nauplii* | 161 | 2.69 | -159 | 0.15 |
| *Acartia* spp. | 277 | 507 | +230 | 0.26 |
| *Centropages abdominalis* | 0 | <<1 | <<1 | 0.18 |
| Zooplankton and Micronekton biomass (mg WW·m$^{-3}$) | | | | |
| *Calanus marshallae* | 510 | 0.09 | -509.9 | <0.001 |
| *Thysanoessa* spp. | 6.3 | 0.5 | -5.8 | 0.007 |
| *Sagitta elegans* | 110 | 2.2 | -107.8 | <0.001 |
| Hydromedusae | <<1 | 54 | +54 | <0.001 |
| *Theragra chalcogramma* YOY | 5.3 | 14.4 | +9.1 | 0.09 |
| *Chrysaora* spp. | 3080 | 69 | -3011 | 0.001 |

[Table BS-8] Mean physical properties and mesozooplankton from the M2 region of the southeastern Bering Sea in August 1999 and August 2004 (modified from Coyle et al. 2008). P indicates ANOVA probabilities for significant differences between years.

## 7.4 Mechanisms

The exact mechanisms determining the presence/absence and local production of important mesozooplankton taxa are still unknown for this region. Several key taxa (i.e. prey for fish, seabirds, and marine mammals) such as *Thysanoessa* spp. and *Calanus* are found in low concentrations during years with minimal sea ice and warm summer water temperatures. The relative contributions of advection and local production are not yet known for these populations and therefore it is difficult to distinguish whether the low concentrations are due to low rate of supply of adults, local processes which result in unfavorable conditions for reproduction, growth, and survival, or both.

Local processes such as water column stability have been invoked to explain low summer concentrations of euphausiids and large copepods (Coyle et al. 2008). Water column stability was approximately three times greater in August 2004 relative to August 1999. Fluorescence measurements at M2 as well as microzooplankton and production studies (Strom and Fredrickson 2008; Sambrotto et al. 2008) indicated that nutrient exhaustion in the euphotic zone was limiting primary production in the Middle Domain during August 2004. Warm temperatures in the surface layer in 2004 would have resulted in elevated respiration rates (relative to 1999) and increased energy demands of zooplankton at the same time as primary production (especially that of large cells) was depressed by nutrient exhaustion. These findings from field observations in 2004 are in apparent conflict with the findings of the BASIS group, whose surveys occurred later in the year (See Section 5, this chapter).

Conversely, cold conditions have been used to explain the success of *Calanus marshallae* on the southeastern shelf (Baier and Napp 2003). They examined the timing of the appearance of the C1 stage as well as the abundance of all copepodid stages from two time periods: 1980-1981 and 1995-1999. In their study, bottom water temperatures, sea ice extension into the southeastern region and spring bloom onset covaried. Cold bottom water, maximal extension of sea ice and an early spring bloom were associated with an early appearance of C1s and high concentrations of all copepodid stages in May.

## 7.5 Significance

Large zooplankters are an important intermediary in the transfer of carbon from primary production to higher trophic levels. Over the Outer and Middle Domains, euphausiids (*T. inermis* and *T. raschii*, respectively) are important prey for seabirds, whales, and fish. Calanoid copepods are also important prey in the region due to their relatively large size and lipid storage. Over the Outer Domain the three *Neocalanus* species (*N. cristatus, N. flemingeri, N. plumchrus*) dominate, whereas over the Middle Domain, there is only one large calanoid species (*Calanus marshallae*).

Many different fish species in the Bering Sea are planktivorous in at least one part of their life history. Larval, juvenile and adult walleye pollock consume large zooplankton (euphausiids and copepods; Dwyer et al. 1986; Ciannelli et al. 2004; Coyle et al. 2008; Hilgruber et al. 1995), and juvenile salmon also consume copepods and euphausiids (Volkov et al. 2007). Oscillations between warm and cold years create match and mismatch situations between larval fish and production of their crustacean prey (Napp et al. 2000; Hunt et al. 2002) and recent low levels of recruitment by walleye pollock have been coincident with the stanza of warm years, which had low levels of available prey for juvenile pollock (Coyle et al. 2008). The region supports a large biomass of resident and migratory planktivorous sea birds. Planktivorous alcids experienced high levels of stress in the summer of 2004 when anomalous circulation features around the Pribilof Islands affected the availability of copepod prey (Benowitz-Fredericks et al. 2008). North Pacific right whales (*Eubalena japonica*) have been observed both over the Outer and Middle Domains (Moore et al. 2002; Tynan et al. 2001; Tynan 2004; Shelden et al. 2005; Wade et al. 2006), and are thought to feed almost exclusively on large copepods, such as *C. marshallae* based on the behavior of their congeners in the North Atlantic (*E. glacialis*; Baumgartner and Mate 2003). Their population levels are at an all time low and they have been listed as endangered under the U.S. Endangered Species Act.

The eastern Bering Sea zooplankton biomass and community structure react quickly to climate variability, and these effects are readily apparent throughout the food web, particularly at higher trophic levels. At present, we are seeing short stanzas of cold and warm conditions with attendant changes in total biomass and species composition manifested, in part, by fluctuations in the boundary between the Arctic and Subarctic faunas, and in part by local production in the two biogeographic provinces. Climate change (i.e. long-term secular change) has the potential to move this boundary and reshape the region to be predominantly Subarctic or Arctic. In addition, climate change will affect local processes responsible for primary and secondary production. For example, if warming and calmer, longer summer conditions persist, there will be attendant decreases in new production that would initially lead to a decrease in production by large zooplankton species and an increase in the abundance of smaller zooplankton. Based on our present understanding, we would expect this to alter trophic relationships and impact living marine resources.

## 8.0 Fishes and Invertebrates

*(Mueter, Baker, Buck, Eggers, Stepanenko, Gritsay)*

### 8.1 Species composition and diversity

High biological productivity in the Bering Sea supports over 400 species of fish and at least 15 species of squid. Of these, at least 40 species are of some commercial importance (Table BS-9). Catches are dominated by walleye pollock (*Theragra chalcogramma*), flatfishes (*Pleuronectidae*), Pacific cod (*Gadus macrocephalus*), crabs (*Paralithodes* spp. and *Chioenocetes* spp.), rockfishes (*Sebastes* spp.) and five species of Pacific salmon (*Oncorhynchus* spp.). The broad shelves along the eastern and western margins of the Bering Sea support rich benthic communities with a large biomass and production of flatfish, Pacific cod,

[Table BS-9] List of commercial species harvested in the Bering Sea. Sources: North Pacific Fisheries Management Council 2008 and FishBase (www.fishbase.org )

| **Gadids** | | **Salmon** | |
|---|---|---|---|
| *Gadus macrocephalus* | Pacific cod | *Oncorhynchus gorbuscha* | Pink salmon |
| *Theragra chalcogramma* | walleye pollock | *Oncorhynchus kisutch* | Coho salmon |
| *Eleginus gracilis* | Saffron cod | *Oncorhynchus tshawytscha* | Chinook salmon |
| | | *Oncorhynchus keta* | Chum salmon |
| **Flatfishes** | | *Oncorhynchus nerka* | Sockeye salmon |
| *Atheresthes evermanni* | Kamchatka flounder | | |
| *Atheresthes stomias* | Arrowtooth flounder | **Rockfishes** | |
| *Glyptocephalus zachirus* | Rex sole | *Sebastes aleutianus* | Rougheye rockfish |
| *Hippoglossoides elassodon* | Flathead sole | *Sebastes alutus* | Pacific ocean perch |
| *Hippoglossus stenolepis* | Pacific halibut | *Sebastes borealis* | Shortraker rockfish |
| *Lepidopsetta bilineata* | Southern rock sole | *Sebastes polyspinis* | Northern rockfish |
| *Lepidopsetta polyxystra* | Northern rock sole | *Sebastes variabilis* | Dusky rockfish |
| *Limanda aspera* | Yellowfin sole | *Sebastes zacentrus* | Sharpchin rockfish |
| *Isopsetta isolepis* | Butter sole | *Sebastolobus alascanus* | Shortspine thornyhead |
| *Limanda proboscidea* | Longhead dab | | |
| *Microstomus pacificus* | Dover sole | **Other** | |
| *Platichthys stellatus* | Starry flounder | *Cololabis saira* | Pacific saury |
| *Pleuronectes quadrituberculatus* | Alaska plaice | *Clupea pallasii pallasii* | Pacific herring |
| *Reinhardtius hippoglossoides* | Greenland halibut | *Mallotus villosus* | Capelin |
| | | *Pleurogrammus monopterygius* | Atka mackerel |
| **Crabs** | | *Anoplopoma fimbria* | Sablefish |
| *Paralithodes camtschaticus* | Red King crab | *Macrouridae* | Grenadiers or rattails |
| *Chionoecetes bairdi* | Tanner crab | *Teuthida* | Squids |
| *Chionoecetes opilio* | Snow crab | | |

crab, and cephalopods. Forage fishes such as capelin (*Mallotus villosus*), eulachon (*Thalichthys pacificus*), Pacific sand lance (*Ammodytes hexapterus*), and juvenile walleye pollock and cephalopods can be locally abundant and provide an important food source to upper trophic level species. Overall biomass along the eastern Bering Sea shelf and slope has been dominated by walleye pollock since the early 1980s, while the western Bering Sea has been dominated by cephalopods and small forage fish (Aydin and Mueter 2007). The surface waters of the central basin of the Bering Sea comprise important feeding areas for abundant Pacific salmon, while the midwater community in the basin is poorly known but is likely dominated by lantern fishes (Myctophidae, in particular *Stenobrachius leucopsarus*) and deepsea smelts (Bathylagidae) (Beamish et al. 1999).

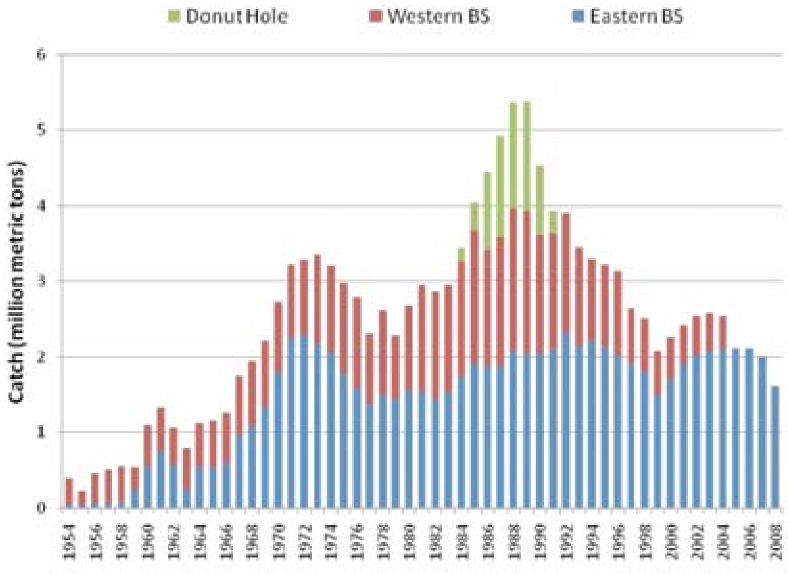
The relative abundances of different species in the Bering Sea have undergone large changes as a result of fishing as well as natural variability. Recent trends in major commercial stocks are summarized below in the context of long-term variability. Variability in forage fishes, including mesopelagic fishes, and most other non-commercial species is poorly understood because no reliable surveys or stock assessments are conducted for these species.

## 8.2 Catches, biomass, recruitment, and survival of major commercial species

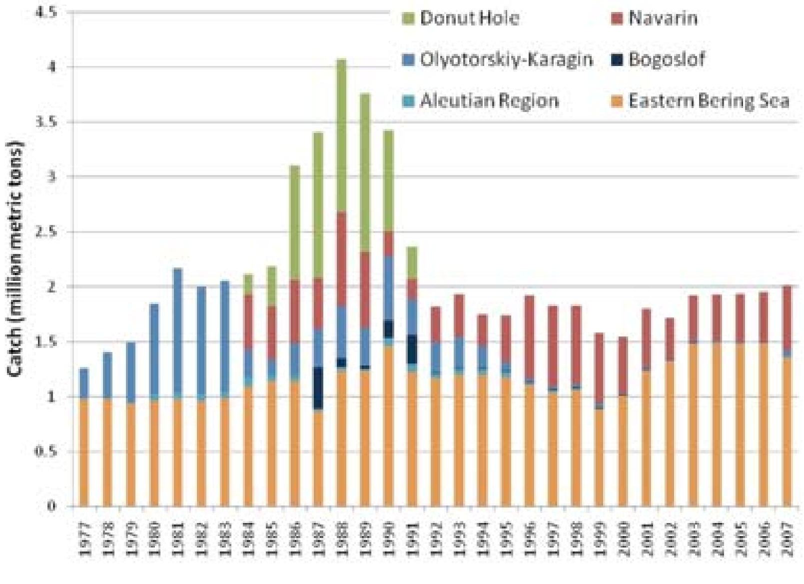
In subsequent sections catches and, where available, biomass and recruitment trends of major commercial species are summarized for three areas: the Russian Exclusive Economic Zones (EEZ) along the continental shelf and slope of the western Bering Sea, the EEZ of the United States along the eastern Bering Sea shelf and slope, and international waters of the central Bering Sea basin (Donut Hole). Modern industrial fisheries in the eastern Bering Sea began to develop in the 1950s (Fig. BS-28). Principal target species were yellowfin sole (*Limanda aspera*) and other flatfishes on the shelf, and Pacific ocean perch (*Sebastes alutus*) and other rockfishes along the slope. During the early period of these fisheries, total catches of groundfish peaked at 674,000 t in 1961. Following a decline in abundance of yellowfin sole and Pacific ocean perch other species (primarily walleye pollock) were targeted and total catches peaked at 2.2 million t in 1972. Walleye pollock, flatfish, and Pacific cod remain the principal fisheries in the eastern Bering Sea, while Atka mackerel (*Pleurogrammus monopterygius*) and Pacific cod are the largest fisheries in the Aleutian Islands. Catches of salmon are much smaller by volume, but are very important economically and as a subsistence food for the people of western and Interior Alaska.

Industrial-scale fishing in the Russian part of the Bering Sea began in the late nineteenth century, expanded greatly in the 1950s (Fig. BS-28), and had become the mainstay of the Kamchatka economy by the 1980s (Vaisman 2001). The main commercial species targeted by industrial fisheries in the Russian part of the Bering Sea are walleye pollock, Pacific cod, saffron cod (*Eleginus gracilis*), several species of crab, Pacific herring (*Clupea pallasi*), rockfishes (*Sebastes* and *Sebastolobus* spp.), Pacific halibut (*Hippoglossus stenolepis*), yellowfin sole, other flatfishes, Commander squid (*Berryteuthis magister magister*), and shrimp. In addition, the inshore salmon fishery, dominated by pink salmon (*O. gorbuscha*), accounts for about one third of the economic value of all Russian Far East fisheries (Johnson 2004). Catch records for the Russian part of the Bering Sea are not readily available, therefore we used estimated catches through 2004 (Fig. BS-28) from the Sea Around Us Project (http://www.seaaroundus.org), which uses a species-specific algorithm to assign FAO reported catches to large marine ecosystems (Watson et al. 2004). The western Bering Sea, for these purposes, consists of Russian waters of the Bering Sea as well as waters south of the Commander Islands to the southern tip of the Kamchatka Peninsula (Sea Around Us 2009).

Two gadid species, walleye pollock and Pacific cod, are of major commercial importance in the Bering Sea and these species were historically among the first target species of commercial fisheries in this region. The walleye pollock is a semi-demersal, schooling gadid, that supports the largest fishery by volume in both the eastern and western Bering Sea and is the only species that has been the target of a large commercial fishery in the international waters of the Donut Hole. Catches in the eastern Bering Sea were remarkably stable between 1977 and 2007, ranging from about 1 to 1.5 million t (Fig. BS-29). Catches in the western Bering Sea increased in the late 1970s, reaching a maximum of 1.3 million t in 1988, and have fluctuated between 400 and 800 thousand t since 1990. However, the distribution of catches has shifted almost completely from the Olyotorskiy-Karagin region (west of 170°W) in



[Figure BS-28] Total estimated fishery removals by major region (million t). Sources: Groundfish catches for the eastern Bering Sea (EBS) are from North Pacific Fishery Management Council (NPFMC) (2008); crab catches are from Zheng and Siddeek (2008), Turnock and Rugolo (2008), and Rugolo et al. (2008); EBS salmon catches are from D. Eggers (Alaska Department of Fish &Game (ADF&G), Juneau, Alaska, pers. comm.), updated with recent catch data from the ADF&G (www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmcatch.php );Eastern Bering Sea ( EBS) herring catches from G. Buck (ADF&G, King Salmon, Alaska, pers. comm.); Western Bering Sea total through 2004 from the Sea Around Us Project (www.saup.org ), more recent updates are not available; Donut Hole catches from the Report of the 13th Annual Conference of the parties to the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea (http://www.afsc.noaa.gov/REFM/CBS/Docs/13th Annual Conference/Report S&T 13 9-2008.pdf )

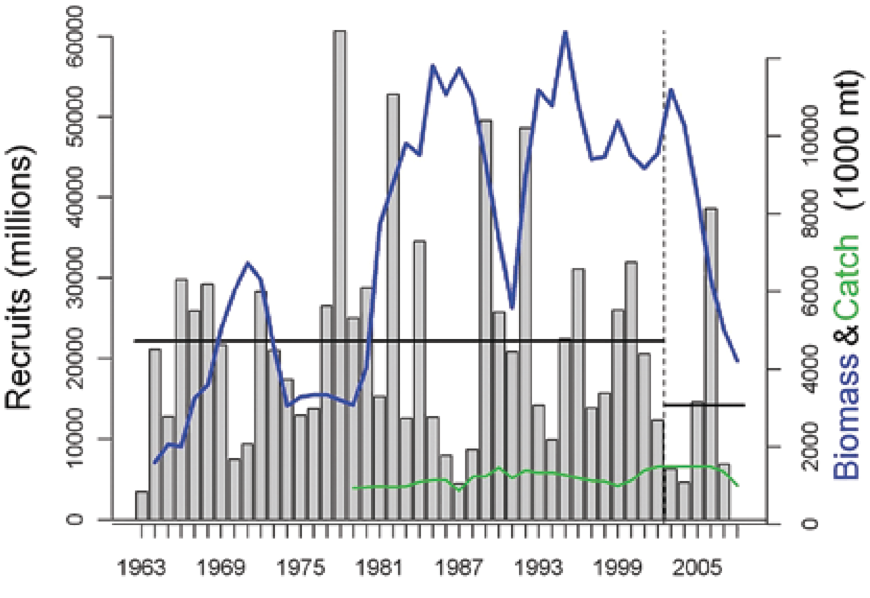


[Figure BS-29] All-nation historical catches of walleye pollock from the Bering Sea (million t), 1977-2008. Source: Report of the 13th Annual Conference of the parties to the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea.

the 1970s to the Navarin region (east of 170°W) since the 1990s (Fig. BS-29). Catches in the central portion of the Bering Sea outside of the waters of the Russian and U.S. EEZ (Donut Hole) increased rapidly after the establishment of EEZs, rising from 181,000 t in 1984 to 1,448,000 t in 1989 (Fig. BS-29), until the fishery crashed in 1992 with no sign of recovery to date (Fig. BS-29). The lack of recovery was evident in the most recent trial fishing conducted by Korea in July/August 2007, which resulted in a total catch of 2 pollock in 40 hauls over 20 days of fishing (Anonymous 2008).

There are currently at least two large stocks of walleye pollock in the Bering Sea – one in the eastern and one in the western Bering Sea. The eastern population spawns primarily on the southeastern Bering Sea shelf, but spawning extends as far north as Anadyr Bay, while the western population spawns in Olutorskiy and Karaginskiy Bays (58° 55´ N 164° 0´ E) (Gritsay and Stepanenko 2003). The subpopulation structure of pollock is poorly understood, but there is some evidence for a separate population spawning over the deep basin waters north of the Aleutian Islands.

The biomass of walleye pollock in the eastern Bering Sea is largely driven by variability in year-class strength (measured as 1-year old fish). An unprecedented series of 5 year-classes with below-average recruitment from 2001 to 2005 led to a pronounced decrease in biomass, which is currently at its lowest level since 1991 (Fig. BS-30). Interestingly, these poor year-classes appeared in large numbers as age-0 juveniles in broad-scale surveys of both the eastern and western Bering Sea (Stepanenko 2006; Moss et al 2009), but subsequently failed to appear in significant numbers as one-year olds or older fish in surveys or in the fishery, presumably due to poor overwinter survival. There are indications that the 2006 and 2008 year-classes are above average, which may result in increased pollock biomass in the coming years (Ianelli et al. 2009).



[Figure BS-30] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of walleye pollock in the eastern Bering Sea (Source: NPFMC 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different, p = 0.223).

Feeding of age-0 and age-1 pollock in the Bering Sea is limited by the availability of prey during summer and fall. In the 1980s and 1990s, high zooplankton abundances in the Bering Sea were observed in 1989, 1992, 1995 and 2000. Strong pollock year-classes in the eastern Bering Sea occurred in 1989, 1992, 1996, and 2000 (Fig. BS-29) (Ianelli et al. 2009) coinciding with high zooplankton abundances in three cases (Stepanenko 2006; Stepanenko and Gritsay 2006; Stepanenko et al. 2007). Zooplankton abundances were estimated to be relatively low in 2002-2005 in the eastern Bering Sea and off the eastern Aleutian Islands. Both low zooplankton production and low overwinter survival of juvenile pollock were observed in the winter of 2003-2004 (Stepanenko 2006; Stepanenko and Gritsay 2006; Stepanenko et al. 2007). In 2003, production of zooplankton was estimated at only 168 $g \cdot m^{-2}$ in the northwestern Bering Sea during fall, in spite of much higher summer production (527 $g \cdot m^{-2}$), and the abundance of small and large copepods was relatively high only in the coastal waters of Anadyr Bay, Norton Sound and northern Bristol Bay (Volkov et al. 2004). In contrast, pollock juveniles were widely distributed over the outer shelf from the southeastern Bering Sea to Zhemchug Canyon (58.1°N 174.9°W) in waters with low zooplankton abundance, supporting the hypothesis that poor feeding conditions for pollock juveniles in fall and winter may have contributed to the for poor survival of the 2003 year-class.

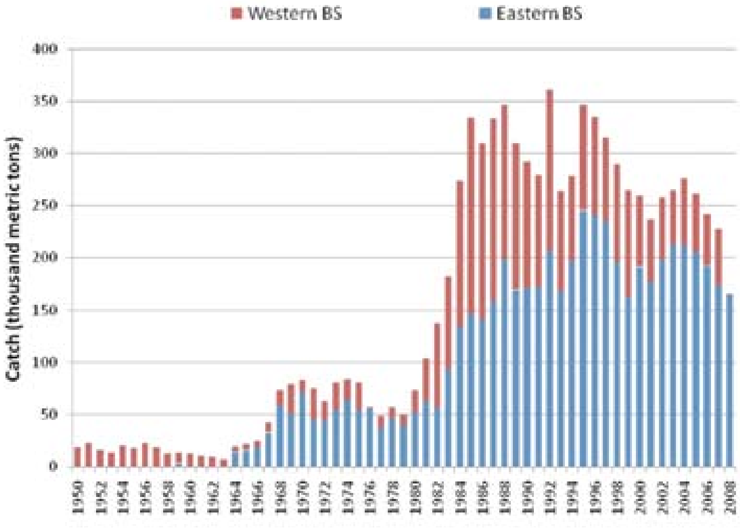
Walleye pollock increasingly shifted their distribution into the northwestern Bering Sea during the summers and falls of 2003-2008, but the reason for this behavior may have differed among years. In 2003-2006, the abundance of zooplankton in the southeastern Bering Sea was relatively low (Volkov et al. 2005; Volkov et al. 2006), and in summer of 2006, high zooplankton abundances were only found northwest of the Pribilof Islands (west of 174°W). Unusual migrations of fish in the southeastern Bering Sea and adjacent waters during 2003-2006 may also have been related to feeding conditions. For example, in February 2003 mature pollock from the Gulf of Alaska migrated through Unimak Pass to the southeastern Bering Sea shelf and Atka mackerel were concentrated off the eastern Aleutian Islands (Stepanenko, unpublished). Moreover, the summer and autumn pollock fisheries in 2006 encountered unusually high abundances of squid in the southeastern Aleutian Basin.

In other years, water temperature may have been responsible for shifts in walleye pollock distribution. In the cold years of 2007-2008, the abundance of zooplankton (euphausiids and copepods) was high throughout the Bering Sea, and zooplankton abundances were similar in the southeastern and northwestern areas. However, during these years, near-bottom temperatures in the southeastern area were below 0°C in the spring and the first part of summer. Walleye pollock are known to avoid areas with temperatures below 1.0-1.5°C, and they were restricted to warmer shelf-edge waters to the northwest during these cold years. Similarly, the distribution of walleye pollock in the northern Bering Sea may be limited by low water temperatures in the near-bottom layer during the feeding period. In the summers of 2004 and 2006, in spite of extremely high abundances of zooplankton (euphausiids) in the shallow (90-100m) near-bottom waters of the northern Bering Sea, the abundance of walleye pollock there was low.

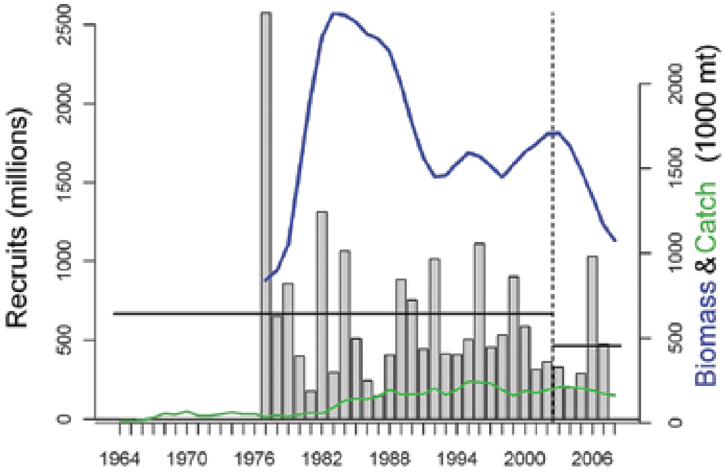
Pacific cod, a large demersal gadid, is abundant throughout the shelf and upper slope areas of the Bering Sea and Aleutian Islands, and is the target of the oldest groundfish fishery off Alaska. Catches in both the eastern and western Bering Sea increased dramatically in the 1980s. Catches since then have decreased to an average of 54,000 t in the western Bering Sea during the most recent 5-year period (2003-2007), while catches in the eastern Bering Sea have remained high at around 200,000 t per year (Fig. BS-31). Recruitment variability in Pacific cod and walleye pollock shows remarkable synchrony (Spearman's rank correlation = 0.78, $p < 0.001$) and Pacific cod, like pollock, had below-average recruitment from 2001 to 2005 (Fig. BS-32). As a result, Pacific cod biomass is currently at its lowest level since the early 1980s, but there is evidence of strong 2006 and 2008 year-classes entering the population.

Rockfishes (family Scorpaenidae) in the Bering Sea include some 10 species of the genera *Sebastes* and *Sebastolobus*, with Pacific ocean perch being by far the most abundant species. Catches have generally been much larger in the eastern than in the western Bering Sea, even when compared to the all-nation catch of rockfishes from the Northwest Pacific Ocean (Fig. BS-33). Rockfish reported from the Northwest Pacific were almost exclusively Pacific ocean perch, whose distribution ranges to northern Japan.

Pacific ocean perch inhabit the outer continental shelf and upper slope regions of the North Pacific and Bering Sea.



[Figure BS-31] Historical catches of Pacific cod in the Bering Sea (thousand t), 1950-2008. Sources: Eastern Bering Sea catches from NPFMC (2008); western Bering Sea catches from the United Nations Food and agricultural Organization (FAO) (http://www.fao.org/fishery/statistics/global-capture-production/en) consist of all cod landings reported by the Soviet Union or Russian Federation in the Northwest Pacific statistical area. Note that an unknown proportion of landings originate in the Sea of Okhotsk.

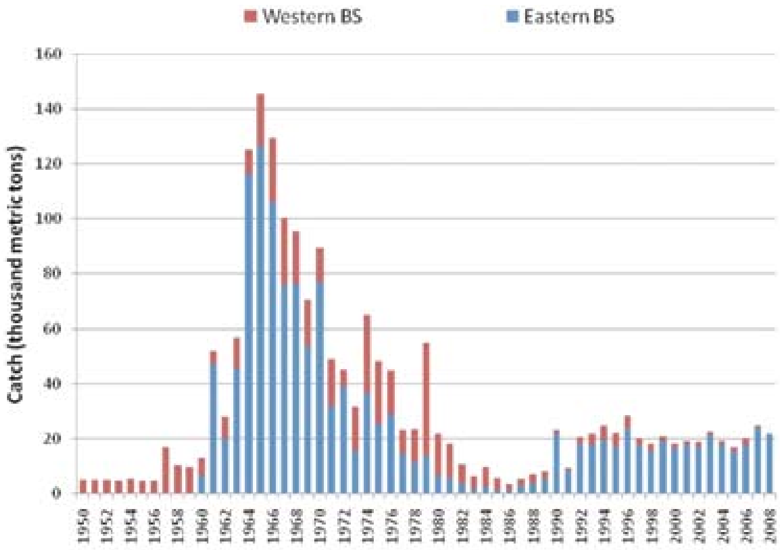


[Figure BS-32] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of Pacific cod in the eastern Bering Sea (Source: NPFMC 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different, p = 0.388).

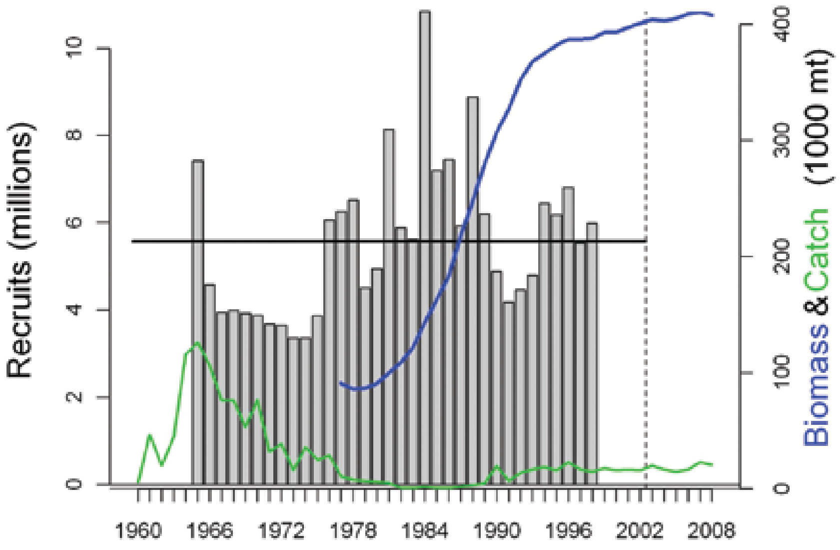
They are the most abundant rockfish species in the area and supported large Japanese and Soviet trawl fisheries in the 1960s (Fig. BS-34). Due to their low productivity and heavy exploitation, abundances and catches declined throughout the 1960s and 1970s, reaching a low in the mid-1980s. The eastern Bering Sea stock has been recovering gradually after a sharp reduction in fishing pressure. Low exploitation rates combined with consistent strong recruitment has resulted in an almost 5-fold increase in biomass since the late 1970s, supporting relatively stable catches around 20,000 t (Fig. BS-34). In contrast, catches have been very low in the western Bering Sea since crashing in the early 1980s (Fig. BS-33).

Flatfishes of the order Pleuronectiformes include at least 20 species that inhabit the shelf and upper slope regions of the Bering Sea and are particularly abundant on the broad eastern Bering Sea shelf. Flatfishes, in particular yellowfin sole, have been the target of trawl fisheries since the 1950s and comprise a large and increasing proportion of the total groundfish biomass on the eastern Bering Sea shelf (NPFMC 2008). Total flatfish landings peaked at over 700,000 t in the early 1960s with the development of the yellowfin sole fishery (Fig. BS-35). The fishery crashed in 1963, and total landings of flatfish have fluctuated around 200,000 t annually since then. Generally, flatfish stocks in the eastern Bering Sea are currently close to or

[Figure BS-33] Historical catches of all rockfishes in the Bering Sea (thousand t), 1950-2008. Sources: eastern Bering Sea catches from NPFMC (2008); western Bering Sea catches from FAO consist of all rockfish landings reported by all nations in the Northwest Pacific statistical area. All reported landings prior to 2005 were Pacific Ocean perch, whose distribution extends from the western Bering Sea into the Sea of Okhotsk and as far south as northern Japan.



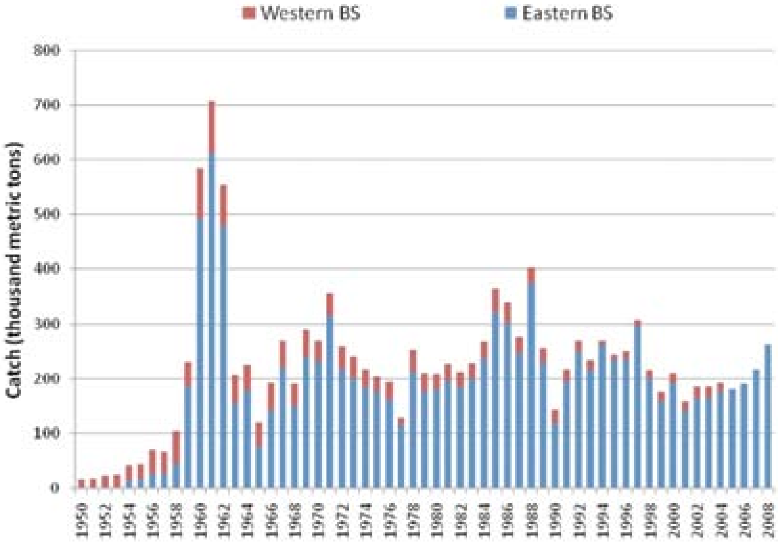
[Figure BS-34] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of Pacific ocean perch in the eastern Bering Sea (Source: NPFMC, 2008). Catches include all species that were reported and managed as part of the "POP complex" prior to 2004. Horizontal bar indicates mean recruitment prior to 2003.



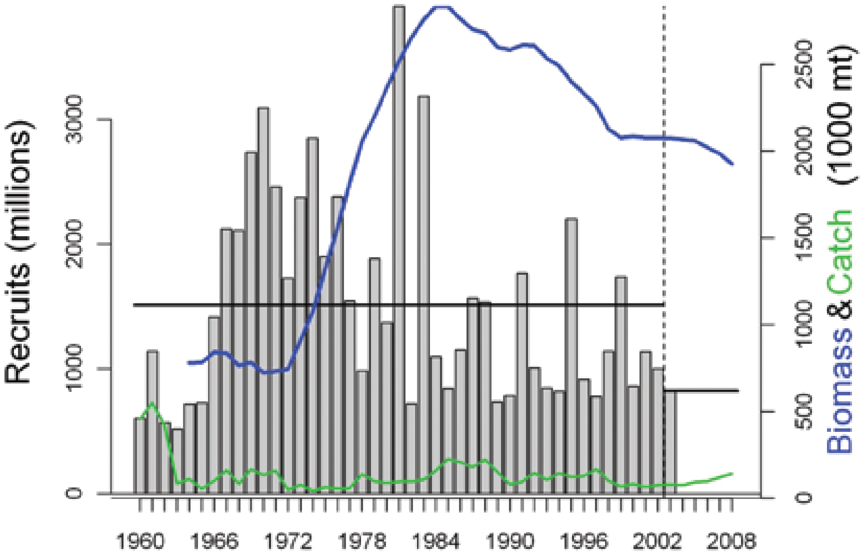
at the highest levels that have been observed over recent decades, reflecting favorable environmental conditions and conservative exploitation rates.

Yellowfin sole is one of the most abundant flatfish species in the Bering Sea and primarily inhabits the shallower regions of the eastern Bering Sea shelf as far north as St. Lawrence Island. After a period of heavy exploitation, catches decreased substantially in 1963, fluctuating between 42,000 and 227,000 t annually since then (Fig. BS-36). These fluctuations largely reflect management measures, as the biomass of yellowfin sole in the eastern Bering Sea increased dramatically in the 1970s to a peak in 1984-1985 as a result of strong recruitment. Biomass has decreased from 2.8 million to 1.9 million t since 1985, while recruitment has been variable and largely below the long-term average in the most recent years (Fig. BS-36).

Other major flatfish species on the eastern Bering Sea shelf, in decreasing order of abundance, include rock sole (*Lepidopsetta* spp.), Alaska plaice (*Pleuronectes quadrituberculatus*), arrowtooth flounder (*Atheresthes stomias*), flathead sole (*Hippoglossoides elassodon*), and Pacific halibut (*Hippoglossus stenolepis*). Relative to the estimated biomass, catches and therefore exploitation rates of all flatfish species have been low throughout the



[Figure BS-35] Historical catches of all flatfishes in the Bering Sea (thousand t), 1950-2008. Sources: Eastern Bering Sea catches from NPFMC (2008); western Bering Sea catches from FAO consist of all flatfish landings reported by all nations in the Northwest Pacific statistical area.

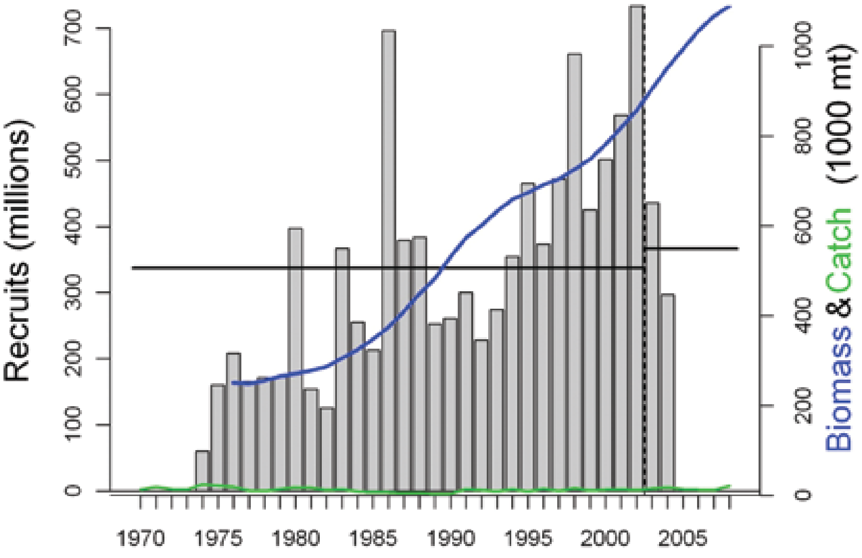


[Figure BS-36] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of yellowfin sole in the eastern Bering Sea (Source: NPFMC, 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different, p = 0.511).

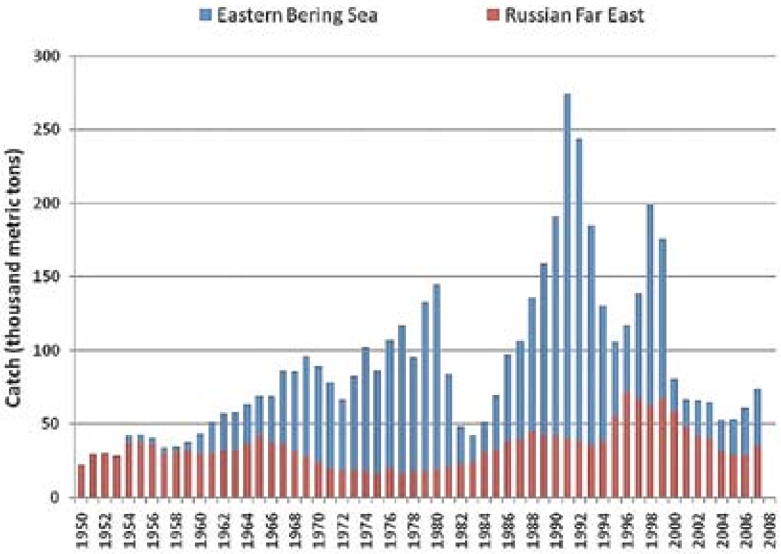
last several decades, hence changes in biomass are largely a result of recruitment variability. Of particular note is the steady increase in arrowtooth flounder biomass from 250,000 t in 1976 to over 1 million t in 2008 (Fig. BS-37). Exploitation rates are very low and arrowtooth flounder recruitment has been above average since 1995, except for the most recent estimate (2004). The biomass of arrowtooth flounder is likely to continue to increase in the absence of a targeted fishery.

Pacific halibut, although a relatively minor component of the eastern Bering Sea flatfish community, are commercially very important throughout the North Pacific. Halibut from British Columbia to the eastern Bering Sea are thought to be part of, and are currently assessed as, a single coast-wide stock. Pacific halibut biomass in the eastern Bering Sea increased in the 1980s and early 1990s and has been relatively stable since the mid-1990s (Hare and Clark 2008).

The most abundant crab species in the Bering Sea are red king crab (*Paralithodes camtschaticus*), tanner crab (*Chioenocetes bairdi*), and snow crab (*C. opilio*). Total crab catches have undergone large cycles in the eastern Bering Sea and, less pronounced, in the Russian Far East (Fig. BS-38).



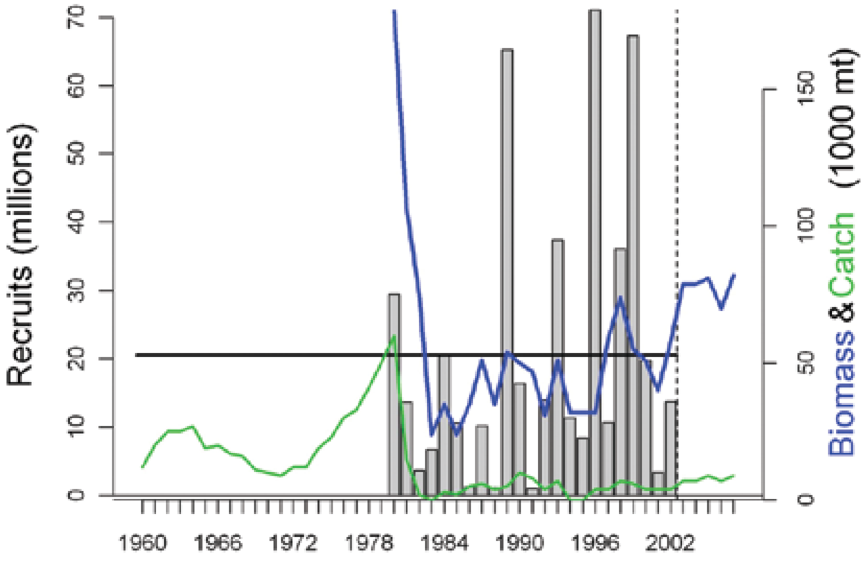
[Figure BS-37] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of arrowtooth flounder in the eastern Bering Sea (Source: NPFMC, 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different, p = 0.216).



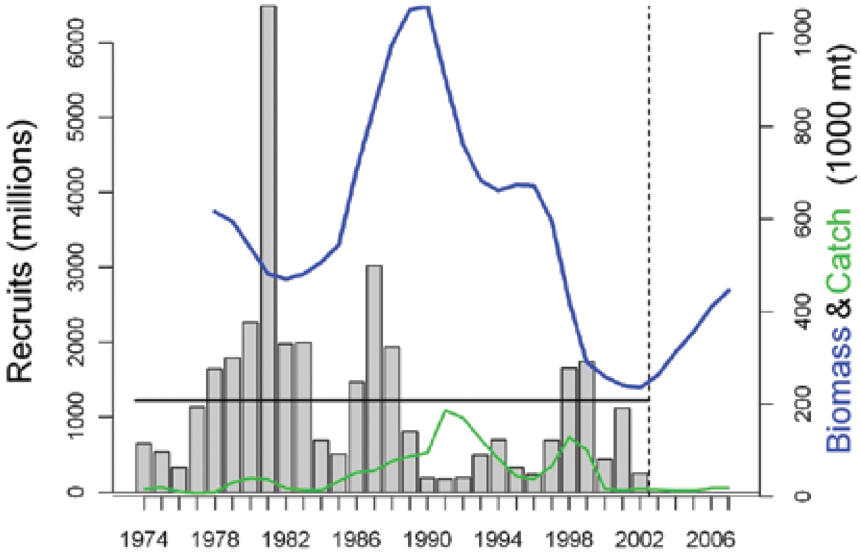
[Figure BS-38] Historical catches of all crabs in the Bering Sea (thousand t), 1950-2008. Sources: Eastern Bering Sea catches from Zheng and Siddeek (2008), Rugolo et al. (2008), and Rugolo and Turnock (2008); western Bering Sea catches from FAO consist of all crab landings reported by the Soviet Union or Russia in the Northwest Pacific statistical area. All landings prior to 2005 were reported as king crab, over 99% of landings since 1996 were reported as king crab or tanner crab.

Red king crab is the largest and economically most valuable crab species and is distributed throughout much of the shelf and upper slope regions of the Bering Sea, with its highest abundances in the southeastern Bering Sea and in the Karaginski Gulf off eastern Kamchatka. The largest stock in the eastern Bering Sea is the Bristol Bay red king crab stock, which supported a large fishery in the late 1970s (Fig. BS-39). The stock collapsed in the early 1980s and has been gradually recovering since then. Recruitment is highly variable, with a number of large recruitment events since 1989. However, relatively few small red king crab have entered into the assessed population in the most recent years, approximately corresponding to the 2000-2002 year-classes.

Snow crab is a cold water species inhabiting the northern shelf areas of the Bering Sea. Catches in the eastern Bering Sea increase in years with extensive ice cover and decrease in warm years (Mueter and Litzow 2008). The estimated biomass has fluctuated widely, peaking at an estimated 1 million t in 1989/90, and decreasing to a low of 235,000 t in 2002 (Fig. BS-40). The biomass has steadily increased since then due to above average recruitments in



[Figure BS-39] Estimated mature male biomass (blue line), fishery removals (green line) and modeled recruits (bars) of red king crab in the eastern Bering Sea (Source: Zheng and Siddeek 2008). Recruitment has been lagged to correspond to approximate year-class. Horizontal bar indicates mean recruitment.

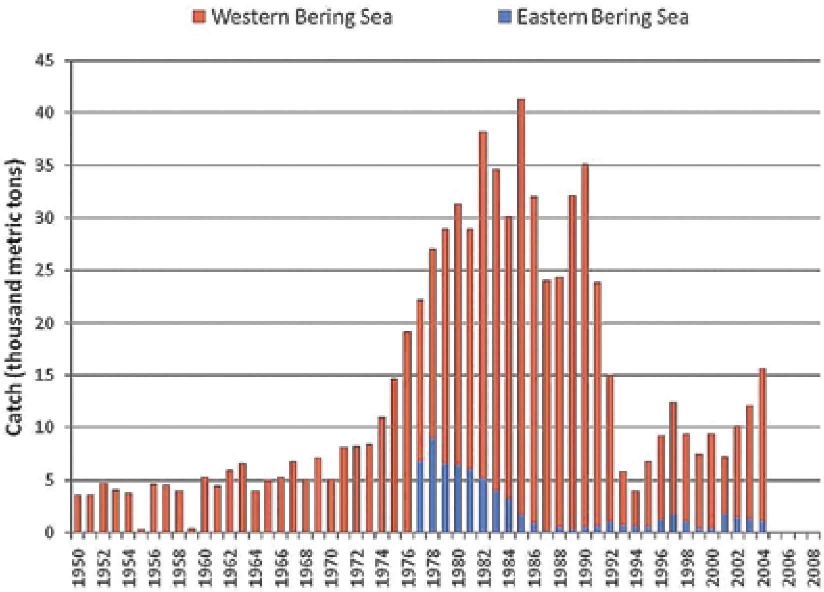


[Figure BS-40] Estimated mature biomass (blue line), fishery removals (green line) and recruitment of the 25-50 mm size class (bars) of snow crab in the eastern Bering Sea (Source: Zheng and Siddeek, 2008). Recruitment has been lagged to correspond to approximate year-class. Horizontal bar indicates mean recruitment.

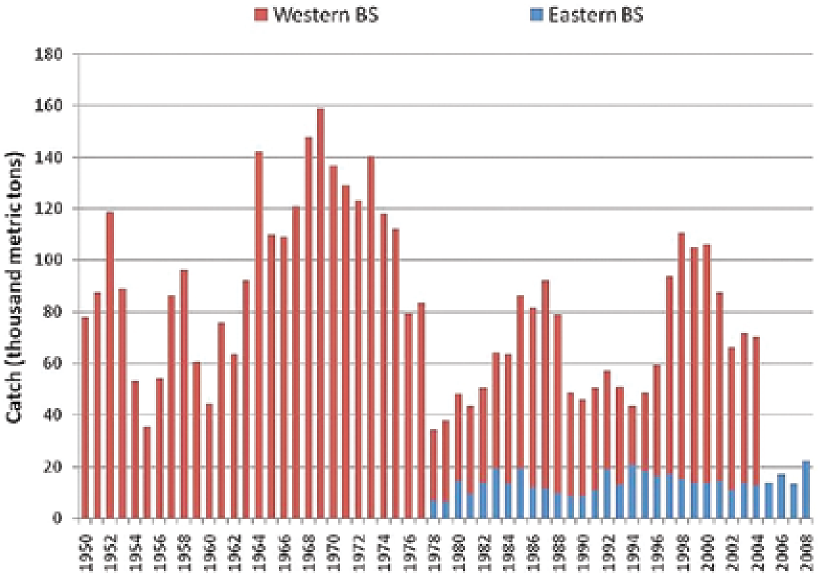
1998 and 1999. The most recent recruitment estimates, which approximately correspond to the 2000-2002 year classes, have all been below average.

At least 15 species of squid have been reported from the Bering Sea, the most abundant of which is *Berryteuthis magister* (Ormseth and Jorgenson 2008). Most squid occur along the slope and in the Bering Sea basin and have not been well sampled, at least in the eastern Bering Sea. Squid have long been a target fishery in the western Bering Sea, and were targeted by Japanese and Korean fisheries in the eastern Bering Sea during the 1970s, but have only been incidentally caught in the eastern Bering Sea since then (Fig. BS-41).

In contrast to the demersal or semi-demersal species that dominate total fish biomass on the eastern Bering Sea shelf, Pacific herring catches are considerably larger in the western Bering Sea (Fig. BS-42), although their production on a unit area basis is estimated to be very similar in both regions (Aydin and Mueter 2007). Herring catches in the western Bering Sea ranged from 40,000 t to 160,000 t prior to 1978, but have been considerably smaller since then (Fig. BS-42). Catches in the eastern Bering



[Figure BS-41] Historical catches of squid in the Bering Sea (thousand t), 1950-2008. Sources: Eastern Bering Sea catches from NPFMC (2008); western Bering Sea catches estimated by the Sea Around Us Project (www.saup.org). Squid catches in the eastern Bering Sea were not reported prior to 1977.

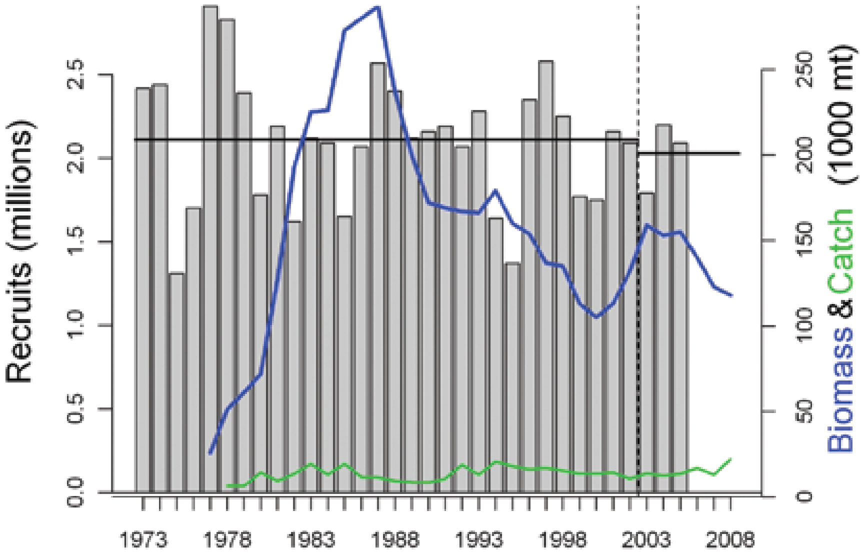


[Figure BS-42] Historical catches of Pacific herring in the Bering Sea (thousand t). Sources: Eastern Bering Sea catches from Gregory Buck (ADF&G, pers. comm.), 1978-2008; western Bering Sea catches through 2004 from the Sea Around Us Project (www.saup.org ).

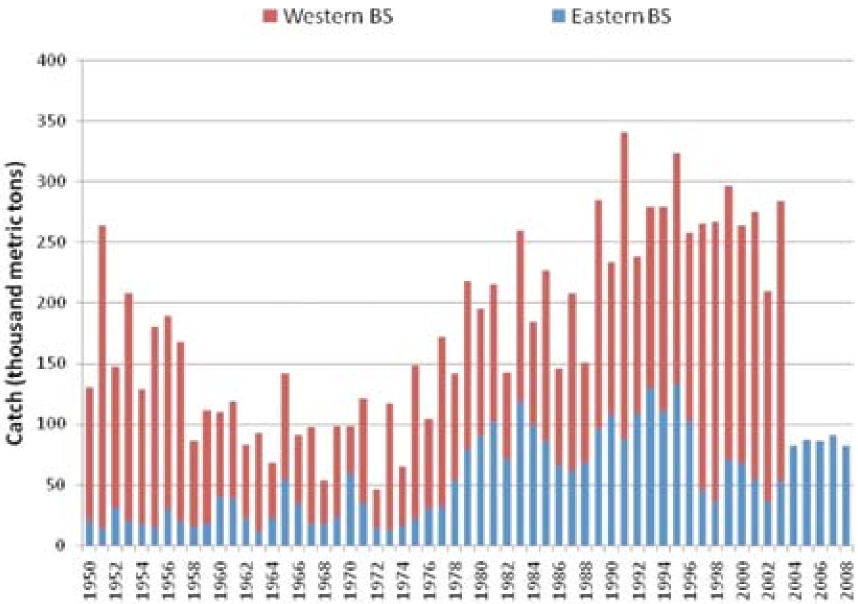
Sea have generally been under 20,000 t. Catches in the western Bering Sea have undergone cyclical fluctuations with peaks in 1952, 1969, 1987, and most recently, in 1998. In the eastern Bering Sea, the estimated biomass of the Togiak herring stock decreased from its peak of 287,000 t in 1987 to between 100,000 and 150,000 t in the most recent decade (Fig. BS-43). Recruitment has been relatively stable and near the long-term average in 2003-2005, the most recent estimates available.

Pacific saury (*Cololabis saira*), a subtropical species, is very abundant in the epipelagic layers of the North Pacific Ocean, but is generally restricted to areas south of the Commander and Aleutian Islands. Large catches of Pacific saury, ranging from 5,000 to 32,000 t, have been reported from the western Bering Sea by the Sea Around Us Project (www.seaaroundus.org). However, these catches probably occur south of the Bering Sea proper and are not further considered here.

Five species of Pacific salmon are common in the Bering Sea and spawn in its tributaries in western Alaska and in the Russian Far East. The most abundant species are sockeye salmon (*O. nerka*) in western Alaska, and pink



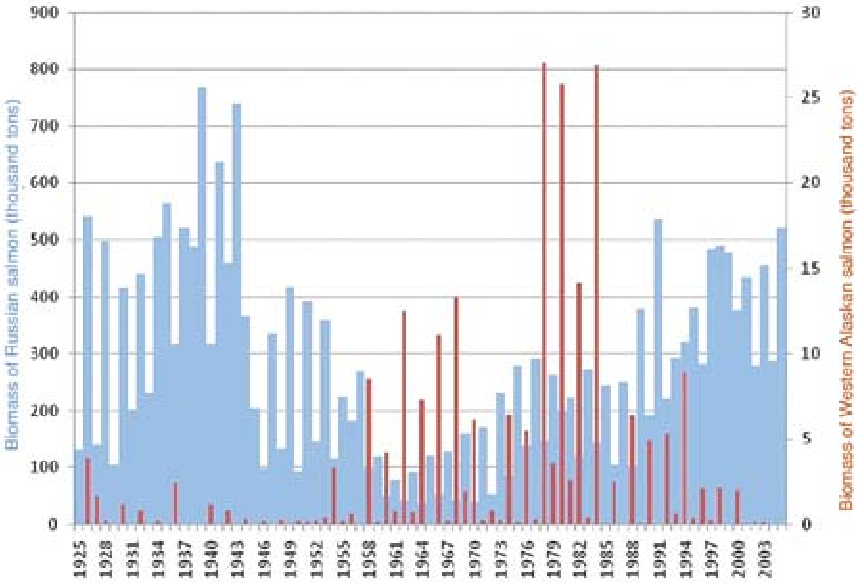
[Figure BS-43] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of Pacific herring (Togiak stock) in the eastern Bering Sea from NPFMC (2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different, p = 0.692).



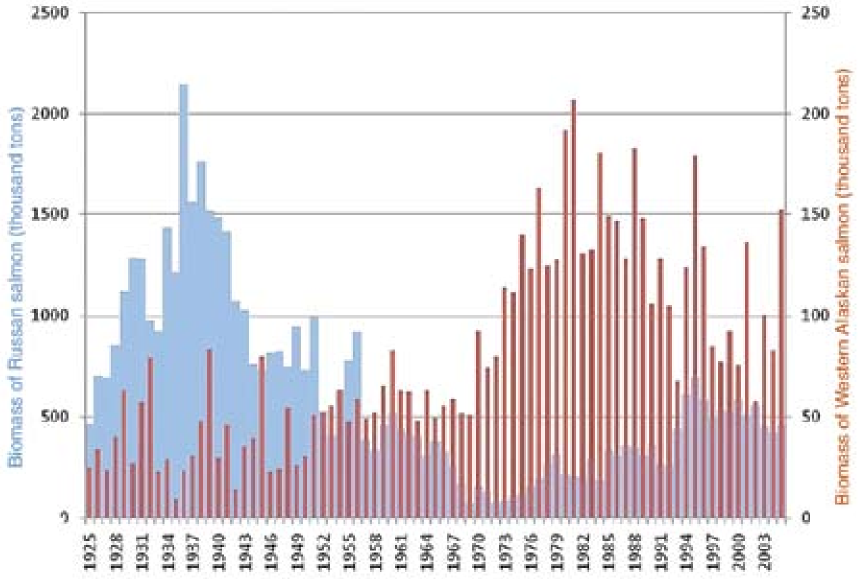
[Figure BS-44] Historical catches of all salmon species in the Bering Sea (thousand t). Source: Eggers (2010). Western Bering Sea catches include all of coastal Russia; an unknown proportion of these catches originate in the western Bering Sea. Catches of Bering Sea (western Alaska) stocks for 2006-2008 updated with data from the Alaska Department of Fish and Game (www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmcatch.php)

(*O. gorbuscha*) and chum salmon (*O. keta*) in the Russian Far East. Total salmon catches since 1950 have ranged from 32,000 t to 253,000 t in coastal Russia and from 11,000 to 133,000 t in western Alaska. Catches on both sides of the Bering Sea increased in the late 1970s and reached historic highs in the 1990s (Fig. BS-44). Catches of all species decreased after the mid-1990s in western Alaska, but remained high in Russia due to large catches of pink salmon. Biomass series and annual catches of chinook and coho salmon are used to examine variability in Bering Sea salmon stocks, although a large portion of the Russian salmon originate in the Sea of Okhotsk. Most salmon species are widely distributed throughout much of the Northeast Pacific, and utilize the Bering Sea during at least part of their life history.

The biomass of pink salmon shows a distinct even- and odd-year pattern with odd years dominating in Russian pink salmon. Even years dominate in Western Alaska pink salmon, but they are far less abundant than Russian pink salmon (Fig. BS-45) (Eggers, 2010). Russian pink salmon have recently been very abundant, near the high levels observed in the 1930s and 1940s. In contrast, Western



[Figure BS-45] Annual estimated biomass of western Alaska and Russian pink salmon (thousand t), 1925-2005, from Eggers (2010). Note difference in scale between the two biomass series.

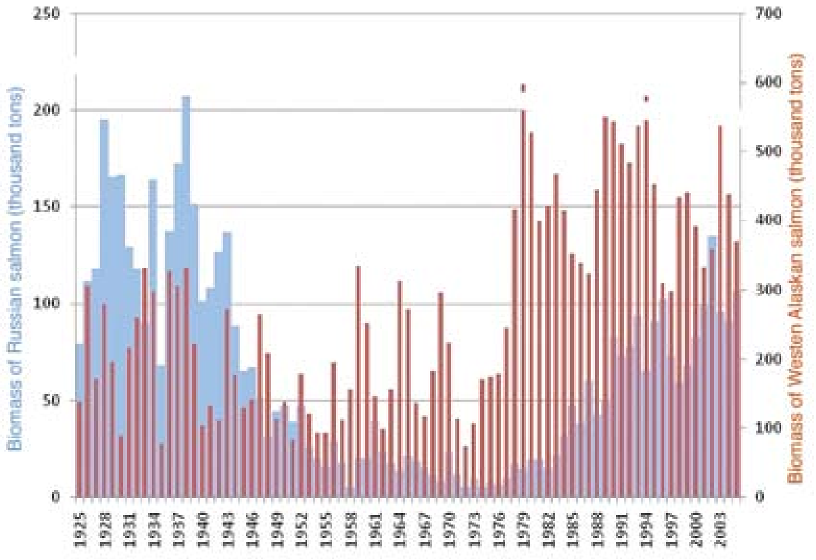


[Figure BS-46] Annual estimated biomass of western Alaska and Russian chum salmon (thousand t), 1925-2005, from Eggers (2010). Note difference in scale between the two biomass series.

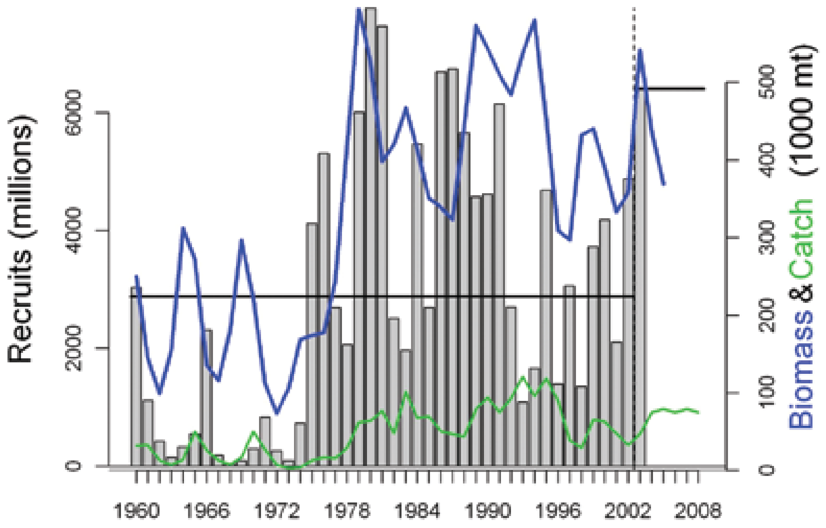
Alaska pink salmon were most abundant from the 1960s through the mid-1980s and decreased substantially after 1985. Both interannual (even/odd year) variability and long-term variability suggest a possible negative interaction between pink salmon from the east and west side of the Bering Sea (Rank correlation between annual biomass series, 1925-2005 = -0.486, $p < 0.001$; Correlation between 4-year running means: $r = -0.480$, $p = 0.191$ when adjusted for autocorrelation).

Chum salmon show a similar pattern of long-term variability in the Russian Far East as pink salmon, but the recent biomass levels are only a third of the estimated peak biomass in the 1930s (Fig. BS-46) (Eggers, 2010). The estimated biomass of Western Alaska chum salmon increased in the mid-1970s and has been relatively high since then. Both biomass (Fig. BS-46) and catches (not shown) have been more variable since the early 1990s.

Sockeye salmon are much more abundant along the eastern rim of the Bering Sea, particularly in the Bristol Bay region, which is home to the world's largest sockeye salmon populations. The biomass of sockeye salmon from Western Alaska increased substantially after the 1976/77 climate



[Figure BS-47] Annual estimated biomass of western Alaska and Russian sockeye salmon (thousand t), 1925-2005, from Eggers (2010). Note difference in scale between the two biomass series.

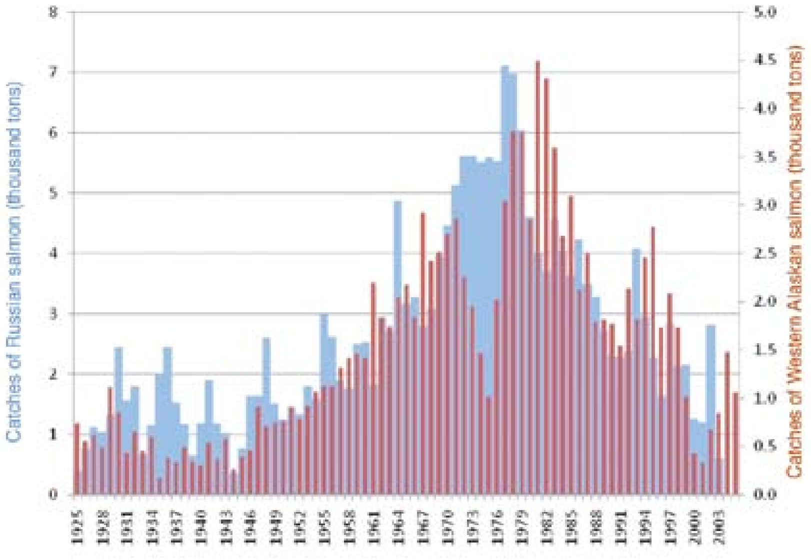


[Figure BS-48] Estimated biomass (blue line), fishery removals (green line) and total recruits by year-class (bars) of Bristol Bay sockeye salmon in the eastern Bering Sea from Eggers (2010) and Tim Baker (ADF&G, pers. comm.). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively.

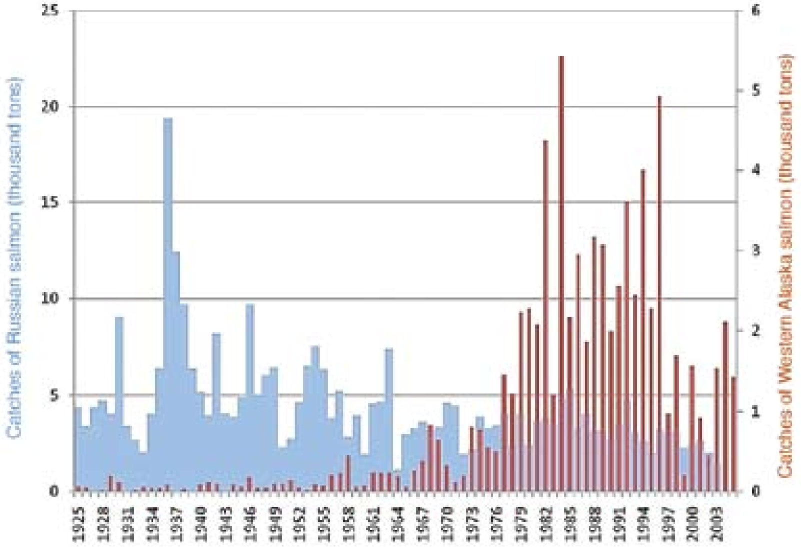
regime shift (Fig. BS-48), which was associated with an increase in marine survival and subsequent recruitment of sockeye salmon (Fig. BS-48) (Eggers, 2010). Russian sockeye salmon have been at their highest abundances in recent years since the peak abundances observed in the 1930s (Fig. BS-47), presumably as a result of good marine survival.

Only catch data are available to examine long-term trends in chinook and coho salmon at the scale of the Bering Sea. Chinook salmon catches display remarkably similar trends on both sides of the Bering Sea with gradually increasing catches from the 1940s to a peak in the 1970s and gradually declining catches since then to very low levels in recent years (r = 0.732, p = 0.061 when adjusted for autocorrelation) (Fig. BS-49).

Coho salmon catch trends show very different patterns in Russia and western Alaska. Russian catches peaked in the mid-1930s and gradually declined since then to very low levels in recent years (Fig. BS-50). In contrast, coho salmon in western Alaska were harvested in low numbers through most of the century, but catches increased sharply after the mid-1970s, suggesting that coho salmon, like sockeye



[Figure BS-49] Annual reported catches of western Alaska and Russian chinook salmon, 1925-2005, from Eggers (2010). Note difference in scale between the two catch series. Western Alaska catches updated through 2008 with data from the Alaska Department of Fish and Game (www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmcatch.php )



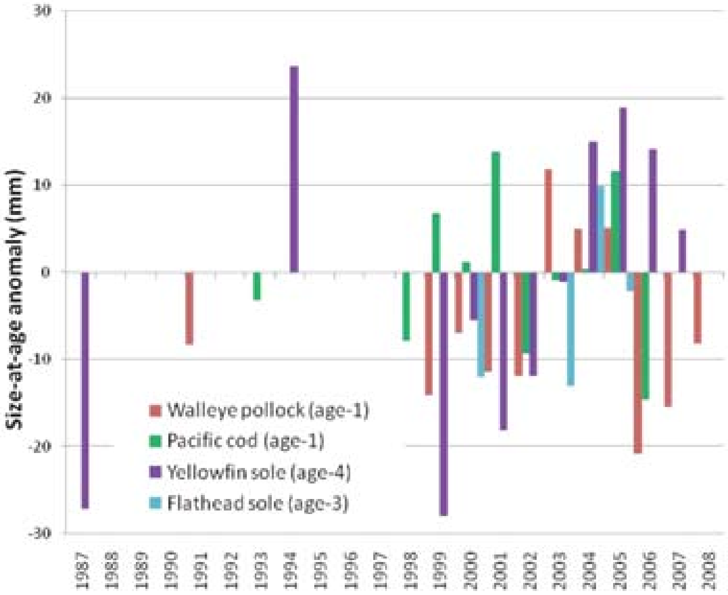
[Figure BS-50] Annual reported catches of western Alaska and Russian coho salmon, 1925-2005, from Eggers (2010). Note difference in scale between the two catch series. Western Alaska catches updated through 2008 with data from the Alaska Department of Fish and Game (www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmcatch.php )

salmon, experienced increased survival after the 1976/77 regime shift. Catches remained high through most of the 1990s but fell sharply in 1997 and have remained at low to moderate levels since then (Fig. BS-50). The sharp decline in 1997 has been observed through much of the range of coho salmon (Shaul et al. 2007).

Variability in size and condition of fish can offer insight into environmental conditions affecting fish growth and provide evidence of growth limitations resulting from density-dependent effects related to the overall carrying capacity of available habitat. For example, widespread observations suggest that salmon have been growing at a slower rate, achieving a smaller size-at-age, and maturing later in life since the pronounced increase in overall salmon biomass in the North Pacific in the mid-1970s (Bigler et al. 1996; Eggers and Irvine 2007; Helle and Hoffman 1998). These observations of density-dependent growth and maturation suggest that the capacity of the North Pacific Ocean to support salmon was approaching its limits during the period of high abundance following the 1976/77 climate regime shift. However, carrying capacity for salmon may not be constant, and the North Pacific appeared to support salmon of large body size even at high population abundances after 1995 (Helle et al. 2007).

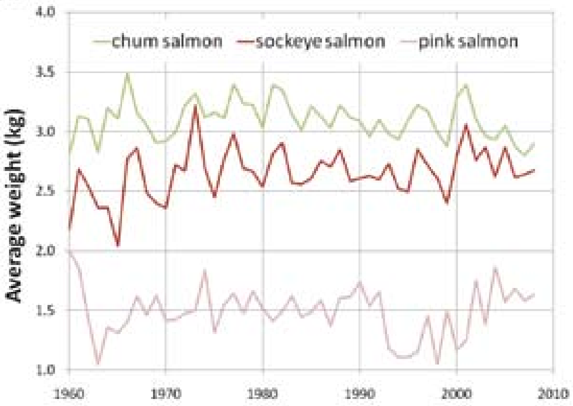
Mean size of harvested individuals is routinely measured and provides a useful measure of the growth rate of fish, which may be affected by temperature, prey availability, density-dependence, and other factors. Size-at-age anomalies were estimated for several groundfish species in the eastern Bering Sea based on samples obtained during bottom trawl surveys (Lauth and Acuna 2007). Annual size-at-age anomalies were estimated by first fitting a von Bertalanffy growth model to all available size-at-age data for a given species, then estimating annual mean deviations from the overall fit for the youngest age-class that was adequately sampled by the trawl survey. There was substantial variability in size-at-age for all species with sufficient data (Fig. BS-51), but some common patterns emerged. Most species had below average size in 1998-2002 and above average size in 2003-2005, corresponding to unusually warm conditions. Size-at-age was mostly below average during the recent cold years (2006-2008). Size-at-age-1 anomalies of walleye pollock were positively correlated with annual average bottom temperatures (r=0.74, p = 0.024), but anomalies of the other species were not. These short data series provided no evidence for a density-dependent relationship between size-at-age anomalies and biomass of the same species.

Changes in overall mean size of salmon in catches were assessed under the assumption that the age composition remains approximately constant, which is a reasonable assumption for some salmon populations when evaluating long-term trends (Helle et al. 2007). Annual mean weights of sockeye and chum salmon catches in western Alaska decreased slightly from about the mid-1970s to the late 1990s, increased in 2000/2001, and decreased again after 2001, particularly for sockeye salmon (Fig. BS-52). Average pink salmon weight was relatively stable from the 1970s through the early 1990s, was considerably lower in the mid- to late 1990s, and increased thereafter to high levels in the 2000s when catches and estimated biomass were at very low levels. These trends are consistent with those reported by Bigler et al. (1996) and Helle et al. (2007). Numerous authors have suggested a density-dependent response of size-at-age to variability in total biomass. However, the average size of sockeye, chum, and pink salmon in western Alaska was not correlated with the estimated biomass of these same populations at any lag. This may be a result of differences in age composition that can mask changes in average size. Moreover, growth anomalies during early marine life are negatively related to growth anomalies during late marine life in sockeye salmon (Ruggerone et al. 2007), hence the average size of returning salmon may be a poor indicator of variability in growth conditions.



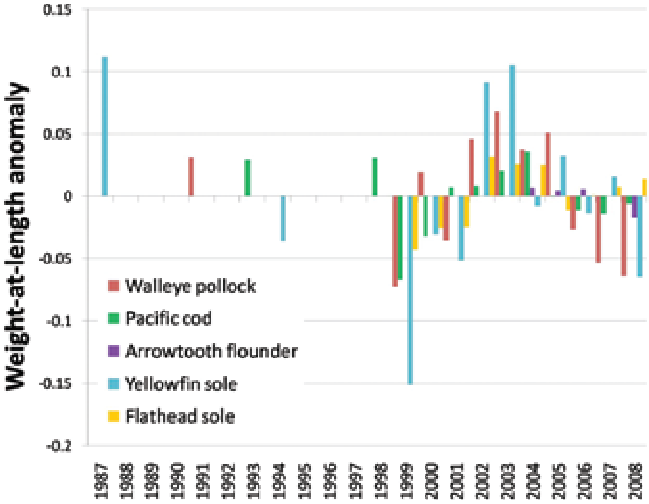
[Figure BS-51] Size-at-age anomalies for four groundfish species in the eastern Bering Sea. Anomalies were computed as deviations from von Bertalanffy growth curves for the indicated ages.

To further examine variability in growth conditions as reflected in body weight, we computed weight-at-length anomalies for several groundfish stocks in the eastern Bering Sea that had sufficient data to examine trends over at least a decade. Weight-at-length anomalies were computed by fitting linear regressions of log(weight) on log(length) by year and expressing the annual fitted values at an arbitrarily chosen small size as anomalies from the mean log(weight) at the same size estimated over all years. These weight-at-length anomalies show a strong pattern of negative anomalies in 1999-2001, changing to positive anomalies in 2002-2005, and back to mostly negative anomalies in 2006-2008 (Fig. BS-53). Weight-at-length anomalies of all five species were strongly and positively correlated with mean annual bottom temperatures on the shelf (correlations ranging from 0.62 to 0.89, except r = 0.34 for flathead sole).



[Figure BS-52] Annual average weights (kg) of harvested sockeye, pink, and chum salmon in western Alaska, 1960-2008.

To compare variability within and between the eastern and western Bering Sea, we examined commonalities and differences in biomass or catch time series. Pair-wise correlations between time series from the eastern and western Bering Sea were computed and were tested for significance using the method recommended by Pyper and Peterman (1998) to account for autocorrelation in each time series (Table BS-10). Biomass time series were used where available (walleye pollock, Pacific cod, and Pacific herring in the eastern Bering Sea; pink, chum, and sockeye salmon in both regions) and catch series otherwise. Catches of groundfish prior to 1964 were excluded to eliminate the period when many of these fisheries first developed and catches are unlikely to reflect changes in abundance.



[Figure BS-53] Weight-at-length anomalies for five groundfish species in the eastern Bering Sea. Anomalies were computed by estimating log(weight) at a given size for each year from linear regressions of log(weight) on log(length).

[Table BS-10] Correlations between the eastern and western Bering Sea based on catch or biomass series (see text) by species or aggregate group. P-values were adjusted for autocorrelation in each time series following Pyper and Peterman (1998). For walleye pollock, correlations are also shown for three subgroups (EBS: Eastern Bering Sea, Oy-K: Olyotorskiy-Karagin).

| Group | Correlation | P-value |
|---|---|---|
| walleye pollock | 0.169 | 0.663 |
| EBS vs. Oy-K | -0.280 | 0.544 |
| EBS vs. Navarin | 0.227 | 0.364 |
| Oy-K vs. Navarin | -0.181 | 0.502 |
| Pacific cod | 0.649 | 0.163 |
| rockfish | 0.240 | 0.429 |
| flatfish | 0.011 | 0.956 |
| crab | 0.053 | 0.858 |
| squid | 0.232 | 0.708 |
| Pacific herring | 0.053 | 0.900 |
| pink salmon | -0.480 | 0.001 |
| chum salmon | -0.550 | 0.201 |
| sockeye salmon | 0.112 | 0.774 |
| coho salmon | -0.239 | 0.298 |
| king salmon | 0.732 | 0.061 |

Comparisons between regions suggest relatively weak and non-significant correlations between eastern and western Bering Sea catches of the same groups after adjusting p-values for autocorrelation in the time series (Table BS-11). The two exceptions are a significant negative correlation between pink salmon stocks and a strong positive correlation between chinook salmon stocks from both sides of the Bering Sea. In contrast, comparisons within regions resulted in a number of significant correlations that were largely positive (Table BS-11), with the exception of a significant negative correlation between flatfish catches and pink salmon biomass in the western Bering Sea. Notable positive correlations include those between pollock biomass, cod biomass, and flatfish catches in the eastern Bering Sea and between a number of salmon catch or biomass series within each region.

[Table BS-11] Significant correlations among species or aggregate groups within the eastern and western Bering Sea, respectively. P-values were adjusted for autocorrelation in each time series following Pyper and Peterman (1998).

| Comparison | Correlation | P-value |
|---|---|---|
| Eastern Bering Sea | | |
| pollock vs. cod | 0.778 | 0.039 |
| pollock vs. herring | 0.702 | 0.035 |
| pollock vs. flatfish | 0.454 | 0.023 |
| herring vs. flatfish | 0.596 | 0.025 |
| squid vs. pink salmon | 0.565 | 0.035 |
| coho vs. pink salmon | 0.418 | 0.047 |
| coho vs. chum salmon | 0.730 | 0.040 |
| coho vs. sockeye salmon | 0.679 | 0.044 |
| chinook vs. pink salmon | 0.460 | 0.021 |
| Western Bering Sea | | |
| Navarin pollock vs. herring | 0.536 | 0.032 |
| Navarin pollock vs crab | 0.521 | 0.022 |
| flatfish vs. pink salmon | -0.748 | 0.020 |
| sockeye vs. pink salmon | 0.632 | 0.027 |
| sockeye vs. chum salmon | 0.752 | 0.051 |
| coho vs. chum | 0.605 | 0.006 |

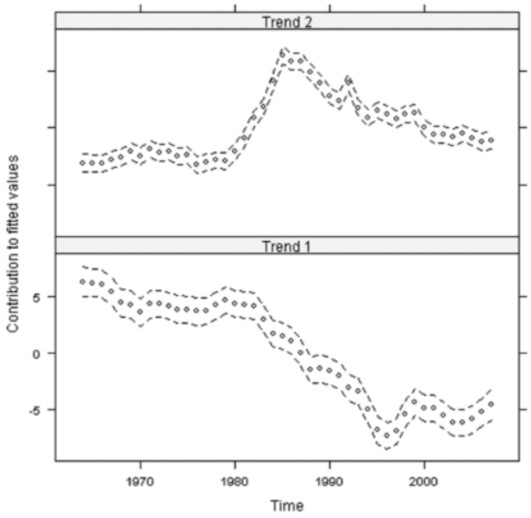
These patterns suggest that there is broad positive covariation among catch trends within both the eastern and western Bering Sea, little or no significant covariation between the two areas for groundfish, and both positive (chinook salmon) and negative (pink, and possibly chum and coho salmon) covariation between salmon stocks spawning along the eastern and western Bering Sea margins. Although there is evidence for opposite trends in primary production between the eastern and western Bering Sea (Iida and Saitoh 2007), aggregated catches of all major fisheries for the period 1954-2004 or 1964-2004 (to remove influence of developing fisheries) tend to be positively correlated (r = 0.64, p = 0.12 and r = 0.36, p = 0.28, respectively).

## 8.3 Common trends in abundance

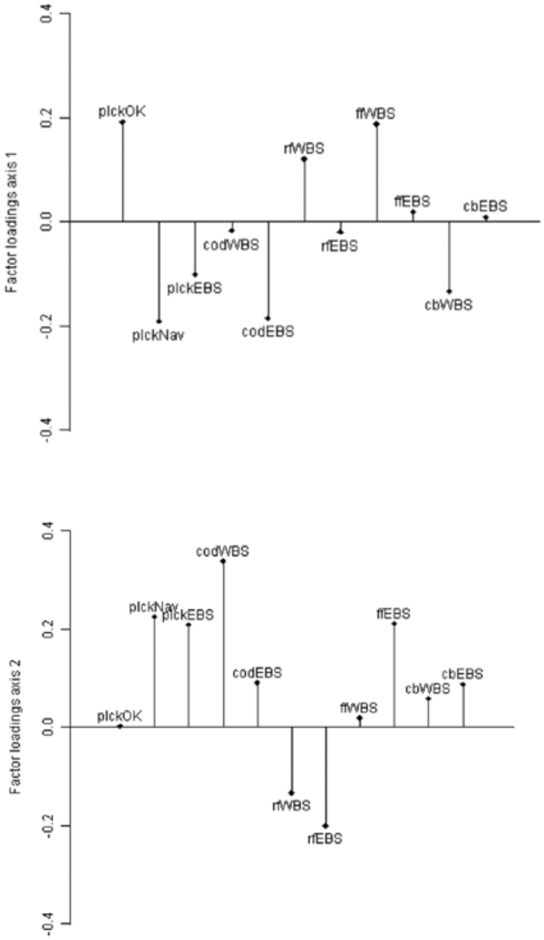
Common trends in the catch series from 1964 to 2007 were identified using Dynamic Factor Analysis (Zuur et al. 2007). The DFA model decomposes a set of time series into a small number of underlying trends plus "noise", where the noise terms may be autocorrelated over time and correlated between species. A number of different models with one, two, or three common trends were compared and the best model was chosen on the basis of the Akaike Information Criterion adjusted for small sample sizes.

### 8.3.1 Common trends among groundfish species

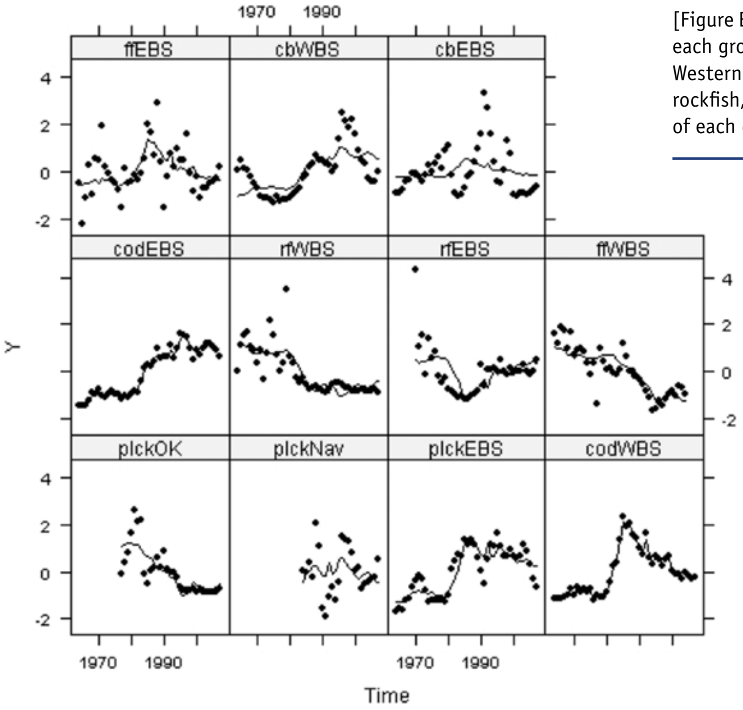
The best model to describe common trends among 11 groundfish groups (catch or biomass series) consisted of 2 common trends (Fig. BS-54) and a diagonal covariance matrix (i.e., no correlation among residual trends). These common trends suggest relatively stable catches in the 1960s and 1970s and a period of change from about 1980 to the mid-1990s (Trend 1), with a particularly sharp transition in the early 1980s (Trend 2). Figure BS-55 shows the factor loadings for each group, which indicate how strongly each group is associated with a given trend. Trend 1 was positively associated with walleye pollock catches in the Olyotorskiy-Karagin region and with rockfish and flatfish catches in the WBS, and was negatively associated with Navarin pollock, with Pacific cod and walleye pollock in the EBS, and with crab in the WBS. Trend 2 was positively associated with most groups but was negatively associated with rockfish (both EBS and WBS), reflecting a widespread increase in the abundance of a number of groundfish species in the early 1980s. Generally, the model fits were reasonably good (Fig. BS-56), although there is obvious serial correlation in the residuals that is not accounted for in the model.



[Figure BS-54] Estimated common trends that underlie the observed time series of catch or biomass of 11 groundfish species or species groups in the Bering Sea with 95% confidence interval.



[Figure BS-55] Factor loadings on catch/biomass trends 1 and 2 for each groundfish species / group (EBS = Eastern Bering Sea, WBS = Western Bering Sea, plck = walleye pollock, cod = Pacific cod, rf = rockfish, ff = flatfish, cb = crab). Loadings reflect the contribution of each catch series to the respective common trend.



[Figure BS-56] Model fits to observed groundfish catch/biomass series based on the two common underlying trends in Fig. BS-54.

### 8.3.2 Common trends among pelagic species

The best model to describe common trends among 14 pelagic groups (catch or biomass series) was a model with 2 common trends (Fig. BS-57), which indicate a pronounced change in catches (and catch composition) from the mid-1970s to the mid-1980s (Trend 1), as well as a continuing long-term trend starting in the early 1980s. The shift in the late 1970s and early 1980s was associated with an increase in the catches of almost all species, as evident in positive factor loadings (Fig. BS-58), except herring in the WBS and squid in the EBS, although the squid series was short and consisted of incidental catches only. Trend 2 reflects a contrast between pink, chum, and sockeye salmon in the western Bering Sea, which are positively associated with the increasing trend, and most other groups, which were negatively associated with this trend. The model fits fairly well (Fig. BS-59) and accounts for much of the variability in most of the time series.

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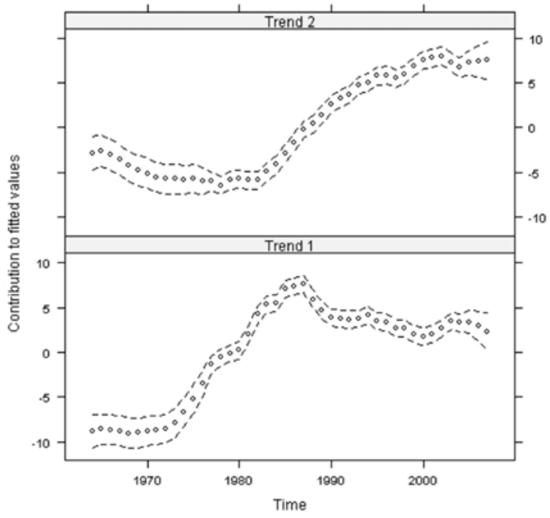
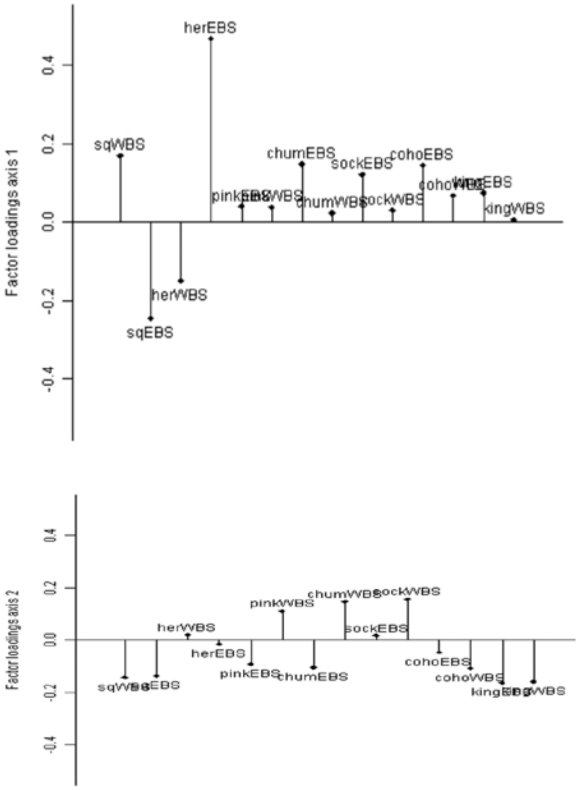
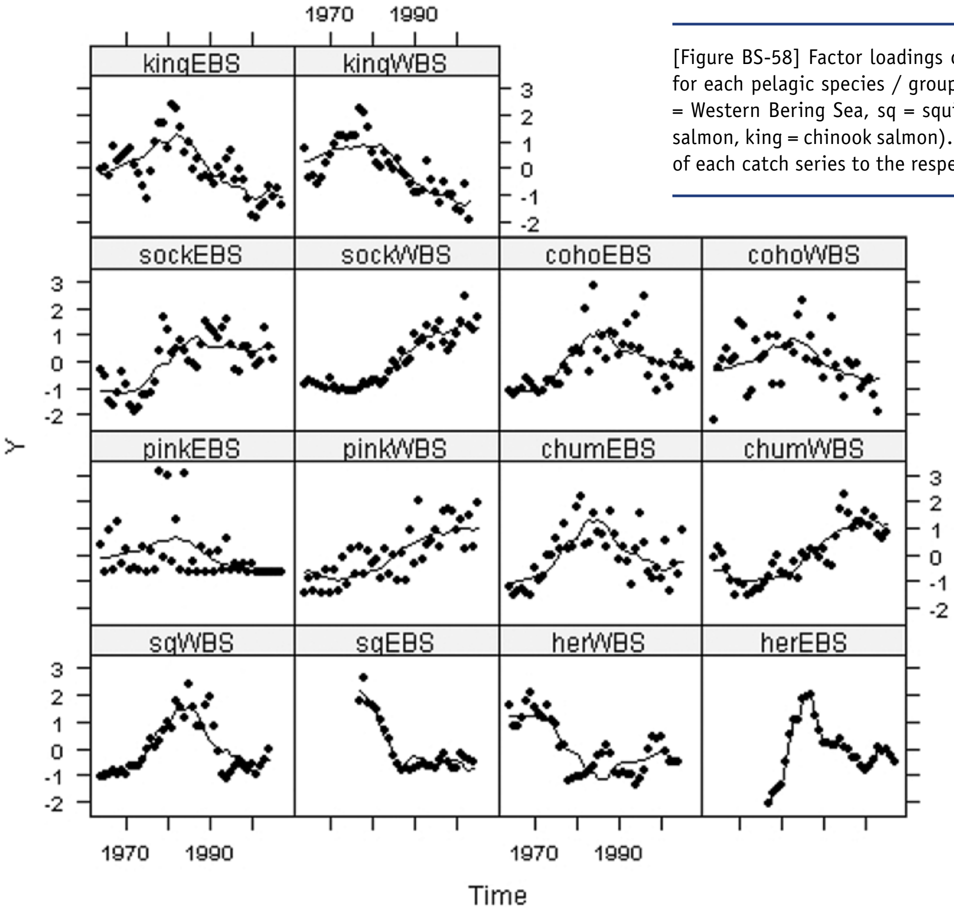


[Figure BS-57] Estimated common trends that underlie the observed time series of catch or biomass of 14 pelagic stocks in the Bering Sea with 95% confidence interval.



[Figure BS-58] Factor loadings on catch/biomass trends 1 and 2 for each pelagic species / group (EBS = Eastern Bering Sea, WBS = Western Bering Sea, sq = squid, her = herring, sock = sockeye salmon, king = chinook salmon). Loadings reflect the contribution of each catch series to the respective common trend.



[Figure BS-59] Model fits to the observed pelagic catch/biomass series based on the two common underlying trends in Fig. BS-57.

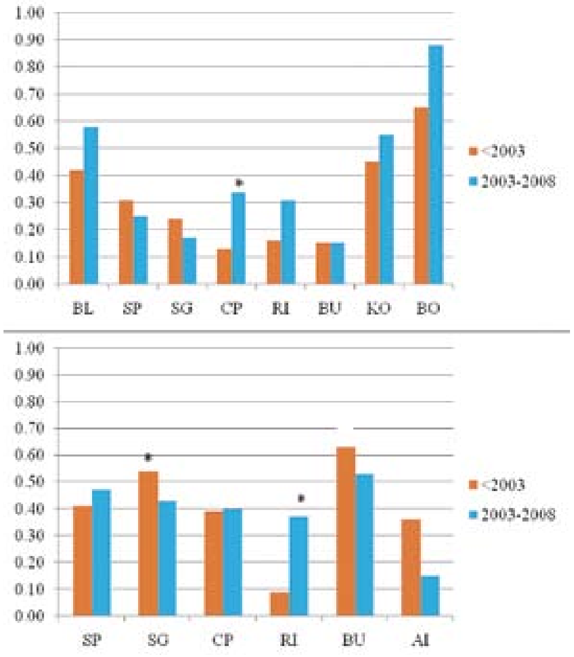
# 9.0 Marine Birds *(Byrd, Fitzgerald)*

## 9.1 Trends in breeding seabirds

Breeding seabirds are monitored to document patterns of change in a suite of response variables at selected colonies in the Bering Sea (see Byrd 2007), and results of monitoring are summarized in annual reports (see Dragoo et al. 2008). Kittiwakes (*Rissa* spp.) and murres (*Uria* spp.) are two of the most widespread types of nesting seabirds in the Bering Sea, and they are included in monitoring schemes at most sites. Kittiwakes and murres typically nest in dense aggregations on sea cliffs, often in mixed species colonies, and they prey primarily on small fish and large zooplankton. During the breeding season, kittiwakes, which are restricted to feeding at the sea surface, are relatively sensitive to changes in prey availability. Periodically they completely fail to produce young at some colonies, and in extreme years, adults can suffer mass mortality. Murres are deep divers and therefore are able to pursue prey at depths not available to kittiwakes. This capacity tends to buffer their response to prey shortages (i.e. shortages may reduce rates of productivity, but seldom cause complete reproductive failures or die offs in summer). Because of these differences in foraging strategies, productivity of kittiwakes varies highly among years, whereas murre productivity is less variable.

Reproductive rate is likely an interannual response variable to changes in the marine environment. Figure BS-60 compares the focus period with historic (earlier than 2003) estimates of average reproductive rates of black-legged kittiwakes (*R. tridactyla*) and common murres (*U. aalge*) at selected colonies for which multiple years of data are available in both periods. Mean estimates of productivity for kittiwakes tended to be higher during the more recent period or similar in the two periods (although the differences were statistically significant only at Cape Pierce (Fig. BS-60). Murre productivity tended to be higher during the earlier period or similar in the two periods, but like kittiwakes, few colonies showed statistically significant differences (Fig. BS-60). The Round Island colony seemed to be an exception, with significantly higher productivity since 2002 than earlier.

Since seabirds are typically long-lived, populations usually respond gradually to changes in rates of recruitment and productivity. Unlike reproductive success, which varies interannually in response to conditions of the marine food web, population indices are considered to be lagged responses to marine conditions. Table BS-12 summarizes recent changes in long-term trends for kittiwakes and murres. It appears that for kittiwakes, relatively recent counts of populations are either down or leveling out after a decline at most sites monitored. The exception was at St. George Island where kittiwakes have been increasing after a decline from the mid-1970s to the mid-1980s (see Byrd et al. 2008 for discussion of contrasting trends between St. George and St. Paul in the Pribilof Islands). For common murres, there appear to be either no trends or recent increases at all colonies except St. George and St. Paul Islands, the latter having been in long-term decline.



[Figure BS-60] Average productivity (chicks fledged/nesting pair on the y axis) of black-legged kittiwakes (above) and common murres (below) at selected colonies in the Bering Sea during 2003-2008 compared to earlier years (Various- 1975-2002, depending on colony). Location codes: BL=Bluff in Norton Sound; SP=St. Paul Island, Pribilofs; SG=St. George Island, Pribilofs; CP=Cape Pierce, Bristol Bay; Round Island, Bristol Bay; BU=Buldir Island, western Aleutians; KO= Koniuji Island, central Aleutians; BO=Bogoslof Island, eastern Aleutians, and AI=Aiktak Island, eastern Aleutians. Asterisk indicates differences are significant at the 0.1 level (t-test).

The influence of sea temperatures and other climate variables on seabirds is typically mediated through the marine food web. There is some indication that diets have shifted for some species in the Bering Sea at decadal

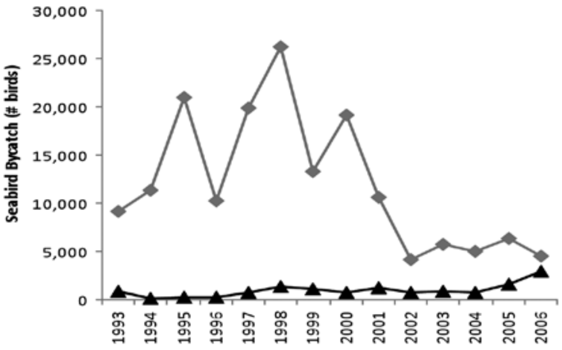
[Table BS-12] Comparison of long-term and recent short-term (2003-2008) population trends for kittiwakes and murres at selected colonies in the Bering Sea (data through 2005 in Dragoo et al. 2008, more recent data from E.C. Murphy—Bluff, Togiak National Wildlife Refuge files—Cape Pierce, and Alaska Maritime National Wildlife Refuge files for data from other sites).

| Species | Location | <2003 | 2003-2008 | Comments |
|---|---|---|---|---|
| Black-legged Kittiwake | Bluff | up | down | Increase 1975-1995, then decline thereafter |
| | St. Paul | down | no trend | Overall decline |
| | St. George | down | up | Decline 1976-mid-1980s, then increase after 1989 |
| | Cape Pierce | down | down | Uptick 2006-2007 |
| | Buldir | up then no trend | down | Decline after 2000 |
| Common Murre | Bluff | no trend | no trend | |
| | St. Paul | down | down | |
| | St. George | no trend | down | Downtick since 2002 |
| | Cape Pierce | down | up | |
| | Buldir | up | up | |
| | Aiktak | down | no trend | |

scales. For instance a recent comparison of diets of kittiwakes and murres in the Pribilof Islands between the mid-1970s and 2000 indicated shifts in types of prey taken by kittiwakes and murres relative to oceanographic shifts in the 1970s and 1990s (Sinclair et al. 2008).

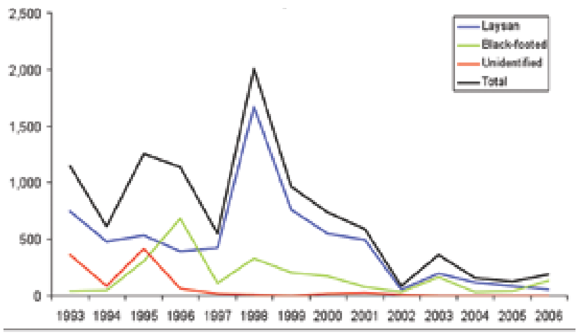
## 9.2 Seabird bycatch in Alaskan groundfish fisheries *(Fitzgerald)*

Groundfish fisheries in Alaskan waters are required to meet regulatory requirements for on-board fishery observers. These observers report on, among many things, seabird bycatch. Estimates have been produced for 1993 through 2006. Observers are able to easily see bycatch during their sampling of the catch on pot and longline gear types. Seabirds are also reported from sampling trawl vessels. However, additional mortalities are known to occur outside of the sampled catch due to interactions with various fishing gear such as third-wire or paravane cables, devices used to monitor net performance, and with the trawl warp itself. Observers are unable to collect seabird mortality data from these interactions, so estimates of the trawl fleet are biased low. No estimates are made of the Pacific halibut demersal longline fishery, which does not carry observers. The state-managed seine, troll, and gillnet fisheries are also not included in these estimates. Seabird mortality as a result of interactions with fisheries has been at much higher rates historically (e.g., DeGange 1993) than in recent years due to cooperative conservation measures such as tori lines in long-line fisheries in both US and Russian (Artukhin et al. 2006) waters of the Bering Sea. Seabird bycatch in the pot fishery is very low, averaging 73 birds per year over 1993-2006. The bulk of seabird bycatch has traditionally occurred in the demersal longline fisheries for cod, Greenland turbot, and sablefish, while bycatch in the trawl fisheries from a suite of fisheries has been much lower (Fig. BS-61).

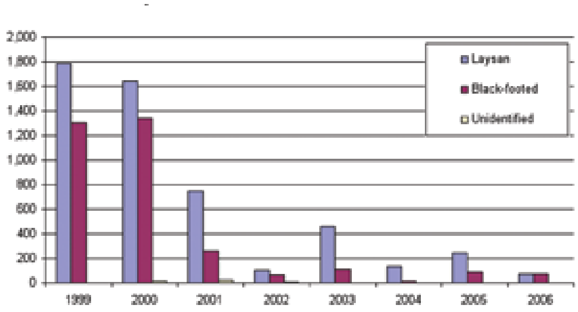


[Figure BS-61] Seabird bycatch totals for demersal longline (diamonds) and trawl (triangles) groundfish fisheries in Alaskan waters.

The large reduction in longline bycatch that occurred from 2000 through 2002 is a direct result of seabird mitigation studies conducted by Washington Sea Grant in close collaboration with the fishing industry, the U.S. Fish and Wildlife Service, and NOAA Fisheries. During the period before widespread use of streamer lines (1993 through 2000) the average annual seabird bycatch rate was 16,507. In the 5 years since streamer line use has become widespread and later required by regulation (2002-2006) the annual average bycatch of seabirds was 5,138. Traditionally, northern fulmars (*Fulmarus glacialis*) have constituted about 50% of the bycatch in Alaskan fisheries. However, with the advent of seabird mitigation gear in the longline fishery that percentage is falling while that of gulls is rising. Overall, the bycatch of birds appears to have remained at these lower levels during the 2007-2009 fishing seasons.



[Figure BS-62] Estimated albatross bycatch in demersal groundfish fisheries, 1993-2006.



[Figure BS-63] Estimated albatross bycatch in the North Pacific, 1999-2006, Hawaii and Alaska combined.

The bycatch of albatrosses in the demersal groundfish longline fishery has also been reduced substantially due to the use of seabird mitigation gear (primarily paired streamer lines) (Fig. BS-62). Similar studies, fisheries closures, and enactment of regulations requiring seabird mitigation occurred at the same time in the Hawaiian fisheries, which also provided for reduction in albatross bycatch throughout the North Pacific Ocean (Fig. BS-63).

## 9.3 Threatened and endangered marine birds

Spectacled eider: The nesting-pair-index on the Yukon Delta, the primary breeding area on the Bering Sea coast, indicates an overall decline since 1985 when the survey started. The index in 2003 was near its lowest level, but since then the index has been increasing. In fact, 2008 marked the "first time in the history of the survey that the recent 10-year average growth rate for spectacled eiders is significantly above 1.00 (alpha > 0.90)" (Fischer et al. 2008).

Steller's eider: Long-term aerial survey data from spring staging areas in the southeastern Bering Sea indicate a 2.6% average annual decline between 1992 and 2008, but the trend since 2002 has been relatively level albeit at a low population level (Larned 2008).

Short-tailed albatross: This endangered species continues to increase although it remains at low population levels (USFWS 2005). A recent review of observations suggests that birds concentrate in hot spots (e.g. at least 200 albatross or about 10% of the total population were observed within sight of a single fishing vessel) and therefore may be vulnerable to perturbations in these locations (Piatt et al. 2006).

# 10.0 Marine Mammals

*(Allen, Angliss, Fritz, Lewis)*

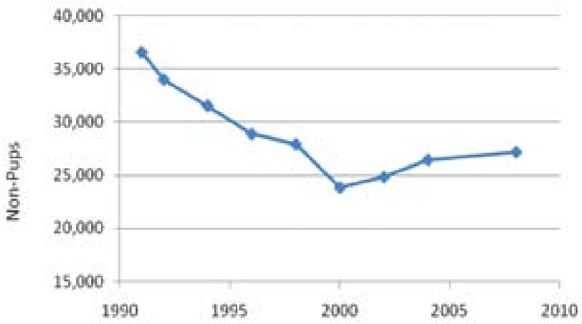
The Bering Sea is a species-rich ecosystem that provides essential resources and habitat for over 23 species of marine mammals representing the orders Pinnipedia, Carnivora, and Cetacea (Table BS-13). These species occur in diverse habitats, including deep oceanic waters, the continental slope, and the continental shelf (Lowry et al. 1982). Marine mammal populations in the Bering Sea have been affected by both natural and anthropogenic causes. Whales in particular were impacted by commercial hunting, during which time population levels declined. Some populations, such as the Eastern North Pacific right whale, have not recovered, while others have largely recovered (e.g., North Pacific humpback and eastern gray whales). Several pinniped species, including northern fur seal, Steller sea lion, and sea otter were severely impacted by the commercial fur trade and subsequently recovered, though at present, populations of these three species are considerably below their recent highs. Investigations into the effects of global climate change on marine mammal species, especially for those species dependent on sea ice, are ongoing.

## 10.1 Species accounts

### 10.1.1 Steller sea lion

The minimum abundance estimate (n = 41,197) of Steller sea lion is based on counts of pups and non-pups on rookeries and major haulout sites in the Gulf of Alaska, Bering Sea, and Aleutian Islands. The most recent minimum abundance estimate for the Aleutian Islands / Bering Sea portion of the western stock of Steller sea lion is 20,157 (Fritz et al. 2008a,b) (Fig. BS-64). Burkanov and Loughlin (2005) estimated a total of 1,000 animals (674 non-pups and 236 pups) on the Commander Islands based on counts from 2004, a minimum estimate for the western Bering Sea.

The first counts of Steller sea lion in Alaska estimated a minimum of 140,000 animals in the Gulf of Alaska and Aleutian Islands in 1956-1960 (Merrick et al. 1987). A major population decrease in the eastern Aleutian Islands was first detected in the mid-1970s (Braham et al. 1980), with the decline spreading eastward towards Kodiak Island during the late 1970s and early 1980s, and then westward to the central and western Aleutian Islands during the early and mid-1980s (Merrick et al. 1987; Byrd 1989). There was a 40% decline at trend sites in the eastern Bering Sea from 1991-2002 (Loughlin and York 2000). Starting in 2000, counts of non-pups increased 5.5% every two years for all trend sites. The Steller sea lion population size in the eastern Bering Sea remained relatively unchanged between 2004 and 2008 and is stable or slightly declining, with considerable regional variability (Fritz et al. 2008a, b). Reasons for the regional variability are unknown.



[Figure BS-64] Trends in abundance of western Steller sea lion in Alaska from 1991-2008 based on non-pup counts.

Reliable data on Steller sea lion counts in eastern Kamchatka and the western Bering Sea only exist for the last 30 years. The numbers in both areas have declined dramatically since the early 1980s, with sea lions nearly disappearing from the western Bering Sea and a greater than five-fold decline along east Kamchatka (Burkanov et al. 2009). As of 2005, the abundance of Steller sea lion along the Asian coast was estimated at 16,000, with half of those inhabiting waters around the Kuril Islands (Burkanov and Loughlin 2005). A survey based on data from 2006-2008 indicated that the abundance has remained relatively stable, although at a low level (Burkanov et al. 2008; 2009). Pup production continued to increase at the Commander Island rookery until 1999, despite the decrease in the number of males present and the decline in overall Steller sea lion abundance in most of the western population during this period. The number of pups stabilized at approximately 220-230 per year from 2000-2008 (Burkanov et al. 2009).

[Table BS-13] Marine mammals of the Bering Sea and Aleutian Islands, status and trends. N/A = not available. Sources: Angliss and Allen, 2009; Allen and Angliss, 2010.

| Species Stock | Scientific Name | Abundance | Trend in Abundance | Primary Forage Species |
|---|---|---|---|---|
| **Pinnipeds** | | | | |
| **Steller sea lion**<br>Western U.S. Stock | *Eumetopias jubatus* | 41,197 | Stable; slightly decreasing | Atka mackerel, pollock, Pacific cod |
| **Northern fur seal**<br>Eastern Pacific Stock | *Callorhinus ursinus* | 665,550 | Decreasing | Pollock, gonatid squid, small schooling fish, Atka mackerel, salmon |
| **Pacific Walrus**<br>Alaska Stock | *Odobenus rosmarus divergens* | 21,610 | Unknown | Mollusks, benthic invertebrates |
| **Harbour seal**<br>Bering Sea Stock | *Phoca vitulina richardsi* | 21,651 | Unknown(thought to be decreasing) | Demersal fish, pelagic schooling fish, octopus, squid |
| **Spotted seal**<br>Alaska Stock | *Phoca largha* | N/A | Unknown | Pollock, capelin, arctic cod, herring, flounder, halibut, sculpin, crabs, octopus |
| **Bearded seal**<br>Alaska Stock | *Erignathus barbatus* | N/A | Unknown | Crabs, shrimp, mollusks, arctic and saffron cod |
| **Ringed seal**<br>Alaska Stock | *Phoca hispida* | N/A | Unknown | Polar cod |
| **Ribbon seal**<br>Alaska Stock | *Histriophoca fasciata* | N/A | Unknown | Pollock and Arctic cod, squid |
| **Cetaceans** | | | | |
| **Beluga whale**<br>Beaufort Sea Stock | *Delphinapterus leucas* | 39,258 | Unknown | Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans |
| **Beluga whale**<br>E. Chukchi Sea Stock | *Delphinapterus leucas* | 3,710 | Unknown | Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans |
| **Beluga whale**<br>E. Bering Sea Stock | *Delphinapterus leucas* | 18,142 | Unknown | Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans |
| **Beluga whale**<br>Bristol Bay Stock | *Delphinapterus leucas* | 2,877 | Increasing | Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans |
| **Killer whale**<br>E. North Pacific Alaska Resident Stock | *Orcinus orca* | 1,123* | Unknown | Variety of fish species |
| **Killer whale**<br>GOA, Aleutian Islands, Bering Sea Transient Stock | *Orcinus orca* | 314* | Unknown | Variety of marine mammal species |

[Table BS-13 continued] Marine mammals of the Bering Sea and Aleutian Islands, status and trends. N/A = not available. Sources: Angliss and Allen, 2009; Allen and Angliss, 2010.

| Species Stock | Scientific Name | Abundance | Trend in Abundance | Primary Forage Species |
|---|---|---|---|---|
| **Cetaceans Continued** | | | | |
| **Harbour porpoise**<br>Bering Sea Stock | *Phocoena phocoena* | 48,215 | Unknown | Herring, capelin, sprat, silver hake |
| **Dall's porpoise**<br>Alaska Stock | *Phocoenoides dalli* | 83,400 | Unknown | Herring, pilchards, hake, squid |
| **Pacific White-Sided Dolphin**<br>North Pacific Stock | *Lagenorhynchus obliquidens* | 26,880 | Unknown | Herring, anchovies, capelin, sardines, cephalopods |
| **Sperm whale**<br>North Pacific Stock | *Physeter macrocephalus* | N/A | Unknown | Squid, octopus, demersal rays, sharks |
| **Baird's beaked whale**<br>Alaska Stock | *Berardius bairdii* | N/A | Unknown | Squid, deep-sea fish |
| **Cuvier's beaked whale**<br>Alaska Stock | *Ziphius cavirostris* | N/A | Unknown | Squid |
| **Stejneger's beaked whale**<br>Alaska Stock | *Mesoplodon stejnegeri* | N/A | Unknown | Meso- and bathypelagic squid |
| **Gray whale**<br>Eastern North Pacific Stock | *Eschrichtius robustus* | 18,813 | Increasing | Benthic amphipods |
| **Humpback whale**<br>Western North Pacific Stock | *Megaptera novaeangliae* | 394 | Unknown | Krill, herring, capelin, sandlance |
| **Humpback whale**<br>Central North Pacific Stock | *Megaptera novaeangliae* | 4,005 | Increasing | Krill, herring, capelin, sandlance |
| **Fin whale**<br>Northeast Pacific Stock | *Balaenoptera physalus* | 5,700 | Unknown | Krill, herring, capelin, sandlance |
| **Minke whale**<br>Alaska Stock | *Balaenoptera acutorostrata* | N/A | Unknown | Krill, herring, capelin, sandlance |
| **North Pacific right whale**<br>Eastern North Pacific Stock | *Eubalaena japonica* | N/A | Unknown | Copepods, krill |
| **Bowhead whale**<br>Western Arctic Stock | *Balaena mysticetus* | 10,545 | Increasing | Copepods, krill |

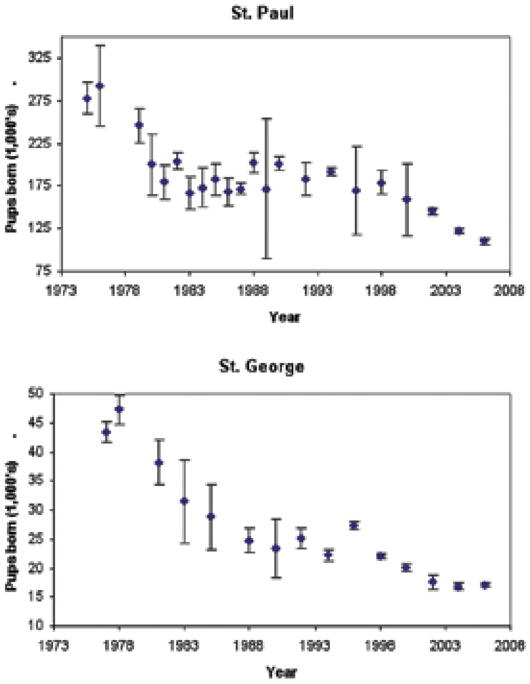
* Estimated population size based on counts of individual animals identified from photo-identification catalogs.

### 10.1.2 Northern fur seal

Northern fur seal ranges from southern California to the Bering Sea, and as far west as the Sea of Okhotsk and Honshu Island, Japan. Most of the population is found on the Pribilof Islands in the southern Bering Sea during the summer breeding season, although some animals remain on rookeries in Russia, on Bogoslof Island (53° 55´N 168° 2´W) in the southern Bering Sea, and on San Miguel Island off southern California (Lander and Kajimura 1982; NMFS 1993). The fur seal population has been subjected to a variety of harvest strategies, both commercial and scientific. The total population estimate in 1983 was 877,000 (Briggs and Fowler 1984). Since the cessation of commercial harvests in 1984, the overall population trend has been declining (Towell et al. 2006). Annual pup production on St. Paul Island remained stable between 1981 and 1996 (Fig. BS-65; York and Fowler 1992). However, since the mid-1990s, there has been a decline in pup production on St. Paul Island. Despite the slight increase in the number of pups born on St. George Island in 1996, there was an overall decreasing trend in births between 1996 and 1998 (Fig. BS-65). During 1998-2006, pup production declined 6.1% per year (SE = 0.45%; P< 0.01) on St. Paul Island and 3.4% per year (SE = 0.60%; P= 0.01) on St. George Island. The estimated pup production in 2006 was below the 1918 level on St. Paul Island and below the 1916 level on St. George Island (Towell et al. 2006). The most recent northern fur seal estimate for the eastern Pacific stock is 687,902 (Angliss and Allen, 2009). This estimate is based on pup counts from Sea Lion Rock (2002), the Pribilof Islands (2006), and Bogoslof Island (2007). The population is declining for unknown reasons. The northern fur seal was designated as "depleted" under the U.S. Marine Mammal Protection Act (MMPA) in 1988.

### 10.1.3 Phocid seals

Five species of phocid seal breed in the Bering Sea. Some of these depend upon sea ice for pupping and hauling out (ringed seal, spotted seal, ribbon seal, bearded seal), whereas others more often use beaches (harbour seals). Population trends for these species are not known, though for some estimates of present population size are becoming available (Table BS-13). For example, the current abundance estimate for the eastern Bering Sea population of harbour seals is 21,651 (Angliss and Allen 2009). In contrast, a reliable estimate of spotted seal population abundance is not available (Boveng et al. 2009). Early population estimates were in the range of 335,000-450,000 animals worldwide, with the population of the Bering Sea estimated to be 200,000-250,000 (Burns 1973). A provisional population estimate of 101,568 (SE = 17,869) spotted seals in the eastern and central Bering Sea was developed based on survey data from 2007 and 2008 (Boveng et al. 2009). Similarly, for bearded seals, early population estimates of the Bering Sea and Chukchi Sea population ranged from 250,000 to 300,000 (Popov 1976; Burns 1981). Reliable estimates of the present abundance and population trends of bearded seals are not available. Data on ribbon seals are somewhat better. Burns (1981) estimated the Bering Sea population of ribbon seals at 90,000-100,000 in the mid-1970s. Boveng et al. (2008) developed a provisional population estimate of 49,000 ribbon seals in the eastern and central Bering Sea based on aerial surveys conducted in portions of the eastern Bering Sea in 2003 (Simpkins et al. 2003), 2007 (Cameron and Boveng 2007; Moreland et al. 2008), and 2008 (Peter Boveng, unpublished). Abundance of ribbon seals in the western Bering Sea is unknown.



[Figure BS-65] (a) Estimated number of northern fur seal pups born on (a) St. Paul Island and (b) St. George Island from 1970 to 2006 (modified from Towell et al. 2006).

### 10.1.4 Killer whale

The killer whale (*Orcinus orca*) has been observed in all oceans and seas of the world and are found throughout most of the Bering Sea, ranging from Bristol Bay, Alaska, along the Aleutian and Commander Islands to Kamchatka, Chukotka, and as far north as the Chukchi Sea (Leatherwood and Dahlheim 1978; Braham and Dahlheim 1982; Burdin et al. 2006). Both transient (mammal-eating) and resident (fish-eating) killer whales occur in the Alaska waters of the eastern Bering Sea as well as around the Commander Islands and Russian Far East in the western Bering Sea (Braham and Dahlheim 1982; Burdin et al. 2007). Based on photo-identification catalogs of individual whales, minimum population estimates are 1,123, for the Alaska Resident stock and 314 for the Gulf of Alaska, Aleutian Islands, and Bering Sea Transient stock, resulting in a minimum total estimate of 1,437 whales in the eastern Bering Sea (Angliss and Allen 2009).

The eastern Kamchatka killer whale catalog consists of 434 individuals from the Avacha Gulf, Kamchatka Peninsula, with 264 resident killer whales and 158 resident-type (fish-eating) whales that may have a broader range than the Avacha Gulf (Burdin et al. 2006, 2007; Ivkovich et al. 2010). Since the late 1990s, transient-type killer whales have been observed regularly feeding on northern fur seal off the Commander Islands (Mamaev and Burkanov 2006). A total of 45-50 killer whales have been sighted off the Chukotka coast from 1983-2001, primarily from July to September, then migrating south in November (Grachev et al. 2002). Melnikov and Zagrebin (2005) reported seeing 788 killer whales over a 10 year period (1990-2000) from the shores of the Chukotka peninsula, 11.6% of which were involved in marine mammal attacks, including gray whales and pinnipeds. Population trends for killer whale throughout the entire Bering Sea are currently unknown (Angliss and Allen 2009; Burdin et al. 2007).

### 10.1.5 Gray whale

Two populations of gray whale (*Eschrichtius robustus*) exist in the North Pacific: the eastern Pacific stock, and a very small western North Pacific stock. The western stock is found primarily in the Sea of Okhotsk, although numerous sightings have been made off southeast Kamchatka. Gray whales have historically been reported to occur off the Commander Islands (Barabash-Nikiforov 1938), but sightings are relatively rare in this area over recent years (Weller et al. 2003; Tyurneva et al. 2009; Savenko et al. 2009). Annual shore-based counts of eastern Pacific gray whales migrating south have been conducted along the central California coast since 1967. Analyses of these data resulted in an estimate of the annual rate of increase from 1967-1968 through 2001-2002 at 1.9% (SE = 0.32%; Rugh et al. 2005). Abundance estimates in the late 1990s-early 2000s have been around 20,000 animals. It is expected that a population close to or at the carrying capacity of the environment, such as the eastern Pacific gray whales, will be more susceptible to fluctuations in the environment, which may explain the recent correlation between gray whale calf production and environmental conditions, as well as the 1999-2000 mortality event (Moore et al. 2001; Perryman et al. 2002; Gulland et al. 2005).

### 10.1.6 North Pacific right whale

The North Pacific right whale (*Eubalaena japonica*) may be the most endangered large whale in the world. Historical whaling records suggest that the North Pacific right whale ranged across the entire North Pacific north of 35°N (Scarff 1986, 2001) but recent data show a pronounced longitudinally bimodal distribution (Josephson et al. 2008). Two stocks of North Pacific right whale are currently recognized: a Western North Pacific and an Eastern North Pacific stock, although the former is believed to feed primarily in the Okhotsk Sea (Rosenbaum et al. 2000; Brownell et al. 2001). During 1965-1999, there were only 82 sightings of right whale in the entire eastern North Pacific with the majority of these occurring in the Bering Sea and adjacent areas of the Aleutian Islands (Brownell et al. 2001). A minimum of 17 individual whales was seen in 2004, including 2 probable calves (Angliss and Allen 2009). In 2008, 9-12 individual right whales were identified during NMFS vessel and aerial surveys (Kennedy, unpublished). Reliable estimates of abundance and population trends for the North Pacific right whale stock are currently not available.

### 10.1.7 Other marine mammals

Limited information on population levels of other marine mammals in the Bering Sea, including Beluga whale, harbour porpoise, Dall's porpoise, Pacific white-sided dolphin, sperm whale, Baird's beaked whale, humpback whale, fin whale, minke whale and bowhead whales, is available (Angliss and Allen 2009; Burdin et al. 2007;

Moore et al. 2002; Savenko et al. 2009; Calambokidis et al. 2008; Zerbini et al. 2006), providing approximate estimates of current or recent population levels (Table BS-13), but no information is available on population trends during the focus period.

## 11.0 Ecosystem Considerations

*(Hunt, Mueter)*

The period 2002 to 2009 was unusual in that the Bering Sea experienced four years with low sea ice cover and extraordinarily warm summers (2002-2005), followed by a series of four years with some of the heaviest sea ice cover since the early 1970s and cold summers (2006-2009). During this time frame (2002-2009), there have been several comprehensive research programs in the eastern Bering Sea including BASIS (2002-present), which also covered parts of the western Bering Sea, the Pribilof Domain Project (2004), BEST (Bering Sea Ecosystem Study) (2007-2010), BSIERP (Bering Sea Integrated Ecosystem Research Program) (2008-2012), and NPCREP (North Pacific Climate Regimes and Ecosystems Productivity) (2004-present). Conducted in the context of striking environmental variability, these programs in sum have provided and continue to provide an unprecedented opportunity to assess how the Bering Sea ecosystem responds to periods of cold and warm conditions. This summary section, examines the impacts of the recent warm and cold periods, newly available contrasts between the northern and southern portions of the eastern Bering Sea shelf, the state of knowledge of controls of year-class strength in walleye pollock and new evidence for density-dependence in fish stocks and determinants of carrying capacity.

### 11.1 Comparison of a warm period (2002-2005) with a cold period (2006-2009)

The occurrence of four unusually warm years (2002-2005) followed by four unusually cold years (2006-2009) provided the opportunity to learn how a warm southeastern Bering Sea might differ from a cold one. Many aspects of the ecology of the southeastern shelf were affected by differences in water temperature, cold pool extent, and stratification. Given that there is evidence for greater weight-at-age in groundfish during the warmer years, it might be concluded that the Bering Sea should be particularly productive in future periods of warmer climate and that post-recruitment fish will enjoy higher growth rates when temperatures are warmer. However, the recruitment of some species of commercially valuable groundfish appeared adversely affected by unusually warm conditions. Although the Oscillating Control Hypothesis predicts that production of strong cohorts of age-0 pollock should occur in warm years (Hunt et al. 2002), strong year-classes failed to emerge in the warm years of 2002-2005 despite a declining biomass, and there were possibly strong year-classes in the cold years of 2006 and 2008. The Oscillating Control Hypothesis also predicts that in years when water temperatures are low, zooplankton prey is expected to be limiting and therefore strong year-classes would be unlikely to result.

The reasons for these results became clear upon examination of data on crustacean zooplankton, the condition indices of age-0 in summer and fall, and diets of age-0 and older pollock (Coyle et al. 2008; Hunt et al. 2008; Moss et al. 2009). In the warm years of 2001-2005, the small neritic species of crustacean zooplankton thrived, whereas the medium-large copepod *Calanus marshallae* and the shelf euphausiid, *Thysanoessa raschii*, were scarce (Coyle et al. 2008; Hunt et al. 2008; this chapter). In these warm years, age-0 pollock were abundant in the BASIS surveys, but they were in very poor body condition with an energy content that was unlikely to be sufficient for overwinter survival (Moss et al. 2009). In contrast, in the cold years of 1999 and 2006-2008, both *C. marshallae* and *T. raschii* were abundant (Coyle et al. 2008; Hunt et al. 2008). In the cold years of 2006-2008, age-0 pollock were in good condition and energy rich, though apparently not as abundant as they were in the warmer years.

The diets of age-0 pollock differed between the warm and cold years. In the warm years, they consumed mostly small crustacean zooplankton and also smaller age-0 pollock, and neither *C. marshallae* nor *T. raschii* were important components of their diets (Moss et al. 2009). In contrast, in the cold years, age-0 pollock diets were dominated by *C. marshallae* and euphausiids; cannibalism was reduced. In the warm years, age-0 pollock were also an important component of the diets of juvenile salmon, whereas in cold years, euphausiids and large copepods were the dominant salmon prey (Moss et al. 2009). These results suggest that the availability of plentiful supplies of large copepods and euphausiids in summer and fall are essential not only to reducing consumption of age-0 pollock, but also to ensure that the age-0 pollock surviving to the fall have sufficient energy reserves to survive their first winter.

The finding that numbers of age-0 pollock are greater in the summers of warm years fits the prediction of the Oscillating Control Hypothesis (Hunt et al. 2002) but the failure of these fish to recruit, particularly in a period of declining adult biomass, does not (Hunt et al. 2008). There is still the possibility of alternating top-down and bottom-up control of pollock populations, but the added factor of starvation over the first winter and the switching of predators from large crustacean zooplankton to age-0 pollock in warm years when the zooplankton are scarce must be taken into account.

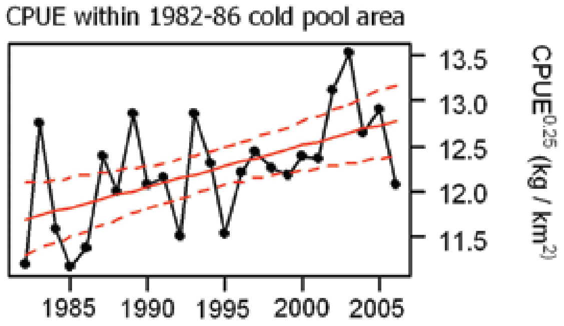
Two non-exclusive hypotheses have been put forward to explain the scarcity of *C. marshallae* and *T. raschii* in warm years. One, based on the work of Baier and Napp (2003) suggests that at least *C. marshallae* requires an early bloom, normally associated with the melting of the sea ice, to provide food essential for the recruitment of copepodites from the nauplii. At present, there are no hypotheses available about the role of sea ice in the recruitment of *T. raschii*, although in the Barents Sea, this species has been found to increase in cold periods and decrease in warm periods (Drobysheva 1967, 1994). The other hypothesis is that strong stratification in summer depresses post-bloom new production and therefore the large crustacean zooplankton, lacking appropriate food resources, leave the water column when the surface layer warms (Coyle et al. 2008). These hypotheses are discussed in some detail in Hunt et al. (2008).

## 11.2 Contrasts between the northern and southern portions of the eastern Bering Sea shelf

The physics of the northern portion of the eastern Bering Sea shelf are dominated by advective processes whereas in the southern portion of the shelf, physical processes are dominated by tidal forcing (Stabeno et al. 2001, 2010). Recently, Stabeno et al. (2010) have shown that the northern and southern portions of the shelf are separated in summer by a strong, cross-shelf front that occurs just south of St. Matthew Island. North of the frontal area, stratification is dominated by salinity whereas south of the front, temperature is the dominant determinant of stratification. End-of-winter nitrate concentrations over the northern shelf were more variable than those over the southern shelf. In both cold and warm years, the seasonal draw-down of nitrate and phosphate was greater and less variable over the southern Middle Domain than it was over the north. These differences may result from the greater on- and off-shelf advection in the north.

Because there is strong pelagic-benthic coupling in the northern shelf region (Grebmeier et al. 1988, 2006; Grebmeier and McRoy 1989; Highsmith and Coyle 1992; Lovvorn et al. 2005), it is perhaps not surprising that there is strong denitrification and (or) anammox removal of nitrogen from the system, thereby creating anomalously low nitrate-phosphate ratios when compared to the global mean or to the southern shelf. Unexpectedly, everywhere on the eastern shelf, nitrate-phosphate ratios were lowest in spring, rather than in fall after summer denitrification. However, summer/fall surface chlorophyll$_a$ biomass was higher in the south than in the north. Subsurface chlorophyll$_a$ concentrations mirrored the pycnocline depth, with deeper blooms observed over the northern shelf.

Less attention has been paid to the species composition and biomass of zooplankton (and fish) in the northern Bering Sea, though useful results should be forthcoming from the BEST / BSIERP programs and from the northward extension of the U.S. NMFS groundfish trawl surveys. However, older work suggests that mesozooplankton species composition in the north is similar to that in the south, with oceanic species that have been advected onto the shelf dominating to the west, and species typical of the Middle Domain in the south dominating in the eastern portions of the northern shelf (Springer and Roseneau 1985; Springer et al. 1989; Hunt and Harrison 1990). Likewise, our knowledge of fish distribution and abundance in the northern Bering Sea is less advanced than in the southeastern Bering Sea where most of the commercially important stocks are found. Species common to the southeastern Bering Sea shelf penetrate north to the Chukchi Sea and beyond (e.g., Wyllie-Echeverria 1995; Barber et al. 1997; NPFMC 2009; Norcross et al. 2010), and recently Mueter and Litzow (2008) have shown that a number of Bering Sea fish species that are typical of temperate waters moved north into the region of the southern cold pool during the warm years of 2002-2005 when there was little sea ice and the cold pool was small and not as cold as usual (Fig. BS-66). However, in the recent stanza of cold years (2006-2008), there is little evidence that these fish shifted back southward to warmer waters (Mueter unpublished). As conditions change, it will be of interest to see if the distributions of these fish populations track climate variability or if there is an environmental ratchet northward (*sensu* Orensanz et al. 2004). A long-term northward shift could have major impacts on the fishing industry and shore-based communities that serve this industry, and it also could have significant impacts on the structure of an ecosystem presently relatively free of groundfish predators.



[Figure BS-66] Change in CPUE for temperate groundfish species in the area occupied by the cold pool in 1982 to 1986 (adapted from Mueter and Litzow; 2008).

## 11.3 Comparison of climate and fisheries patterns in the eastern and western Bering Sea

Between 2000 and 2008 there has been only a very weak correspondence in air temperatures on the two sides of the Bering Sea. Although temperatures appeared out of phase early in this period, they were largely in phase for the years 2002 to 2005, after which they were again briefly out of phase. Although we were unable to obtain data on zooplankton populations in the western Bering Sea to compare with those available from the eastern shelf, comparison of fisheries statistics between the eastern and western areas showed that over the periods 1954 to 2004 and 1964 to 2004, the aggregated catches of all major fisheries tended to be positively correlated (r= 0.64 and r= 0.36, respectively), suggesting that the two sides of the Bering Sea were responding similarly to shared climate forcing.

## 11.4 Issues of carrying capacity and density-dependent control

Weight-at-age and weight-at-length were used as indicators of fish condition and then examined to determine the relationships of these indices to both the biomass of a particular species and to temperature. Although most species had anomalously high weight-at-age and weight-at-length in periods of warm water and bottom temperatures, there was no evidence in the short time series available that density-dependent constraints on growth were significant.

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# Sea of Okhotsk

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# highlights

- When determined from a broad area located upwind of the Sea of Okhotsk, average winter air temperatures indicated a warming trend. At individual meteorological stations in the Okhotsk region, the preferred model at 9 of 10 stations was an abrupt shift to warmer winters in 1989 rather than a long-term trend.

- Sea ice extent in the Sea of Okhotsk has decreased by about 20% in 30 years; ice cover in April 2009 was the minimum observed in the last 50 years.

- The co-occurrence of warming and decrease in dissolved oxygen concentration in the northwestern North Pacific, originating from the Sea of Okhotsk (Nakanowatari et al. 2007), implies that overturning in the northwestern North Pacific has weakened. Such a trend could possibly affect the material cycle and biological productivity in the North Pacific.

- Reductions in the formation of intermediate layer water have been reported but the most recent data from the central Sea of Okhotsk do not exhibit a continuation of this trend, despite the decreasing ice cover and warmer air temperatures.

- Recent observations (Nishioka et al. 2007) suggest that the ventilated intermediate water from the Sea of Okhotsk is a potential source of iron for the iron-limited, high-nitrate, low-chlorophyll North Pacific.

- The advection of Pacific water into the Sea of Okhotsk was near average from 2002-2009.

- Returns of pink salmon continued to increase in both even- and odd-year cycles and coastal catches in 2006 and 2007 reached record highs of 180,700 and 178,500 mt, respectively. Total salmon catch on the Russian coast of the Sea of Okhotsk reached the historical high in 2009 at 345,000 mt, including 275,000 mt of pink salmon.

- The walleye pollock spawning stock increased by 10.1 billion fish in 2009 with the 2004 and 2005 year-classes accounting for 80% of this growth.
- The abundance of commercially valuable invertebrate species (crabs, shrimp, and snails) remains at a low level.
- Surveys conducted in 2002 indicated that the macrozoobenthic community in the Sea of Okhotsk has changed little since the last major survey twenty years earlier.
- Large-scale ecological changes developed from a causal chain of changing oceanographic conditions that led to earlier declines in abundances of walleye pollock and Japanese sardine, which in turn decreased the grazing pressure on zooplankton resulting in an increase of zooplankton forage species and subsequently an increase in the abundance of predatory zooplankton and the biomass of other fish species.

# Introduction

The Sea of Okhotsk is a semi-enclosed marginal sea bounded by Russia to the north and west and Japan to the south (Fig. OK-1). The Kuril Island archipelago separates it from the Pacific Ocean. Its area (1,528,100 km²) is similar in magnitude to the Bering Sea (2,315,000 km²). The exchange of water with the North Pacific Ocean has a considerable effect on circulation and intermediate-water formation. The bottom topography is rugged, featuring the deep Kuril Basin, Academy of Science of USSR Rise, and the Oceanology Institute Rise in the southern deepwater part of the Sea of Okhotsk. Two troughs connect the deeper waters of the Sea of Okhotsk with its two hollows (Derjugin's Hollow and TINRO Basin). These are deep cuts in the wide northern shelf. The shelf zone occupies almost 40% of the total area (Larina 1968) and is widest in the north (up to 400 km). Two large bays (Shelikhov in the northeast and Sakhalinsky in the southwest) constitute ›25% of the shelf zone. The shelf zone is somewhat isolated from direct water exchange with the open ocean by the Kamchatka Peninsula. Waters of Pacific origin penetrate mainly through the northern Kuril straits: from the shallow First Kuril Strait to the northern part of Boussol Strait (depth: 2318 m).

[Figure OK-1] Sea of Okhotsk. Modified from Udintsev (1957).

Large-scale circulation in the Sea of Okhotsk is cyclonic with northward flow in the northeastern part due to the West Kamchatka Current, and southward flow in the west due to the East Sakhalin Current (Leonov 1960; Moroshkin 1966; Kitani 1973; Favorite et al. 1976). Their interaction with the coastline and bottom relief generates several smaller currents (Chernyavsky 1981; Markina and Chernyavsky 1984; Chernyavsky et al. 1981; Luchin 1982; Tally and Nagata 1995). On the northern shelf, the westward current is deflected southward by the shore, then leaves via the southern Kuril straits. A branch of the East Sakhalin Current turns eastward off eastern Sakhalin Island and carries water and ice out to the Pacific Ocean through Boussol Strait. Two-way flow has been reported through this strait with outflow in the upper layers in the southwestern part and inflow in the northwestern part and in deeper layers (Leonov 1960; Kurashina et al. 1967; Riser 1996).

The heat balance at the sea surface (usually calculated without taking horizontal advective heat flux into consideration) is -25 kcal·cm$^{-2}$·yr$^{-1}$ (Batalin and Vasyukova 1960), but this apparent deficit is compensated by warmer water entering from the Pacific Ocean or by poleward flow through Soya Strait. Over an annual cycle, the sea absorbs heat in the northwest and gives it back to the southern and eastern parts, especially near the western Kamchatka coast.

Seasonal changes are distinctive. There can be ice from November (rarely in October) to June. In March, the Sea of Okhotsk is mostly covered by ice, except near Kamchatka and the Kuril Islands. A meridional region of open water occurs along the western Kamchatka coast in winter, reflecting the influence of warmer Pacific waters. Because of severe cooling on the northern shelf in winter, the water structure of the Sea of Okhotsk is characterized by a residual frigid layer whose core is -2°C. This cold intermediate (dicothermal) layer is a unique feature of the Sea of Okhotsk and it can remain throughout the warm season. There is a significant temperature difference between the surface and subsurface waters. The sea surface temperature (SST) rises to 11°-13°C over most of the area and to 18°-19°C near Hokkaido and southern Sakhalin due to insolation, vertical mixing and increased Pacific water influx during the warm season.

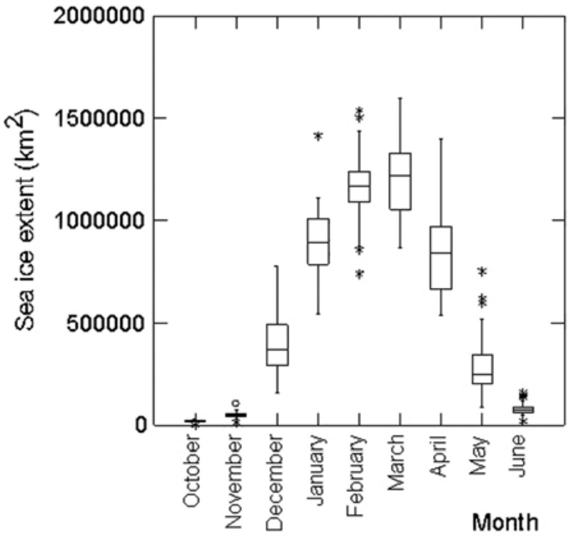
What follows in the remainder of this chapter is an attempt to capture the current status and trends in the Sea of Okhotsk, especially during the period from 2003-2008 (hereafter, the *focus period*). Analyses and descriptions of the focus period, to the extent that data are available, have been interpreted within the context of historical observations and the extent of sampling during the focus period.

## 2.0 Climate

### 2.1 Air temperature and sea ice

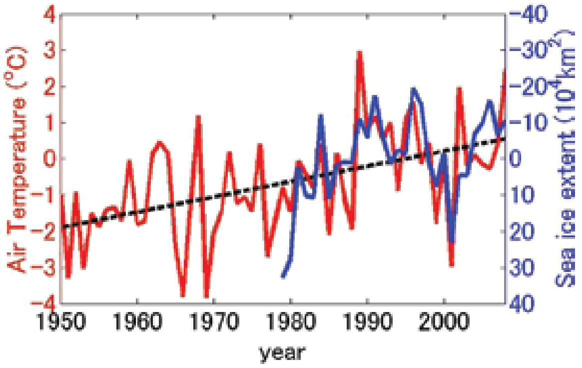
*(Ohshima, McKinnell)*

The coldest place in the northern hemisphere is located immediately upwind of the Sea of Okhotsk so sea ice is prevalent in the cold season (Ohshima 2008). The seasonal expansion and contraction of ice cover affects air-sea heat flux, water column mixing and stratification, and renewal rates of the subsurface cold residual layer, etc. Therefore, the extent of ice cover is usually closely correlated with the other physical and biological indices. Interannual variability is greatest on the shoulders of the main part of the ice season (maximum in March and April) (Fig. OK-2).

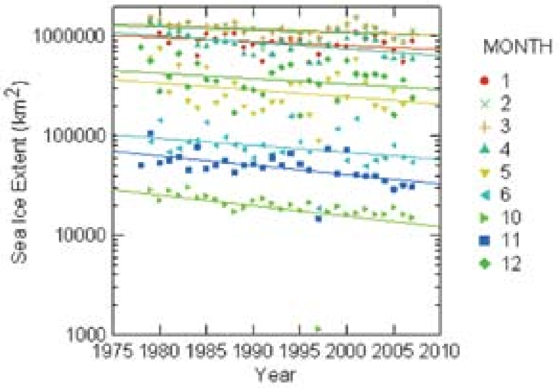


[Figure OK-2] Box and whisker plots indicating median ice extent by month in the Sea of Okhotsk. Data available from the U.S. National Snow and Ice Data Center (http://nsidc.org/data/smmr_ssmi_ancillary/area_extent.html#graphs).

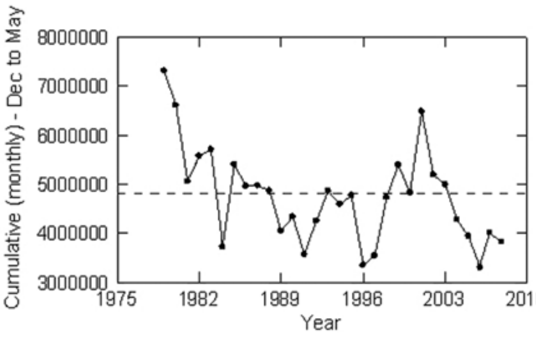
Since accurate observation by satellite became possible, the sea ice extent in the Sea of Okhotsk (blue line in Fig. OK-3) has decreased by about 20% in 30 years, or by approximately 150,000 km², equivalent to ~10% of the entire area. The maximum extent of sea ice has a linear declining trend in all months when sea ice is present, although the trend is not statistically significant in every month (Fig. OK-4). From 2002-2006, the area of maximum ice cover decreased gradually after experiencing the second largest value in March of 2001 (1,516,700 km²), or 97% of the total Sea of Okhotsk area. After this progressive decline, the seasonal maximum ice cover has dropped to 903,800 km², or 57.8% of the total area. The winter of 2005-2006 had the least integrated sea ice cover (sum of the monthly sea ice areas from December to May) of any year in the record up to that time (Fig. OK-5). In the winters of 2006-2007 and 2007-2008, maxima of the Sea of Okhotsk ice cover recovered up to 1,073,000 – 1,106,900 km² but remained less than average (Ishizaki 2008, 2009).



[Figure OK-3] Time series of surface air temperature anomaly in the cold season (October to March) and the linear trend over northeastern Eurasia (50°-65°N, 110°-140°E) from 1950 to 2008 (red solid and dashed lines, respectively), and the annual sea ice extent anomaly in the entire Sea of Okhotsk in February from 1979 to 2008 (blue line). The scale of the sea ice extent anomaly is indicated on the right axis and inverted. The surface air temperature anomaly is derived from (Jones 1994), and the sea ice extent anomaly is derived from the Met Office Hadley Centre's sea ice data set (Rayner et al. 2003). The surface air temperature anomaly with respect to the 27 year average from 1979 to 2005 is shown for the benefit of comparison with the sea ice extent anomaly. Updated after Nakanowatari et al. (2007).



[Figure OK-4] Linear trends in sea ice extent (km²) in the Sea of Okhotsk , by month from 1978 to 2007. Data available from the U.S. National Snow and Ice Data Center (http://nsidc.org/data/smmr_ssmi_ancillary/area_extent.html#graphs).



[Figure OK-5] Cumulative monthly sea ice extent from December to May for each year 1978/1979-2007/2008; plot points correspond to the year of the January in each sum.

A feature that was characteristic of 2007-2009 was a quick retreat of ice in the second half of the cold season. In the spring of 2009, for example, the thaw occurred so intensively that the ice extent quickly decreased to 320,000 km² by late April, 37% below the long-term average. Average ice cover in April of 2009 was 428,000 km². This is the minimal value observed since the winter of 1956-1957 and is 30% lower than the recent minimum observed in April of 1989 (611,000 km²). The month of maximum extent of sea ice has moved from March to February during the last two years.

Interannual variability of sea ice extent in the Sea of Okhotsk is highly correlated with that of surface air temperature (red line in Fig. OK-3) in the preceding fall and winter (October to March) in the region immediately upwind (50°-65°N, 110°-140°E) of the Sea of Okhotsk (r = -0.61) (Ohshima et al. 2006). Of particular note is that this air temperature has increased considerably during the past 50 years (2.0±1.4°C). This value of 2.0° far exceeds the rate of average temperature increase worldwide (0.65° over the past 50 years), thereby clearly indicating that the region is significantly affected by global warming. The correlation between this temperature and the sea ice extent suggests that decreases in the sea ice preceded the beginning of satellite observations. Visual observations at the Hokkaido coast, located on the southern boundary of sea ice extent in the Sea of Okhotsk, also show the decreasing trend of sea ice season length during the past 100 years (Aota 1999). These suggest that sea ice generation has decreased during the past 50 years. Since Dense Shelf Water is produced by active sea ice production on the northwestern shelf of the Sea of Okhotsk (Shcherbina et al. 2003), the properties of intermediate waters in the Sea of Okhotsk and the North Pacific, which are ventilated through Dense Shelf Water, are possibly affected by global warming.

## 2.2 Shift or trend *(McKinnell)*

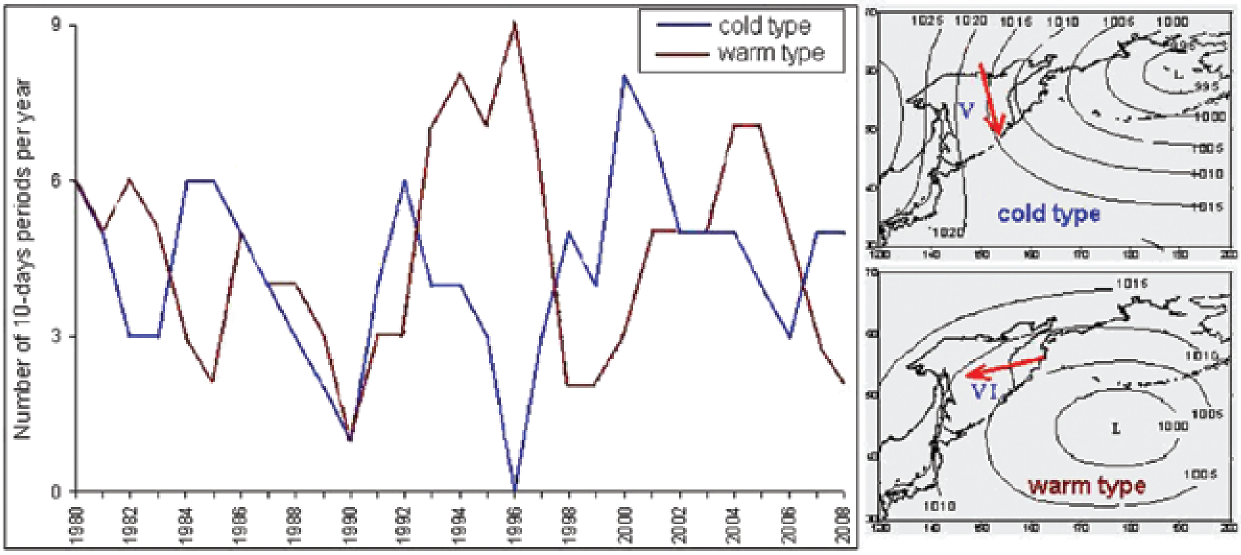
An issue of some interest is whether the higher average winter air temperatures in the last 20 years are the result of a persistent trend or an abrupt change. When average temperatures are determined over a broad area upwind of the Sea of Okhotsk, the result is an increasing trend in air temperature (Fig. OK-3; Ohshima 2008). However, when data from individual meteorological stations in the region are examined, the preferred model at 9 of 10 stations was an abrupt shift to warmer winters at 1989 rather than a long-term trend (Table OK-1). The trend model was preferred at only one station (Okhotsk) which also had the least average increase after 1989. The magnitude of the average increase from 1989 at all other stations varied from a low of 1.06°C to a high of 2.96°C. At least some of the higher average temperature can be attributed to a decrease in average winter monsoon over the region from 1989.

[Table OK-1] Evaluation of two models of increasing mean winter (JFM) air temperatures in the Okhotsk region (linear trend versus sudden shift in 1989). The model with the lowest AICC is the better fit to the observed data (best fit in red). Average increases after 1989 are reported under Temperature Difference. The name of the meteorological station is reported in the last column. Data from U.S. NASA GISS (Goddard Institute for Space Studies) Surface Temperature Analysis.

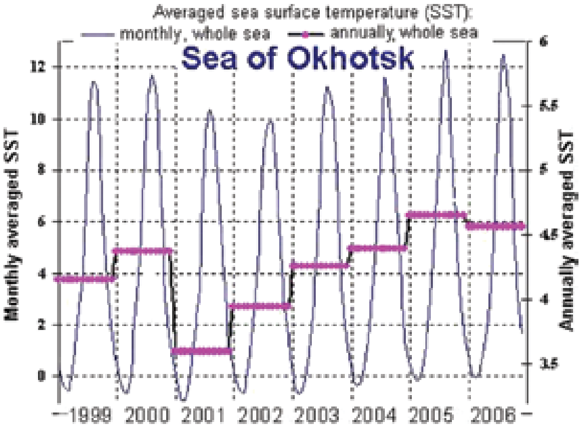
| Corrected Akaike Information Criterion | | Temperature Difference (°C) | Station |
|---|---|---|---|
| Trend | Shift at 1989 | | |
| 184.55 | 165.24 | 1.93 | Abashiri |
| 206.04 | 200.72 | 1.58 | Ajan |
| 242.87 | 233.61 | 2.56 | Im. Poliny Osipenko |
| 234.87 | 228.55 | 2.96 | Jakutsk |
| 177.10 | 161.88 | 1.60 | Nemuro |
| 214.11 | 209.16 | 1.64 | Nikolaevsk-na-Amure |
| 227.27 | 226.92 | 1.06 | Ojmjakon |
| 189.18 | 190.86 | 0.73 | Okhotsk |
| 177.26 | 160.79 | 1.49 | Wakkanai |
| 206.60 | 198.71 | 1.68 | Yuzhno-sakhalinsk |

## 2.3 Sea level pressure *(Radchenko)*

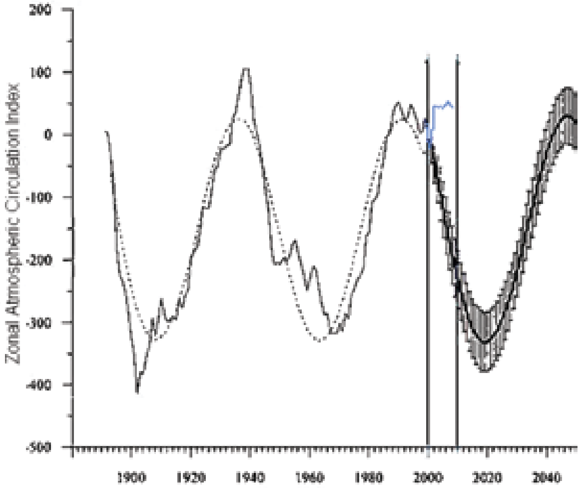
There is a large pressure gradient between the Siberian High Pressure Core and the Aleutian Low Pressure region. The gradient causes powerful winds over the northern Sea of Okhotsk coast and Shelikhov Bay. Beginning in the early 1990s, the magnitude of the pressure gradient declined and a warmer zonal atmospheric circulation has predominated (Fig. OK-6). Local cooling was observed in the Sea of Okhotsk in 2000-2002 with the strongest northeasterly (cold) air flow from January–March of 2001 (Glebova 2006) which produced heavy ice conditions in winter of 2000-2001. A relatively short period of cooling was followed by a warmer period that has lasted until the present (Fig. OK-7) which defies an earlier forecast of a strong reversal to a “cold” meridional epoch from 2000- 2010 (Klyashtorin and Lyubushin 2005). The warm zonal circulation type persists (Fig. OK-8) (Dumanskaya and Fedorenko 2008).



[Figure OK-6] Patterns of "cold" (V) and "warm" (VI) types of atmospheric circulation above the Sea of Okhotsk, in accordance to classification by Glebova (2006, updated).



[Figure OK-7] Monthly and annual SST dynamics in the Sea of Okhotsk, 1999-2006 (after Khen et al. 2008).



[Figure OK-8] Long-term dynamics of the Atmospheric Circulation Index:WE zonal atmospheric circulation index (thin solid line), 1891-1999, dashed line – its model (harmonic oscillation). Thick solid line with standard deviation error bars is the forecast for 2000-2050 (Klyashtorin and Lyubushin 2005). Blue fragment – additional observed data from Dumanskaya and Fedorenko (2008).

During the warm season (April to September), the Far-Eastern Low is situated above the eastern edge of the Asian continent. It has a significant influence on the synoptic conditions above the Sea of Okhotsk region where it reaches its full development in July before diminishing. In the first half of the 2000s, atmospheric pressure at the center of the Far-Eastern Low was relatively high and the centre of the Far-Eastern Low moved eastward. This tends to weaken the summer monsoon, increase air temperatures throughout the region in late summer and autumn, and decrease precipitation in the northeastern part of the Sea of Okhotsk region (Shatilina and Anzhina 2008).

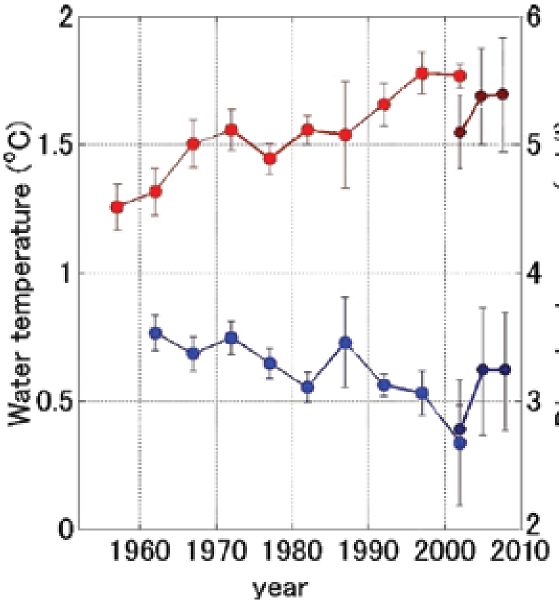
# 3.0 Physical Ocean

## 3.1 Ocean circulation and temperature

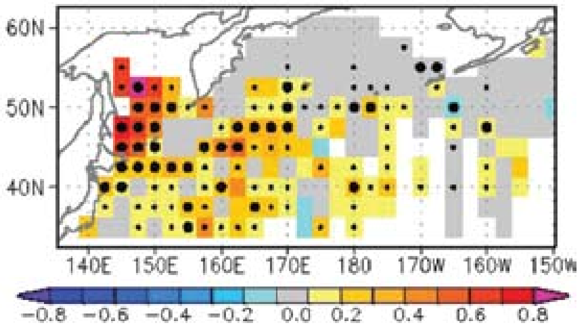
*(Radchenko, Ohshima, Figurkin)*

Vertical mixing in the Sea of Okhotsk in winter affects the oceanography of much of the North Pacific Ocean (Yasuda 1997). Sinking cold, oxygen rich, dense water from the surface creates a vertical circulation (i.e. overturning) down to intermediate depths (200-800 m). The temperature of the intermediate layer in the Sea of Okhotsk has increased over the past five decades. As warmer water generally holds less oxygen, the dissolved oxygen concentration in this layer has decreased (Fig. OK-9) suggesting a reduction in the formation of the intermediate layer as a result of decreased sea ice production. The downstream effects are evident in the intermediate water in the Northwest Pacific (Ono et al. 2001; Nakanowatari et al. 2007). However, this interpretation was based on data collected before 2003 and on the limited area of the Sea of Okhotsk (Wakatsuchi 2006; Gilbert et al. 2009). The most recent data from the central Sea of Okhotsk do not exhibit a continuation of this trend despite the negative trends of seasonal ice cover parameters (Fig. OK-4). In 2005 and 2008, the temperature of intermediate water in the Sea of Okhotsk (50°12' - 50°40' N, 146°52' - 149°00' E) at 27.0 $\sigma_\theta$, corresponding to 200-600 m depth, was 1.67-1.69°C. The average oxygen concentration varied little, from 3.23-3.24 $ml \cdot l^{-1}$. Oxygen concentrations in this part of the water column varied from 5.04 $ml \cdot l^{-1}$ at 200 m to 1.60 $ml \cdot l^{-1}$ at 600 m.

From 1955-2004, water temperature in the intermediate layer of the North Pacific has a warming trend that is most prominent in the Sea of Okhotsk (Fig. OK-10). This could be a result of reduced volumes of Dense Shelf Water sinking in the Sea of Okhotsk which has weakened the overturning in the North Pacific, but this is not the sole mechanism of intermediate layer ventilation. In summer, cold water intrusions appear at depths of 250-400 m near the north-eastern Sakhalin Island coast. Tides stimulate propagation of the cold shelf water enriched by oxygen at depths of intermediate water layers (Sosnin et al. 2007). It can therefore be concluded that the situation did not worsen during the focus period.



[Figure OK-9] Time series of temperature (red line) and dissolved oxygen (blue line) of intermediate water in the Sea of Okhotsk at the 27.0 $\sigma_\theta$ isopycnal (~250-550 m depth) during the past 50 years. Additions for 2002, 2005 and 2008 are from the TINRO-Center surveys.

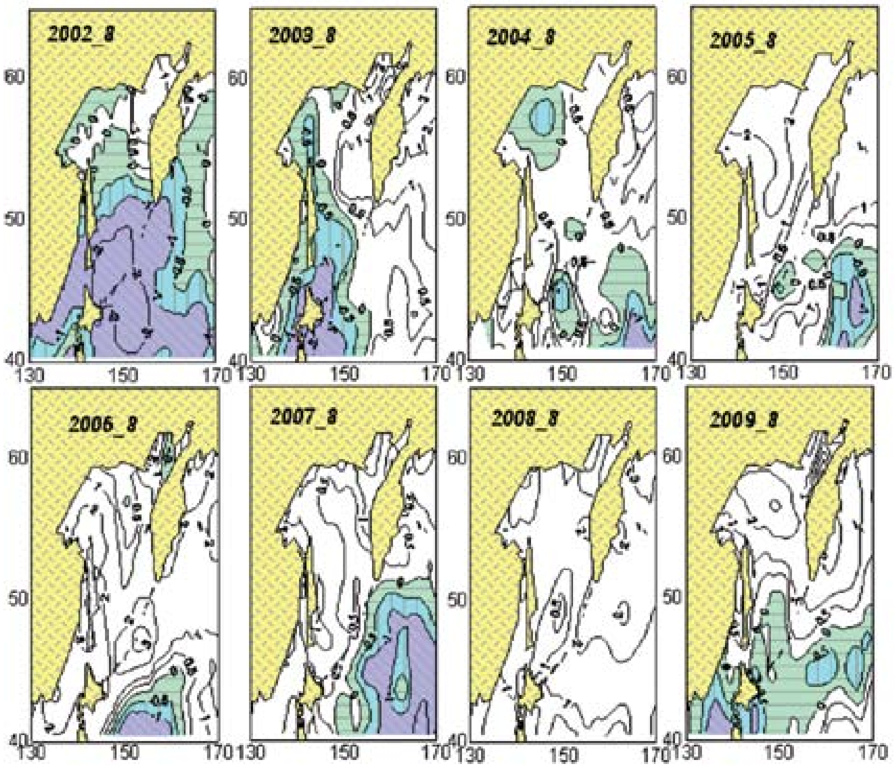


[Figure OK-10] Linear trend of water temperature anomalies (°C per 50 y) at density of 27.0 $\sigma_\theta$ from 1955-2004 in the northwestern North Pacific. Large and small dots indicate the grid boxes at which the linear trend is significant at the 99% and 95% confidence level, respectively. White color indicates the grid boxes with <10 years of data for the linear trend calculation (after Nakanowatari et al. 2007).

A recent review on progressive hypoxia in the coastal and open ocean (Gilbert et al. 2009) shows that oxygen trends from 1976–2000 are more negative than was observed during the 1951-1975 period. However, the trend in median oxygen from published results is more negative than the trends in median values computed from raw oxygen data. It suggests a publication bias in favor of strongly negative trends that is likely due to the adverse ecosystem implications of hypoxia.

The advection of Pacific water into the Sea of Okhotsk was near average from 2002-2009. It had decreased in the 1990s during a period when zonal atmospheric circulation dominated. The observed decrease was likely due to an intensification of the Subtropical Gyre (with the strengthening of the California Current) and decrease in the Subarctic Gyre (with the weakening of the Alaska Stream along the North America coast). The East Kamchatka Current, flowing along the eastern Kamchatka Peninsula coast from the Bering Sea weakened considerably (to 0.7-1.5 Sv) in the period from 1950 to the mid-1960s. Thereafter, a more active period (3-5 Sv) persisted from 1965 until 1989 when it weakened again in the 1990s with the minimum occurring in 1999 (0.2 Sv). In the beginning of the 21st century it has intensified but still remains below the climatic value of 2.3 Sv (Khen and Zaochny 2009). SST changes in the Sea of Okhotsk tend to occur two years later than in the Bering Sea. Through most of the focus period (2003-2006), the warmest years were 2003 in the Bering Sea and 2005 in the Sea of Okhotsk (Khen et al. 2008). The SST anomalies above +2°C occupied a vast domain in the northern Sea of Okhotsk in 2005 (Fig. OK-11).

Surface layer inflow from the Pacific Ocean intensified during the second half of the 1990s (Fig. OK-12). However, the waters carried by this flow originated in the East Kamchatka Current, where the average annual SST was low (3.63°C) in 1999 (Khen et al. 2008). It has increased gradually and reached 5.04°C in 2003, two years before the warmest year in the Sea of Okhotsk. Therefore, the warm conditions in the Sea of Okhotsk in 2005 were determined not only by the most intensive water transport by the West Kamchatka Current but also by the high heat budget of propagated waters. The situation was almost repeated



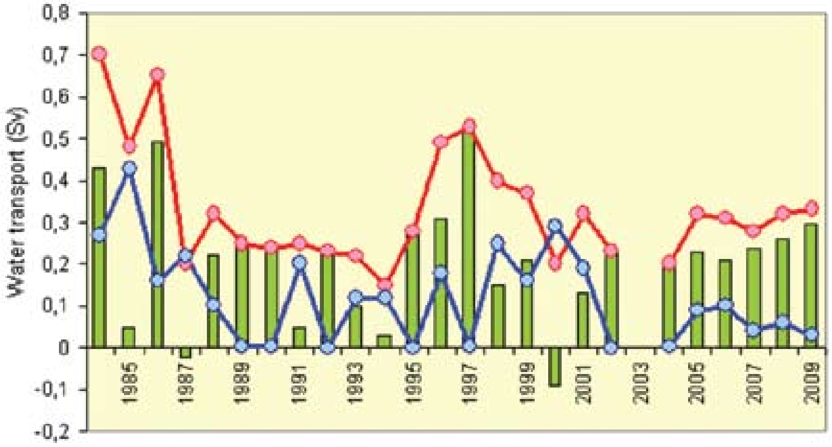
[Figure OK-11] SST anomalies (°C) in the northwestern Pacific Ocean in August of 2002-2009 (after Figurkin et al. 2008) with additions for the last years.

in 2008 when positive SST anomalies covered not only the Sea of Okhotsk but also the Pacific Ocean off Kamchatka and the Kuril Islands (Fig. OK-11).

Thermal conditions in the northern Sea of Okhotsk are also dependent on the distribution of West Kamchatka Current waters. In winter, the circulation pattern in the northern Sea of Okhotsk varies with the ice cover conditions (Figurkin et al. 2008). The most significant extremes were an icy 2001 and an iceless 1997. In the iceless winters, relatively warm waters of the West Kamchatka Current propagated westwards farther than 148°E longitude. In winter of 1997, they even reached the Okhotsk Settlement coast (59°23' N 143°18' E). In icy winters, the West Kamchatka Current waters did not penetrate the northern shelf area farther than 149° - 150°E. In 2001, there was a unique situation, when these warm waters did not reach the shelf on the whole. The warming influence of the West Kamchatka Current was limited by the continental slope in the TINRO Basin and the Shelikhov Bay mouth. The Compensational Current (Figurkin et al. 2008) flows in the opposite direction (southward) to the West Kamchatka Current and carries away penetrations of relatively warm waters. This current has intensified slightly since 1998 (Fig. OK-12). The balance of the relatively warm water transport on the northern shelf shifted to negative values in 2000. Since 2002, the volume of the poleward water transport and total transported waters balance was restored and has persisted at an average level of 0.31 Sv.

Correlation between ice extent and cold, saline water on the northern shelf diminished during 2002-2008 (Fig. OK-13). In 2002 and 2004, lower amounts of dense salty water corresponded with a reduction in ice cover. However, the correlation was disrupted after the relatively ice-free winters of 2005 and 2006 (Fig. OK-13). After the winter of 2006, negative temperature anomalies occupied almost all shelf areas. Note that the intensity of the southward flowing Compensational Current in 2005 and 2006 was maximal in these years. In 2007, the situation resembled what had occurred in 1997, at least in the northeastern part of the Sea of Okhotsk where the intensity of southward flow along the Kamchatka Peninsula decreased (Fig. OK-12). The diminished correlation likely emphasizes a growing significance of spring conditions and the changing formation of warmer waters suggests a change in the thermal structure of the Sea of Okhotsk shelf waters since 2005 (Figurkin et al. 2008).

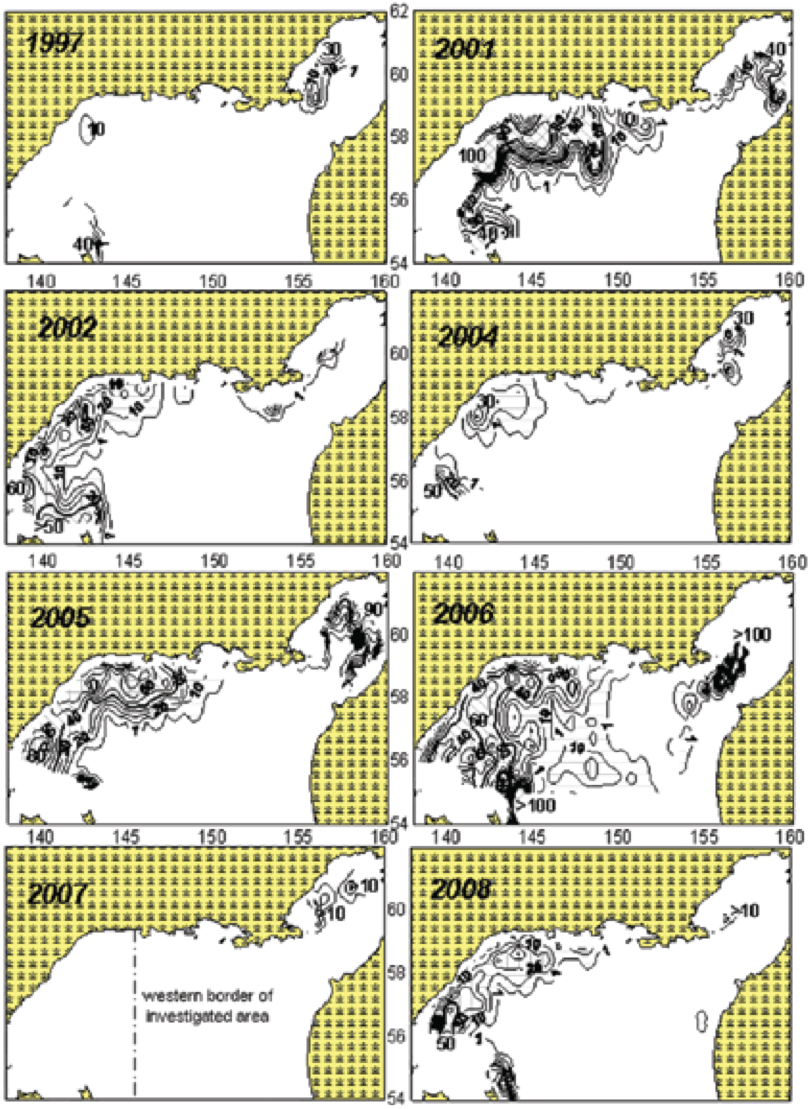
In the southern Sea of Okhotsk where circulation patterns were traditionally determined by the locations of eddies, hydrographic conditions were more stable than in the north. In the month of August, SST has increased gradually through the focus period, from negative anomalies (>2°C) covering nearly the whole region in 2002 (see Fig. OK-11). From 2006 to 2008, SST anomalies in the southern Sea of Okhotsk in August were positive despite a noteworthy decreased in temperature in 2007. In 2009, negative SST anomalies in August returned. In autumn (October-November), SST in recent years was the lowest in 2001 (Table OK-2). Autumns of 2004, and 2006-2008 can be defined as relatively warm. In 2005, there was local cooling related to more intensive water transport by the East Sakhalin Current from the northern shelf and more intensive seasonal vertical water mixing after the SST maximum in August.



[Figure OK-12] Water transport (1,000,000 m³·s⁻¹) in the upper 200 m in April to early May along the Kamchatka Peninsula west coast from 1984-2009 in the West Kamchatka Current northern branch (red) and Compensative Current (blue). Columns indicate northward and southward transport.

[Table OK-2] Mean water temperature at the different depths in the southern Sea of Okhotsk, October – November 2001-2008. (after Figurkin et al. 2008).

| Year | 0 m | 50 m | 100 m | 150 m | 200 m |
|---|---|---|---|---|---|
| 2001 | 6.62 | 3.53 | 0.43 | 0.77 | 0.90 |
| 2002 | 7.92 | 2.98 | 0.81 | 1.06 | 1.09 |
| 2003 | 8.06 | 3.04 | 1.19 | 1.17 | 1.18 |
| 2004 | 7.78 | 4.10 | 1.07 | 1.10 | 1.25 |
| 2005 | 6.95 | 3.68 | 0.87 | 0.95 | 1.06 |
| 2006 | 7.54 | 3.51 | 0.96 | 1.17 | 1.30 |
| 2007 | 7.37 | 3.03 | 0.76 | - | 1.28 |
| 2008 | 7.42 | 3.18 | 0.85 | - | 1.16 |
| Average | 7.46 | 3.38 | 0.87 | 1.04 | 1.15 |

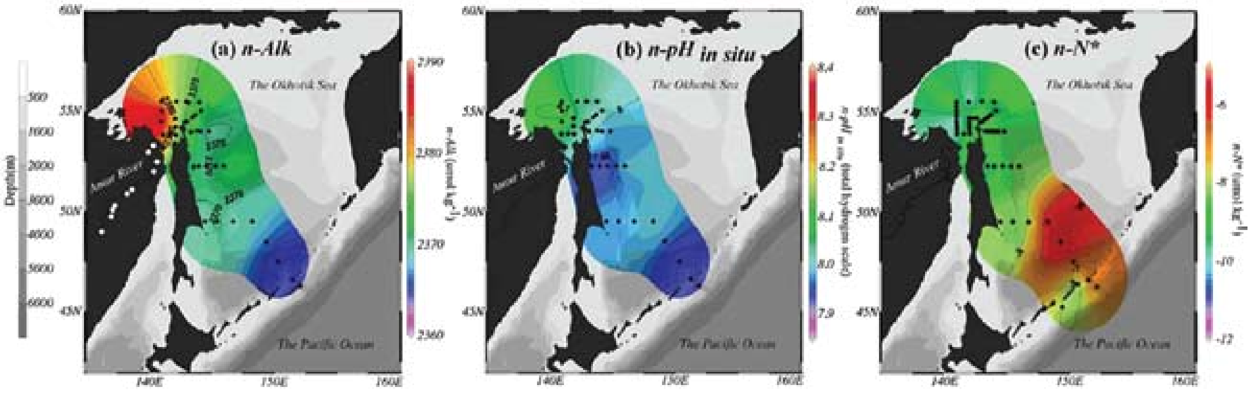


[Figure OK-13] The thickness (m) of near-bottom water layer with temperatures ≤1.5°C and salinity ≥33.2 psu in the northern Sea of Okhotsk in spring of 1997, and 2001-2008 (after Figurkin et al. 2008) with additions for the last years.

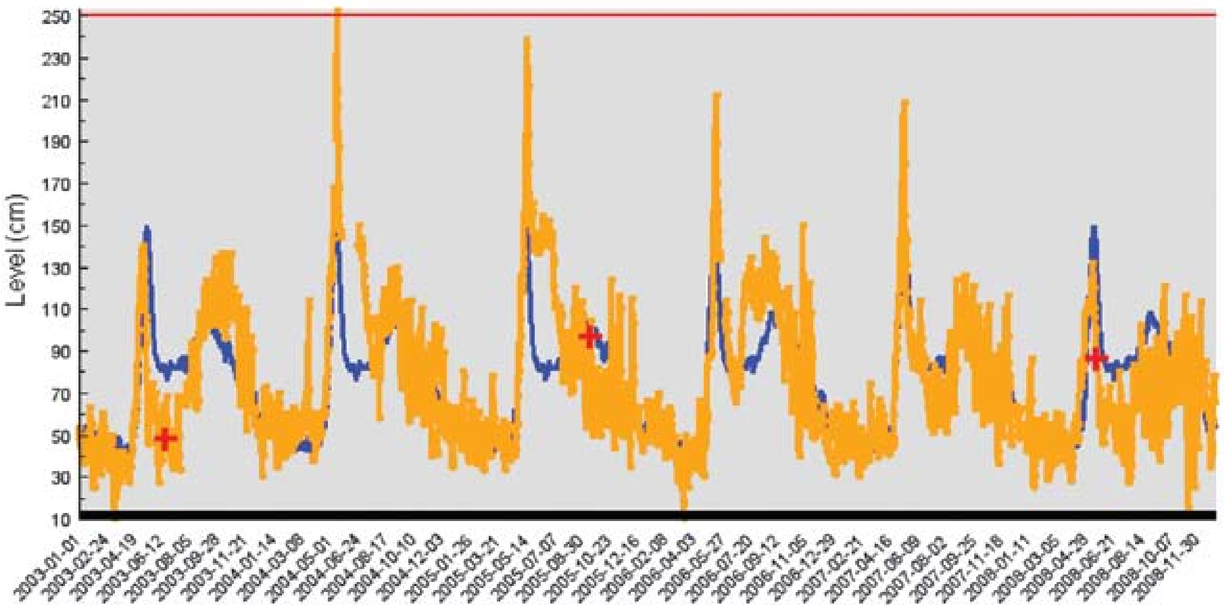
## 4.0 Chemical Ocean *(Radchenko, Nishioka)*

The high biological productivity in the Sea of Okhotsk is a result of nutrients that enrich the surface layer during the period of intensive vertical mixing in autumn and winter. They are almost completely used by phytoplankton during the spring bloom. Production continues through the summer by nutrient recycling and by upwelling. The post-winter nutrient concentrations in the deeper parts of the Sea of Okhotsk are roughly: 1000-1250 mmol·m$^{-2}$ of nitrogen, 60–100 mmol·m$^{-2}$ of phosphorus, and 1000–1500 mmol·m$^{-2}$ of silica (Arzhanova and Zubarevich 1997). Amur River discharge also contributes notably to the Sea of Okhotsk chemistry including an effect on the acid-base balance (Watanabe et al. 2009).

Hydrochemical studies were not conducted regularly in the Sea of Okhotsk from 2003 to 2008 although a few expeditions were associated with other scientific projects (KOMEX, Amur-Okhotsk Project, TINRO-Center cruises). An expedition on the R/V *Professor Khromov* sampled the water column from 0 m to 3000 m at 34 stations in a region of intermediate water formation, measuring alkalinity and dissolved inorganic carbon. At 51 stations samples were collected for nutrient assays ($NH_3$, $NO_2$, $NO_3$, $PO_4$, $Si(OH)_4$, DO) during August to early September in 2006 (Fig. OK-14, after Watanabe et al. 2009). An index of nitrogen fixation-denitrification was estimated from the collected and normalized nutrient data as N* (= [NO3] + [NO2] + [NH3] - rN/P * [PO4] + 2.9. Significant changes of alkalinity, pH, and nitrogen fixation-denitrification indices were identified in subsurface waters (26.5 – 27.3 $\sigma_\theta$) in comparison with 1999-2000. Salinity-normalized alkalinity increased by 2.6±0.1 mmol·kg$^{-1}$·y$^{-1}$ while the increase in dissolved inorganic carbon (DIC) was almost half of that of alkalinity. Therefore, pH has increased by 0.013 ± 0.001 pH unit·y$^{-1}$ (Watanabe et al. 2009). On the other hand, the rate of change of the n-N* index was from -0.8 to -0.5 mmol·kg$^{-1}$·y$^{-1}$ which implies an intensification of the denitrification process in the intermediate waters in the Sea of Okhotsk. It was also reported that the increase of alkalinity in the Amur River was the dominant cause for the increased alkalinity in the Sea of Okhotsk from 1999 - 2006. The average concentration of $Ca^{2+}$ in the Amur River increased from 0.16 to 0.26 mmol·l$^{-1}$ from 1999-2006 and the discharge of the Amur River has been increasing over the past five years at an average of 2.2×10$^{10}$ m$^3$·y$^{-1}$ (Watanabe et al. 2009). Amur River water levels exceeded the multi-year average from 2003-2008 (Fig. OK-15). Bottom sediments are another notable deep water source of $Ca^{2+}$ due to intensive geochemical activity in the near-bottom layer of the Derjugin's Basin (Pavlova et al. 2008).

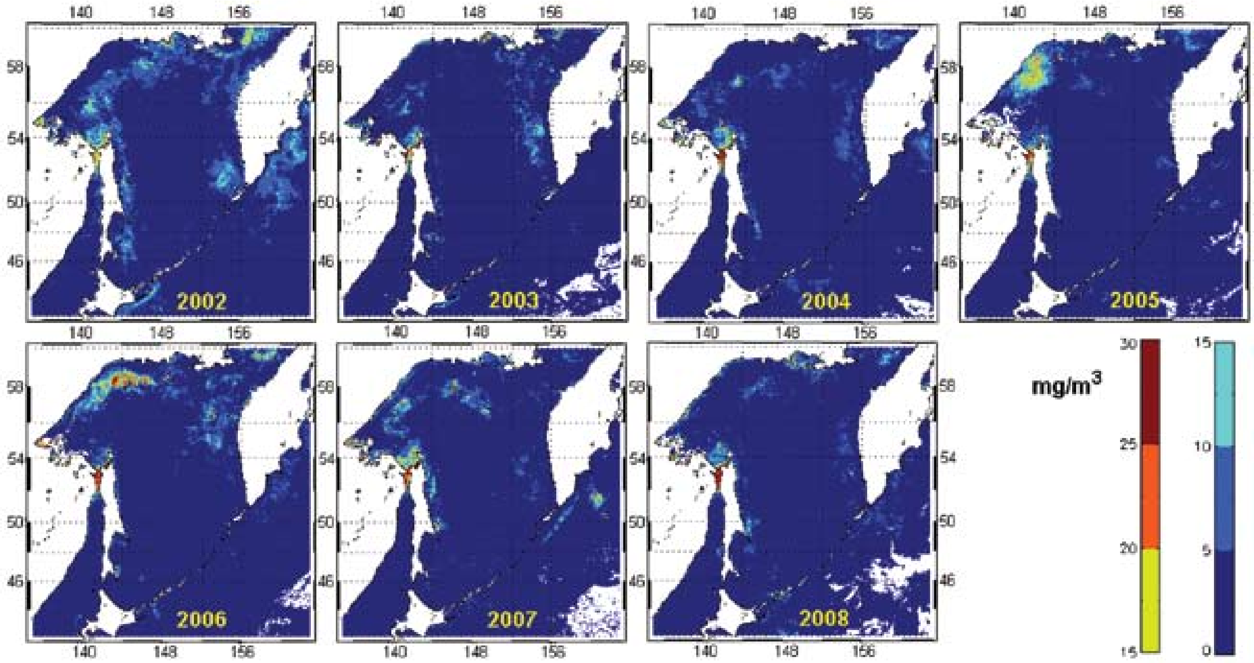


[Figure OK-14] Distributions of (a) n-Alk, (b) n-pH *in situ* and (c) n-N* on the 26.5$\sigma_\theta$ isopycnal in 2006. Black and white circles are the oceanic and riverine sampling locations. Pairs of n-Alk and n-DIC, were used to calculated n-pH *in situ* based on Dickson and Goyet (1994). After Watanabe et al. (2009).



[Figure OK-15] Dynamics of the Amur River water-level at the Nikolayevsk control post, 2003-2008. Floodplain height is indicated by orange line. Blue line indicates the multi-year average. Red crosses indicate corrected data. Data/image are courtesy of FSUE Center of Register and Cadastre in Khabarovsk, Russia.

Waters around the Kuril Islands have high concentrations of iron (Nakatsuka et al. 2004; Nishioka et al. 2007). The main sources of iron in the water column are atmospheric deposition, fluxes from sediments, and regeneration. The contributions from riverine discharge are small (Okunishi et al. 2007). Iron plays an important role in maintaining high primary production in the Sea of Okhotsk. Dense Shelf Water that is formed in the polynyas of the northwestern shelf during winter plays an essential role in transporting all chemical materials. Chlorofluorocarbons (CFCs) and dissolved inorganic carbon (DIC) concentrations in this water are high and almost saturated with respect to atmospheric CFCs, indicating that the Dense Shelf Water experiences active gas exchange with the atmosphere during its formation (Wong et al. 1998; Yamamoto-Kawai et al. 2004; Wakita et al. 2003). Due to strong tidal mixing on the shelf, Dense Shelf Water contains large amounts of re-suspended sedimentary particles, which include particulate and dissolved organic carbon (POC, DOC) and iron (Nakatsuka et al. 2002, 2004; Nishioka et al. 2007). Therefore DIC, CFCs, POC, DOC, and iron are transported with this water from the northwestern shelf of the Sea of Okhotsk to the Kuril Basin via intermediate water transport. These intermediate waters affect the chemical properties of the North Pacific Intermediate Water (Tally 1991; Watanabe et al. 1994; Hansell et al. 2002; Nishioka et al. 2007; Yamashita and Tanoue 2008).



[Figure OK-16] Chlorophyll concentrations (mg·m⁻³) in the Sea of Okhotsk surface layer from 2002 to 2008, averaged for April-June of each year. Data are from TeraScan remote sensing, SakhNIRO, Yuzhno-Sakhalinsk.

# 5.0 Biological Ocean

## 5.1 Phytoplankton and primary production *(Radchenko, Dulepova, Tsoy)*

The ungrazed spring production is estimated at 500,000 cal·m⁻², or about 52 gC·m⁻² (Sorokin and Sorokin 1999). Diatom blooms occur in spring but also in autumn in the western Sea of Okhotsk. The estimated seasonal proportions of production are: 35% in spring, 45% in summer, 18% in autumn, and 2% in winter (Shuntov 2001). Nakatsuka et al. (2004) considered that silicate chemistry must play an important role in the growth of phytoplankton in both spring and autumn in this region. Whereas nitrates are used first by phytoplankton cells, they can be supplemented by recycling. Silicate recycling, on the other hand, is complicated by slow rates of dissolution of diatom frustules and their rapid sedimentation (Arzhanova and Zubarevich 1997). In spring and autumn, the maximum concentration of chlorophyll is located at the uppermost depth at which silicate can be detected. The surface layer of the western Sea of Okhotsk is continuously re-supplied with silicate because of riverine input, especially by the Amur River which provides large amounts of nutrients, especially silicate, to the surface water (Nakatsuka et al. 2004; Nagao et al. 2008). Biological production, especially diatom production, along the East Sakhalin Current may be influenced directly by Amur River discharge into this region, as well as being influenced by re-suspended nutrients from the shelf (Andreev and Pavlova 2010).

While the skill of determining chlorophyll concentrations from remote sensing data is still under discussion, interannual comparisons from ocean color data are informative. The lowest chlorophyll concentrations occurred in 2003 and 2008 corresponding to lower Amur River discharge in those years (Figs. OK-15, OK-16). Near the Hokkaido coast, the phytoplankton bloom timing was closely related to ice conditions. Longer ice cover in 1999, 2001 and 2003 with the presence of ice until early April and shortened ice cover in 1998, 2000, 2002 and 2004 with the occurrence of ice until early March were recognized at this area (Mustafa and Saitoh 2008). Higher chlorophyll concentrations were observed in the initial bloom when sea ice melting was delayed. As sea ice extent decreased in the southern Sea of Okhotsk after 2004, it may have influenced gross primary production in those waters.

## 5.2 Zooplankton *(Radchenko, Dulepova)*

New data on the Sea of Okhotsk zooplankton were obtained in the 2000s confirming previous observations of region-specific characteristics made from the 1980s to the beginning of the 1990s (Volkov 1996; Shuntov 2001; Dulepova 2002). Zooplankton biomass and distribution in the epipelagic layer have varied at interannual and longer periods (Fig. OK-17). Nighttime sampling in the Sea of Okhotsk can be stratified by period: 1984-1990, 1991-1995, and 1996-2006. Average zooplankton biomass in the epipelagic layer over the shelf was highest in the early 1990s and approximately equal before and after that period. Over the continental slope, biomass was lowest in the early 1990s and highest in the more recent period. Over deeper waters, biomass declined after the 1980s reaching its lowest level in the 1996–2006 period.

Taxonomic and size-based measures of diversity of zooplankton differ because of daily vertical migration as well as from seasonal changes. Average zooplankton concentrations in the upper layers decrease during the cold season. Within the top 200 m layer, the magnitude of the overall decrease is generally twofold, and rarely threefold so the epipelagic layer remains inhabited by zooplankton even in winter (Volkov 1996; Shuntov et al. 1993; Shuntov 2001). High zooplankton biomass, especially in spring, summer and autumn, create favorable conditions for planktivorous fish (Table OK-3).

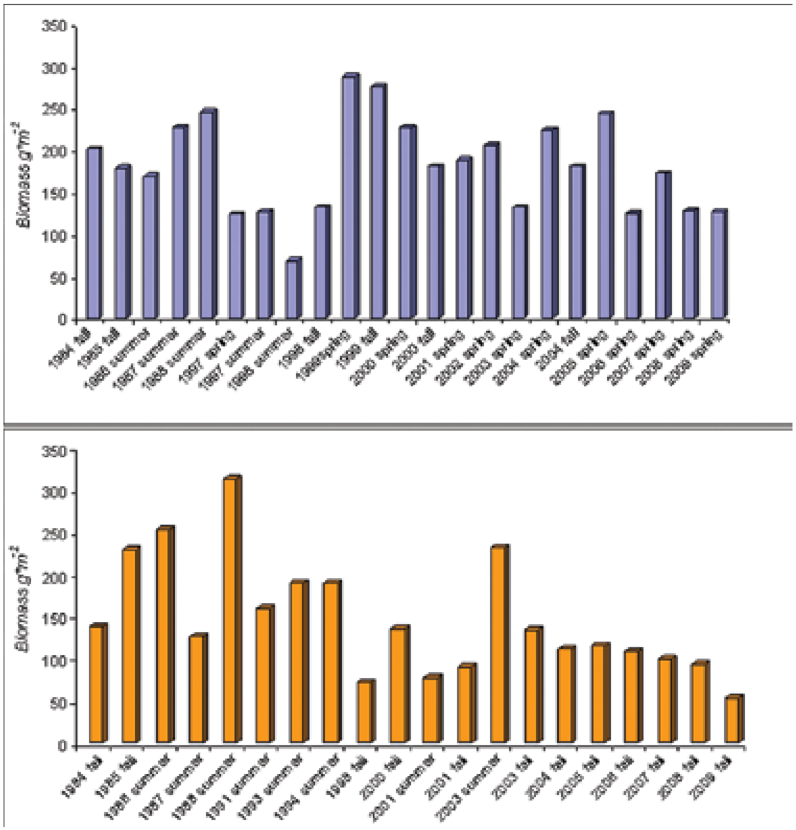
| | 1984-90 | 1991-95 | 1996-06 |
|---|---|---|---|
| 1 | 1261 | 1525 | 1218 |
| 2 | 1055 | 812 | 1139 |
| 3 | 1159 | 1022 | 793 |

[Figure OK-17] Long-term average composition (%) and biomass (mg·m$^{-3}$) of night-time macroplankton in the Sea of Okhotsk epipelagic layer in three regions: (1) inner shelf, (2) outer shelf and continental slope and (3) deepwater. Portion of macroplankton in the total plankton biomass is indicated in brackets. After Shuntov et al. (2007).

[Table OK-3] Average biomass (mg·m$^{-3}$, wet weight) of night-time zooplankton in the Sea of Okhotsk in the different seasons, 1984-2006.

| Season | Biomass |
|---|---|
| Winter | 452-2019 |
| Spring | 1057-6890 |
| Summer | 1151-2042 |
| Autumn | 630-1948 |

Interannual analysis of the size and taxonomic composition and trophic structure in the Sea of Okhotsk identifies two plankton communities: northern and southern. In the southern Sea of Okhotsk, the macroplankton portion of the total zooplankton biomass is always higher (76-92%) than in the northern part (56-78%). Portions of small and medium zooplankton are correspondingly lower in the southern part. Euphausiids and copepods predominate in the northern and southern communities, ranking either first or second place by biomass. Usually, copepods predominate in the south and euphausiids in the north. Productivity of the plankton communities was higher in the north during the period of investigation (1997-2006) since animals with higher individual production rates predominate there (Dulepova and Merzlyakov 2007). Faster growing small- and middle-sized zooplankton are more abundant in the north and the portion of predatory planktonic animals is notably lower. Multi-year monitoring reveals the cyclic nature of zooplankton biomass with a multi-year period (Fig. OK-18) and occasional extremes. Zooplankton biomass was low for the entire period of observation throughout the Sea of Okhotsk in 1998. During the focus period, no trends were evident in Sea of Okhotsk zooplankton biomass or distribution. In general, during the last 25 years, zooplankton standing stock has not decreased below a level that would limit the abundance of things that eat zooplankton (Shuntov et al. 2007).



[Figure OK-18] Long-term dynamics of the average biomass (mg·m$^{-2}$) of zooplankton in the northern (upper) and southern (lower) Sea of Okhotsk from 1984 to 2006. Update from Shuntov et al. (2007).

# 6.0 Fishes and Invertebrates

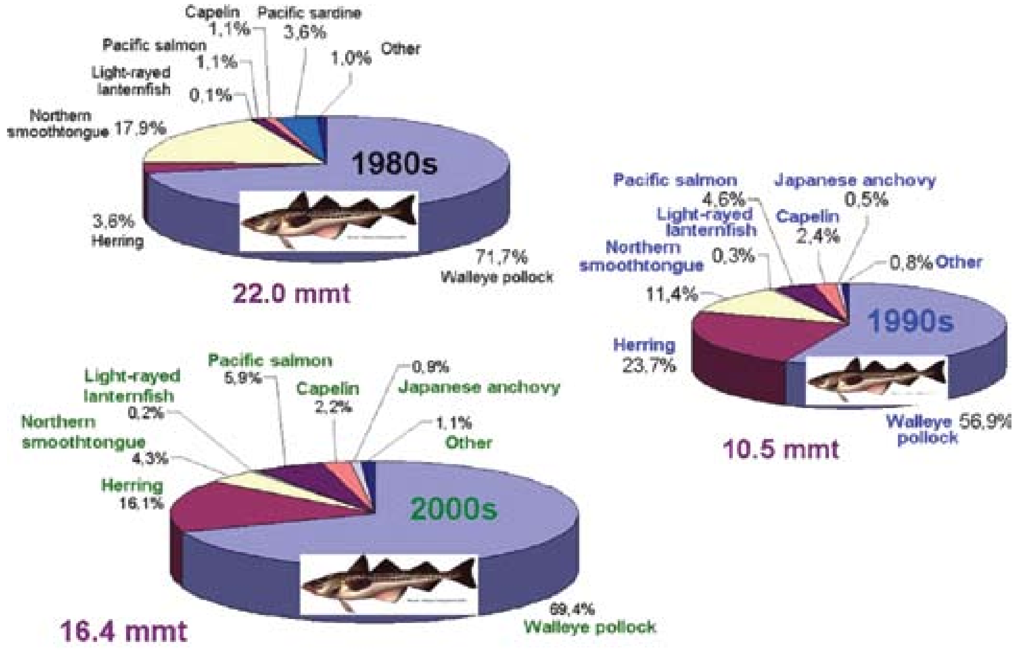
*(Radchenko)*

In the 1980s, total fish biomass in the Sea of Okhotsk was likely >55 million metric tons (mmt) with walleye pollock at about 15.6 mmt, groundfish at 5.7 mmt, and other epipelagic fish at 2-3 mmt (Fig. OK-19). The predominance of walleye pollock in the Sea of Okhotsk pelagic fish community was evident for those years (Shuntov et al. 1993). About 1 mmt of Pacific sardine migrated annually into the Sea of Okhotsk for summer feeding until the beginning of the 1990s. The estimated biomass of mesopelagic nekton was 27.8 mmt (Iljinskiy and Gorbatenko 1994). Other gadid fish (Pacific cod and saffron cod) also had high biomass in the demersal fish community on the shelf. Among the benthic groundfish, grenadiers predominated with biomass of about 2.0 mmt and small flatfish species combined for a total of 0.94 mmt. Pacific cod biomass reached 0.66 mmt, saffron cod 0.2 mmt, Greenland turbot 0.57 mmt, eelpouts 0.43 mmt, skates 0.37 mmt, and others 0.57 mmt.

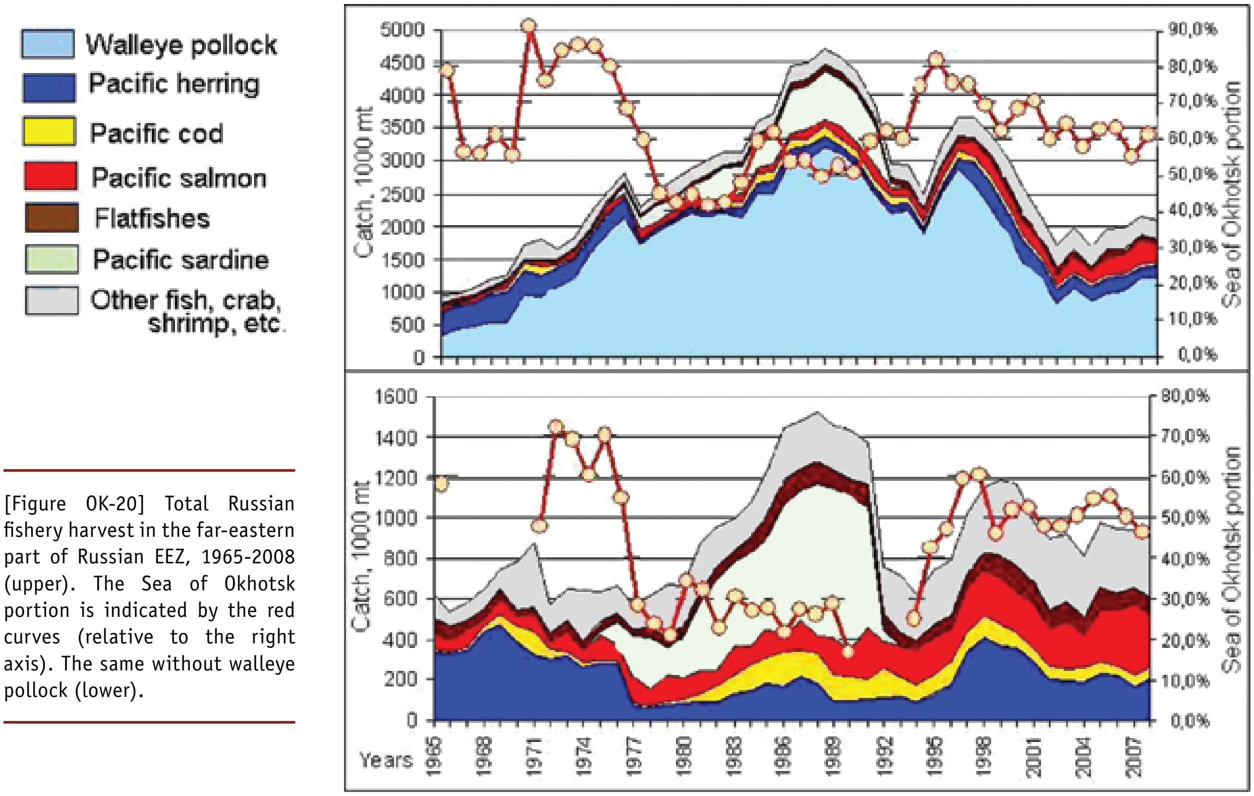
There is an opinion that the maximum biomass of commercial fish species is observed in the North Pacific during warm periods (Klyashtorin and Lyubushin 2005). The 1980s were warmer and notably more productive years for fish harvests than the relatively cool period during the late 1990s. The years 2003-2009 were a period of stabilization and gradual growth in abundance of the pelagic fishes, especially walleye pollock, groundfish species, and notably, Pacific salmon (Fig. OK-20, Fig. OK-21).

## 6.1 Walleye pollock

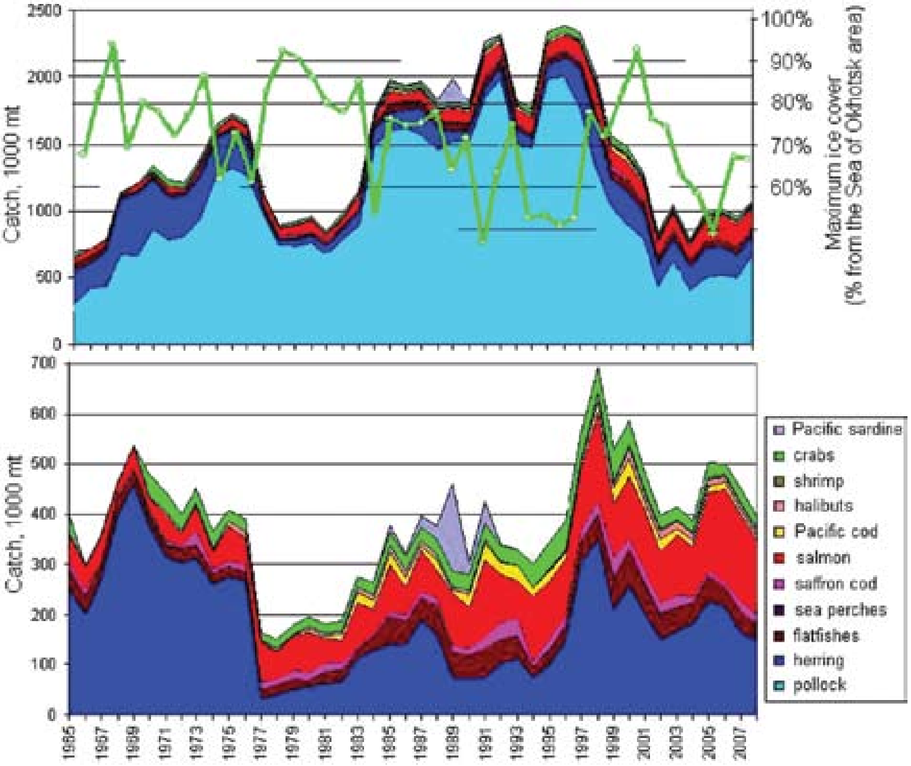
The walleye pollock is a relatively long-lived fish that keeps the fishery in good conditions when the stock consists of several strong and super-strong year-classes. When in poor condition it is usually made up of solely one strong year-class. Two strong year-classes in 1995 and 1997 maintained an exploitable level of biomass in the first half of the 2000s (Fig. OK-22). The 2004 and 2005 year-classes initially appeared to be relatively strong and this was reflected later by surveys and fishery statistics. In 2009, the walleye pollock spawning stock increased by 10.1 billion fish with the 2004 and 2005 year-classes accounting for 80% of this growth. The combination of an intensive inflow of Pacific water with the West Kamchatka Current, a low intensity of the Compensating Current, and mild ice conditions create favorable pre-conditions for strong recruitment. There are weak correlations between the Compensative Current volume transport and walleye pollock year-class abundance at age 2 (with lag = 2 years): r = -0.46, year-class abundance in ages 3-4, r = -0.30 (with lag = 3.5 years).



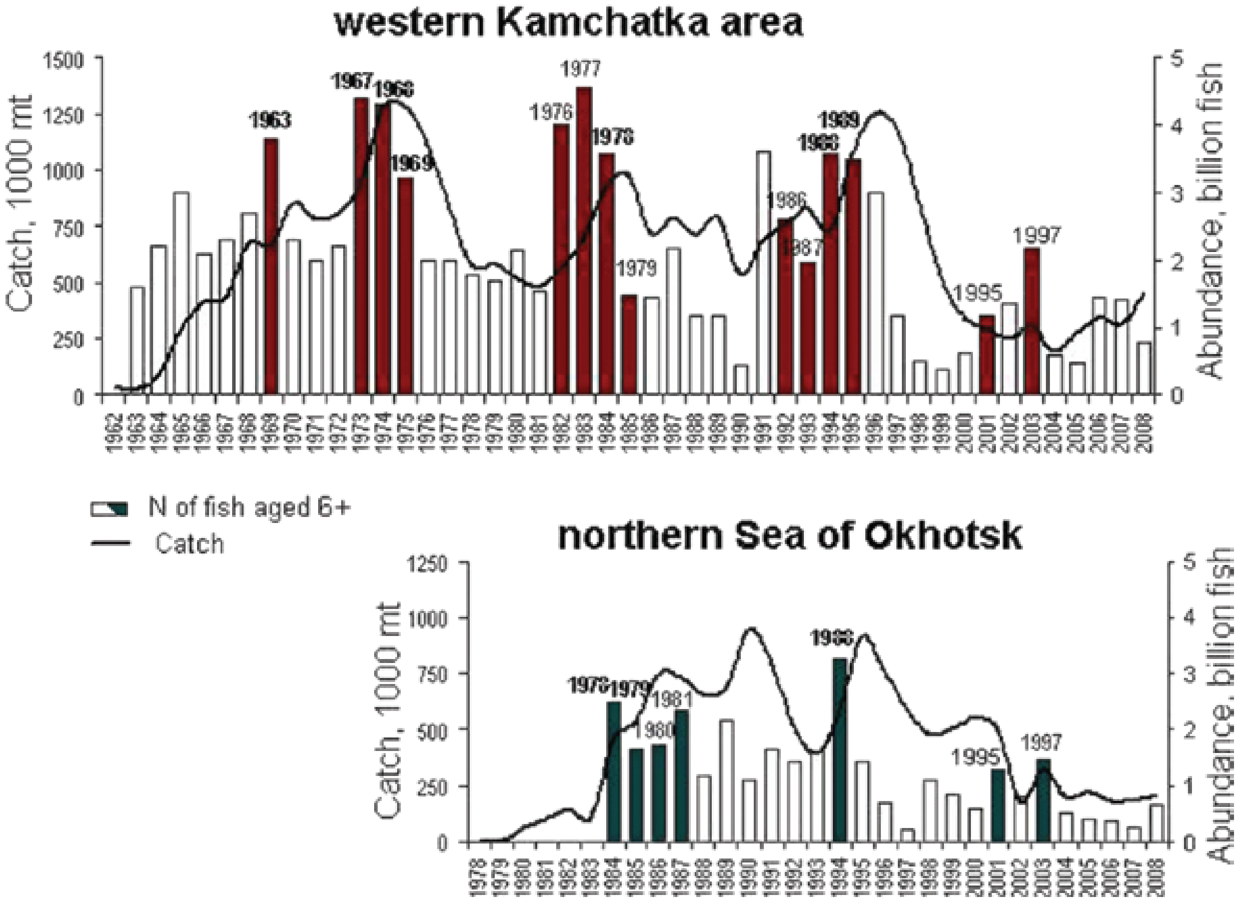
[Figure OK-19] Quantitative composition of the epipelagic fish community in the Sea of Okhotsk in the 1980s, 1990s, and 2000s (2000-2005).



[Figure OK-20] Total Russian fishery harvest in the far-eastern part of Russian EEZ, 1965-2008 (upper). The Sea of Okhotsk portion is indicated by the red curves (relative to the right axis). The same without walleye pollock (lower).



[Figure OK-21] Total Russian fishery harvest in the Sea of Okhotsk, 1965-2008 (upper). The maximal ice cover in the Sea of Okhotsk is indicated by the green line (relative to the right axis). The same without walleye pollock (lower).



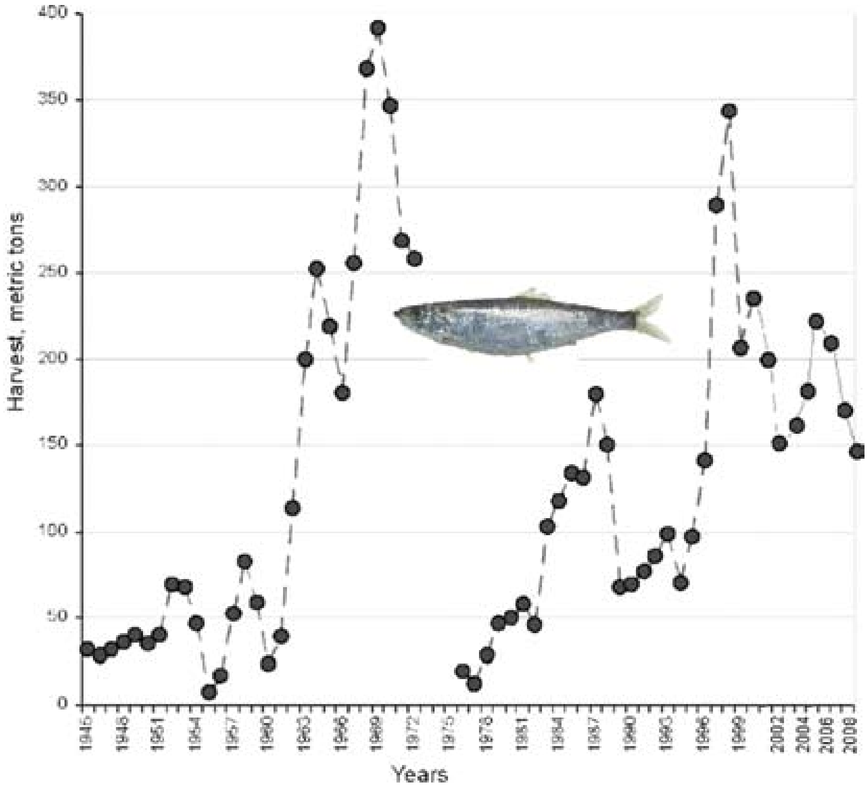
[Figure OK-22] Walleye pollock catch in the northern and north-western Sea of Okhotsk and abundance of fish aged 6+, 1962-2008 (after Ovsyannikov 2009). Bars indicating strong year-classes are colour-filled with the year of occurrence indicated above each.

## 6.2 Herring

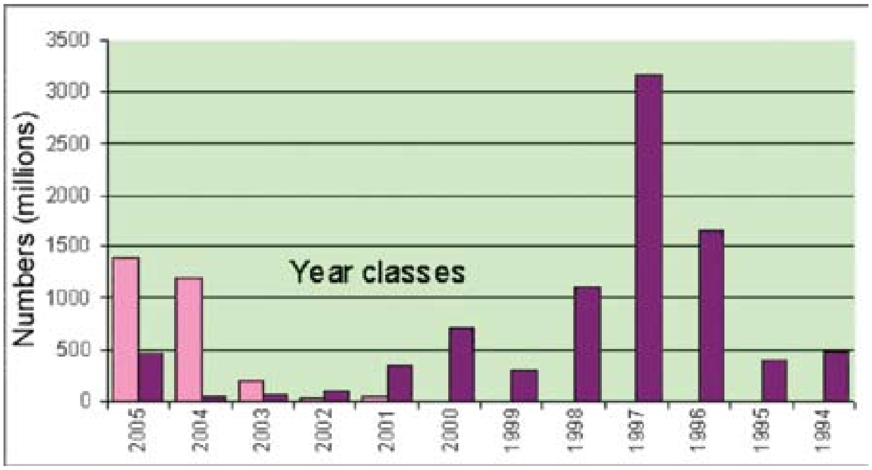
In the northern Sea of Okhotsk, herring biomass reached 2.5 mmt in 1997 and 3.0 mmt in 2003-2004. In recent years, the herring stock declined and the annual harvest was <150,000 t (Fig. OK-23). A decrease was anticipated due to a lack of strong year-classes in the first half of the 2000s (Fig. OK-24, after Loboda 2007). In 2006, herring biomass decreased to 2.5 mmt, and by 2007 it was <1.24 mmt (Loboda 2008).

## 6.3 Groundfish

Biomass declined suddenly (and unexpectedly) in 1998 from 1.437 to 0.849 mmt and continued at 0.623 mmt in 1999, and 0.645 mmt in 2000. Thereafter, groundfish biomass began growing and returned to higher levels of the 1980s by 2005. The decline was caused by reductions in common flatfish species and Pacific cod, whose biomass decreased fourfold. Increases in saffron cod and several sculpin species were responsible for the growth observed in 2005. These dynamics cannot be explained by fishing pressure since the harvest rates never reached the recommended TAC for common groundfish. Increasing biomass was observed in several regions of the northwestern Pacific, including the southwestern Bering Sea (Balykin 2006). These changes have been attributed to a climate regime shift and autocorrelation processes in the fish populations (Shuntov et al. 2007).



[Figure OK-23] Okhotsk herring stock harvest by the Russian fishery, 1945-2008. Fishing was prohibited from 1973-1975.



[Figure OK-24] Numbers of Pacific herring (1+ and older) in the autumn of 2006 in the northeastern Sea of Okhotsk (rose, n = 2.68 billion) and northwestern Sea of Okhotsk (purple, n = 8.48 billion). After Loboda (2007).

## 6.4 Capelin

Capelin was abundant in the pelagic communities during the period of low abundance of walleye pollock and herring in the 1970s. In the early 1990s capelin abundance in the Sea of Okhotsk increased for only two-three years. Since 2002, there was a new "splash" of capelin in the northeastern and southwestern parts of the Sea of Okhotsk. Near the East Sakhalin coast, capelin biomass was estimated at 0.5 mmt in 2001. The historically high spawning abundance occurred in 2002 (Velikanov et al. 2003). The spawning stock biomass on the southern Sakhalin coast exceeded 0.13 mmt, but there was no comparable abundance in the 2003-2009 when the spawning stock did not exceed 6,000 t. On the West Kamchatka coast, capelin was abundant in 2001-2003 when the harvest reached 1600-1750 t (Naumova 2008). From 2004 to 2007, it decreased to an average of 516 t and dropped to 60 t in 2008. These abundance dynamics follow the positive trends of walleye pollock abundance in recent years.

## 6.5 Pacific Salmon

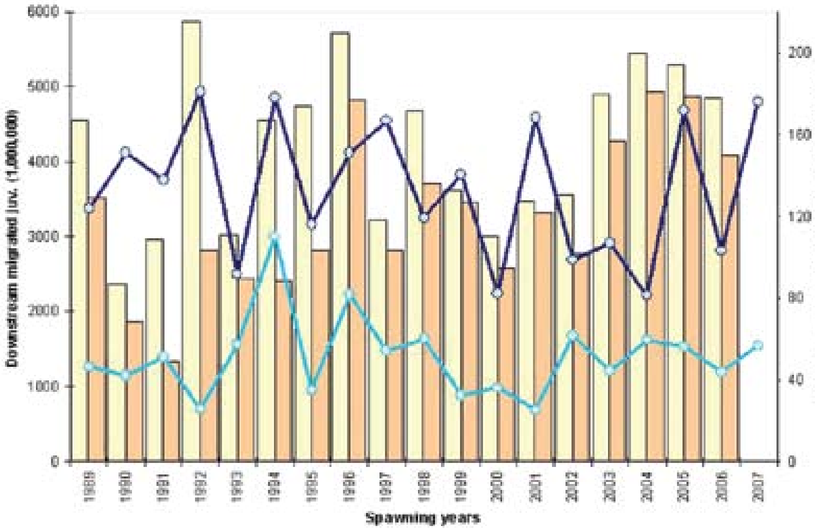
### 6.5.1 Pink salmon

The dynamics of pink salmon abundance in the Sea of Okhotsk basin did not undergo significant changes in the 2000s (Fig. OK-25). Returns of pink salmon continued to increase in both even- and odd-year cycles and coastal catches in 2006 and 2007 reached record highs of 180,700 and 178,500 mt, respectively. In 2008, the total Russian catch of pink salmon decreased slightly including that of the Sea of Okhotsk. Compared with the 1990s, the number of outmigrating juveniles increased by 13.2% for odd year spawners, and decreased by 34.6% for even year spawners (Fig. OK-25). The difference is likely related to the divergence that is apparent in the abundance trends for the odd- and even-year cycles (Radchenko 2006).

High yielding pink salmon populations like the odd-year East Sakhalin stock and the even-year West Kamchatka stock were characterized by high abundance in the 2000s. On the other hand, the odd-year West Kamchatka pink salmon stock had a catch of 15,600 t in 2007 after zero catches during the 1990s and negligible catches (54-322 t) at the beginning of the recent decade. On the East Sakhalin coast, the situation was even more extreme with 86,000 t caught in 2006. That year, the annual catch in Aniva Bay (south Sakhalin Is.) exceeded the previous regional historical high (1994) by 5.5 times.

Return rates calculated from total pink salmon fry outmigration exceeded 20% (Kaev 2007). Some have linked these unexpectedly high abundances with the success of the hatchery program. Another hypothesis is a "change of dominance" event, which sometimes occurs in the regional pink salmon groupings. However, the abundance of these pink salmon broodlines began to decrease in all regions of the Sea of Okhotsk coast. It is remarkable that the decreasing abundance of these formerly non-productive populations along the eastern and western Kamchatka coasts has occurred during the freshwater stage not during the early marine or oceanic stages (E. Shevlyakov, pers. comm.).

On the Japanese coast, pink salmon are found mainly in eastern Hokkaido. Their population size was low, ranging from one million individuals for the even year cycle to two million for the odd year cycle during the 1970s and 1980s. In the early 1990s, however, the population increased sharply and shifted from odd-year to even-year dominance. More recently, odd-year dominance has resurged (Nagata 2009).



[Figure OK-25] Pink salmon escapement (light blue line, right ordinate axis) and numbers of downstream migrants (navy line, left ordinate axis) superimposed on total returns (light columns) and catch (darker columns) of corresponding brood years in the Sea of Okhotsk, 1989-2007. Note that the years indicated are spawning years of the parent broodline.

### 6.5.2 Chum salmon

Russian catches of chum salmon continued a gradual growth. In 2008, the chum salmon harvest by coastal fishery doubled in comparison with 2004 and reached 62,200 t (45,368 t in the Sea of Okhotsk basin). After 2005, almost all notable chum salmon groupings showed increasing abundance. Trends for southern and northern regions became slightly different in the last three years. Southern chum salmon populations had significant increases in fishery yields, especially in the Amur River and southern Kuril Islands (Fig. OK-26). The latter can be attributed to hatchery program development. Declining abundance in chum salmon populations at their southern range limit (due to global warming) was not observed on the Russian coast. Although Hokkaido chum salmon have maintained high abundance (over 40 million fish), recent return rates have varied between brood years and between local populations. Return rates of chum salmon on the Sea of Okhotsk side of Hokkaido have increased sharply since the 1990s. The same trend occurred on eastern Sakhalin Island (Fig. OK-27). In contrast, return rates of chum salmon toward the southern extent of their range in Asia, including those released from Korean, have declined (Fig. OK-28). High mortality of chum salmon occurs in their early ocean life. Recent coastal studies in the Sea of Okhotsk suggest that a long period of optimal seawater temperature from 8-13°C in coastal waters after seaward migration may positively effect survival of chum salmon (Nagata et al. 2007). However, if a decrease in sea ice is caused by global warming, optimal seawater temperatures for chum may become scarce within 50 years.

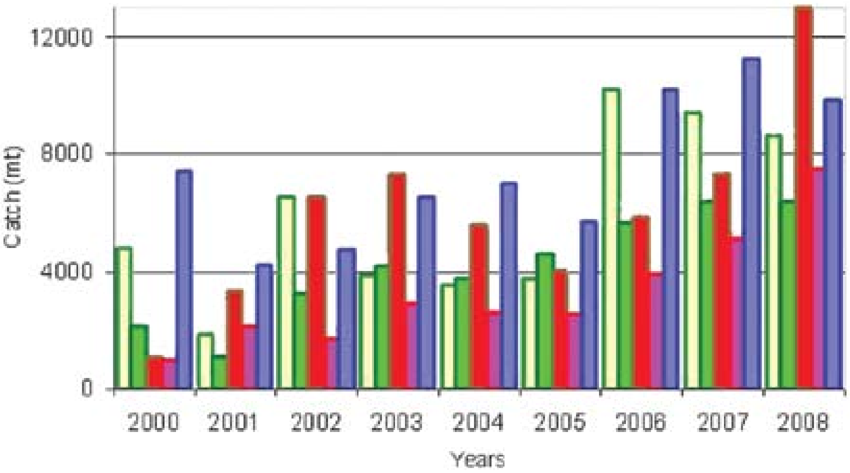
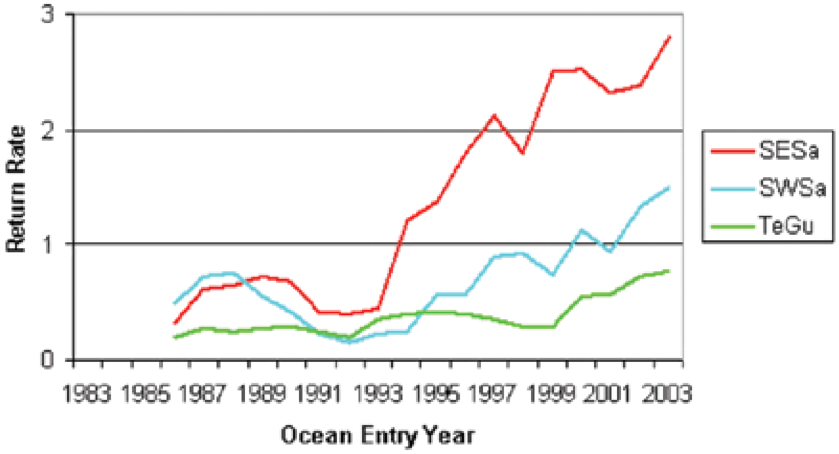
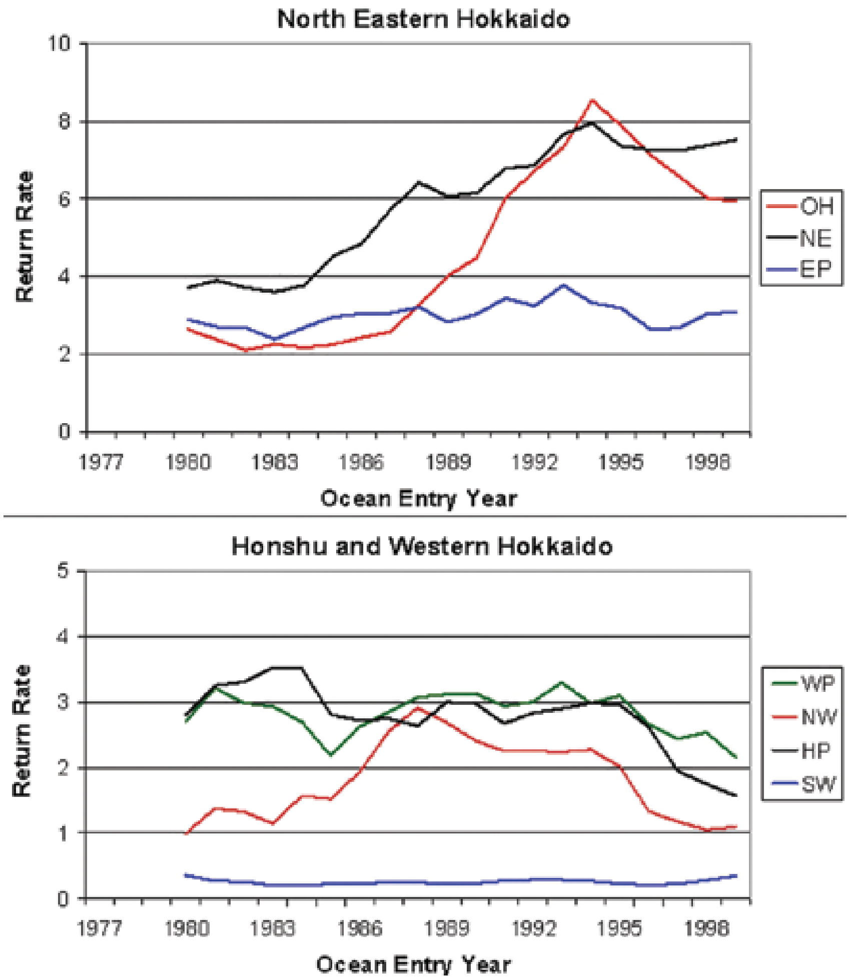


Figure OK-26 Russian chum salmon catch in the main fishery regions in the Sea of Okhotsk, 2000-2008. Columns (from left to right): western Kamchatka Peninsula, eastern Sakhalin, southern Kuril Islands, Amur River, northern Sea of Okhotsk coasts.



[Figure OK-27] Four year running average of return rates (%) starting at 1983-1986 ocean entry year for hatchery chum salmon from Sakhalin Island (data from Kaev and Ignatiev 2007, courtesy of A. Kaev). Regions are indicated by SESa for SE Sakhalin (Okhotsky Hatchery), SWSa for SW Sakhalin (Kalininsky Hatchery); and TeGu for the Gulf of Terpenia (Buyuklovsky Hatchery).



[Figure OK-28] Four year running average of return rates (%) starting at 1977-1980 ocean entry year for hatchery chum salmon from seven regions of Japan (data from Saito and Nagasawa 2009, courtesy T. Saito). Region abbreviations are: NE-Nemuro; OH-Okhotsk; WP-West Hokkaido Pacific; EP-East Hokkaido Pacific; HP-Honshu Pacific; NW-Northwest Hokkaido; and SW-Southwest Honshu.

### 6.5.3 Sockeye salmon

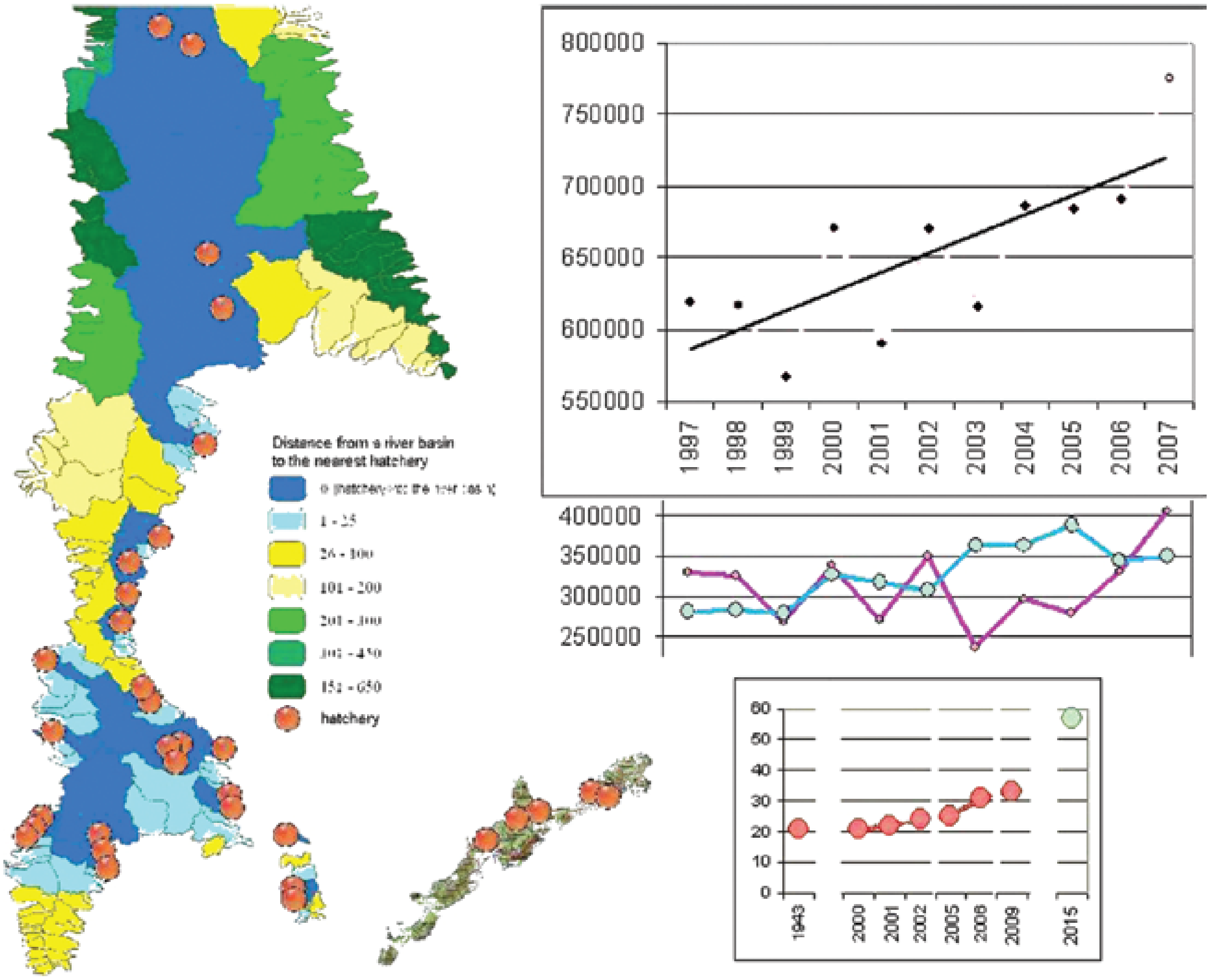
Coastal catches of sockeye salmon doubled in comparison to 2000 and reached 30,000 t in 2007. In 2008, sockeye salmon catch was lowered to 27,000 t (20,000 t in the Sea of Okhotsk basin). The increase in catch was related to an increase in the quota for pre-season marine monitoring in the Russian EEZ. In 2009, no quota was allotted for this purpose due to administrative changes in the organization of scientific research. According to preliminary data, the coastal catch of sockeye salmon did not exceed 30,000 t.

### 6.5.4 Salmon production

Some climate indices suggest that oceanic conditions for Pacific salmon stocks will change in the near future (e.g. PDO of Mantua et al. 1997). Contrary to expectations for a notable decrease to levels of the 1980s and early 1990s, Pacific salmon have remained abundant in the Sea of Okhotsk. Some of this is due to hatchery renovations and some to the construction of new hatcheries. Some hatcheries are producing chum salmon where hatching was not possible previously. According to long-term plans, the total number of hatcheries on the Sakhalin and Iturup Islands will reach 57 at 2015 (Fig. OK-29). In 2009, Pacific salmon catch on the Russian coast of the Sea of Okhotsk reached the historical high at 0.345 mmt, including 0.275 mmt of pink salmon.

## 6.6 Macrozoobenthos *(Radchenko, Dulepova)*

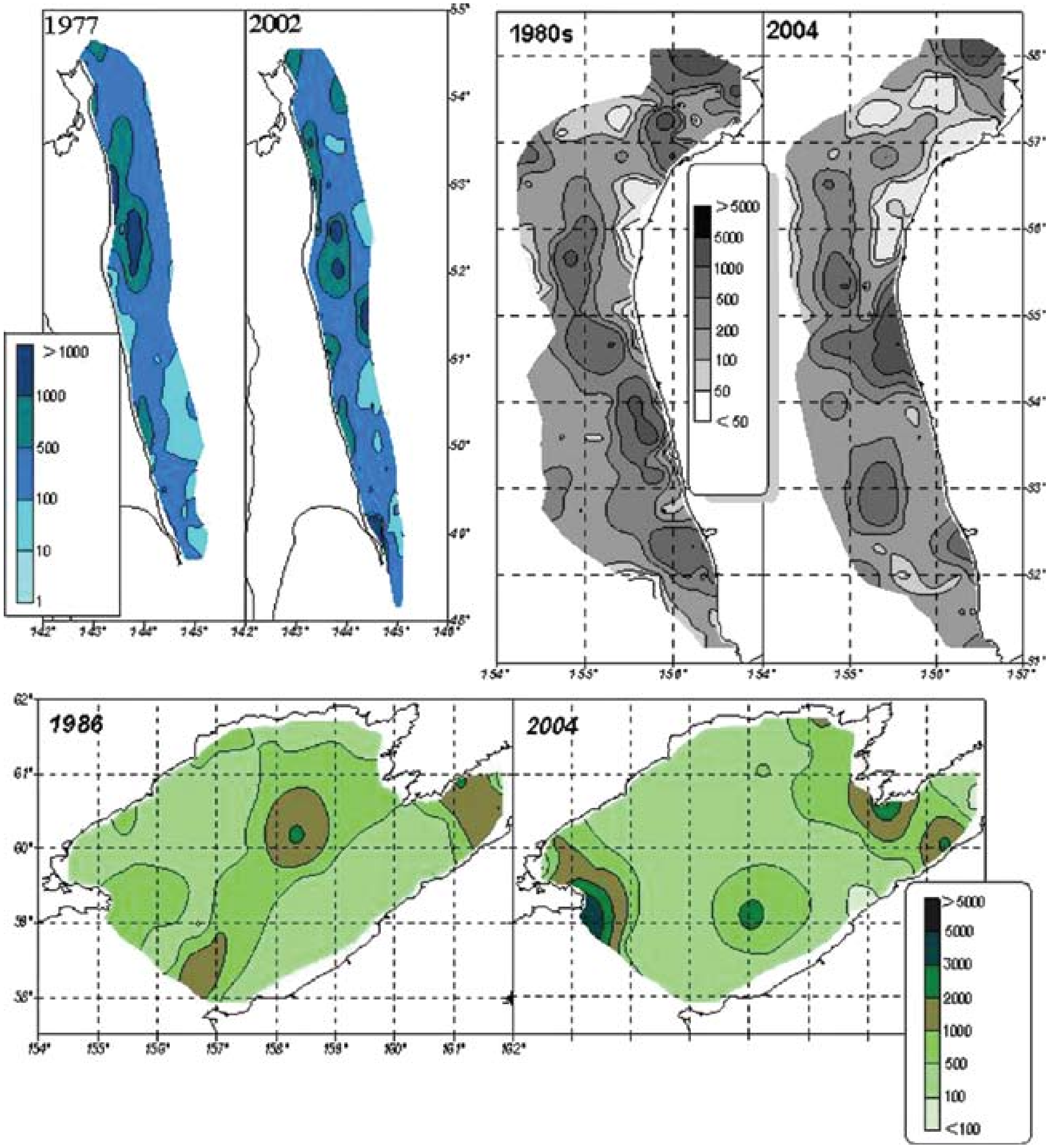
After a 20 year gap, a new series of macrozoobenthos surveys was conducted on the Sea of Okhotsk shelf in 2001-2005: near eastern Sakhalin, western Kamchatka, and in Shelikhov Bay (Nadtochy et al. 2004, 2007; Nadtochy and Budnikova 2005). Sampling was conducted using the same spatial grid and the same sampling gear. Benthic biomass was slightly higher in all regions surveyed. In most cases, there were relatively insignificant changes in the main



[Figure OK-29] Characteristics of Pacific salmon artificial propagation in the Sakhalin-Kuril region: hatchery distribution on the Sakhalin and Iturup Islands, modified after Springmeyer et al. (2007); number of fry released (1,000 fish, upper panel) on the Russian Far East, including pink (middle panel, pink line) and chum (middle panel, blue line); number of functioning hatcheries on the Sakhalin and Iturup Islands (lower panel, green dot indicate projected number for 2015).

taxonomic groups contributing to the food supply of demersal fish, crabs, and other benthic consumers. On the eastern Sakhalin shelf, benthic biomass varied from 19 to 4454.5 g·m$^{-2}$, averaging 421.5 ±58.7 g·m$^{-2}$, for a total of about 15.0 mmt. The main taxonomic groups were sand dollars, bivalves, polychaetes, amphipods, barnacles, sponges and sipunculid worms, contributing to 80% of total biomass. Most of the bottom was occupied by benthic communities with a biomass range of 100-500 g·m$^{-2}$. In 1977, benthos biomass varied from 9.2 to 2167.4 g·m$^{-2}$ and averaged 408.2 ±44.3 g·m$^{-2}$. Comparison of distributional maps for 1977 and 2002 showed that the largest biomass (>1,000 g·m$^{-2}$) occurred in the central shelf at depths 50-150 m near 52°N latitude in both years (Fig. OK-30). In this region, the benthos was made up of mostly echinoderms, amphipods, cumaceans, bivalves, sipunculid worms, polychaetes, and actiniae.

On the West Kamchatka shelf (depths 19-241 m) benthic biomass varied from 7 to 5173.5 g·m$^{-2}$, averaging 323.1 ±50.1 g·m$^{-2}$, and totaling about 17.0 mmt. Most of the bottom was occupied by communities with biomasses in the range 100-300 g·m$^{-2}$. The largest biomasses occurred in the same places as before (Fig. OK-30). However, if echinoderms, polychaetes, and bivalves were the dominant groups in 1982, the last two of these had exchanged



[Figure OK-30] Total macrozoobenthos biomass (g·m⁻²) distribution on the eastern Sakhalin shelf (left), western Kamchatka shelf (right), and Shelikhov Bay (lower). After Nadtochy et al. (2004, 2007) and Nadtochy and Budnikova ( 2005).

places by 2004. The main taxonomic groups included sand dollars (29.7%), bivalves (28.0%), polychaetes (16.5%), and holothurians (6.3%), all contributing ~80% of total biomass in the region. Sand dollars also predominated in the 1980s (40%) while bivalves and holothurians were significantly less abundant (10.6% and 1.8%, correspondently). The proportion of biomass in sponges decreased from 11% to 3.2%. The average polychaete biomass did not change.

The largest average benthic biomass (604.87 ±135.61 $g \cdot m^{-2}$) was found in Shelikhov Bay where it had increased slightly from 544.69 ±80.62 $g \cdot m^{-2}$ in 1986. The same six taxonomic groups predominated including bivalves, brittle stars, sea urchins, barnacles, polychaetes, and sponges. Their composition changed to a degree with bivalves remaining as the most abundant group, and sea urchins at third place in total benthic biomass. The proportion of brittle stars had increased threefold by 2004 and proportion of sponges decreased by 2.5 times. The contribution by barnacles and polychaetes changed insignificantly.

In Aniva Bay, benthic biomass decreased about twofold on the shelf areas affected by inflow from Soya Strait (Labay and Kochnev 2008). The decrease was related to a notable change in the abundance and distribution of common bivalve mollusks. The cause of the decline was attributed to a general negative trend in productivity of the benthos communities in the southern part of the north-western Pacific (Labay and Kochnev 2008).

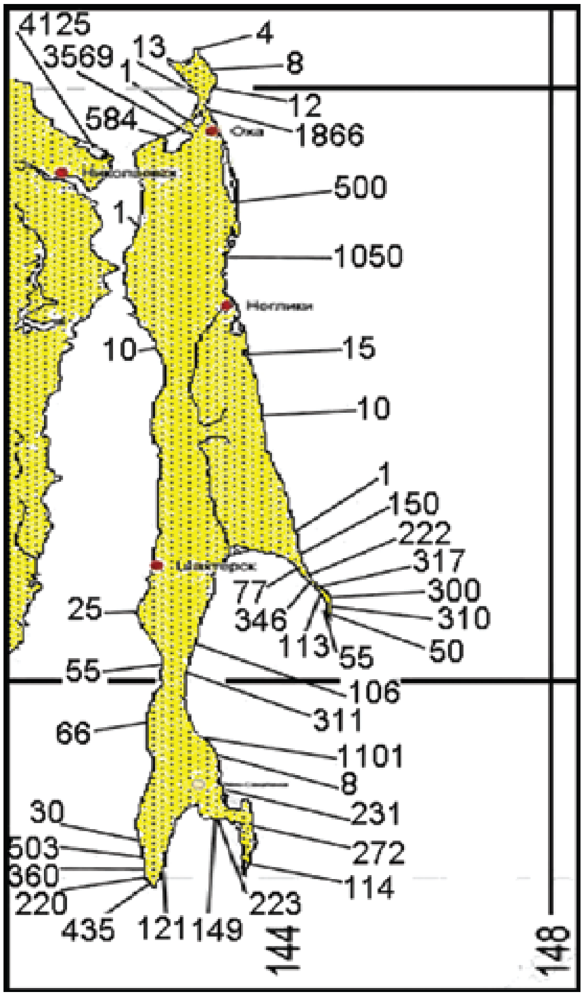
On the whole, the macrozoobenthos community in the Sea of Okhotsk has remained at previous high levels, despite an intensive bottom trawl fishery in western Kamchatka and eastern Sakhalin regions during the 1980s. The proportions of the main taxonomic groups varied gradually, except in Shelikhov Bay where there was little change. Some negative changes in benthic biomass appeared in the southern Sea of Okhotsk but this information needs verification.

## 6.7 Crabs

The current abundance of the commercial invertebrate species (crabs, shrimp, and snails) remains at a low level. For the shelf crab species, status is mainly assessed as “deep depression” with unclear perspectives for restoration. Some commercially significant abundances remain for the blue king crab (*Paralithodes platypus*) on the West Kamchatka shelf, golden king crab (*P. aequispinus*) and snow crab (*Chionocoetes opilio*) on the northern shelf and continental slope, and brown king crab (*P. brevipes*) in the north-western part of the Sea of Okhotsk. As for the famous red king crab (*P. camtschaticus*) stock on the West Kamchatka shelf, issuing a zero quota is widely discussed among scientists and managers for maintaining the overfished crab population. The assessment of the status of deepwater crab species was likely too optimistic for the triangle Tanner crab (*Chionocoetes angulatus*). Its TAC will decrease for 2010, in comparison with the 2008-2009 values, which were not supported by corresponding high catches. Total crab harvest in 2003-2008 decreased twofold from 47,400 t in 1996-2002. Snow crab has contributed 48.2% to the total crab harvest. Vermilion crab (*Paralomis verrilli*) stock abundance was recently assessed and the species has been recommended for a fishery target but it does not meet the current market demands.

[Table OK-4] Estimates of marine mammal abundance and biomass in the Sea of Okhotsk, 1999-2003 (after Miyashita et al. 2005).

| Species | Abundance | Individual weight (t) | Biomass (t) |
|---|---|---|---|
| Fin whale | 13,105 | 45 | 589,725 |
| Minke whale | 19,209 | 2.5 | 48,023 |
| Humpback whale | 232 | 27 | 6,264 |
| Gray whale | 100 | 30 | 3 |
| North Pacific right whale | 922 | 90 | 82,980 |
| Killer whale | 721 | 4.5 | 3,245 |
| Sperm whale | 86 | 40 | 3,440 |
| Dall's porpoise | 316,646 | 0.17 | 53,830 |
| Harbour porpoise | 6,517 | 0.065 | 424 |
| Pacific white-sided dolphin | 27,759 | 0.15 | 4,164 |
| Baird's beaked whale | 660 | 9 | 5,940 |
| Other beaked whales | 159 | 2.5 | 398 |



[Figure OK-31] Seal abundance in vicinities of the Sakhalin Island coast. Data of air visual survey in August and September of 2009.

## 7.0 Marine Birds and Mammals

*(Radchenko)*

From 1999-2003, three visual surveys were conducted in the Sea of Okhotsk to estimate the abundance of whale and dolphin species (Table OK-4). They showed a significant increase of numbers of baleen whales including fin whale (13,200 specimens), and Minke whale (19,200). In comparison, total numbers of baleen whales in the Russian EEZ from the late 1980s to the early 1990s were estimated at 7,200 specimens in summer and 3,200 in autumn (Shuntov 1993). This visual survey was conducted beyond the Russian territorial waters and limited to 155°E and 58°N, so whale abundance is probably underestimated.

True seal (Phocidae) abundance was not surveyed throughout the Sea of Okhotsk scale in the 2000s. In the 1990s, however, it was estimated that there were 1,300,000 seals by species as follows: ringed seal – 543,000, ribbon seal – 345,000, bearded seal and spotted seal – 190,000 each, and harbour seal – 7,000. Seals have likely increased in the 2000s due to a cessation of sealing and food supply stability. Positive trends were also determined for the Steller sea lion (Burkanov and Loughlin 2005).

Local seal abundance was estimated by aerial visual surveys conducted around the Sakhalin Island coast in August and September of 2009 (Fig. OK-31). Almost 14,000 seals were estimated in 40 groups. Additionally, 4,125 seals were found off the south-western coast of Sakhalin Bay (near the mainland) but the main concentrations were found in the northern and north-eastern bays, and also along the southern Sakhalin coast from Cape Terpeniya to Cape Krilyon. These were main areas of pink salmon spawning migrations so the spotted seals were concentrated there to feed on them. In comparison with data of previous calculations, the seal abundance has increased during the last 30 years.

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# Marine Ecosystems of the North Pacific Ocean 2003-2008

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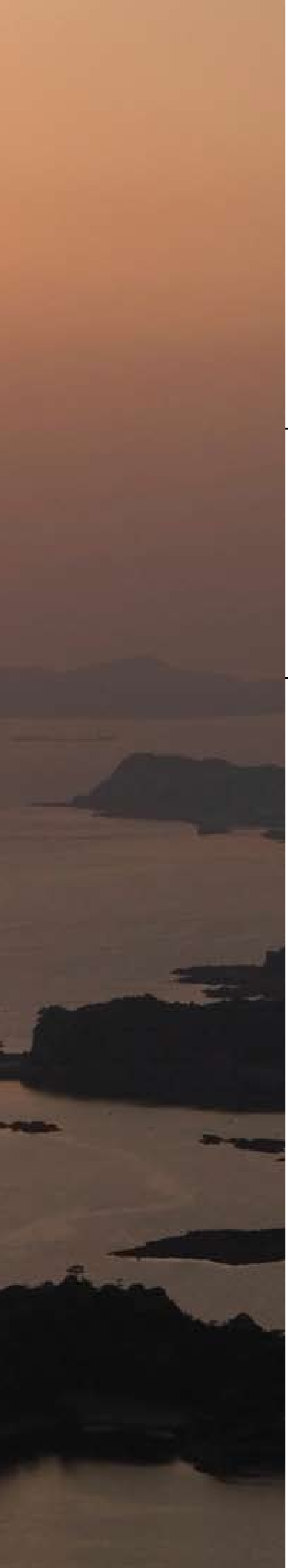
PICES Special Publication Number 4



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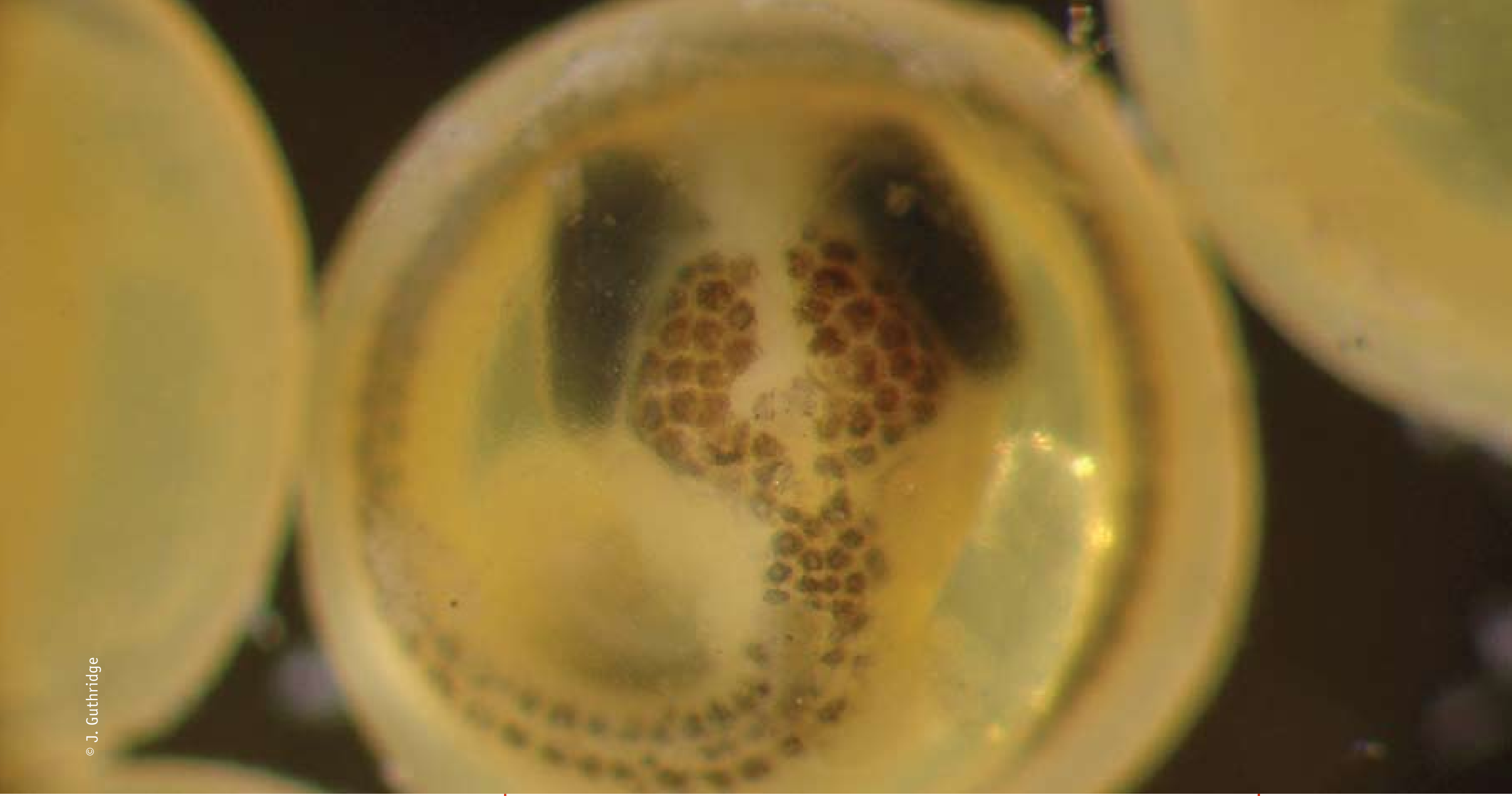
# highlights

- The West Pacific atmospheric pattern was conspicuous after 2003. It was associated with windy, lower sea surface temperature conditions during winter compared to the preceding warm period.
- Unlike the previous cool period (mid 1970s to mid 1980s), a southward shift of the Oyashio coastal branch was less extensive after 2003.
- There is no long-term trend in SST after the mid 1980s.
- Subsurface dissolved oxygen and mixed layer phosphate concentrations had decadal variation superimposed on a long-term declining trend. The decadal-scale variation is likely related to the North Pacific index and extent of mixing with Okhotsk Sea water. The long-term decline after the 1970s might indicate a gradual increase in water column stratification. Both dissolved oxygen and phosphate increased from the late 1990s and remained relatively constant after 2003.
- Contaminant levels remained low through 2008 compared to previous years.
- The geographical distribution and seasonality of phytoplankton in Oyashio water adjacent to Japan were similar before 2002 with a peak in May. In the wide range of the northern offshore areas however, chlorophyll$_a$ peaked in June after 2003, possibly related to cool winter conditions.
- Zooplankton seasonality was similar from the 1960s to 2007 although a comparison of zooplankton biomass before and after 2002 was difficult due to incompatible data.
- After 2003, zooplankton biomass in July was significantly lower in 2005 than in other years.



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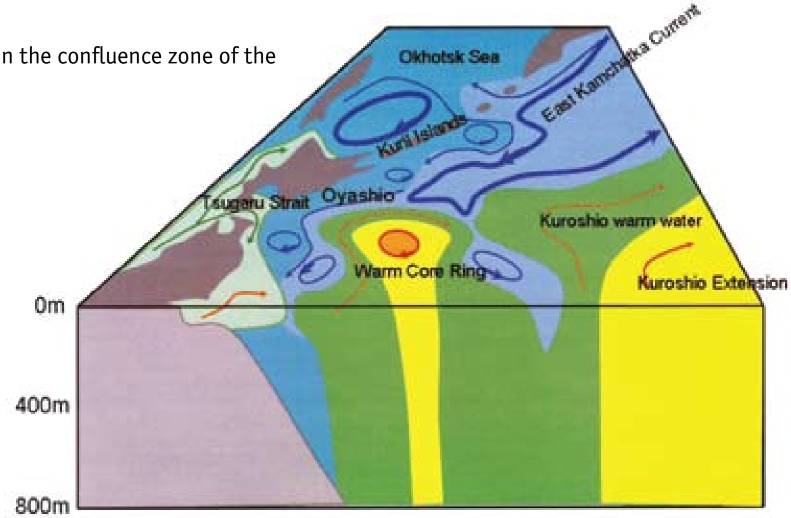
- No clear relation was detected between sea surface temperature and lower trophic levels at the interannual time-scale.
- The anchovy regime (high anchovy and common squid biomass and low sardine and chum mackerel biomass), which started in the mid 1990s (at the end of the sardine regime), continued until 2007. Anchovy biomass peaked in 2003 and decreased toward 2007.
- Catch and biomass of salmon (pink, chum, sockeye) increased markedly after the mid 1970s, peaked in the mid 1990s, and has remained at a relatively high level after 2000. The increase in chum salmon catch and biomass was mainly from hatchery fish.
- Catch of threadfin hakeling increased after the late 1990s and remained at a high level after 2000.
- Catch and biomass of walleye pollock showed a decreasing trend from the mid 1970s and remained at a low level after 2003.
- No clear link was detected between interannual variation in phytoplankton and zooplankton or between lower and higher trophic levels after 2003. Low summertime zooplankton biomass in 2005 might have had a negative influence on seabird density in the Oyashio shelf area and pink salmon return.

# Introduction *(Ito)*

## The Oyashio is the western boundary current of the Subartic North Pacific.

It is characterized by low temperature, low salinity, and high nutrient concentrations (Stommel and Yoshida 1972). The Oyashio is a continuation of the East Kamchatka Current (Fig. OY-1) and is fed by waters from the Western Subarctic Gyre and the Sea of Okhotsk (Shimizu et al. 2001). Strong tidal mixing along the Kuril Islands inputs the low salinity characteristic of the intermediate Oyashio. The Oyashio is a possible source of North Pacific Intermediate Water (NPIW) (Yasuda 1997) and its contribution to the North Pacific overturn cannot be ignored. The Oyashio flows southward along Hokkaido Island and Honshu Island, then changes direction and flows to the east, with meanders. The meander crests are called the First and Second Branches of the Oyashio according to their sequence from land. The eastward flowing Oyashio forms the Subarctic Front (Oyashio Front), which is a distinctive temperature front. Between the Subarctic Front and the Kuroshio Extension Front, cold and warm waters mix in a complex manner and many mesoscale features are formed. Therefore, this region is called the Kuroshio-Oyashio-Transition Zone (KOTZ) or mixed water region. The outflow of the Kuroshio, the Kuroshio Extension, feeds into the North Pacific Current, while the outflow from Oyashio feeds into the Subarctic Current. Between these two eastward flows, the Transition Domain is formed (Favorite et al. 1976). The Oyashio brings nutrient-rich water into the western North Pacific, resulting in high productivity in the confluence zone of the two currents, the KOTZ.



[Figure OY-1] Schematic picture of the Oyashio and mixed water region (modified from Shimizu et al. 2001).

The Oyashio transport and its southward extent show large seasonal variation and comparable interannual variations (e.g. Qiu 2002). The response to large-scale atmospheric circulation is a combination of barotropic (less than one year lag) and baroclinic (several year lag) responses (Ito et al. 2004a). The dominant climate variability in the western North Pacific is decadal although there are also high-frequency variations associated with ENSO events. Much of the variability in the Oyashio System is via remotely generated ocean Rossby waves that may create a lag in the response to the Aleutian Low. Variations in the strength of the Aleutian Low can be decomposed to bi-decadal and penta-decadal oscillations (Minobe 1999), but only the penta-decadal signal reaches the western boundary region (Tatebe and Yasuda 2005). Moreover, many local factors contribute to environmental variability in the Oyashio, making it quite unlikely that these systems respond to climate forcing on the same time frame as the rest of the North Pacific. The physical condition of Oyashio water varies primarily due to: i) wind stress changes associated with the Aleutian Low; ii) Rossby wave propagation; iii) upstream conditions in Western Subarctic Gyre and Sea of Okhotsk; and iv) tidal mixing along the Kuril Islands.

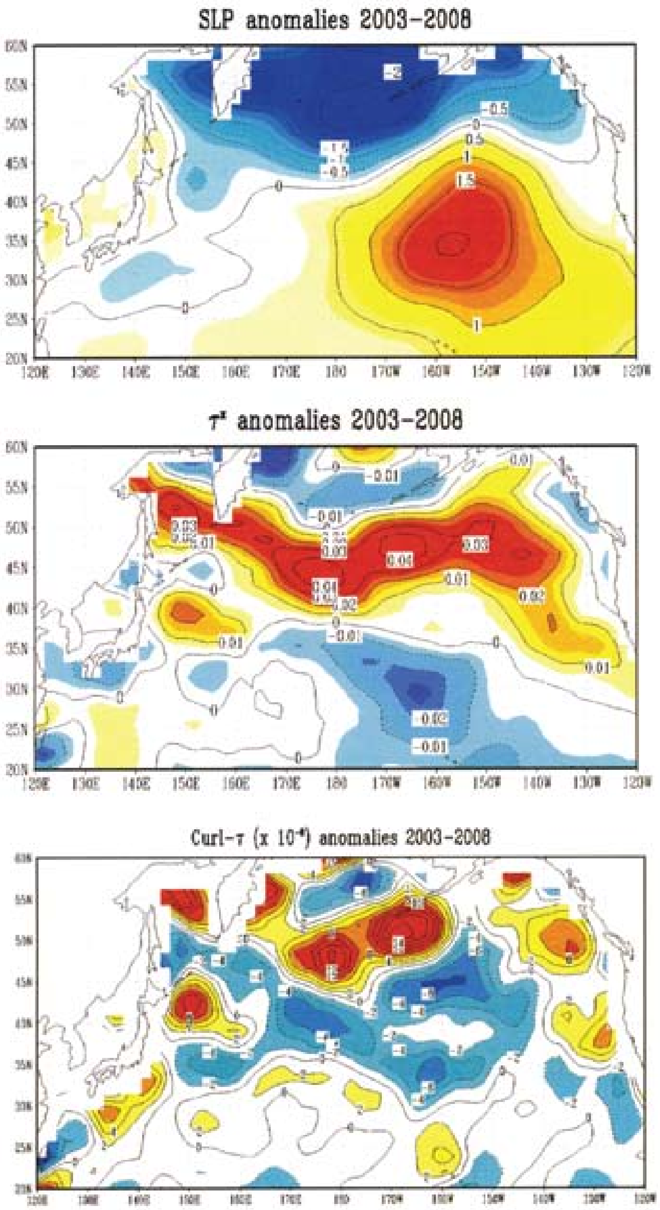
This chapter is a review of the status and trends of the Oyashio region from 2003-2008, hereafter the *focus period*.

## 2.0 Atmosphere *(Minobe)*

### 2.1 Wind and pressure

Major components of atmospheric circulation anomalies are associated with large scale structures. Thus regional atmospheric changes in the Oyashio region can often be best understood in the context of basin- or hemispheric-scale changes. Winter conditions receive special attention because winter is when the most prominent atmosphere-to-ocean influences generally occur.

Wintertime sea-level pressure (SLP) anomalies during the focus period were characterized by negative anomalies to the north and positive anomalies to the south in the North Pacific (Fig. OY-2). This pattern is reminiscent of the North Pacific Oscillation (NPO) (Walker and Bliss 1932), though the southern pole is shifted eastward from the typical NPO pattern. Zonal (east-west) wind stress anomalies were positive from the Okhotsk Sea to the central and eastern


SLP anomalies 2003–2008

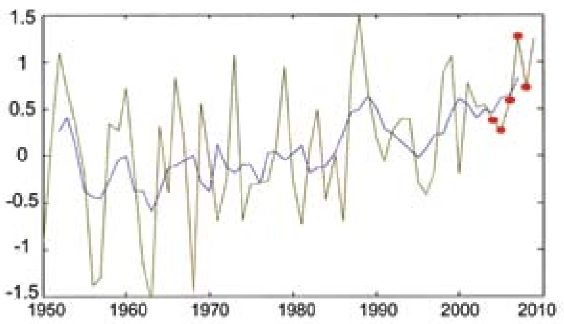
$\tau^x$ anomalies 2003–2008

Curl-$\tau$ (x $10^{-8}$) anomalies 2003–2008

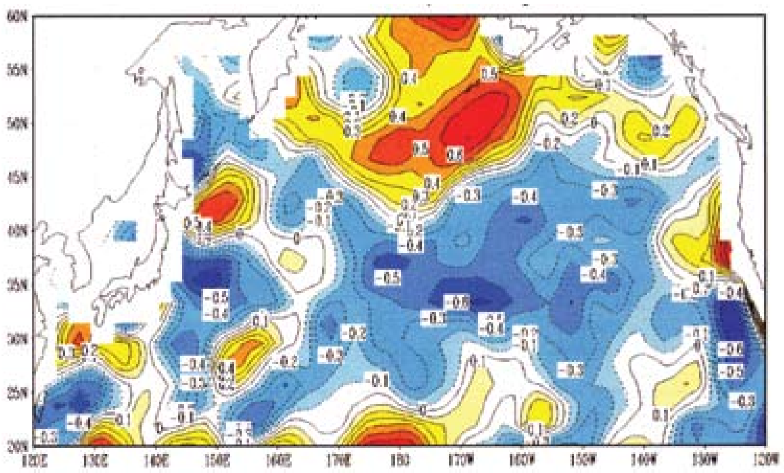
[Figure OY-2] Anomalies of (top) SLP, (middle) zonal wind stress and (bottom) wind stress curl averaged for a period from 2003 to 2008 in the winter season (December-February) based on NCEP-NCAR reanalysis. Contour interval is 0.5 hPa for SLPs, 0.01 $N \cdot m^{-2}$ for wind stress, and $2 \times 10^{-8} N \cdot m^{-3}$ for wind stress curl. Base period for the anomalies is 1970-2000.

North Pacific, with isolated weaker positive anomalies around 40°N 150°E. The extending positive wind stresses occur roughly along the perimeter of the negative SLP anomalies. Zonal wind stress contributes to zonal wind stress curl anomalies that were characterized by strong positive anomalies centered at 43°N 150°E surrounded by negative anomalies in the western North Pacific.

Figure OY-3 shows that the winter West Pacific (WP) index exhibited a prominent increasing trend during the focus period. Therefore, the anomalous meridional dipole in SLP shown in Figure OY-2 and the related wind stress and wind stress curl are most likely expressions of the trend component of the WP pattern. Actually, a correlation map between the WP index and wind stress curl in winter shows a striking similarity with the wind-stress curl anomalies in the western North Pacific (Fig. OY-4). Therefore, it can be concluded that anomalous conditions of the wind stress and wind stress curl in winter during the focus period are aspects of the trend-like increase of WP pattern.



[Figure OY-3] Winter WP index from 1950 to 2009. Raw data are shown by the green line, data smoothed by a 5-year running mean are shown by the solid blue line, and raw data from 2003 to 2008 are also shown by red circles. The monthly WP pattern index was obtained from the Climate Prediction Center. Base period of anomalies is 1950-2000. Five year running means are calculated from 1952 to 2007.

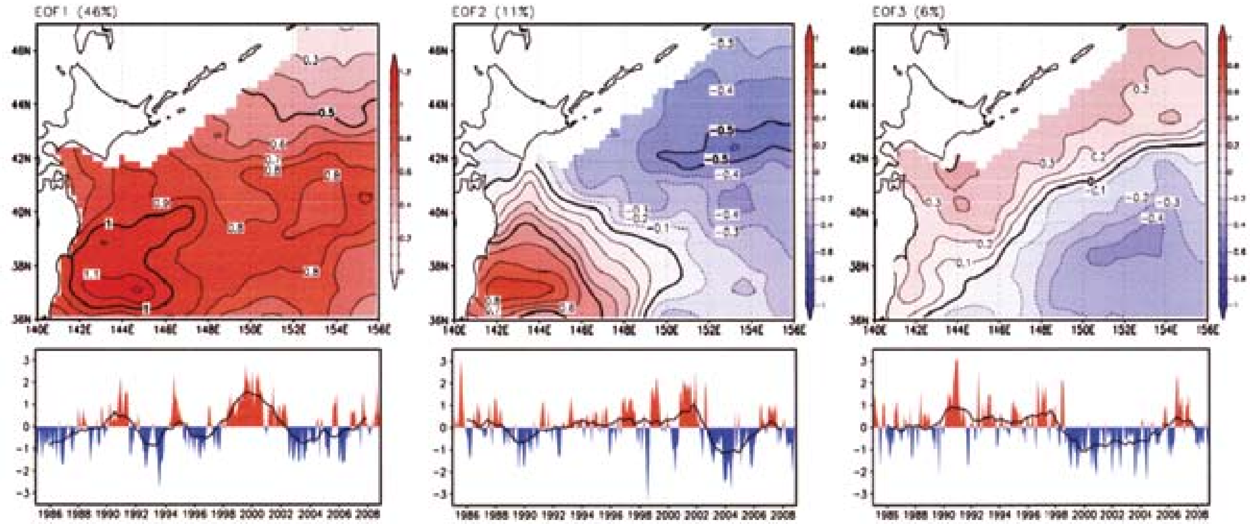


[Figure OY- 4] Correlation coefficient between the WP index and wind stress curl in winter. Data are smoothed by a 5-year running mean before calculating correlations. Correlation coefficients corresponding to the 90% and 95% confidence levels are 0.50 and 0.57, respectively, with the assumption that one datum in five years is independent.

## 3.0 Physical Ocean *(Ishizaki)*

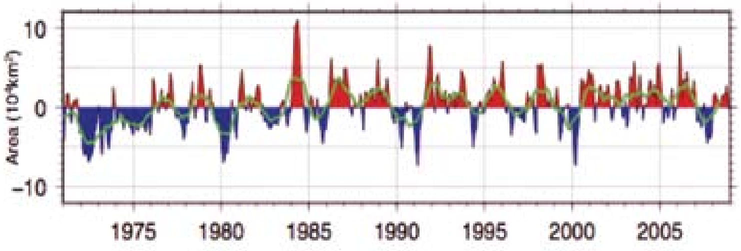
The main feature of sea surface temperature (SST) variation in the Oyashio region is a single EOF pattern covering the entire area (Fig. OY-5). The time sequence of the first mode of the EOF shows both interannual and decadal variations. Sea surface temperatures in the Oyashio region were warmer than average from 1998 to 2002, but turned cooler in 2003. The spatial pattern of the second EOF mode has two centers of action, located east of Japan (around 37°N, 143°E) and southeast of the Kuril Islands. Both the first and second EOF modes indicate that sea surface temperature east of Japan were cooler than average from 2003 to 2006. This cold surface temperature is consistent with the nature of variation of Oyashio water described below.

The Tohoku National Fisheries Research Institute defines the Oyashio region as that having a temperature <5°C at 100 m. A time series of the spatial extent of Oyashio water shows that the Oyashio area has been generally above average since 1984 (Fig. OY-6). The southernmost position of the Oyashio First Branch varies from year to year (Fig. OY-7). It was located south of average from 2003 to 2006. The southward shift of the Oyashio First Branch from 2003 to 2006 corresponds with the negative SST anomalies observed east of Japan.

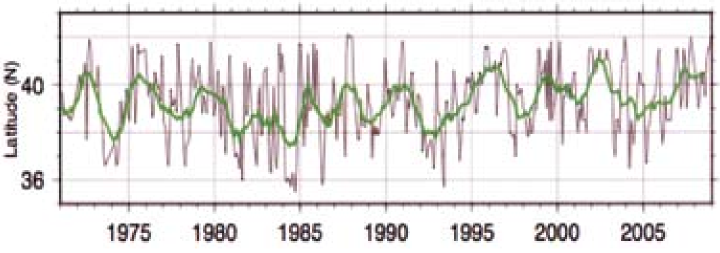


[Figure OY-5] Time sequences (bottom panels) and corresponding spatial patterns (top panels) for the three dominant modes of the EOF for monthly mean SST anomalies. Black line in the bottom panels shows the 13-month running mean value.

[Figure OY-6] Time series of monthly mean of the extent of Oyashio water (104 km$^2$) from 1971 to 2008. Thick line denotes the 13-month running mean value. Anomalies are deviations from the 1971-2000 climatology.



[Figure OY-7] The monthly southernmost position of the coastal branch of the Oyashio cold water from 1971 to 2008. The thin line denotes the monthly change and the thick line shows the 13-month running mean value.



# 4.0 Chemical Ocean

## 4.1 Oxygen *(Sasano, Takatani)*

Recent studies of dissolved oxygen (DO) in the North Pacific report a significant decreasing trend over the past several decades (Emerson et al. 2004; Mecking et al. 2008). For example, at Station Papa (50°N 145°W), oxygen levels declined by 23% between 1956 and 2008 (updated from Whitney et al. 2007), with the strongest declines occurring between 150 and 400 m. The largest decrease in DO occurs at around $26.6\sigma_\theta$, the densest isopycnal surface that outcrops in the northern North Pacific. The modeling work of Deutsch et al. (2005) shows that the primary explanation for this oxygen loss is reduced ventilation of the ocean but other factors also contribute to variability.

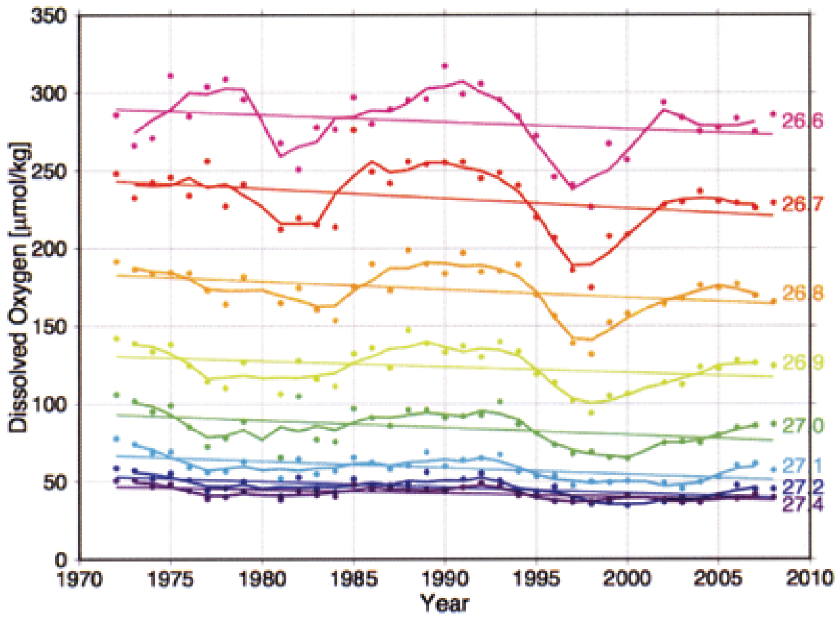
The Oyashio region is a subarctic western boundary current that originates from the mixing of Okhotsk Sea Water (OSW: low temperature and high oxygen) with Western Subarctic Gyre Water (WSAGW: high temperature and low oxygen). Here, a decreasing trend in DO superimposed on a decadal oscillation in DO has been observed (Ono et al. 2001; Watanabe et al. 2008). The decadal variations over the North Pacific could be related to the 18.6-year nodal tidal cycle (Yasuda et al. 2006; Osafune and Yasuda 2006). This cycle is apparently similar to the variation of the North Pacific index (NPI) but their relationship is yet to be clarified. Takatani et al. (2007) suggested that the decadal oscillation of DO is caused by oscillation in the mixing ratio of the source waters rather than DO changes in the source waters and correlates well with the NPI.

Following Takatani et al. (2007), we reanalyzed the long-term variation of DO on various isopycnal surfaces in the Oyashio region at 41° 30'N, 146-147°E up to the year 2008. The extended time series of DO showed a decadal oscillation that is consistent with the former period; the higher DO condition is continuing after 2002 (Fig. OY-8).

We define the mixing ratio of OSW in Oyashio water, Ro, as Eq (1):

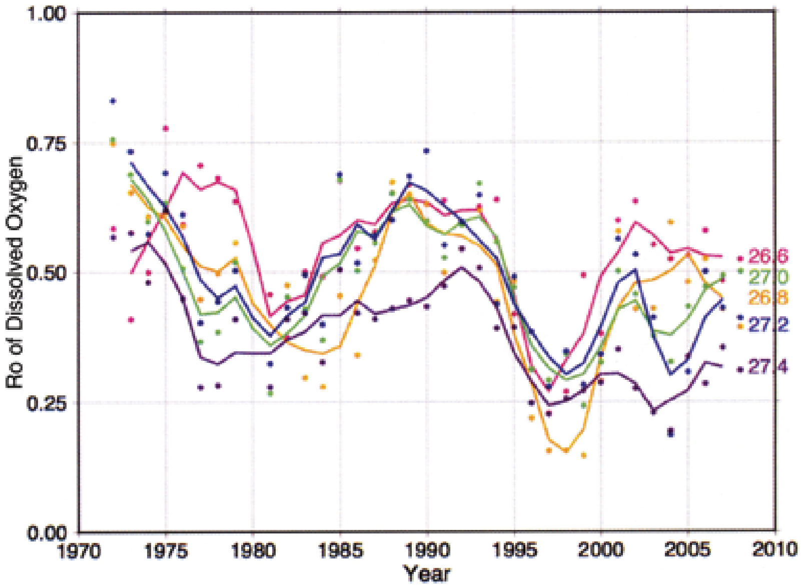
$$Ro = (DO_{obs} - DOW_{SAGW}) / (DO_{OSW} - DOW_{SAGW}) \qquad (1)$$

where $DO_{obs}$, $DOW_{SAGW}$, $DO_{OSW}$ represent observed DO concentration, and climatological DO in the WSAGW and the OSW, respectively. Phases of lower DO in the early 1980s and late 1990s correspond with phases of a lower mixing ratio of OSW, and phases of higher DO periods, including the most recent condition, correspond with a higher mixing ratio of OSW (Fig. OY-9). These correspondences between DO, mixing ratio and the NPI indicate the linkage of DO variation in the Oyashio with variation in the atmospheric circulation over the North Pacific and mixing processes of OSW and WSAGW forming the Oyashio water.



[Figure OY-8] Time series of DO on isopycnals from 26.6 to $27.4\sigma_\theta$ in the Oyashio region at 41°30'N, 146-147°E. The solid line denotes the 3-year running average.

[Figure OY-9] Time series of Ro estimated from DO on isopycnals from 26.6 to 27.4$\sigma_\theta$ in the Oyashio region at 41°30'N 146-147°E. Original WSAGW is defined at 0, and original OSW is defined at 1. The solid lines denote the 3-year running averages of DO on isopycnals from 26.6 to 27.2$\sigma_\theta$.



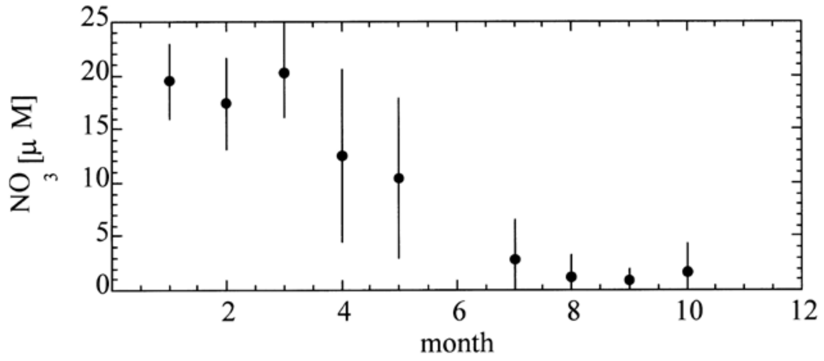
In the long-term, the decreasing DO trend has been observed over isopycnals ranging from 26.6 to 27.4$\sigma_\theta$. The largest decreasing rate (-0.55 ± 0.18 $\mu$mol·kg$^{-1}$·y$^{-1}$) was seen on 26.7$\sigma_\theta$ (Fig. OY-8), nearly identical to 26.6$\sigma_\theta$ where the largest decrease in DO has been observed in the North Pacific. Decreases in DO have been reported in the source water of WSAGW (Andreev and Watanabe 2002) and OSW (Nakanowatari et al. 2007). However, this long-term DO decrease in the Oyashio is also attributable to the change in the mixing ratio of OSW and WSAGW, i.e., the trend of a smaller contribution of OSW (Fig. OY-9). The increasing trend of potential vorticity in 26.7-27.0$\sigma_\theta$ (data not shown) indicates a larger contribution of WSAGW with high potential vorticity (Takatani et al. 2007).

Monitoring DO and hydrographic parameters for an extended period is key to understanding the linkages among decadal to longer-term variations in atmospheric circulation, ocean circulation and DO. Clarifying the changes in DO in the Okhotsk Sea and in the Western Subarctic Gyre and changes caused by biological activities are also very important to better understanding the causes of long-term DO decrease in the Oyashio region and across the North Pacific.

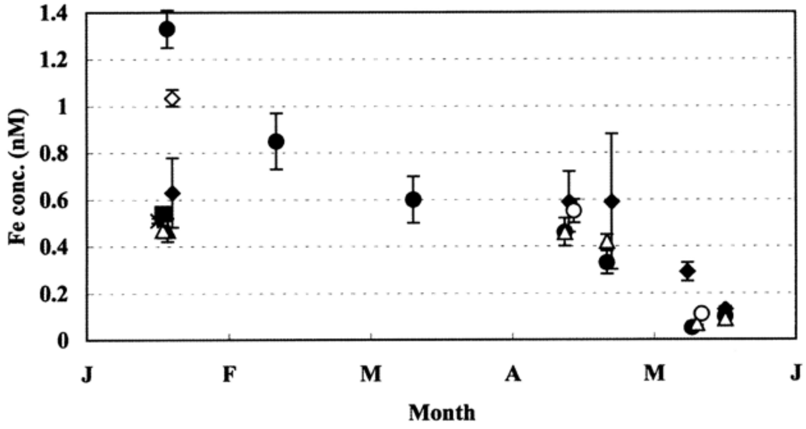
## 4.2 Nutrients *(Ono)*

Nutrient dynamics in the Oyashio mixed layer are characterized by a larger seasonal amplitude compared to other regions of the Subarctic North Pacific. While the annual maximum concentration in winter differs only slightly from other Subarctic North Pacific regions, the large seasonal amplitude results from nutrients being almost completely exhausted from the mixed layer at the end of the summer season (Fig. OY-10).

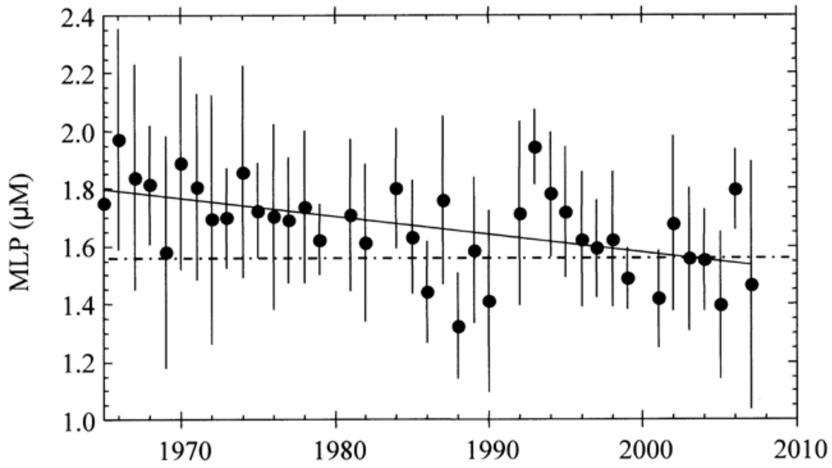
Although this non-HNLC (high nitrogen, low chlorophyll) characteristic indicates that nitrate is the ultimate limiting factor for annual primary production in this region, iron limitation in the Oyashio ecosystem at the end of the spring bloom was hypothesized by Saito et al. (2002) and later demonstrated by Nishioka et al. (2007) through seasonal observations of surface iron concentration (Fig. OY-11). A high concentration of dissolved iron occurs in the Oyashio surface water in winter. It is caused by vertical mixing with the iron-rich Oyashio subsurface waters that originated from Okhotsk Intermediate Water (Nishioka et al. 2007). This iron sustains an enormous phytoplankton bloom in the Oyashio region in spring but it is exhausted by the end of the bloom and thereafter limits the amount of primary production (Fig. OY-11). At this time, significant amounts of major nutrients remain in the Oyashio surface water, as in other Subarctic North Pacific regions (Fig. OY-10). In the Oyashio however, primary production is reactivated by small phytoplankton, and nutrient levels are decreased further until complete exhaustion in late August (Saito et al. 2002). This unique summer production in the Oyashio may be maintained by iron originating from dust input after the spring bloom.



[Figure OY-10] 40-year climatology of surface nitrate in the Oyashio region. Data are calculated from the Japan Meteorological Agency (JMA) and Japanese Fisheries Research Agency (FRA) hydrographic database from 1965 to 2008. The amplitude of seasonal variation (March - September) is 19±5 μM, which is about 3 and 1.4 times larger than that of Stn. P (Whitney and Freeland 1999) and Stn. KNOT (Tsurushima et al. 2002), respectively.



[Figure OY-11] Seasonal variation of surface dissolved iron concentration in the Oyashio region observed in 2003, January - June. Symbols indicate individual stations. After Nishioka et al. (2007).



[Figure OY-12] Time series of phosphate concentration in the winter (January-March) mixed layer in the Oyashio region. Dash-dotted line indicates the 2003-2007 average while the thin line indicates a linear regression of the whole time series. The slope of the linear regression is -0.0060 ± 002 μM $y^{-1}$ (Updated from Ono et al. 2002).

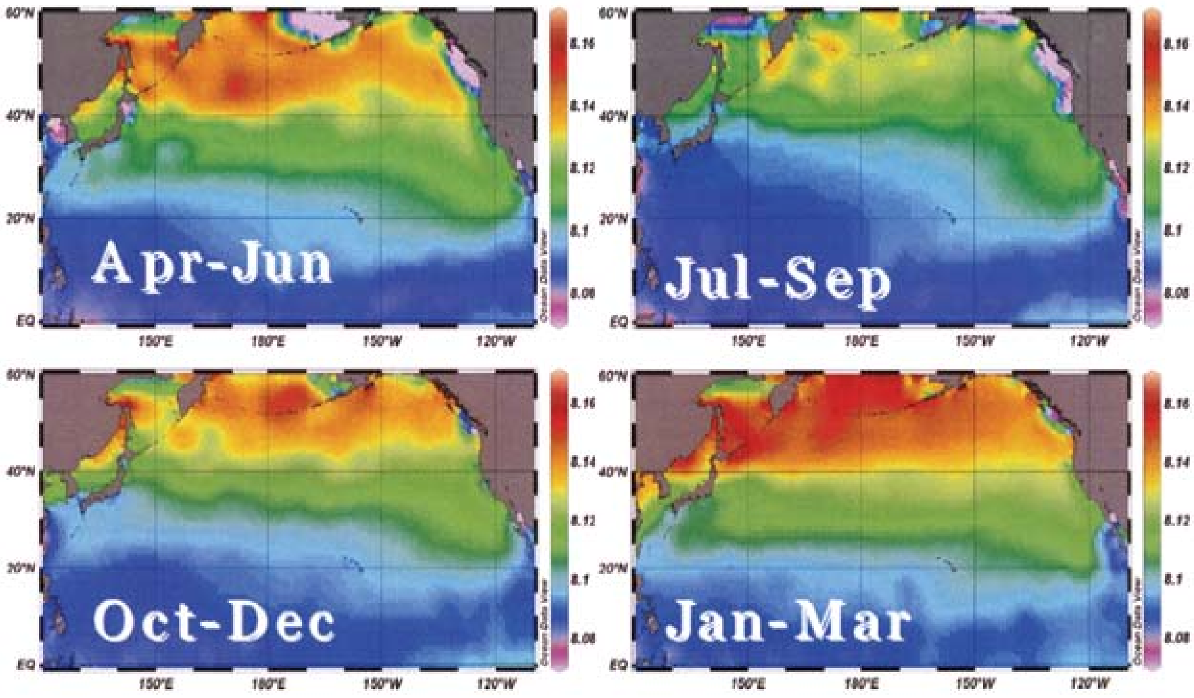
From at least the late 1960s until the present, the nutrient content of the winter mixed layer in the Oyashio region has gradually diminished (Ono et al. 2002)(Fig. OY-12). The average concentration of winter mixed-layer phosphate for the five years since 2003 has dropped to 1.55 ±0.11 μM, the lowest level in the past 40 years except for the latter half of the 1980s. This decline is thought to be caused by diminished winter vertical mixing attributed to increased upper-water stratification in the Subarctic North Pacific (e.g. Ono et al. 2001). Because the winter vertical mixing supplies a significant part of the iron observed in the winter mixed layer (Nishioka et al. 2007), it is believed that winter iron concentration has also diminished in parallel with the major nutrient decrease. Consistent with this, several reports show a multi-decadal decrease of primary production in the spring Oyashio region (e.g. Chiba et al. 2008).

## 4.3 Ocean acidification *(Watanabe)*

Model results predict that a decrease of pH in the ocean surface water will result from an increase of atmospheric $CO_2$ in the future (Orr et al. 2005). Based on a time series of oceanic carbonate species, Feely et al. (2008) reported a decreasing trend in pH of 0.0019 ± 0.0003 $y^{-1}$ during recent decades in the central North Pacific, although there were assumptions of no land-ocean interactions with increasing temperature. Unfortunately, there are few reports for the region west of 155°E. However, some efforts have been made to clarify the spatiotemporal changes of pH and its related hydrographic parameters. Wakita et al. (2003) found that dissolved inorganic carbon (DIC) had an increasing trend of 1.3 - 2.3 $\mu mol \cdot kg^{-1} \cdot y^{-1}$ at 44°N 155°E (Station KNOT) during the past decade, suggesting that oceanic acidification may be affecting the western North Pacific. Nakano and Watanabe (2005) described the seasonal spatial distributions of pH over the North Pacific surface water by using a simple algorithm relating pH to subsurface temperature and chlorophyll$_a$. They showed that pH in the western North Pacific is generally higher than in the eastern region, and increases westward (Fig. OY-13). Therefore, the western North Pacific has the potential to absorb large amounts of $CO_2$, suggesting that the marginal seas may affect the spatiotemporal distributions of seawater pH in the western North Pacific. To elucidate whether oceanic pH decreases with increasing atmospheric $CO_2$ over the western North Pacific, further study on the carbonate system in this region, including its marginal seas, is needed.

## 4.4 Contaminants *(Midorikawa, Kamiya)*

Time series data of contaminants are limited in the Oyashio region but the Japan Meteorological Agency (JMA) and Hakodate Marine Observatory have been conducting seasonal monitoring of cadmium (Cd), floating tar balls, and petroleum hydrocarbons (JMA 2008). Time series of Cd in surface waters at an inshore monitoring site at 41.5°N 142°E (PH-1) and an offshore monitoring site at 41.5°N 147°E (PH-6), south of Hokkaido, from 1990 to 2008 are shown in Fig OY-14. Cd concentrations at these two monitoring sites showed large seasonal variations: high in winter and low in summer and autumn. These variations are highly correlated with nutrients, especially

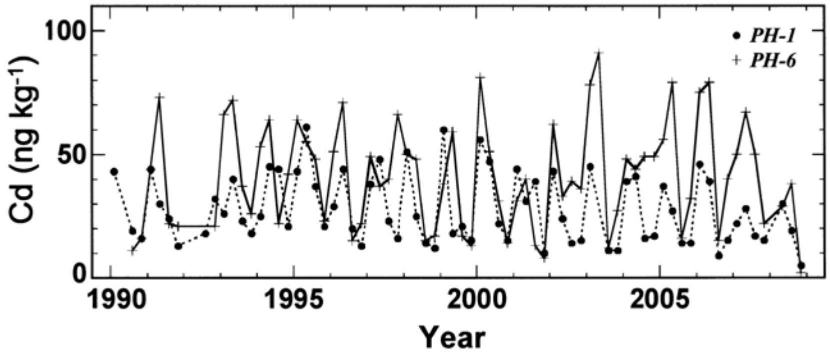


[Figure OY-13] Seasonal distribution of *in situ* pH in the North Pacific (redrafted from Nakano and Watanabe 2005). This scale is shown as pH *in situ* temperature. To describe the distribution of pH over the North Pacific with their algorithms, Nakano and Watanabe (2005) used the data for each of the four seasons (Apr–Jun, Jul–Sep, Oct–Dec and Jan–Mar) from the World Ocean Atlas (WOA) 2001 (Ocean Climate Laboratory National Oceanographic Data Center, 2002).

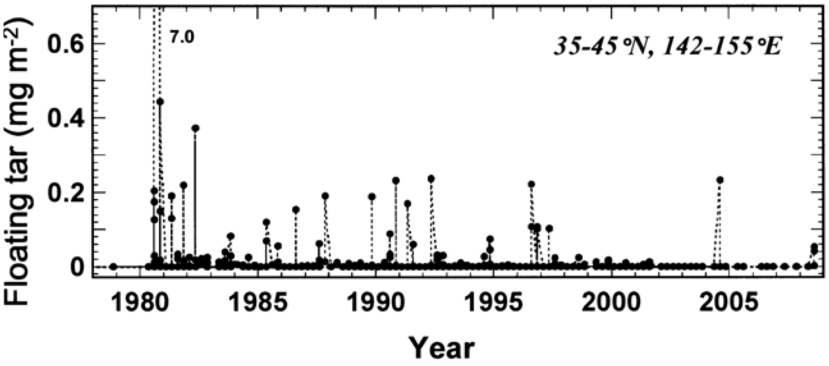
phosphate ($r^2 = 0.57$, n= 69 at PH-1; $r^2 = 0.72$, n= 68 at PH-6), suggesting these variations are due to Cd supply through entrainment and removal by active biological consumption, but not to anthropogenic contamination. Relatively high Cd concentrations at PH-6 in winter and spring were attributable to larger entrainment due to deeper convection, as evidenced by temperature at 100 m, which is the index of the Oyashio region (where a temperature-minimum layer is formed, corresponding to the bottom of the winter mixed layer). Temperature at PH-6 (2.0 ± 1.2°C) was lower than that at PH-1 (4.9 ± 1.3°C). Temperature at 100 m at PH-6 was low especially in 2000 (0.93°C) and 2003 (0.97°C), when the Cd concentration was high. At PH-1, the average annual mean and maximum for Cd concentration decreased from 29±5 $ng \cdot kg^{-1}$ and 48±7 $ng \cdot kg^{-1}$ in the 1990s to 24±3 $ng \cdot kg^{-1}$ and 40±7 $ng \cdot kg^{-1}$ after 2002, respectively, corresponding to an increased annual temperature minimum at 100 m from 9.2±0.9°C to 10.4±0.5°C. At PH-6, the decadal mean Cd concentration increased from 41±10 $ng \cdot kg^{-1}$ in the 1990s to 48±4 $ng \cdot kg^{-1}$ after 2002, corresponding to an increased annual minimum of temperature at 100 m from 3.3±1.2°C to 4.3±1.4°C. The difference between the two sites can be attributed to the occasional displacement by Tsugaru Warm Water at PH-1.

A time series of floating tar balls was created by horizontal tows of a 0.35 mm mesh net in the region of 35-45°N 142-155°E (Fig OY-15). In this region, 3 to 22 (average, 14) samples a year were obtained during the period of 1980-2008. Before 1983, the concentration of tar balls was high (average, 0.14 $mg \cdot m^{-2}$) and a large tar ball concentration exceeding 0.4 $mg \cdot m^{-2}$ was found. After 2000, the tar ball concentration was low (average, 0.0048 $mg \cdot m^{-2}$) and few tar balls were collected throughout the year, although a high tar ball concentration was occasionally observed as in 2004 (0.23 $mg \cdot m^{-2}$).

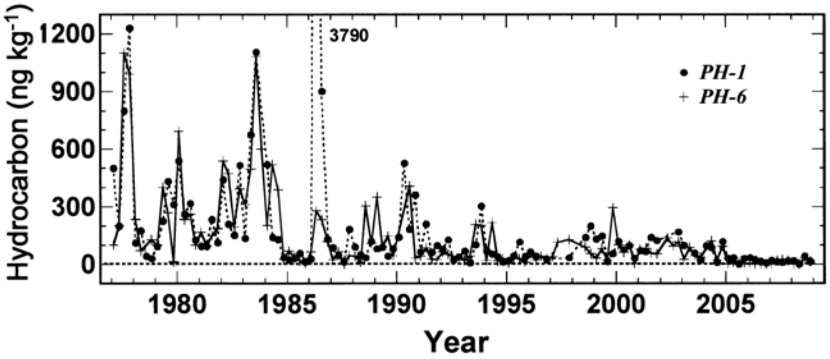
The concentrations of petroleum hydrocarbons in surface waters at two monitoring sites were high (averages, 383 $ng \cdot kg^{-1}$ at PH-1 and 295 $ng \cdot kg^{-1}$ at PH-6) before 1987 (Fig. OY-16). After 2002, the hydrocarbon concentrations (averages, 34 $ng \cdot kg^{-1}$ at PH-1 and 24 $ng \cdot kg^{-1}$ at PH-6) were low compared with the levels for 1995 to 2002 (averages, 85 $ng \cdot kg^{-1}$ at PH-1 and 70 $ng \cdot kg^{-1}$ at PH-6).



[Figure OY-14] Temporal variations of cadmium concentration in surface waters at the two monitoring sites : PH-1 (41.5°N, 142°E) and PH-6 (41.5°N, 147°E), in the western North Pacific for 1990-2008.



[Figure OY-15] Temporal variations of floating tar balls collected in the region of 35-45°N, 142-155°E for 1978-2008.



[Figure OY-16] Temporal variations of petroleum hydrocarbon concentration in surface waters at PH-1 and PH-6 for 1977-2008. The hydrocarbon concentration is expressed as the chrysene equivalent in the fluorescence measurements.

# 5.0 Biological Ocean

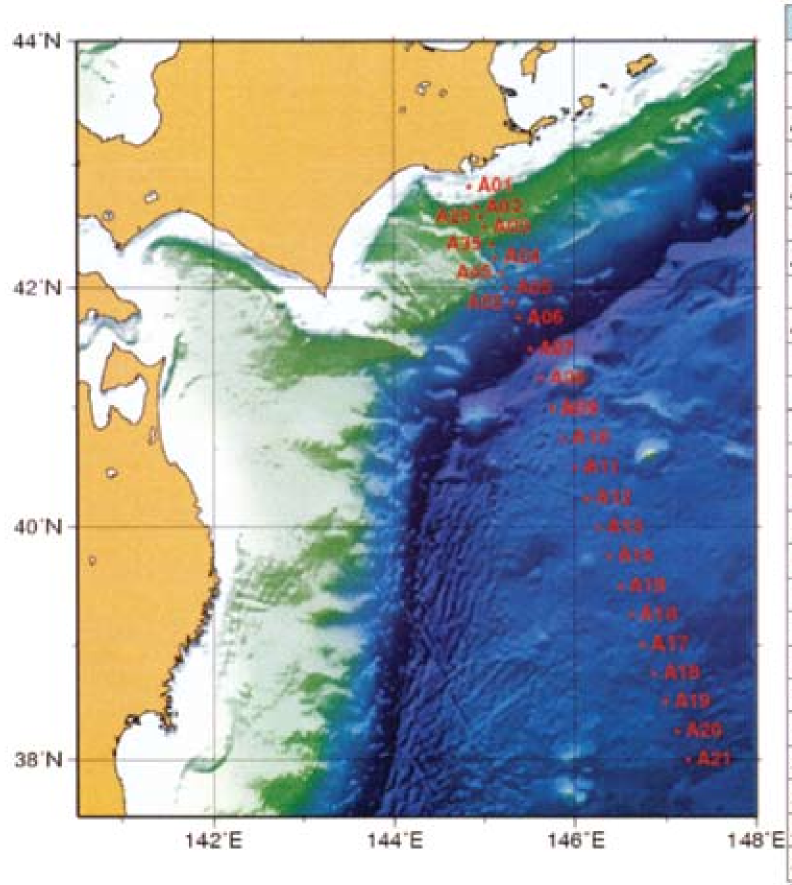
## 5.1 Phytoplankton

### 5.1.1 Chlorophyll measurements *(Saitoh, Kuwata)*

Shipboard measurements of chlorophyll$_a$ concentration were carried out at near bimonthly intervals at 12 stations along the A-line, off Hokkaido, Japan (38-42°50'N 147°25' - 144°50'E) (Fig. OY-17). Spring and fall phytoplankton blooms were observed during April through June and during September through November, respectively, although the fall bloom was indistinct in the southern region (Fig. OY-18). In general, the chlorophyll$_a$ concentration was higher on the continental shelf and in the Oyashio First Branch (>41°30'N) compared with the southern region. Lowest chlorophyll$_a$ concentrations were observed in regions with SST>20°C where nutrients were depleted. SST was cooler after 2006 than in 2003-2005, particularly north of 40°N, and chlorophyll$_a$ concentration was low during early spring but its peak was high.

In the Oyashio region, mean chlorophyll$_a$ concentration peaked in May and the lowest values were observed in January and July (Fig. OY-19). The median value in April was only 0.48 mg·m$^{-3}$, which indicates that the spring bloom begins in May at most stations. The seasonal pattern and the concentration in each month were similar to previous reports (Saito et al. 2002; Yokouchi et al. 2006).

On the continental shelf, the spring bloom began in March and continued until July (Fig. OY-20). High concentrations were observed throughout the water column (100 m) during the spring bloom, which indicated a high sinking flux of phytoplankton from the euphotic zone. The initiation of the phytoplankton bloom in the Oyashio First Branch was late compared with that in the Second Branch, due to the late development of the thermocline. A subsurface chlorophyll maximum (SCM) due to nutrient depletion in the warm surface layer was observed in summer in the Oyashio Second Branch. A weak phytoplankton bloom was observed in the Oyashio-Kuroshio Inter-frontal Zone south of the Subarctic Front. Chlorophyll$_a$ concentration in the sea surface was low in summer, and the SCM developed in the 40-60 m layer. These latitudinal differences in the seasonal pattern and vertical profiles of chlorophyll$_a$ concentration observed during 2003-2008 were similar to those reported in previous studies (Kasai et al. 1998; Taguchi et al. 1992).

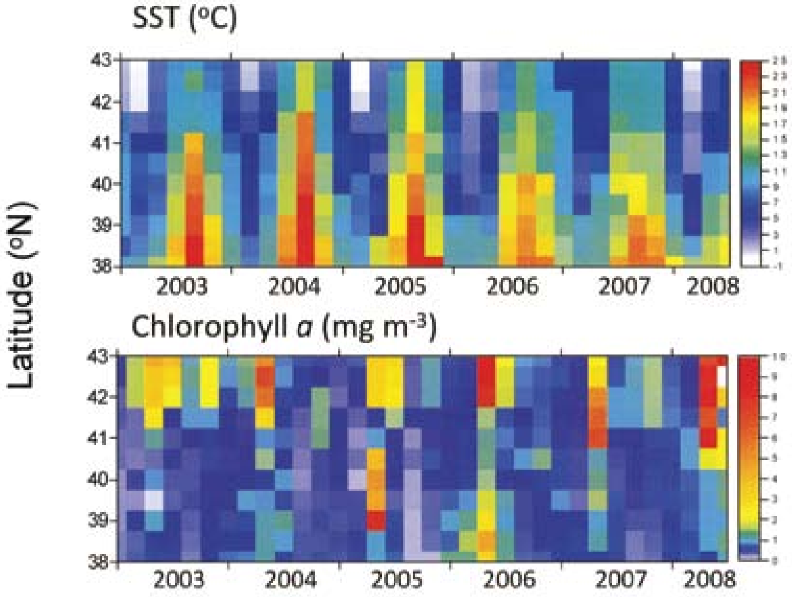


**A-Line Stations**

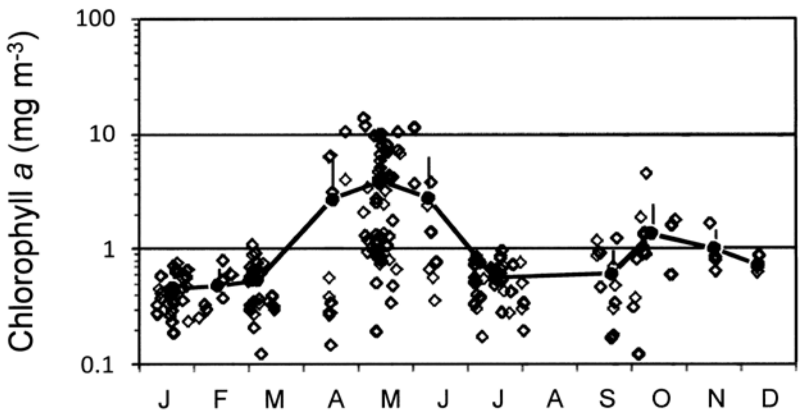
| St # | Latitude | Longitude | Depth (m) |
|---|---|---|---|
| A1 | 42°50'N | 144°50'E | 99 |
| A2 | 42°40'N | 144°55'E | 400 |
| A25* | 42°35'N | 144°57.5'E | 1200 |
| A3 | 42°30'N | 145°00'E | 1780 |
| A35* | 42°21'N | 145°04.5'E | 2574 |
| A4 | 42°15'N | 145°07.5'E | 2950 |
| A45* | 42°07.5'N | 145°11.3'E | 3200 |
| A5 | 42°00'N | 145°15'E | 4000 |
| A55* | 41°52.5'N | 145°18.8'E | 4500 |
| A6 | 41°45'N | 145°23'E | 5280 |
| A7 | 41°30'N | 145°30'E | 7150 |
| A8 | 41°15'N | 145°38'E | 6320 |
| A9 | 41°00'N | 145°45'E | 5580 |
| A10 | 40°45'N | 145°53'E | 5280 |
| A11 | 40°30'N | 146°00'E | 5160 |
| A12 | 40°15'N | 146°08'E | 5150 |
| A13 | 40°00'N | 146°15'E | 4900 |
| A14 | 39°45'N | 146°23'E | 5170 |
| A15 | 39°30'N | 146°30'E | 5200 |
| A16 | 39°15'N | 146°38'E | 5220 |
| A17 | 39°00'N | 146°45'E | 5210 |
| A18* | 38°45'N | 146°52.5'E | 5200 |
| A19* | 38°30'N | 147°00'E | 5200 |
| A20* | 38°15'N | 147°7.5'E | 5200 |
| A21* | 38°00'N | 147°15'E | 5200 |

*: operated from Jan 2003

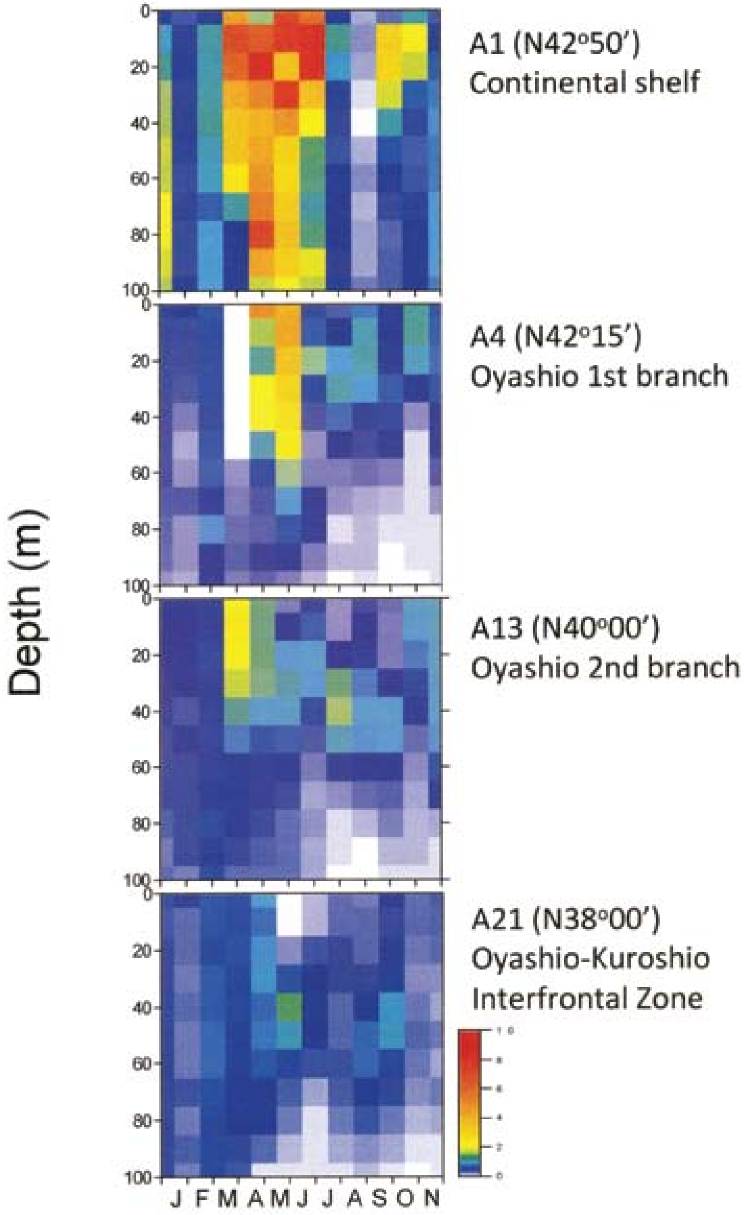
[Figure OY-17] Map of the A-line stations occupied by the Hokkaido National Fisheries Research Institute / Tohoku National Fisheries Research Institute (http://hnf.fra.affrc.go.jp/a-line/intro/index_e.html)



[Figure OY-18] Temporal variations in temperature (top) and chlorophyll$_a$ concentration (bottom) at the sea surface along the A-line during 2003-2008.



[Figure OY-19] Seasonal variation in the chlorophyll$_a$ concentration at the sea surface during 2003-2008. Circles connected with the thick line and the vertical bars indicate the mean and standard error in each month, respectively.



[Figure OY-20] Temporal variations in the vertical profile of chlorophyll$_a$ concentration at Stns A1 (continental shelf), A4 (Oyashio 1st branch), A13 (Oyashio 2nd branch) and A21 (Oyashio-Kuroshio interfrontal zone) during 2003-2008.

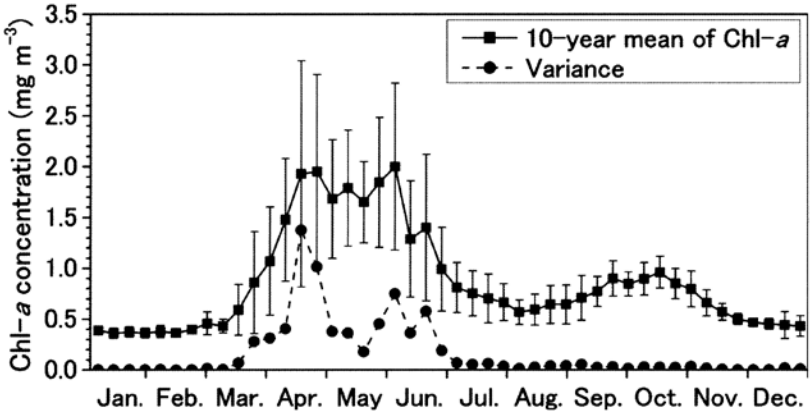
### 5.1.2 Chlorophyll from satellite

*(Okamoto, Saitoh, Hirawake)*

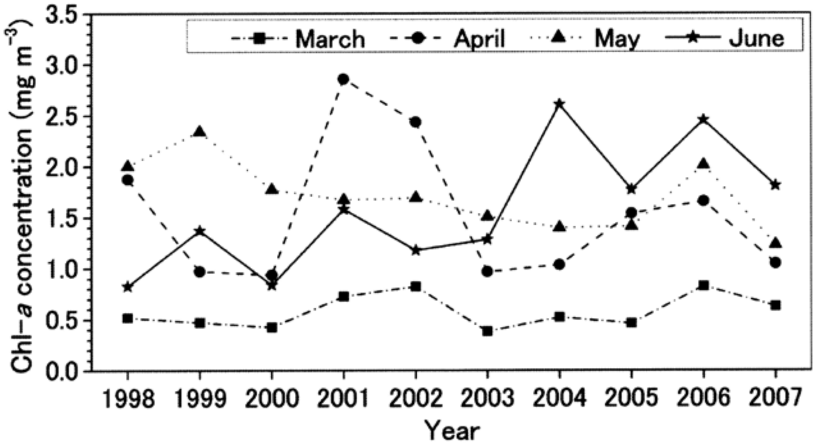
From 1998 to 2007, sea surface chlorophyll$_a$ concentration was generally high (>1 $mg \cdot m^{-3}$) from April to June, followed by a summer low from July to August, and the interannual variability was substantial from late March to June (Fig. OY-21). Fall blooms were observed from September to October, but the interannual variability in chlorophyll$_a$ concentration was low during these months.

In April, chlorophyll$_a$ concentration was comparatively high in 2001 and 2002, and low in 1999, 2000, 2003, 2004 and 2007 (Fig. OY-22). No distinctive trend was observed in April during the 10 years from 1998 to 2007. On the other hand, chlorophyll$_a$ concentration tended to decrease in May and to increase in June. Until 2003, it was lower in June than in May but from 2004 on, it was higher in June. From 2003 on, chlorophyll$_a$ concentration was also higher in June than in April. These patterns indicate changes in the timing and duration of the spring bloom.

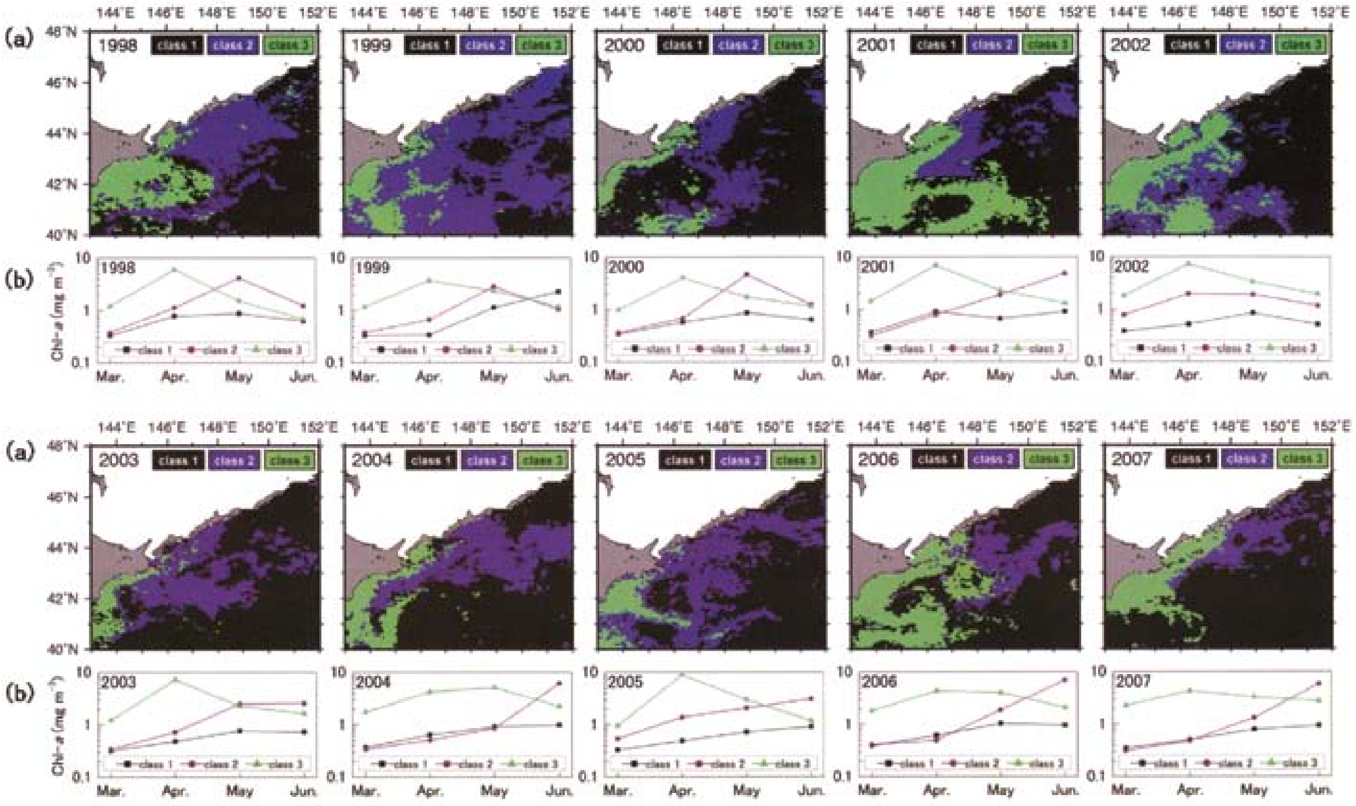
The seasonal and spatial variability in chlorophyll$_a$ concentration from March to June were examined by cluster analysis. Each grid was classified into one of the 3 cluster groups based on the peak timing and extent of chlorophyll$_a$ concentration: class 1 had low chlorophyll$_a$ with its peak in May-June; class 2 had moderate chlorophyll$_a$ with its peak in May-June; and class 3 had high chlorophyll$_a$ with its peak in April-May. The results show that chlorophyll$_a$ concentration during spring was greatly different between areas and years (Fig. OY-23). In 2001, 2002 and 2006, the area where chlorophyll$_a$ concentration was highest in April was more extensive than usual, whereas it was very narrowly distributed in 2003. In 1999, the area where chlorophyll$_a$ concentration was highest in May was the widest among the 10 years, due to the bloom in May of that year (Fig. OY-23). The areas which had peak chlorophyll$_a$ concentration in April or May were extensively distributed until 2002 (Fig. OY-23). From 2003 on, increasing temporal variation in chlorophyll$_a$ concentration from March to June was observed over a broad area. From 1998-2002 to 2003-2007, the season of high chlorophyll$_a$ concentration shifted to June in this broad area.



[Figure OY-21] The seasonal variability in sea surface chlorophyll$_a$ concentration (from a satellite ocean color sensor, SeaWiFS) averaged for 10 years (solid line) and its variance from 1998 to 2007 (dashed line) in the Oyashio region.



[Figure OY-22] Interannual variability in chlorophyll$_a$ concentration from March to June.



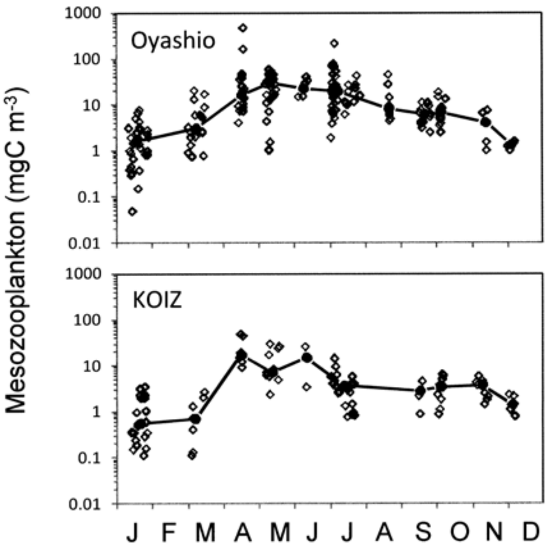
[Figure OY-23] (a) Spatial distribution of seasonal variation pattern of chlorophyll$_a$ concentration from 1998 to 2007 for each class specified by cluster analysis based on the timing and extent of peak chlorophyll$_a$. (b) Seasonal variability of chlorophyll$_a$ concentration in the region of each class. Class 1: low chlorophyll$_a$ with its peak in May-June, Class 2: moderate chlorophyll$_a$ with its peak in May-June, Class 3: high chlorophyll$_a$ with its peak in April-May.

## 5.2 Zooplankton

*(Saito, Okazaki, Tadokoro, Takahashi)*

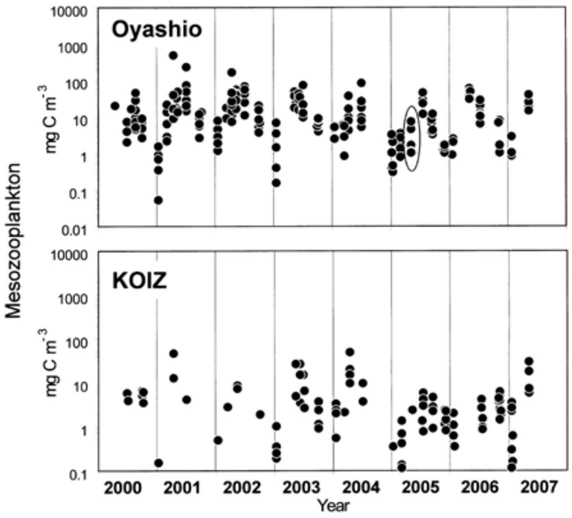
### 5.2.1 Biomass and seasonal cycle

Along the A-line, the mesozooplankton biomass in the upper 150 m showed clear seasonal variation both in the Oyashio region and the Kuroshio-Oyashio Inter-frontal Zone (KOIZ) (Fig. OY-24). The highest values were observed during April to July, and the lowest in December and January. The magnitude of the seasonal variation (max - min of median in each month during 2001-2007) was 28.2 $\mathrm{mgC \cdot m^{-3}}$ and 16.7 $\mathrm{mgC \cdot m^{-3}}$ in the Oyashio and KOIZ, respectively, and the ratio of the maximum to minimum was 22 and 31, respectively. In the Oyashio region, the mean biomass in each month was higher than in the KOIZ except for December, and the mean ratio of the Oyashio to KOIZ was 2.8. The highest ratio was observed in July (7.58), at which time the mesozooplankton biomass in the KOIZ declined from June, probably due to the decreasing chlorophyll$_a$ and/or increasing sea surface temperature.



[Figure OY-24] Seasonal change in the mesozooplankton biomass in the top 150 m of the water column in the Oyashio region (top) and Kuroshio-Oyashio Interfrontal Zone (KOIZ, bottom). Data were obtained at stations along *A-line* during 2001-2007. Circles connected with thick line indicate the median in each month.

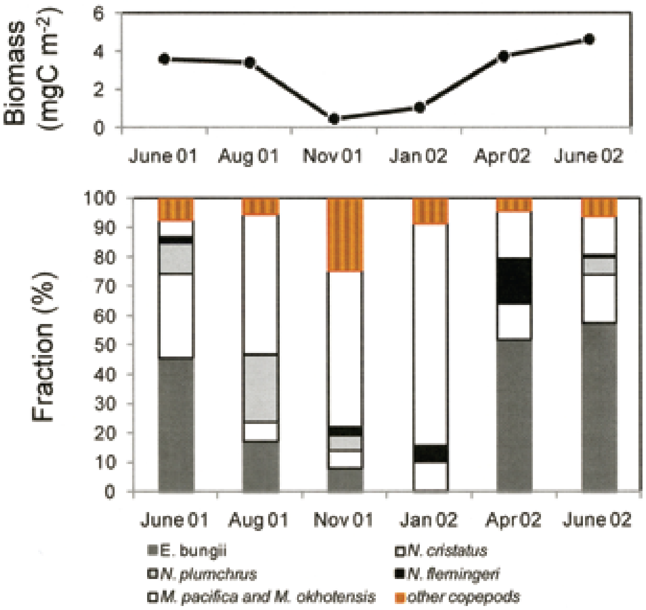
The mean and median biomass in July in the Oyashio region (29.3 mgC·m$^{-3}$ and 19.8 mgC·m$^{-3}$) were comparable to those in April, May and June. No statistical difference in the mean biomass in January and July was observed among years. On the other hand, the mean biomass in July 2005 was significantly lower than other years (Fig. OY-25). In the KOIZ, the peak biomass was relatively low also in 2005 and in 2006 (Fig. OY-25).



[Figure OY-25] Interannual change in the mesozooplankton biomass in the top 150 m of the water column in the Oyashio region (top) and Kuroshio-Oyashio Interfrontal Zone (KOIZ, bottom). Data were obtained at the stations along *A-line* during 2000-2007. July biomass in 2005 in Oyashio is indicated by the circle.

## 5.2.2 Copepods

During the period of June 2001 and June 2002, the seasonal dynamics and annual ingestion rate of copepod populations were investigated in the Oyashio region, off Hokkaido (Takahashi et al. 2008). Total copepod biomass in the upper 150 m ranged between 0.47 - 4.6 gC·m$^{-2}$ (converted from wet weight using a C:WW ratio of 0.08). The dominant species in spring to early summer was *Eucalanus bungii* (Fig. OY-26). Adult females and copepodid stage 5 (C5) were most abundant in April, and C1 and C2 were numerically dominant in June. *Neocalanus* spp. were abundant in spring and summer. *N. flemingeri* was most abundant in April and *N. plumchrus* in June and August. *N. cristatus* occurred throughout the year, and was most abundant from spring to early summer. *Metridia* spp. also occurred throughout the year and was most abundant in summer. The contribution of *Metridia* spp. to the copepod assemblage was high in late summer and winter when most *E. bungii* and *Neocalanus* spp. were dormant in the mesopelagic zone. The seasonal succession of copepods was consistent with previous studies (Tsuda et al. 1999, 2004; Padmavati et al. 2004).



[Figure OY-26] Seasonal change in mesozooplankton biomass (0-150 m) at a fixed station in the Oyashio region (top) and species composition (bottom) from June 2001 to June 2002.

The annual ingestion rate of phytoplankton and particulate organic matter (POM) by the copepod assemblage was 37.7 gC·m$^{-2}$·y$^{-1}$ and 137.9 gC·m$^{-2}$·y$^{-1}$, respectively, which was equivalent to 13% and 46% of the annual primary production (Takahashi et al. 2008). *E. bungii* contributed 33.1% and 46.5% of the ingestion rate on phytoplankton and POC, respectively. The biomass of *E. bungii* was comparable to that of the Bering Sea and 1-2 orders of magnitude higher than that of the western and eastern Subarctic gyres. The high biomass of *E. bungii* in the Oyashio region probably reflects the high food availability during the spring bloom. *Neocalanus* spp. and *Metridia* spp. annually contributed 26.5% and 19.9% respectively to the total copepod ingestion of POC.

Copepods are important drivers of the biological carbon pump to the ocean interior because they package small prey particles into fast sinking fecal pellets and because of their diel or ontogenetic vertical migrations. Based on the observation from September 1996 to October 1997 in the Oyashio region, *Neocalanus* spp. transported 6.5 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ to 200 m by ontogenetic vertical migration and fecal pellet production, and 4.3 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ to 1000m (Kobari et al. 2003). *Metridia* spp. are the dominant diel vertical migrators in the Oyashio region and their annual carbon transport to 150 m was estimated to be 3.0 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ based on observations from June 2001 to June 2002 (Takahashi et al. 2009). The *Metridia* spp. contribution to the active biological pump was high from late summer to winter when both sinking particle flux and the *Neocalanus* and *Eucalanus* contributions to the active biological pump were low.

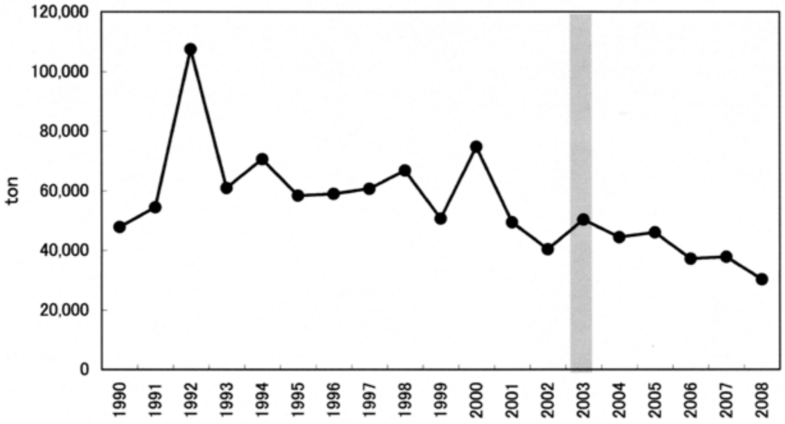
### 5.2.3 Euphausiids

Twenty-six euphausiid species are recorded in the coastal area of northeastern Japan (Taki 2007a). *Euphausia pacifica* is the most abundant species in this region, and *Thysanoessa inspinata* is the second most abundant. Along the A-line, 21 species of euphausiids were collected in the Oyashio and mixed water region (Okazaki, unpublished data). *E. pacifica* and *Thysanoessa* spp. were the two most abundant taxa in the Oyashio region. *Euphausia recurva*, *E. mutica* and *Nematoscelis microps* occurred year round in the mixed water region (temperature at 100 m ≥5°C). *Stylocheiron* spp., *Thysanopoda* spp. and *E. brevis* occurred from summer to autumn in the mixed water region.

The diet of *E. pacifica* off northeastern Japan depends on both heterotrophic (microzooplankton) and autotrophic (phytoplankton) prey. Based on a study during 1997-1998 (Nakagawa et al. 2001), seasonal change in the number of prey items consumed by *E. pacifica* showed diatoms (88.0%) were the most abundant prey items in April, whereas the most abundant prey items in other seasons (June, August, October, December and February) were dinoflagellates, tintinnids and copepods. On the other hand, seasonal change in carbon composition of prey items showed that the most important prey items throughout the survey period were copepods (more than 98.5%).

*E. pacifica* is an important prey item for many fish, marine mammals and seabirds. In the Oyashio and mixed water region, Pacific saury (*Cololabis saira*) was reported to feed mainly on *E. pacifica* during 1999-2001 (Sugisaki and Kurita 2004). In demersal environments, Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theragra chalcogramma*) were reported to have a high proportion of *E. pacifica* in their diets during 1989-1992 (Yamamura et al. 1998). *E. pacifica* is not only an important prey item for commercial fishes, but also for non-commercial fishes. For example, it was reported that many Myctophidae fishes (*Diaphus theta, Stenobrachius leucopsarus, Notoscopelus japonicas* and *Lampanyctus jordani*) fed on *E. pacifica* in the mid to late 1990s (Moku et al. 2000; Uchikawa et al. 2002, 2008) in the western North Pacific.

In Japanese waters, euphausiids are not only important to higher trophic organisms as prey but are also a direct fishery resource. A euphausiid (mostly *E. pacifica*) fishery is conducted in Sanriku and Joban waters off northeastern Japan in late winter to spring. In recent years, euphausiids have been caught by boat seines. In the last 10 years, total landings were from 30,000 to 50,000 t annually (Fig. OY-27). The annual landings are regulated by prefectural governors to keep stable prices, therefore we should note that landing data do not represent euphausiid biomass or stock status.



[Figure OY-27] Catch (t) of *Euphausia pacifica* off northeastern Japan. Note that the total catch is regulated by prefectural governors and does not represent its biomass.

Long-term changes of euphausiid biomass have not been reported in the western North Pacific because the data are limited. Taki (2007b) showed interannual variation in abundance of *E. pacifica* collected from 1993-2000. The abundance of adult *E. pacifica* in summer-autumn was higher in 1993, 1994 and 1999 than other years during the study period. He also reported that the abundance of eggs and larvae in spring were highly correlated with adult abundance in the subsequent summer-autumn. This implies that interannual variation in abundance of euphausiid eggs and larvae could be a good indicator of euphausiid population changes. Eggs and larvae can be estimated by a small plankton net such as a NORPAC net. Thus, eggs and larvae collections are a possible way for long term analysis because sampling by NORPAC net in the western North Pacific has been conducted since the 1950s.

# 6.0 Fishes and Invertebrates

## 6.1 Pelagic fish and squid

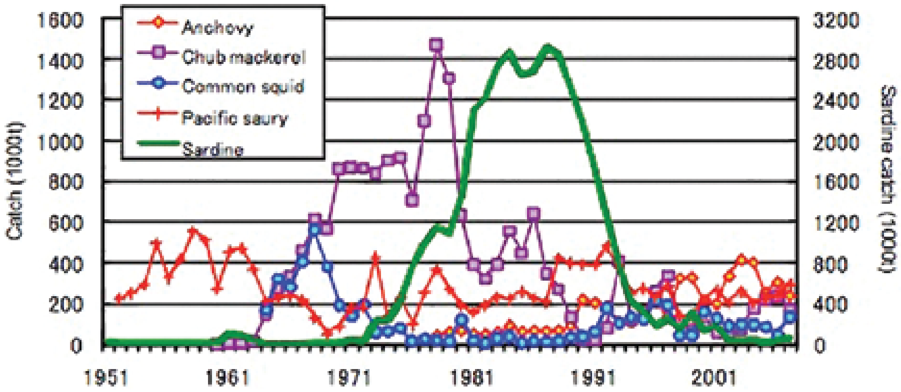
*(Yatsu, Yamashita, Watanabe)*

Japanese fishers have been harvesting various marine organisms in the Oyashio, Kuroshio and its adjacent regions for a very long time. Small pelagic fish such as Japanese sardine (*Sardinops melanostictus*), Japanese anchovy (*Engraulis japonicus*), chub mackerel (*Scomber japonicus*), Pacific saury (*Cololabis saira*) and Japanese common squid (*Todarodes pacificus*) have constituted most of the commercial landings since the early 20th century, but the landings have varied considerably (Fig. OY-28).

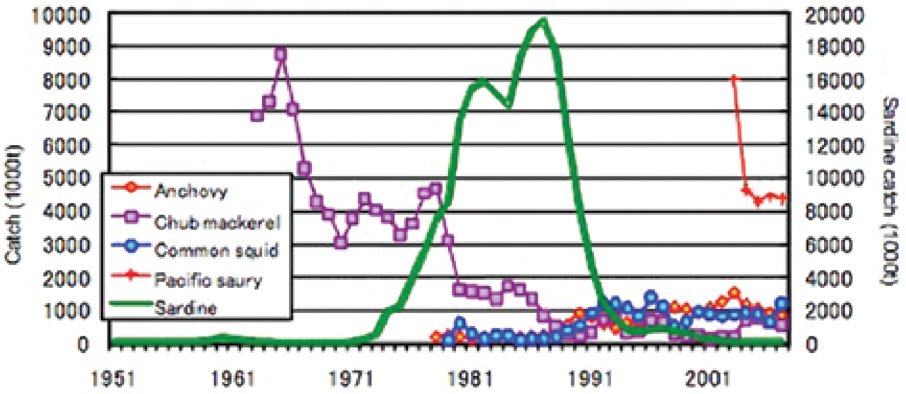
These species undergo seasonal north-south migrations between spawning grounds in the subtropical, Kuroshio region (see Sugisaki et al. 2010) during autumn-winter-spring and feeding grounds in the subarctic, Oyashio water in summer. One of the distinctive features of the Kuroshio-Oyashio system is the large latitudinal contrast of environments. The dominant zooplankton size increases with latitude, and the start of active plankton production is earlier in the year in the south than in the north. Therefore, ontogenetic migration in the Kuroshio-Oyashio system favors small pelagic fish (Ito et al. 2004b). Consistent with the "surf riding theory", reproduction occurs on time and space scales that take advantage of the “wave” of food supply that propagates from south to north (Pope et al. 1994). The spawning grounds of these species usually extend from Kyushu Island (southern Japan) to Cape Inubo (36°N), except for the common squid, which has its major spawning grounds in the East China Sea in winter, and for anchovy and Pacific saury, whose spawning grounds extend from southern Japan to the extensive area of the Transition Zone, presumably beyond the International Date Line in recent years when stock level has been high (anchovy) or to the California Current (Pacific saury).

Biomass patterns and Japanese commercial catches of these small pelagic fishes indicate decadal changes or alternations of dominant species called “species replacements” (Figs. OY-28 and OY-29). Although mechanisms of species replacements have not been fully resolved, ocean-climate regime shifts together with species interactions have profound impacts on dynamics of small pelagic fishes. Sardine biomass and catch were high during the 1980s and decreased in the 1990s. The onset of increase and decrease of the biomass occurred in the early 1970s and 1989, respectively, which coincided with regime shifts found in SST and mixed layer depth (Nishikawa and Yasuda 2008) around the Kuroshio Extension. The observed recruitment of sardine was above the Ricker curve, which indicates a relationship between net reproduction and stock density during 1971-1987, and below the curve during 1951-1970 and after 1988, suggesting unfavorable environmental conditions after 1988. Reproductive success, which is determined by interannual changes in survival rates of larvae and juveniles, is affected by the SST of the Kuroshio Extension southern area and locations around the southern boundary of the Oyashio intrusion. Spawning stock biomass (SSB) was around 0.5 million t in the late 1990s, and has decreased to less than 0.3 million t since 2002. Therefore, recruitment in recent years has been extremely low and catch has been less than 60,000 t since 2002. Mean body weight of age 0-2 sardines was low during the 1980s when sardine biomass was high, and then suddenly increased in the early 1990s (Fig. OY-30).

Chub mackerel biomass and catch were high during the 1970s and decreased in the early 1990s, thereafter increasing slightly. The observed recruitment of chub mackerel was above the Ricker curve during 1970-1977, 1991-1992, and 1995-1996, and below the curve during 1978-1980 and 1986-1990. Despite the occurrences of strong year-classes in 1992 and 1996, intensive fishing



[Figure OY-28] Japanese catch of sardine, anchovy, chub mackerel, Pacific saury and common squid (winter spawning stock) along the Pacific coast of Japan.

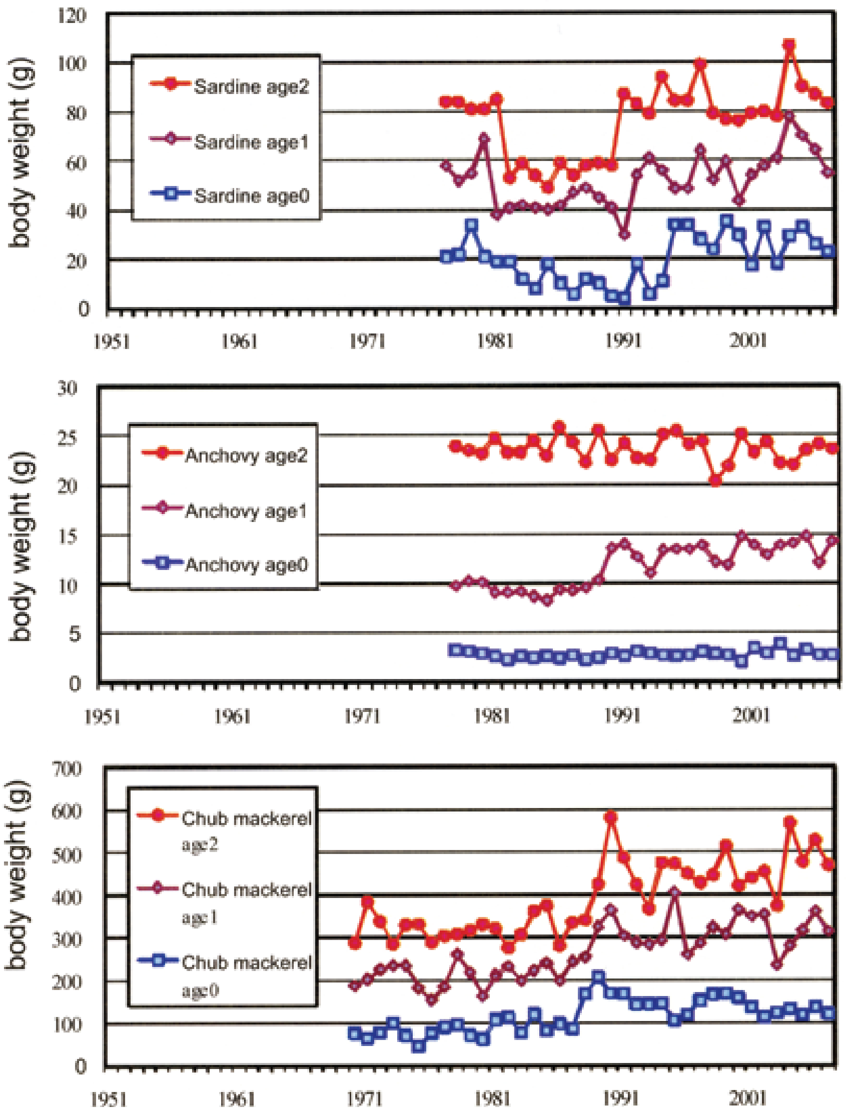


[Figure OY-29] Biomass of sardine, anchovy, chub mackerel, Pacific saury and common squid (winter spawning stock) along the Pacific coast of Japan. NB: anchovy biomass represents only Japanese coastal and offshore waters. Biomass of Pacific saury was estimated for western and central North Pacific west of 177°W.

on immature fishes prevented stock recovery. In 2004, an occurrence of a strong year-class together with a "stock recovery plan" slightly improved stock biomass and catch in subsequent years. Thus, recruitment and catch since the 1990s have been variable. The biomass of chub mackerel fluctuated between 0.15 million t (2001) and 0.78 million t (2005) during the 2000s. Mean body weight of age 0-2 chub mackerel was low until the mid 1980s, when chub mackerel biomass was high, and gradually increased in the late 1980s (Fig. OY-30).

Anchovy and common squid biomass and catch have been relatively high since the 1990s, but with considerable year-to-year fluctuations (e.g. a drastic decline of squid catch in 1998 and 1999 when an extremely strong El Niño occurred), which reflects their relatively short life spans (anchovy - 2 or 3 years and squid - 1 year). The biomass of anchovy gradually decreased from 2003 (1.5 million t) to 2007 (0.8 million t). The biomass of common squid fluctuated between 0.8 and 0.9 million t between 2000 and 2005, and decreased to 0.7 million t in 2006. However, a strong year-class appeared and biomass increased to 1.2 million t in 2007. Fluctuations of biomass in recent years, as well as during the 1990s, have been large. Catch and biomass of sardine seem to be negatively related with those of anchovy and common squid. Mean body weight of age 0-2 anchovy has been relatively stable since the late 1970s, except for a slight increase in body weight of age-1 fish in the late 1980s, which coincided with the increase in body weight of chub mackerel (Fig. OY-30).

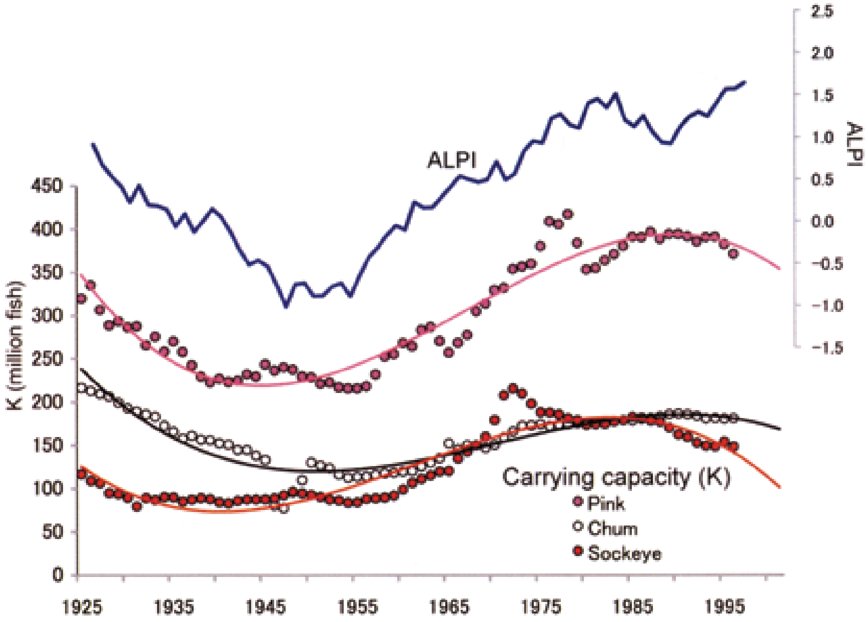
Catch of Pacific saury, which has a 2-year life span, showed a decadal fluctuation before the 1990s but has stabilized at 0.2-0.3 million t per year since the late 1990s when the Japanese Total Allowable Catch system took effect to prevent overexploitation. Exceptions were the considerable declines of catch and biomass in 1998 and 1999. Biomass data directly estimated with a pelagic trawl are available only since 2003, and indicate biomass was stable during 2004-2007.



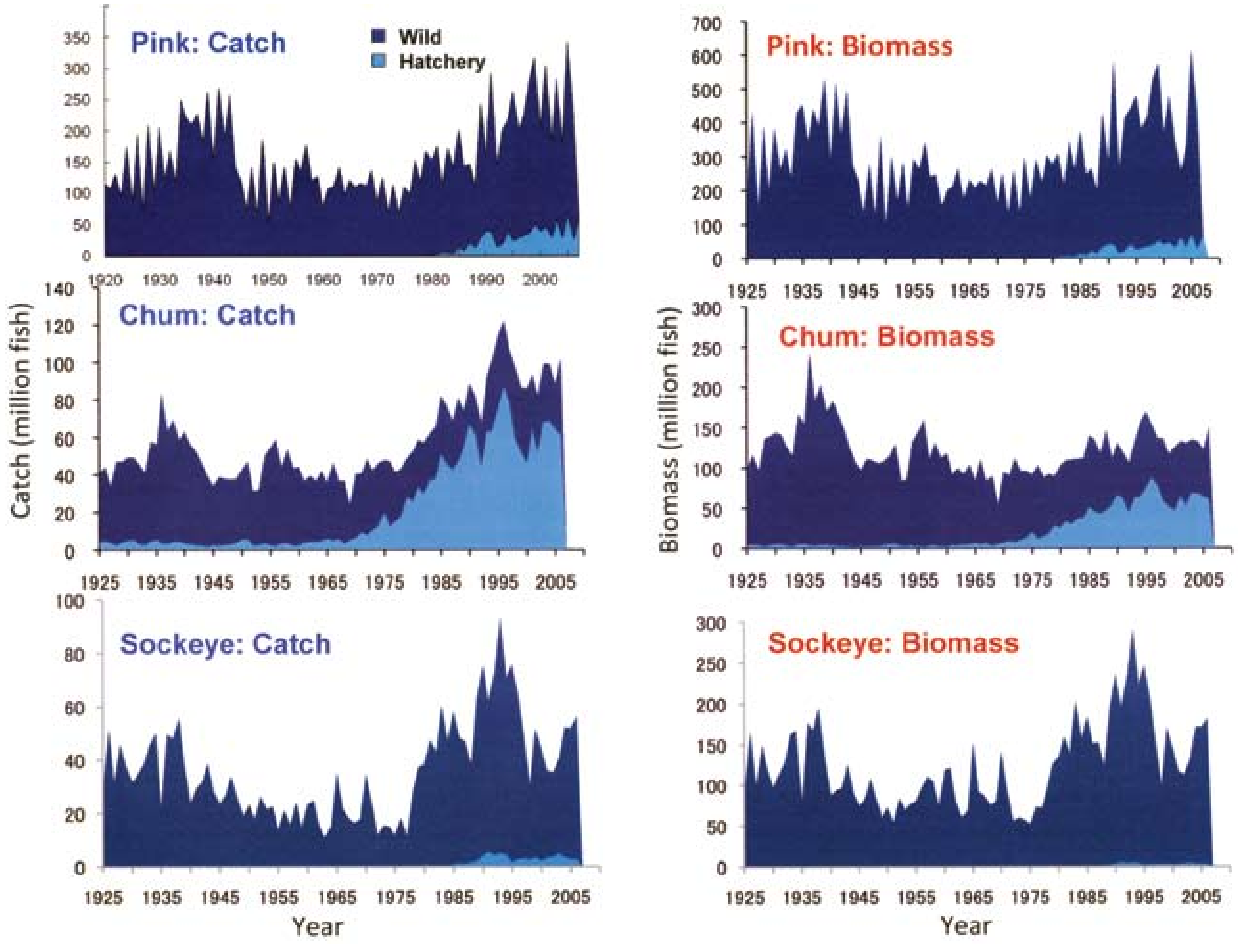
[Figure OY-30] Mean body weight by age of sardine, anchovy and chub mackerel along the Pacific coast of Japan.

### 6.1.2. Pacific salmon *(Kaeriyama)*

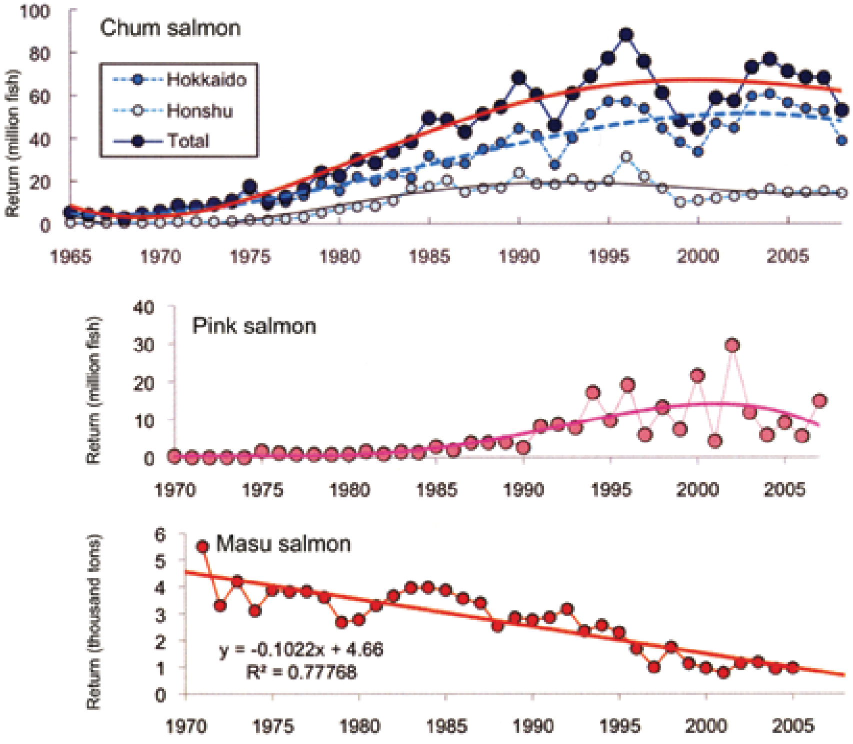
Pacific salmon occupy the fourth and fifth trophic levels in the Subarctic ocean ecosystem and can be considered as key species. Because they are anadromous, they sustain biodiversity and productivity in riparian ecosystems by bringing marine-derived materials to the rivers. Salmon carrying capacity (K) in the North Pacific Ocean has been synchronized with long-term climate change (Kaeriyama and Edpalina 2004). Interannual variation of average K of three species [sockeye (*Oncorhynchus nerka*), chum (*O. keta*), and pink (*O. gorbuscha*) salmon] was significantly correlated with Aleutian Low Pressure index (Beamish and Bouillion 1993) for the 1920s to present ($R^2 = 0.87$, $P < 0.001$) (Fig. OY-31). There have been gradual downward trends in K since the early 2000s (Fig. OY-31) suggesting a declining trend in biomass despite an increase in total catch during the focus period. Catches of pink and chum salmon since the 1990s have increased but catches of sockeye, coho, and masu salmon have decreased. Chinook salmon catches have been relatively stable Since the late 1970s, releases of hatchery chum and pink salmon have increased exponentially in Japan and Alaska. Hatchery chum salmon recently accounted for >80% of chum salmon catch, and >50% of chum salmon biomass. There has been no increase in wild chum salmon (Fig. OY-32). Pacific chum salmon returning to Japan (Fig. OY-33) peaked in the late 1990s, and shifted to a decreasing trend in the 2000s. Pink salmon increased until 2002 but has decreased since then. Masu salmon which live in freshwater over one year before going to sea have declined sharply since the 1970s.



[Figure OY-31] Aleutian Low Pressure index (ALPI) from Beamish and Bouillion (1993) and temporal changes in carrying capacity (K) of sockeye, chum, and pink salmon. The time span of data used to estimate the parameters (a, b, K) for year class, *t*, was 10 generations of odd- and even-year groups for pink salmon, and 10-20 brood years for sockeye and chum salmon from *t* to *t* +10/20. K of the year class *t* was estimated based on the salmon recruited during the year of *t* + 20.



[Figure OY-32] Temporal changes in catch and biomass of hatchery and wild pink, chum and sockeye salmon.

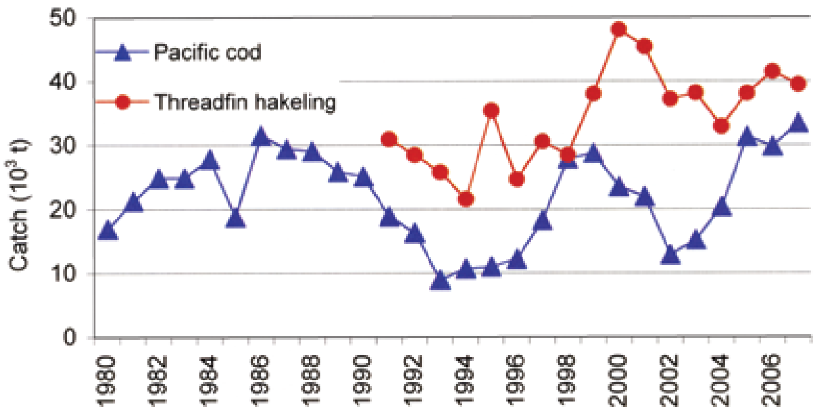


[Figure OY-33] Recent trends on returns of chum, pink, and masu salmon in Japan.

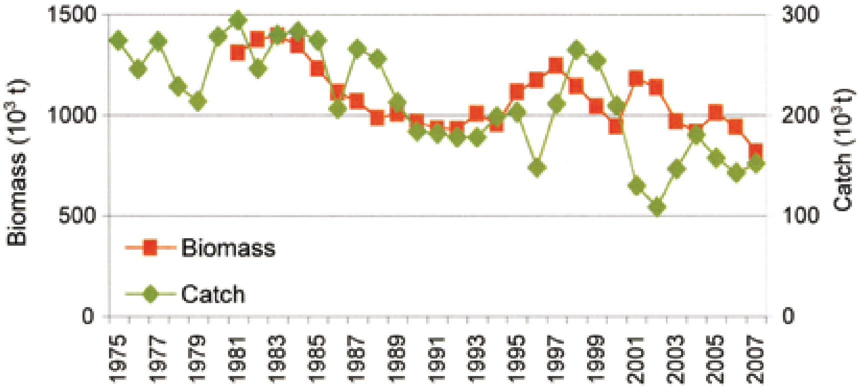
### 6.1.3. Demersal fish *(Yamamura)*

Three gadiform species, threadfin hakeling (*Laemonema longipes*), Pacific cod, and walleye pollock are abundant along the Pacific coast of northern Japan. For threadfin hakeling and Pacific cod, only catch statistics are available (FAJ and FRA 2009). The catch of Pacific cod has fluctuated between 9-34 thousand t with a decadal-scale oscillation (Fig. OY-34). Since 2004, >70% of the total catch is from the Tohoku area (northeastern coast of the mainland). Threadfin hakeling are distributed over the upper continental slope and are caught by Japanese and Russian trawlers. The catch has fluctuated between 21 – 48 thousand t since 1991 (Fig. OY-34).

The Japan Pacific Stock of walleye pollock is distributed along the Pacific coast of northern Japan. Its biomass is estimated by cohort analysis (Fig. OY-35) (FAJ and FRA, 2009) which shows a decreasing trend from the late 1970s (1.3 million t) to the most recent 5 year period (0.9 million t). This decrease reflects decadal variation in recruitment of the stock (Hamatsu et al. 2004). Whereas substantial numbers of walleye pollock recruited successfully and were caught in the Tohoku area in the early years, only a limited portion of this stock has been distributed in the Tohoku area since the 1990s. The decreasing trend in the catch of walleye pollock also reflects an abrupt decrease of the catch quota in the area of the northern four islands during the late 1980s (Fig. OY-35) (FAJ and FRA 2009).



[Figure OY-34] Catch of Pacific cod and threadfin hakeling.



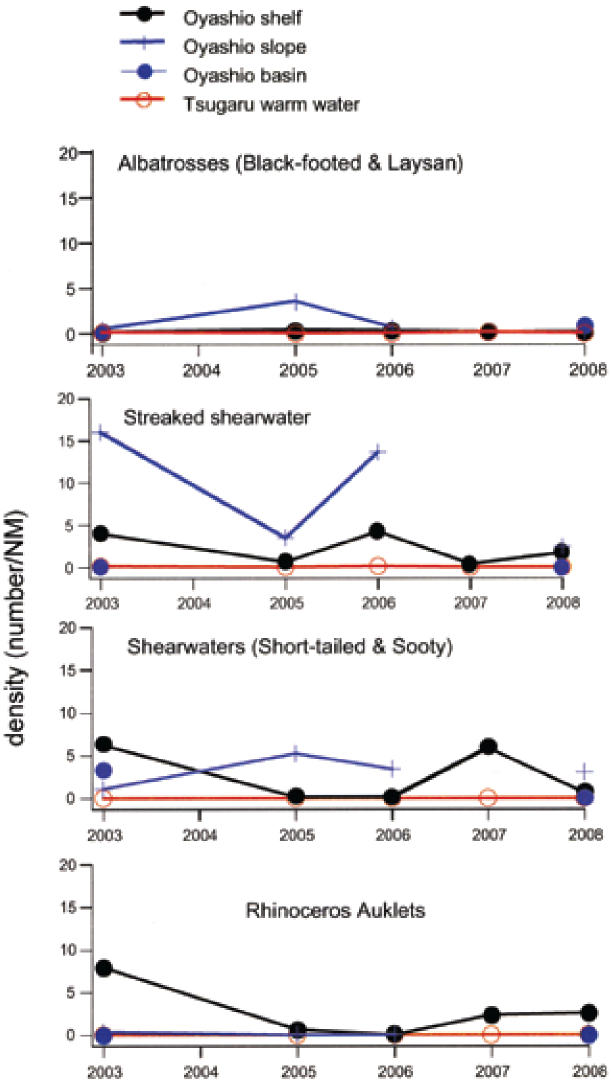
[Figure OY-35] Biomass and catch of the Japan Pacific Stock of walleye pollock.

# 7.0 Marine Birds *(Watanuki)*

The coastal area off eastern Hokkaido, Japan is an important foraging area for many seabird species in autumn. To understand the distribution and inter-annual variation of seabirds in shelf, slope and basin regions in this coastal area, ship-based censuses have been conducted in late September and early October from the T/S *Oshoro maru* (Department of Fisheries Sciences, Hokkaido University) since 2003. Seabirds sitting on the water and flying across a 300 m fan area of either the port or starboard side were counted. In every year, the warm (>19°C SST) Tsugaru water affected the eastern area of Cape Erimo, while cold (< 14°C SST) Oyashio water affected the western area. Coastal upwelling was observed along the slope. The density of seabirds was higher on the Oyashio shelf and slope area than in the Oyashio basin, and lower in the warm Tsugaru water (Table OY-1). Densities of rhinoceros auklet (*Cerorhinca monocerata*), a diving bird, were high on the shelf, and densities of other diving birds, short-tailed and sooty shearwater (*Puffinus* spp.) were high in some years in the shelf, too. Densities of surface feeders, streaked shearwater (*Calonectris leucomelas*), black-footed albatross (*Diomedia nigripes*) and Laysan albatross (*D. immutabilis*) were higher in the slope region. Within the 5 year observation period, no trends were apparent (Fig. OY-36).

[Table OY-1] Mean density (numbers per nautical mile) of albatrosses (black-footed and Laysan), shearwaters (short-tailed and sooty), streaked shearwaters and rhinoceros auklets sitting in Tsugaru warm water, Oyashio shelf, Oyashio slope and Oyashio basin areas in the coastal area of eastern Hokkaido.

| | Tsugaru water | Oyashio shelf | Oyashio slope | Oyashio basin |
|---|---|---|---|---|
| Albatrosses | 0.03 | 0.15 | 1.20 | 0.53 |
| Shearwaters | 0.00 | 2.61 | 3.21 | 1.65 |
| Streaked Shearwaters | 0.06 | 2.22 | 8.90 | 0.04 |
| Rhinoceros Auklet | 0.00 | 2.68 | 0.14 | 0.00 |



[Figure OY-36] Density of seabirds in numbers per nautical mile (NM) sitting on the sea surface in each water type in the coastal area of eastern Hokkaido.

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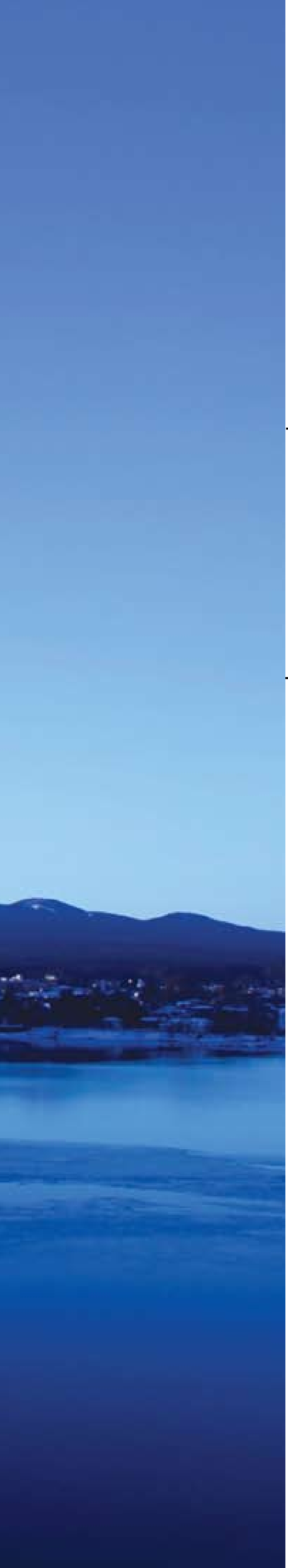

# Kuroshio

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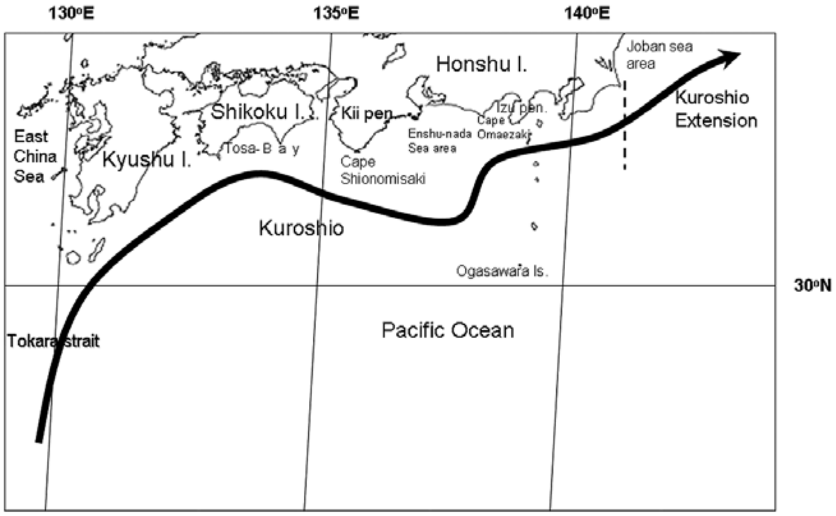
# highlights

- The strength of the Kuroshio is related to the magnitude of the Aleutian Low with a 5-year lag time. Weakening of the Aleutian Low in recent years suggests the Kuroshio should be weakening, and data indicate transport has been gradually decreasing since 2006.
- From 2003 to 2007, large anomalies and trends were not observed in the physical and biological properties of the Kuroshio. Some annual variation of atmospheric and oceanic conditions was observed. The Large-Meander pattern of the Kuroshio was observed during late 2004 and early 2005.
- Low nutrient concentrations and low seasonal variations of chlorophyll concentration and copepod biomass were observed after the Large-Meander year. During meander years, the species composition of diatoms was different from that of non-Large-Meander years. The meander may cause a change in species composition of the plankton community. Some clear ecological differences were observed before and after the large meander. The meander may cause an abrupt ecological change.
- Since physical conditions and biological production have not changed or fluctuated strongly except for the meander period during late 2004 and early 2005, the survival of pelagic fish larvae is thought to have been relatively stable during the focus period. This stability may have been the cause of low recruitment of Japanese sardine and jack mackerel that, in turn, led to continued low abundance from 2003 to 2007. On the other hand, Japanese anchovy were abundant and widespread during these years. High temperature conditions on land and in coastal areas in recent years may favor anchovy rather than sardine (Takasuka et al. 2008).

# Introduction

Originating in the North Equatorial Current, the Kuroshio is the western boundary warm current in the North Pacific (Fig. KU-1). It flows along the south side of the Japanese Archipelago, crossing three shallow ridges – one east of Taiwan, through Tokara Strait, and across the Izu-Ogasawara ridges. The width of the Kuroshio is about 100 km and a current speed is 1-2 $m \cdot s^{-1}$. The depth of the current axis is usually >500 m and the transport volume is about 50 Sv. Large amounts of water are exchanged with several stable eddies in the region such as the large warm eddy to the south of Shikoku Island. The Kuroshio feeds the Kuroshio Extension off eastern Japan where it forms a broad Mixed Water Region to the north of the Kuroshio Extension. Usually there is a large meander east of Honshu Island which frequently ejects large warm-core rings into the Mixed Water Region. The high temperature and high salinity of Kuroshio water brings a high diversity of tropical marine life northward (to ~40°N) to the coastal area of the Japanese archipelago and off eastern Japan. Many species of invertebrates (e.g. corals) and vertebrates (e.g. butterfly fishes) from more southern latitudes have been recorded near the south coast of Japan but most of them cannot survive and reproduce because of the cold winter water temperatures in the coastal area and the low nutrient concentrations of the Kuroshio. However, this indicates that the Kuroshio can support, at least temporarily, these species in more northern areas.



[Figure KU-1] The typical path of the Kuroshio and Kuroshio Extension and geographical names used in this chapter.

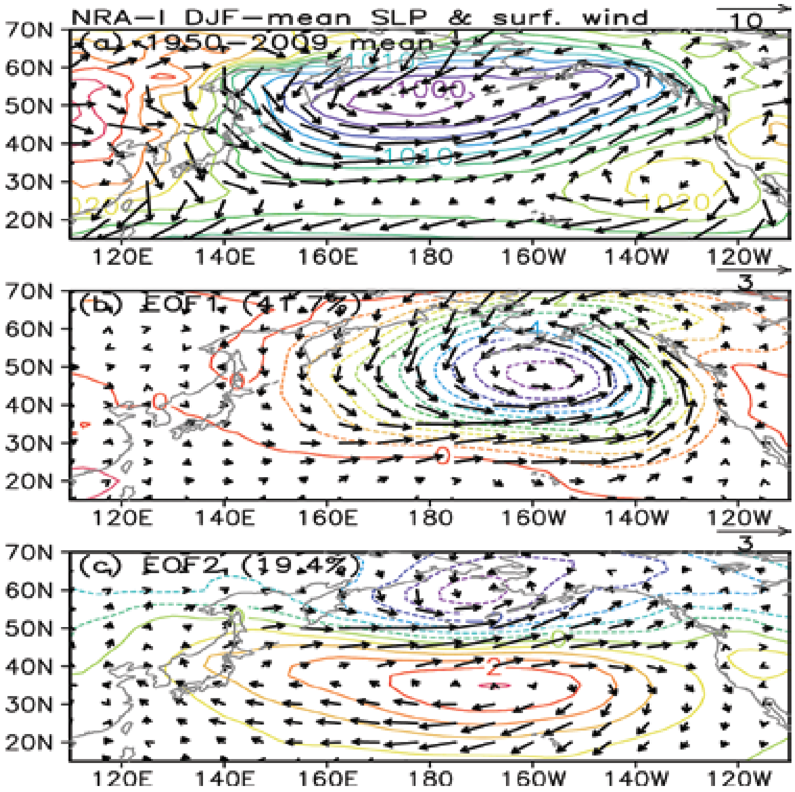
Since nutrient concentrations and biological production in the Kuroshio are much lower than in the cold western boundary current (Oyashio) to the north, commercial fishing in the Kuroshio is small compared to the Oyashio area. Nevertheless, the Kuroshio is a major spawning area for many species of pelagic fishes such as Japanese sardine (*Sardinops melanostictus*) and Pacific saury (*Cololabis saira*) that have their nursery and feeding grounds in the Oyashio area. Therefore, the environment of the Kuroshio affects the spawning conditions and survival rate of early life stages of many species of pelagic fish. These species exhibit high amplitude variation in stock size and community composition. The mechanisms of stock size variation and species alternation are thought to be related to survival of early life stages. Therefore, environmental change in the Kuroshio region affects the broader ecosystem around Japan (both the Kuroshio and Oyashio oceanic areas and the coastal area of the Japan trench). The status of the Kuroshio is important for understanding both global change and fisheries conditions of the North Pacific. This chapter contains a review of the status and trends of the Kuroshio Region from 2003-2008, hereafter termed the *focus period*.

# 2.0 Atmosphere *(Nonaka)*

## 2.1 Sea surface wind field

### 2.1.1 Wind and Kuroshio transport

Figure KU-2 shows the mean wintertime sea level pressure (SLP) and surface wind fields based on the NCEP/NCAR reanalysis data (Kalnay et al. 1996). The Aleutian low pressure region, centered near 50°N 180°E, is responsible for northwesterly and westerly winds that blow over the Kuroshio and Kuroshio Extension regions, respectively. The combination of easterly trade winds to the south and westerly winds over the mid-latitude North Pacific induce negative (anti-cyclonic) wind stress curl to the south that drives the subtropical gyre. The Kuroshio forms the western boundary of the subtropical gyre in the North Pacific. Deepening of the Aleutian Low can strengthen the current by accelerating flow within the gyre. Transport of the Kuroshio at 137°E has been monitored by the Japan Meteorological Agency (JMA) twice per year since 1972 (Fig. KU-8). These data reveal interannual and decadal variations, and it has been shown that the decadal variations are correlated with the North Pacific Index (NPI) with 5-year lags (Hanawa and Kamada 2001; Yasuda and

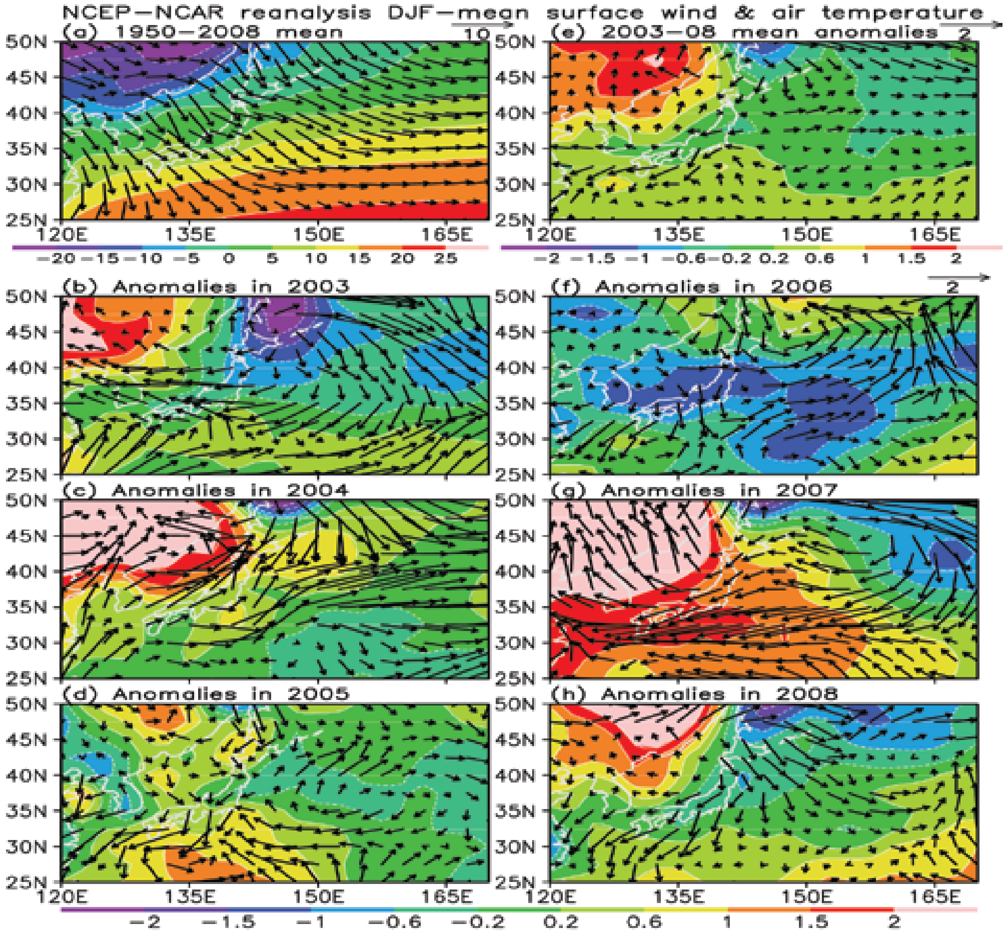


[Figure KU-2] (a) 1950-2009 mean wintertime (December-February) SLP (contours with intervals of 2.5 hPa) and surface wind vectors. (b, c) Maps for SLP (contours with intervals of 0.5 hPa) and surface wind (vectors) regressed linearly on the (b) PC 1 and (c) PC 2 time series for the EOF analysis conducted for the SLP field in (20°-85°N, 120°E-120°W). The scaling for the vectors ($m \cdot s^{-1}$) is indicated at the upper-right corner of each panel. All variables are based on the NCEP/NCAR reanalysis monthly mean data.

Kitamura 2003). The NPI is defined as an area-weighted mean SLP over the region 30°N-65°N, 160°E-140°W (Trenberth and Hurrell 1994) and its variations represent changes in the intensity and extent of the Aleutian Low in winter. The NPI is highly correlated (r = -0.99 for 1950-2009) with the first empirical orthogonal function (EOF) mode for the SLP field that extends from the central to eastern North Pacific (Fig. KU-2b). Although the NPI has tended to be negative since the mid-1990s, it turned positive after 2005 (Figs. KU-4a and KU-4c), indicating the Aleutian Low weakened in recent years. This suggests that the Kuroshio can be expected to weaken in the near future as pointed out at the JMA website* if the relationship between the NPI and the Kuroshio is causal.

### 2.1.2 Wind and surface air temperature

Comparison of the wind anomaly fields during the focus period with the climatological mean (Fig. KU-3a) suggests that northwesterly winds from the Eurasian continent and accompanying cold advection associated with the East Asian winter monsoon were weaker in this period. In contrast to this, northwesterly winds to the northeast of Japan were intensified and cold anomalies were found there. These patterns were found in 2003, 2004, 2007, and 2008. Especially in 2007, winds from the northwest were weak, as indicated by the relatively strong wind anomalies from the direction generally opposite to that for the mean winds. Warm air temperature anomalies extended southeastward from the Eurasian continent to the Kuroshio Extension region (Fig. KU-3g). In contrast, during 2006, the northwesterly (westerly) winds to the northwest (east) of Japan were intensified (Fig. KU-3f) and cold air temperature anomalies covered the Kuroshio and Kuroshio Extension regions. Honda et al. (2009) suggest that part of this extent of cold air from the Eurasia continent in 2006 was associated with anomalies in large-scale atmospheric circulation caused by a decrease of sea-ice cover in the Arctic Ocean, more specifically, in the Barents and Kara seas, in the preceding summer-to-autumn seasons.



[Figure KU-3] (a) 1950-2008 mean wintertime (December-February) surface air temperature and surface wind. (e) 2003-2008 mean anomaly fields of surface air temperature and surface wind from the climatological mean field shown in (a). Panels(b-d, f-h) are the same as (b) but for each winter from 2003 to 2008 as indicated above each panel. Shadings show surface air temperature and its anomalies (°C) as indicated below each panel for (a) and (e), and below all panels for (b-d, f-h). The scaling for the wind vectors ($m \cdot s^{-1}$) is indicated at the upper-right corner of each panel for (a) and (e), and at the upper-right of panel (f) for (b-d, f-h). All variables are based on the NCEP/NCAR reanalysis monthly mean data.

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* http://www.data.kishou.go.jp/kaiyou/shindan/b.2/kuroshio-slow/kuroshio_flow.html

### 2.1.3 Wind and the Kuroshio Extension

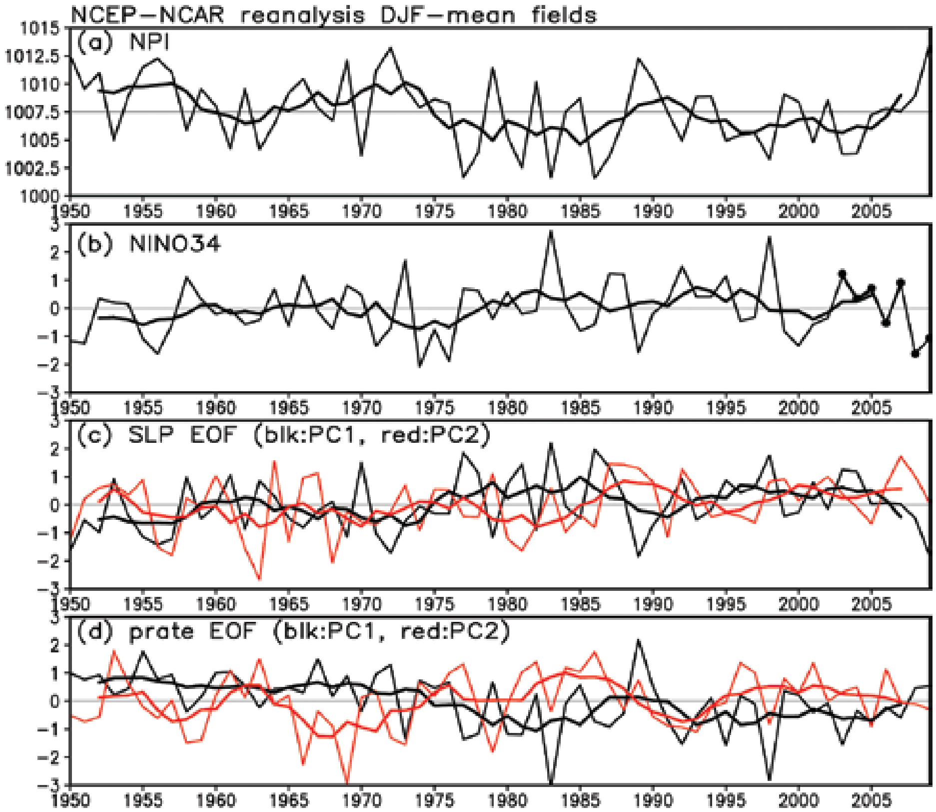
The strength and latitude of the Kuroshio Extension Current (KEC) varies decadally (Qiu and Chen 2005; Taguchi et al. 2007). Sea surface height observations since the 1990s have shown that the KEC intensifies when its axis shifts northward (Qiu and Chen 2005), although a 50-year-long hindcast simulation by an eddy-resolving ocean general circulation model suggests that this relation was not clear before the 1980s (e.g. Taguchi et al. 2007; Nonaka et al. 2006). The meridional shift of the KEC may be caused by atmospheric changes over the whole North Pacific like the first EOF mode of SLP (Seager et al. 2001; Miller et al. 1998; Deser et al. 1999). In contrast to this, the aforementioned hindcast simulation result has found that the KEC tends to intensify following central North Pacific wind variations associated with the North Pacific Oscillation (NPO) with a 2.5-year lag, probably through propagation of Rossby waves (Ceballos et al. 2009). The NPO is the second EOF mode of SLP over the North Pacific and has a meridional dipole structure with the opposite signs over Alaska and Hawaii (Fig. KU-2c; Walker and Bliss 1932; Wallace and Gutzler 1981). Meanwhile the first EOF mode shows a monopole pattern over the northern North Pacific corresponding to the variations of the Aleutian Low (Fig. KU-2b).

The time series of the second EOF mode (Fig. KU-4c, red curve) indicates that the NPO was positive around 1990 and 2000, which corresponded to intensification of the KEC in the early 1990s and 2000s (Taguchi et al. 2007; Qiu and Chen 2005). Although the NPO was negative around 2005, it recovered and was positive for several years after 2006. The positive NPO in recent years is consistent with the recent (2003-2008 mean) properties in the wind anomaly fields in the Kuroshio region (Fig. KU-3e).

## 2.2 Precipitation

### 2.2.1 Winter precipitation

Variations in precipitation or in precipitation minus evaporation (P-E) can influence not only surface and subsurface salinity fields (Overland et al. 1999; Lukas 2001), but also the strength of the $CO_2$ sink at the sea surface (Dore et al. 2003). The long-term mean wintertime precipitation field (Fig. KU-5a) has a local maximum over the KEC around 35°N associated with the storm-track in the North Pacific (Nakamura et al. 2002, see their Fig. 1). An EOF analysis for wintertime precipitation (and also P-E) indicates that the first EOF mode (Fig. KU-4d, black curve for its principal component, PC1, and Fig. KU-5b) is associated with the



[Figure KU-4] Interannual (thin lines) and 5-year running mean (thick lines) time series of (a) NPI, (b) NINO3.4 index, (c) PC 1 (black) and PC 2 (red) for the EOF analysis of SLP in (20°-85°N, 120°E-120°W), and (d) the same as (c) but for precipitation rate in (8.5°-62°N, 120°E-120°W). All variables are based on the NCEP/NCAR reanalysis monthly mean data except for the SST data for (b) that is based on the HadISST (solid curve for 1950-2004) and AMSR-E SST (solid curve with dots for 2003-2009) compiled at the UK Met office and Remote Sensing Systems, respectively. NINO3.4 index based on AMSR-E SST is plotted just for comparison. Nino3.4 index is defined as area mean SST anomalies in (5°S-5°N, 170°W-120°W).

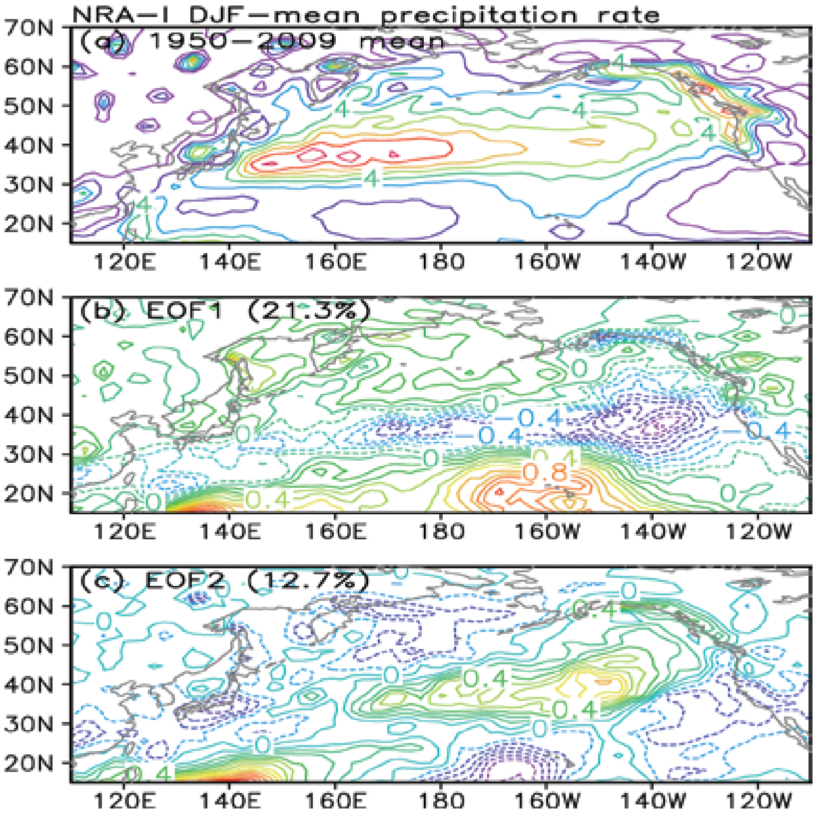
El Niño/Southern Oscillation (ENSO) (r = -0.78 between NINO3.4 (Fig. KU-4b) and PC1 for 1950-2009) and has a weak signal in the Kuroshio and Kuroshio Extension regions (Lukas 2001, see also his Fig. 2b and Fig. 3).

In contrast to this, the second EOF mode shows three bands of positive and negative precipitation anomalies extending from southwest to northeast, and one of the centers of action extends from south of Japan to the Kuroshio Extension region (Fig. KU-5c; Lukas 2001, see also his Fig. 3), indicating the possible importance of this mode for rainfall variations in the Kuroshio and Kuroshio Extension regions. Similar southwest-to-northeastward band-like structures of precipitation anomalies are also shown in other studies (Overland et al. 1999; Minobe and Nakanowatari 2002; Nakamura et al. 2002; Honda et al. 2005).

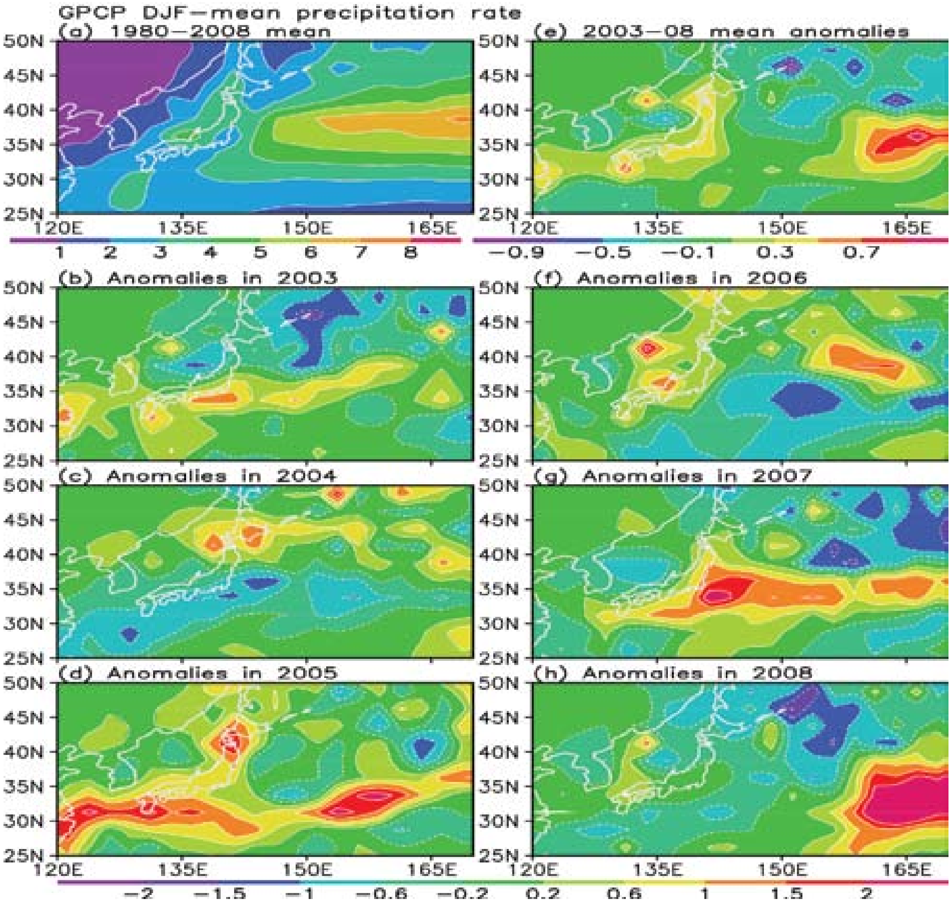
The time series corresponding to the second EOF mode (Fig. KU-4d, red curves) is dominated by decadal variation. Focusing on the decadal timescale by applying the 10-30-year band-pass filter, the band-like structure of precipitation anomalies is correlated with the NPI (Minobe and Nakanowatari 2002). This shows that precipitation in the northern part of the North Pacific region varies in association with large-scale SLP anomalies. In the Kuroshio region, stronger rainfall tends to occur with positive NPI anomalies and a weakened Aleutian Low (Minobe and Nakanowatari 2002).

Except for the southernmost of the three bands, the precipitation anomalies in the northern North Pacific are associated with meridional shifts of the storm-track (Nakanowatari and Minobe 2005; Nakamura et al. 2002). Significant decadal-scale variation in latitude of the storm-track and its activity were found at the end of 1980s in conjunction with decadal-scale weakening in the East Asian winter monsoon (Nakamura et al. 2002). From the late-1980s to the mid-1990s, the midwinter Siberian High and the Aleutian Low were weak, and the winter storm-track was located to the north of its climatological position. At the same time, midwinter activity of the storm-track and thus precipitation in the region were enhanced (Nakamura et al. 2002).

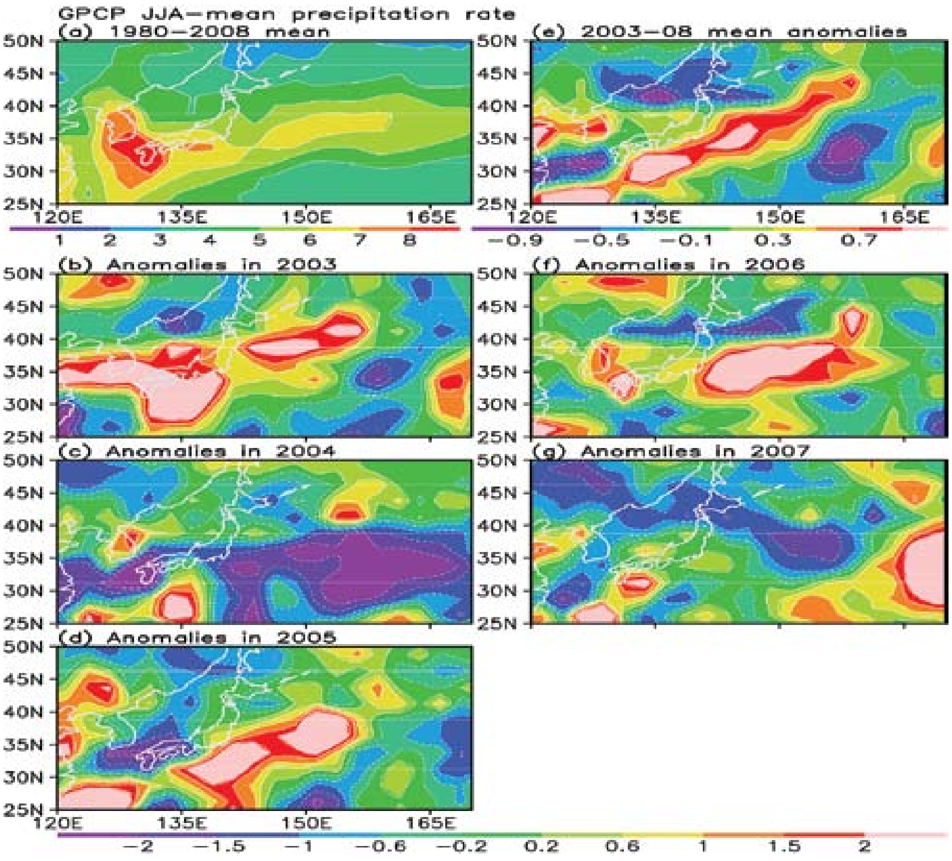
As indicated in Figure KU-4d (red curves), the second EOF mode has tended to be positive since the early-1990s in association with a negative NPI and deepened Aleutian Low (Fig. KU-4a). However, in recent years, the Aleutian Low has started to weaken and the East Asian winter monsoon was also weak in 2003-2008 (Fig. KU-3e).



[Figure KU-5] NCEP/NCAR reanalysis wintertime (Dec-Feb) precipitation ratio fields. (a) 1950-2009 mean (contours intervals are 1 mm·d⁻¹). (b, c) Maps for the field (contours intervals are 0.1 mm·d⁻¹) regressed linearly on the (b) PC 1 and (c) PC 2 time series for the EOF analysis conducted for the field in (8.5°-62°N, 120°E-120°W).



[Figure KU-6] (a) 1980-2008 mean wintertime (Dec-Feb) precipitation rate. (e) 2003-2008 mean anomaly field of precipitation rate from the long-year mean field shown in (a). (b-d, f-h) The same as (b) but for each winter from 2003 to 2008 as indicated above each panel. Shadings show precipitation rate and its anomalies (mm·d⁻¹) as indicated below of each panel for (a) and (e), and below panels (d) and (h). All variables are based on the Global Precipitation Climatology Project (GPCP; Adler et al. 2003) monthly mean data.



[Figure KU-7] (a) 1980-2007 mean summertime (June-August) precipitation rate. (e) 2003-2007 mean anomaly field of precipitation rate from the long-year mean field shown in (a). (b-d, f-g) The same as (b) but for each winter from 2003 to 2007 as indicated above each panel. Shadings show precipitation rate and its anomalies (mm·d⁻¹) as indicated to the right of each panel for (a) and (e), and below panels (d) and (h). All variables are based on the GPCP monthly mean data.

In association with these changes, precipitation increased around Japan and also around the storm-track to the east of 150°E (Fig. KU-6e). This is consistent with the aforementioned relationships among the East Asian winter monsoon, the Aleutian Low and wintertime precipitation. In the plots for each winter (Fig. KU-6), it is apparent there was large year-to-year variability. Enhanced precipitation was observed in 2003, 2005, and 2007 in the Kuroshio and Kuroshio Extension regions.

### 2.2.2 Summer precipitation

The climatological mean of summer (June-August) precipitation in the Kuroshio region (Fig. KU-7a) indicates that a high precipitation band (mei-yu/baiu front) extends northeastward from southern China to the western North Pacific through the southern part of Japan. The leading EOF mode of interannual variation in summertime precipitation over the subtropical western North Pacific (20N°-50°N, 100E°-180°E) indicates pronounced centers of action along the mei-yu/baiu front (Lee et al. 2005, their Fig. 1), while the opposite anomalies are found to the south around 10°N-20°N. This mode is closely linked to variations in the East Asian summer monsoon, and tends to occur in the "post-El Niño" summer or the decaying phase of El Niño (Lee et al. 2005; Wang et al. 2008). Heavy rainfall was observed in July 1998 and July 2003 in the Kuroshio and the Kuroshio Extension region following El Niño winters, although heavy rainfall also occurred in 2006 when no El Niño occurred. The 2003-2007 mean anomaly field (Fig. KU-7e) indicates that rainfall in the mei-yu/baiu front was enhanced in 2003, 2005, and 2006 (Fig. KU-7). Enhanced rainfall in the Kuroshio region is associated with relatively continuous warm eastern equatorial Pacific SST during the earlier part of the focus period (Fig. KU-4b). This is consistent with the aforementioned interannual relation between El Niño and the East Asian summer monsoon. The mechanisms that are responsible for the impact of El Niño that peaks in winter on the East Asian summer monsoon have been discussed by Wang et al. (2000) and Xie et al. (2009). The former suggests the importance of air-sea interaction in the western tropical Pacific, and the latter suggests that the prolonged impact is due to a capacitor effect of the Indian Ocean.

## 3.0 Oceanography

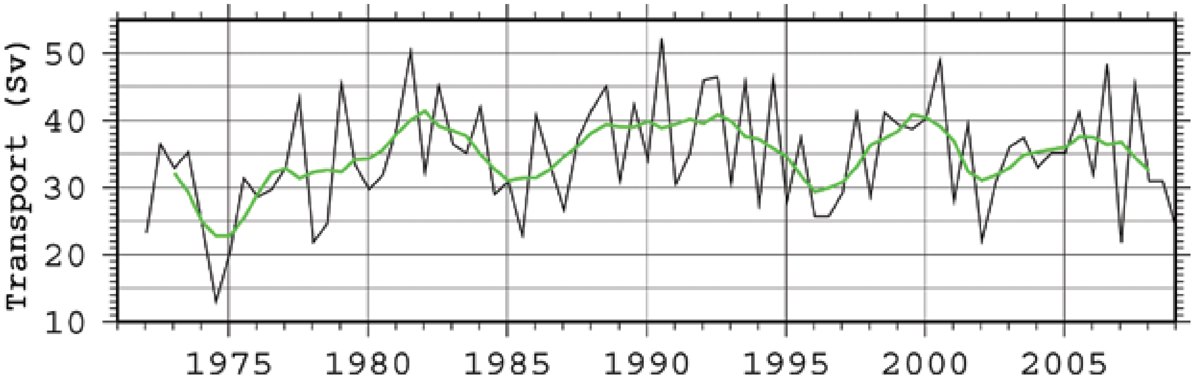
### 3.1 Hydrography *(Ishizaki)*

The properties of Kuroshio water (e.g. salinity, oxygen concentration) are considerably more stable than those of the Oyashio and Kuroshio-Oyashio transition waters. The annual variation of hydrography in the Kuroshio region is caused mainly by variations in the pathway and transport of Kuroshio water. A time series of the Kuroshio transport along 137°E shows interannual and quasi-decadal variation (Fig. KU-8) corresponding to changes in the wind stress curl in the central North Pacific (Yasuda and Kitamura 2003). During the focus period, transport peaked in 2006 then decreased, but was high again in late 2007 and has decreased since.

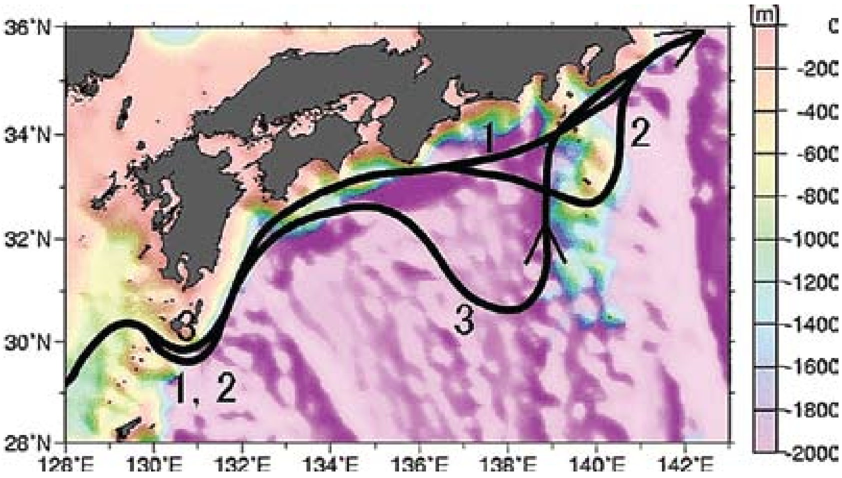
The Kuroshio takes three major paths south of Japan: the nearshore and offshore non-Large-Meander paths (nNLM and oNLM), [(1) and (2) in Fig. KU-9], and the typical Large-Meander path (tLM) [(3) in Fig. KU-9] (Kawabe 1995). When it takes the tLM path, the Kuroshio makes a detour around Enshu-nada (between 136°E to 140°E) and its southernmost position is located south of 32°N, while the two NLM paths, which are distinguished by their position over the Izu Ridge (140°E), are close to the coast of Japan (Fig. KU-9). Several experiments for reenacting the path of the Kuroshio using inflow-outflow models (Akimoto et al. 1991, 1997) successfully replicated the three patterns of Kuroshio meanders.

The Kuroshio often took the LM path from 1975-1991 (Fig. KU-10) but it has been taking the NLM path since 1992, except from the second half of 2004 to first half of 2005. The first mode of the EOF of sea surface temperature in the Kuroshio region shows area wide variation. Negative SST anomalies dominated in the Kuroshio region before 1998 (Fig. KU-11a). SST anomalies turned positive in 1998 and continued until 2002. After 2002, distinct trends or events have not been observed in SST in the Kuroshio area. This means that the temperature of the Kuroshio has been moderate and stable since 2002, in contrast to the previous decades.

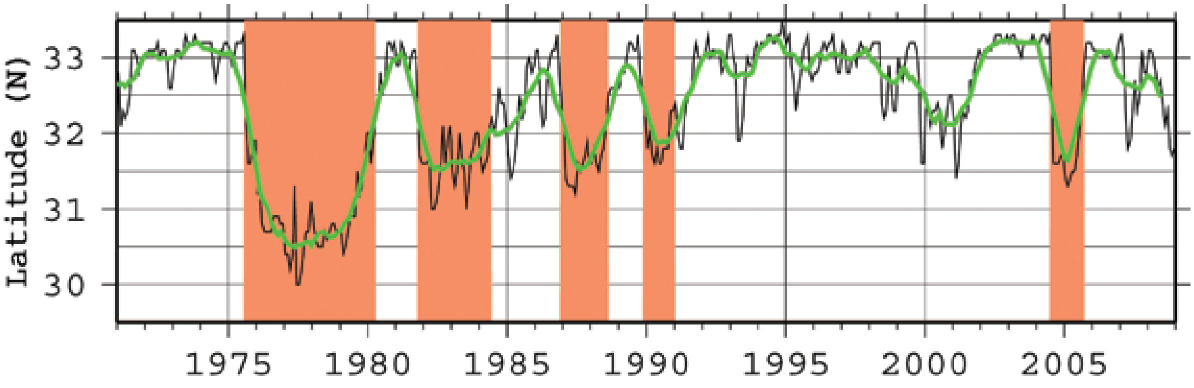
The second and third EOFs of the SST anomalies have a center of action around Enshu-nada. The second EOF shows negative SST anomalies around Enshu-nada in 1987, 1991, 2001, 2005, corresponding to the period when the Kuroshio took the tLM path (except the Kuroshio took the



[Figure KU-8] Time series of the Kuroshio transport (Sv) along 137°E referenced to 1250 m depth. Thick green line indicates the 2 year running mean value.



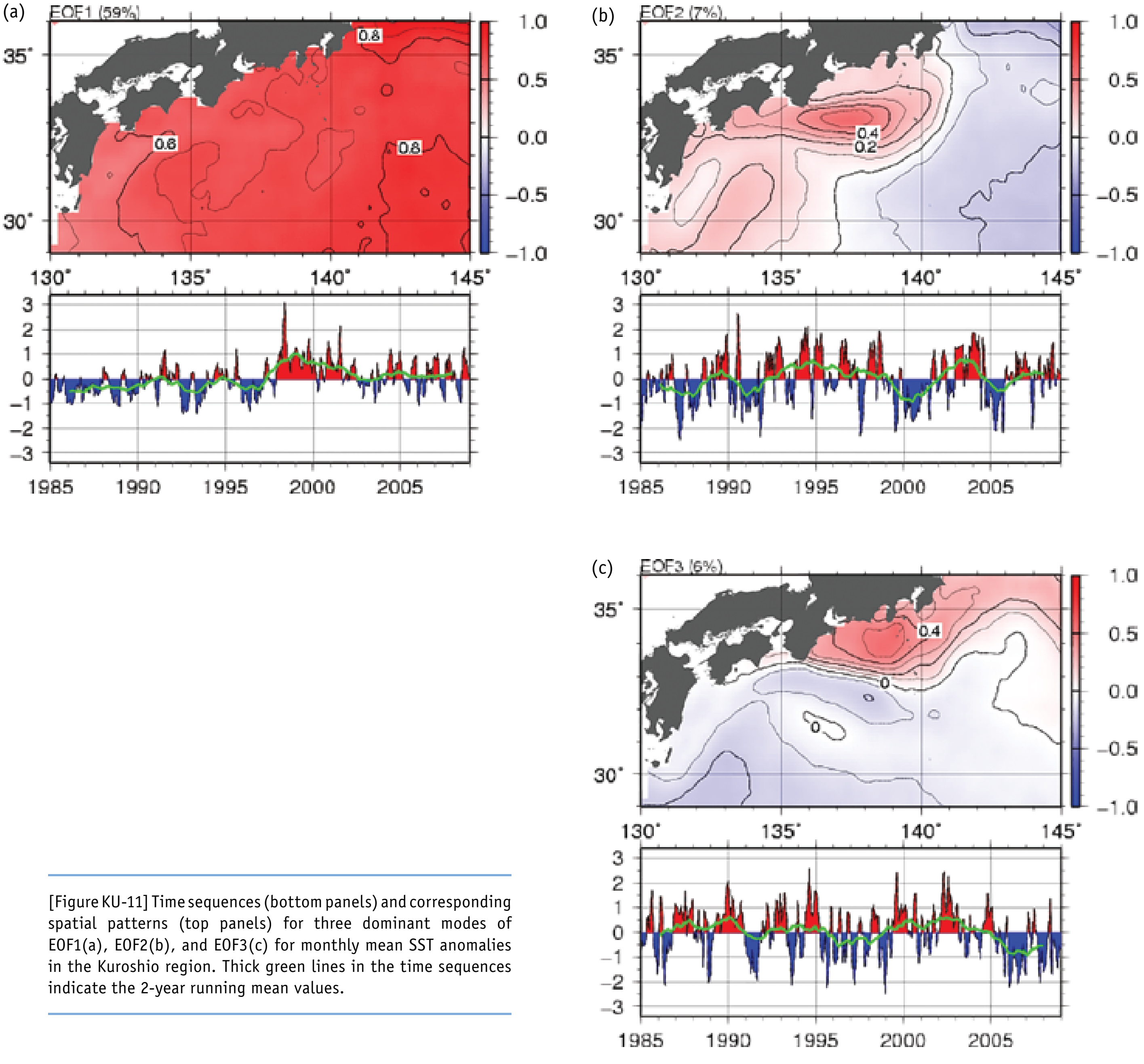
[Figure KU-9] Typical paths of the Kuroshio Current south of Japan: (1) nearshore Non-Large-Meander path (nNLM), (2) offshore Non-Large-Meander (oNLM), (3) typical Large-Meander (tLM).



[Figure KU-10] The monthly southernmost latitude of the Kuroshio Current south of Japan (between 136°E and 140°E). The period when the Kuroshio took the Large Meander Path is shaded. The thick green line denotes the 13-month running mean value.

oNLM path in 2001). This implies that EOF2 and EOF3 are related to the meander pattern of the Kuroshio. It is likely that when the meander is east of 140°E, typical of the oNLM path, high temperature is observed in the coastal area west of 140°E because the warm Kuroshio passes near the coastal area, and low temperature is observed in the coastal area east of 140°E because the Kuroshio turns away from the coast. This meander pattern seems to affect EOF2. It is likely that when the meander is west of 135°E, the typical tLM path, low temperature is seen in the coastal area west of 140°E because the warm Kuroshio current runs away from the coast west of 140°E. This meander pattern seems to affect EOF3.

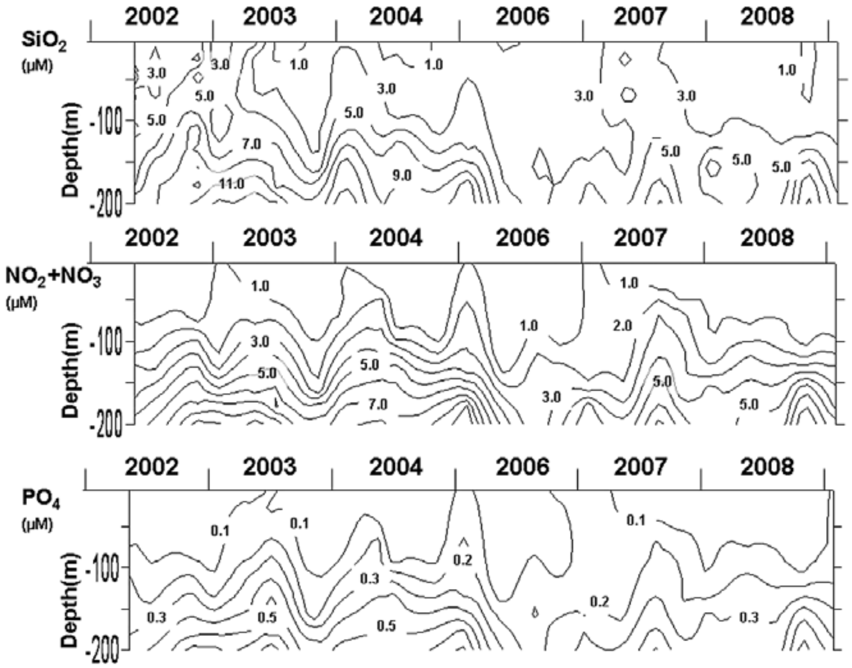
The volume of Kuroshio transport is thought to be related to atmospheric conditions. The relationship between wind conditions and Kuroshio transport in recent years has not been analyzed but unusually weak northwesterly wind was observed in 2007 (Fig. KU-3) and Kuroshio transport was low in 2007. The continued accumulation of both atmospheric and oceanic physical data is necessary to clarify the mechanisms determining transport and meandering of the Kuroshio.



[Figure KU-11] Time sequences (bottom panels) and corresponding spatial patterns (top panels) for three dominant modes of EOF1(a), EOF2(b), and EOF3(c) for monthly mean SST anomalies in the Kuroshio region. Thick green lines in the time sequences indicate the 2-year running mean values.

## 3.2 Nutrients *(Sugisaki)*

Since 2001, the status of the Kuroshio ecosystem has been monitored along 138°E, called the O-line, by the Fisheries Research Agency of Japan (Fig. KU-13). Physical and biological data have been collected during seasonal research cruises in January, March, August and November using R/V *Soyo-maru*. Figure KU-12 shows the time series of nutrient concentrations at 15 depths from 0 m to 200 m at stations on the O-line from 2002 to 2008. Generally, nutrient concentrations are high during winter. The mixed layer is deep at this time because of seasonal wind and there is associated nutrient supply to the shallow layers from deeper layers. This supply of nutrients during winter supports high biological production in the Kuroshio ecosystem and most of the important pelagic fish species (e.g. Japanese sardine, Pacific saury etc.) spawn at this time. In recent years, especially since 2005, the seasonal pattern has become obscure and the average nutrient concentrations from 0 to 200 m have been significantly lower than in previous years. A decreasing trend in nutrient concentrations has also been observed in the Oyashio and Oyashio-Kuroshio transition areas and is attributed to shoaling of the mixed layer depth (Tadokoro et al. 2009) caused by an increase in temperature (Levitus et al. 2000). Positive anomalies of surface temperature in the Kuroshio region were observed from the late 1990s to the early 2000s (Fig. KU-11a), implying that a similar decreasing pattern in the long-term variation of nutrients has been occurring in western boundary current areas extensively throughout the North Pacific. In 2005, a significant meander of the Kuroshio was observed and the southernmost latitude of the Kuroshio was low compared to other years (Fig. KU-10). The meander causes a large gap between the Kuroshio and the high-nutrient coastal area. This may have restricted the supply of nutrients to Kuroshio water during 2005. Although the meander pattern of the Kuroshio returned from tLM to NLM (Fig. KU-10) after 2005, nutrient concentrations have remained low. There is no information or data explaining the mechanisms of this nutrient change but it is likely the same mechanism that causes the decreasing trend in the Oyashio; shoaling of mixed layer depth caused by climate change. Compared with the Oyashio, the pattern of change in nutrient concentration of the Kuroshio was stepwise and discontinuous. The change of the meander pattern of the Kuroshio may affect not only the supply of nutrients, but also may be a "trigger" of the manifestation of the distinct change of nutrients.



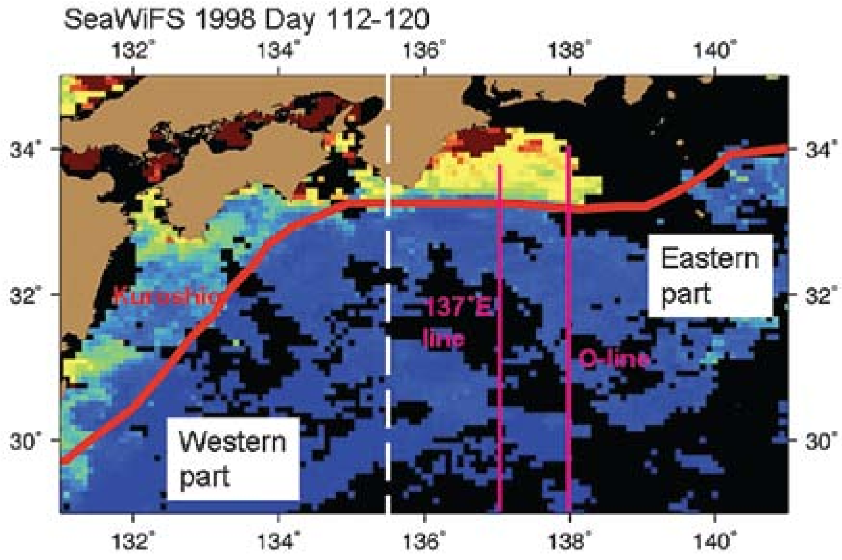
[Figure K-12] Time series of vertical nutrient concentrations (SiO2: upper, NO2 and NO3: middle, PO4: lower) between 0 and 200 m at a station on the Kuroshio axis of the O-line (138°E) during routine seasonal (January, May, August, November) cruises of each year.

## 3.3 Phytoplankton

### 3.3.1 Satellite chlorophyll *(Hidaka)*

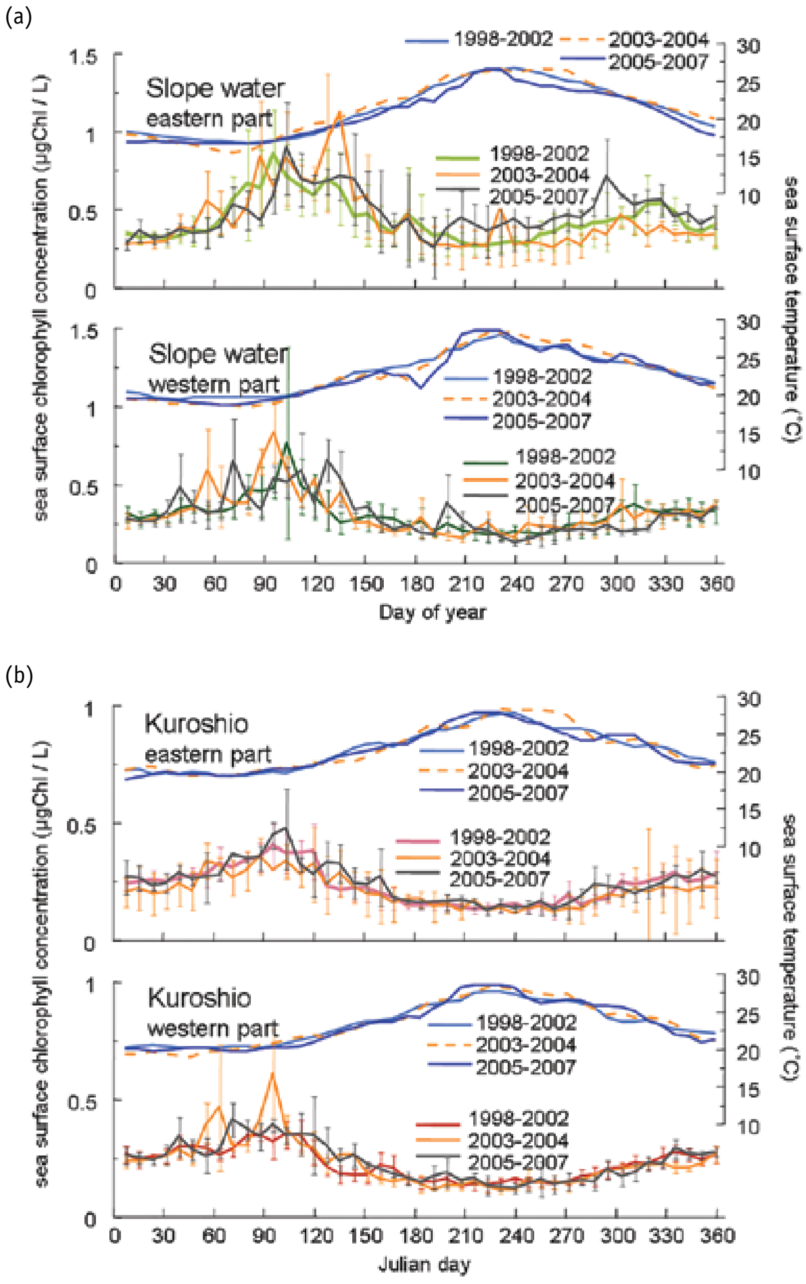
Primary producers in the Kuroshio and slope water south of Honshu support important spawning grounds for pelagic fishes such as sardine, anchovy (*Engraulis japonicus*) and Pacific saury. The water south of the Kuroshio has different ecosystem properties and is influenced by fluctuations in the development of subtropical mode water. Satellite data provide an overview of geographical variation in surface ocean properties in the area (Fig. KU-13). Fig. KU-14 shows seasonal change of sea surface temperature (SST) and surface chlorophyll$_a$ concentration. The region can be divided into west (131°00'E -135°30'E) and east (135°30'E -139°00'E) sections at about Cape Shionomisaki and data compiled for the slope water and the Kuroshio in each section. Slope water is defined as the area between the 1000 m isobath on the continental slope and 56 km north of the Kuroshio axis. Slope water had higher chlorophyll$_a$ concentrations than the Kuroshio. The seasonal cycle of chlorophyll$_a$ in the Kuroshio was similar in the east and the west with a peak at the end of March. The pattern in the slope water in the western part was similar although chlorophyll$_a$ was higher than in the Kuroshio. The eastern part of the slope water showed a different seasonal pattern. Here, chlorophyll$_a$ started to increase from the end of February (day 24-40) and reached maximum values (0.71-0.85 µg·l$^{-1}$) in March (day 72-104) as in the western part. But the chlorophyll$_a$ pattern after mid-March differed and high chlorophyll$_a$ (>0.6 µg·l$^{-1}$) remained until mid-May (ca. day 132).

Seasonal variation of chlorophyll$_a$ is well synchronized with SST in both regions. Blooms start at the end of the low temperature season (day 60-90) and decrease as SST increases (day 120-240). The trends described above were consistent between the focal period and a previous



[Figure KU-13] The area analyzed for phytoplankton in the Kuroshio region.

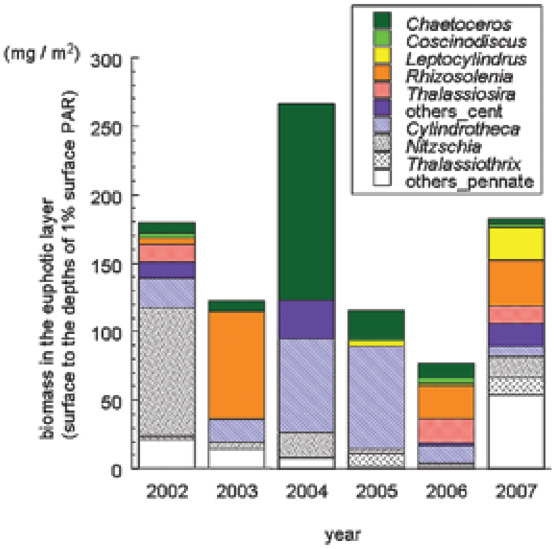
period (1998-2002) in each area. Because the nutrient concentrations changed after 2005 (large meander year), seasonal variations of chlorophyll$_a$ and SST were compared before (2003-2004) and after (2005-2007) the large meander. Except for the eastern part of the Kuroshio, higher peaks of chlorophyll$_a$ were observed during late winter and early spring (day 60-120) in 2003-2004 than in 2005-2007. On the other hand, chlorophyll$_a$ values in 2005-2007 were similar or higher than 2003-2004 after day 180. This shows that the characteristic seasonal variation of chlorophyll$_a$ (high in spring and low after summer) became obscure after 2005. Because SST patterns were not clearly different between 1998-2002 and 2003-2007, no relationships between SST and chlorophyll$_a$ were seen at this time. Although mechanisms causing the difference in the seasonal pattern of chlorophyll$_a$ between 2003-2004 and 2005-2007 are not known well, the large meander that occurred from late 2004 to early 2005 may have affected the distribution of nutrients which subsequently caused the changing seasonal patterns.



[Figure KU-14] Seasonal change of sea surface chlorophyll$_a$ concentration and sea surface temperature in the slope water (a) and Kuroshio (b). Sea surface temperature (SST) was derived from the 8-day averaged AVHRR dataset (pathfinder ver. 5.0, 8-days, 1990-2002, distributed by the NOAA-National Oceanographic Data Center). The line graph of SST was developed using a moving average representing 3 sets of 8-day data to smooth variability. Error bar means SD.

### 3.3.2 Species composition *(Sugisaki, Hidaka)*

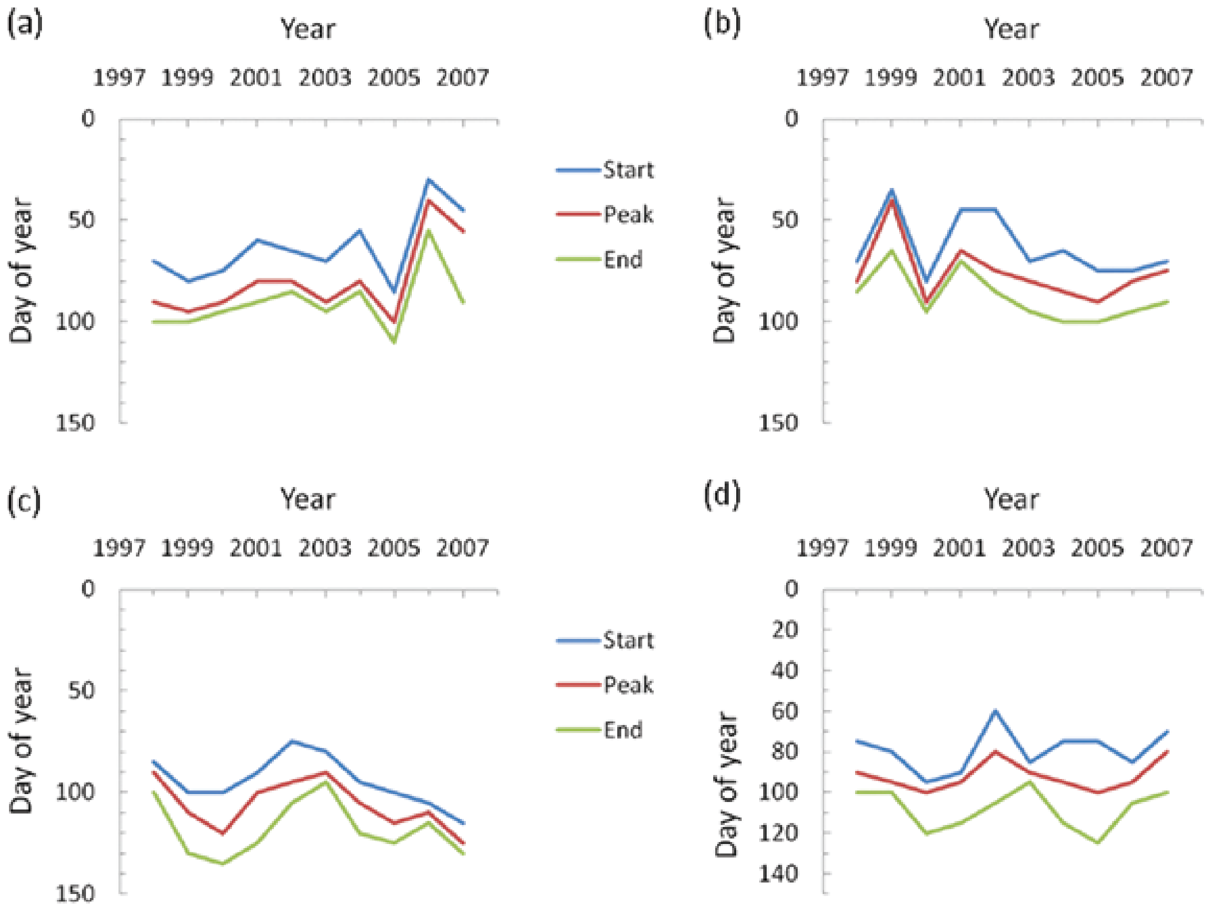
Long-term monitoring of phytoplankton species composition in the Kuroshio region is limited. The Japan Meteorological Agency occupies a meridional line for field observation along 137°E and the Fisheries Research Agency has another line along 138°E (the O-line) but coverage of each line is limited. The 137°E line is investigated once or twice per year and observations on the O-line began only in 2002. On the O-line program, taxonomic composition of phytoplankton has been monitored at two stations, one in the slope water (34°N 138°E) and another in the offshore water south of the Kuroshio (30°N 138°E). Fig. KU-15 shows the composition of diatom genera at 34°N late in the spring phytoplankton bloom (May). The dominant genera are variable among years but *Rhizosolenia* (most dominant in 2003, 2006, 2007) and *Cylindrotheca* (>20% in 2004 and 2005) were important. The diatom composition is influenced by the phenology of the phytoplankton bloom and the nutrient conditions, the latter being influenced by both vertical mixing and horizontal advection. Controls on the annual variation of phytoplankton species composition are not clear but high biomass and change of species composition were observed in 2004. The Kuroshio meander was also observed during 2004 and 2005 (Fig. KU-10). It is possible that Kuroshio oceanic water intruded into the near-shore area of the Kuroshio region because of the Kuroshio Countercurrent, causing the oceanic genera *Chaetoceros* and *Cylindrotheca* to become abundant in these years.



[Figure KU-15] Composition of diatoms in the euphotic zone at Station B03 (34°N 138°E) in May.

### 3.3.3 Timing of the spring bloom *(Kameda)*

Since it is likely that the timing of the spring bloom is sensitive to climate change, its annual variation was analyzed using objective indices that were originally developed to characterize the spring phytoplankton bloom on the Nova Scotia-Labrador shelf (Fuentes-Yaco et al. 2007). Bloom initiation, date of the maximum, and bloom duration were determined for slope water and the Kuroshio from satellite data. SeaWiFS data cover the period from 1998 to 2007 (Fig. KU-16). Indices were averaged by year and area. Though distinct trends in timing of the spring bloom were not observed, interannual differences in bloom timing and duration were evident. In the western part of the slope water, the spring bloom began earlier in 2006 and 2007 than in other years (1998 to 2005). In the eastern part of the slope water, bloom initiation was early in 2002 and 2003 and showed a progressive delay in the period from 2004 to 2007. In the Kuroshio area, the spring bloom started earlier in the western part than in the eastern part before 2004 but this pattern was not seen after 2005.



[Figure KU-16] Phytoplankton spring bloom characteristics: (a) Slope water western part (b) Kuroshio western part (c) Slope water eastern part (d) Kuroshio eastern part.

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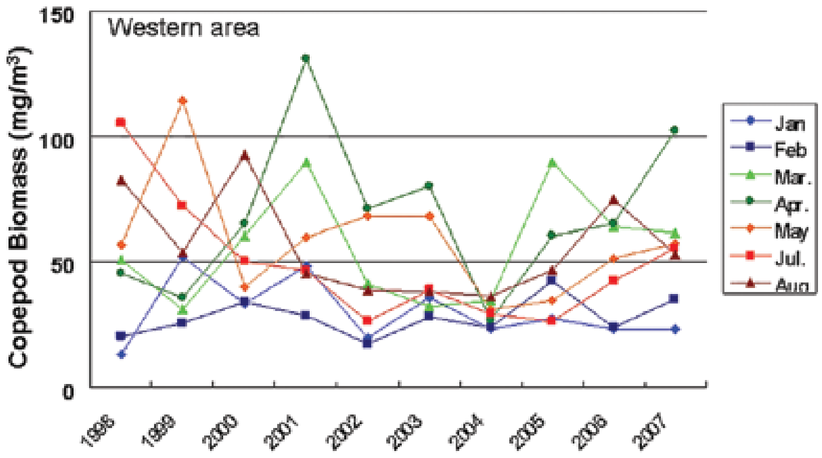
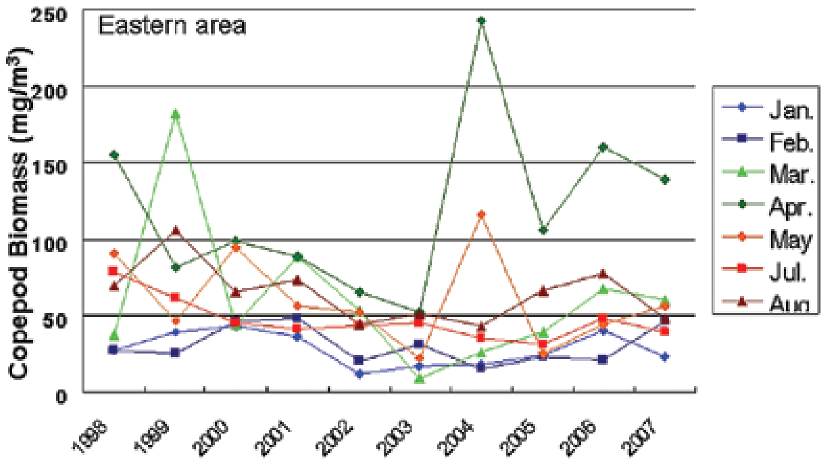
## 4.0 Zooplankton *(Hirota, Sugisaki)*

Interannual changes of zooplankton in the Kuroshio and surrounding area before 2002 have been reported (e.g. Shimizu et al. 2004; Nakata and Hidaka 2003) but there have been few observations since 2003. Hydrographic conditions in the Kuroshio and the surrounding area allow three areas to be distinguished, the onshore side of the Kuroshio, the main stream zone of the Kuroshio and the offshore side of the Kuroshio. Since the character of the Kuroshio varies according to location, the mainstream zone of the Kuroshio on the west side of Cape Shionomisaki south of Japan was defined by temperatures higher than 16.5°C at 200 m depth and with flow >1 $m \cdot s^{-1}$ at the surface, and the zone on the east side of Cape Shionomisaki was defined by temperatures higher than 15°C at 200 m depth (Kawai 1969) in this section.

The 18 year mean zooplankton biomass from 1971 to 1988 in the western area (south of Kyushu to south of Cape Shionomisaki) of the Kuroshio during January and February was 439.45 $\mu gC \cdot m^{-3}$, and positive anomalies of 0-400 $\mu gC \cdot m^{-3}$ were observed in the first half of the 1970s. After 1976, the anomaly fluctuated between -400 and +50 $\mu gC \cdot m^{-3}$ until 1988. The 19 year mean zooplankton biomass from 1971 to 1989 in the eastern area of Kuroshio (from south of Cape Shionomisaki to south of the Enshu-nada region, called "central Japan" in the original paper of Nakata and Koyama 2003) during February and March was 854.49 $\mu gC \cdot m^{-3}$, and positive anomalies of 0-400 $\mu gC \cdot m^{-3}$ were observed in the first half of the 1970s. After 1976, the anomaly fluctuated between -300 to +50 $\mu gC \cdot m^{-3}$ until 1989 (Nakata and Koyama 2003). The zooplankton biomass anomaly in winter (January and February) of 1972-2000 on the line of 137°E became negative in the



[Figure KU-17] Zooplankton biomass (wet weight $mg \cdot m^{-3}$) from samples collected in the day time with a NORPAC net of 0.33-0.35 mm mesh aperture towed vertically from 200 m to surface in January to February of 1998-2007 in the western area of the onshore side of the Kuroshio.



[Figure KU-18] Zooplankton biomass (wet weight $mg \cdot m^{-3}$) from samples collected in the day time with a Norpac net of 0.33-0.35 mm mesh aperture towed vertically from 200 m to surface in March to May of 1998-2007 in the eastern area of the onshore side of the Kuroshio.

first half of the 1970s and positive in the latter half of the 1970s and then it continued negative until 1994 (Nagai 2004). The zooplankton biomass anomaly during July and August was positive in the first half of the 1970s and generally became negative from 1976 to 1994 (Nagai 2004). In sum, a decreasing trend in zooplankton biomass was observed in the Kuroshio region before 2000.

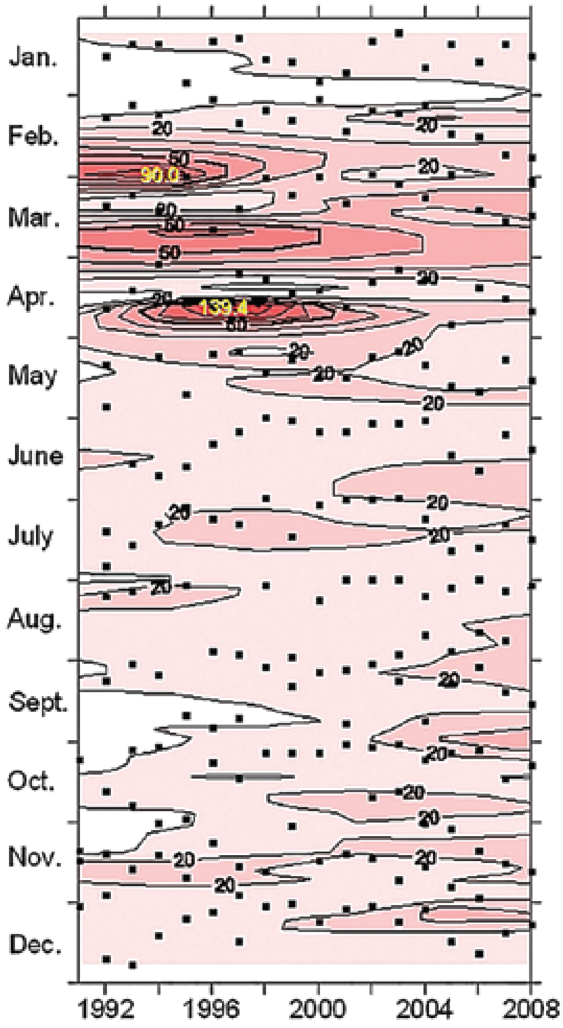
Research on the oceanography, zooplankton biomass and distribution of larval fish and eggs has been conducted by the National Research Institute of Fisheries Science, Fisheries Research Agency for many years. Data collected at the stations in the western area between 31° and 34°N and 131° and 136°E with associated water temperature at 200 m depth <16.5°C and the stations in the eastern area between 32° and 36°N and 136° and 140°E with associated water temperature at 200m depth <15°C were analyzed in order to observe the annual and seasonal variations of zooplankton biomass. In both areas, the daytime zooplankton biomass in summer (July and August) generally decreased from 1998 to 2005 and increased after 2005 (Figs. KU-17, 18). Winter biomass (January and February) was low and did not vary annually. The spring biomass (March, April and May) was highly variable among years and month of maximum biomass has gradually changed from May to March in the western area.

Figure KU-19 shows interannual and seasonal variation in biomass (volume) of copepods at a fixed single station (33°12'N, 133°46'E). Although high abundance was observed during March and April in the 1990s, only weak seasonality has been observed since the early 2000s. The dominant species in this area, *Calanus sinicus*, also showed an increase during March and April, though only a small peak has been observed during July since the late 1990s (Fig. KU-20). Thus, the seasonal variation of copepod biomass has become weak to non-existent and the seasonal pattern of the dominant copepod species has changed in recent years.

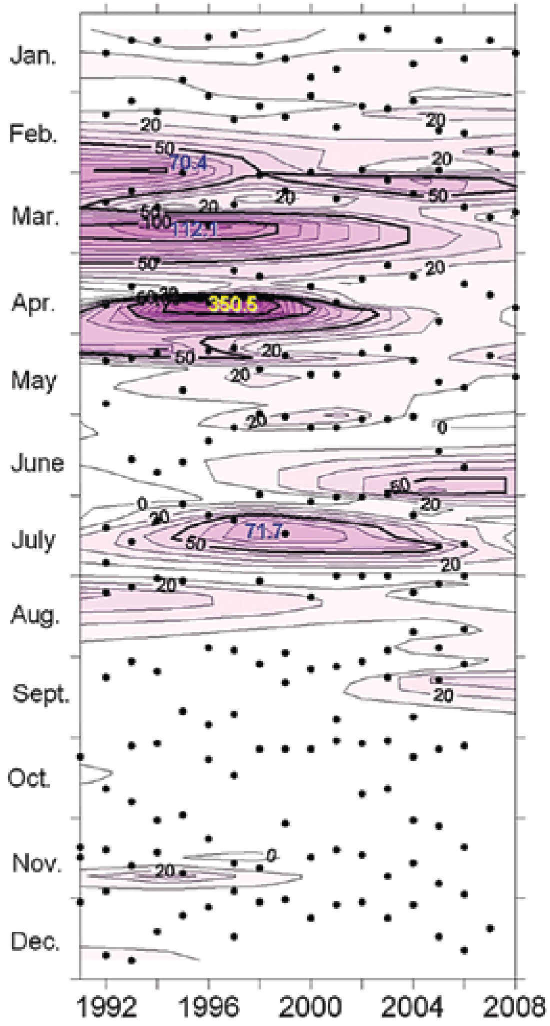
The biomass of chaetognaths and crustaceans other than copepods was correlated with wind speed at Cape Shionomisaki (Nakata and Koyama 2003). The biomass of large copepods (prosome length ≥1 mm) in the mainstream zone of the central area in the winter (February to March) of 1971-2000 was positively correlated to the Southern Oscillation index, while the biomass of small copepods (prosome length <1 mm) changed in cycles of 2-4 years. These changes are related to regional climate factors like the meander of the Kuroshio, surface temperature, and the average temperature between 0 and 200 m (Nakata and Hidaka 2003). The interannual changes of zooplankton biomass in the offshore side of the Kuroshio (30-32°N) on the 137°E line in winter was negatively correlated with the wind speed between 25-35°N and the depth of the mixed layer between 30-32°N (Sugimoto and Tadokoro 1998). The zooplankton biomass south of Shikoku and south of the Kii peninsula (28-32°N, 132-137°E) in January to March of 1971-2001 was positively correlated with the depth of the winter mixed layer (Limsakul et al. 2001; Chiba et al. 2008). Zooplankton biomass in the spring (April to June) of 1974-2002 in the same area (28-32°N, 132-137°E) was positively correlated with the depth of the winter mixed layer in the offshore side of the Kuroshio (Chiba et al. 2008). The interannual change in wet weight of zooplankton at stations on the line of 137°E in the Kuroshio mainstream and Kuroshio Countercurrent during 1972-2000 was positively correlated with chlorophyll$_a$ (Nagai 2004). In and offshore of the Kuroshio, the winter mixed layer becomes deeper during strengthening of the Aleutian Low, more nutrients were supplied to the mixed layer, and the biomass of phytoplankton and zooplankton increased in spring.

Average zooplankton biomass at PN1 in the Kuroshio Countercurrent (27.5°N, 128°E) from 1973-2002 tended to decrease. Moreover, the interannual changes of zooplankton biomass, the number of chaetognaths, *Pterosagitta draco*, and the concentration of phosphate varied similarly to the MOI (monsoon index) (Shimizu et al. 2004).

After 2000, a clear trend in zooplankton biomass was not observed even though there was a decreasing trend in nutrients and phytoplankton. In contrast to previous studies, relationships between zooplankton biomass and climate indices were not obvious. On the other hand, geographical differences in zooplankton biomass were observed. For example, extremely high biomass of zooplankton during spring (March or April) was observed frequently in the eastern area but not in the western area. These differences imply that Kuroshio water transports and accumulates nutrients or organic matter as it flows along the southern Japanese archipelago. The transportation and accumulation status may vary according to the status



[Figure KU-19] The seasonal and annual variations of volume (mm³·m⁻³) of copepods collected with a NORPAC net towed vertically from 200 m to the surface at a single station (33°12′N, 133°46′E) in 1991 to 2008.



[Figure KU-20] The seasonal and annual variations of the abundance (inds.·m⁻³) of *Calanus sinicus* collected with a NORPAC net of 0.33 mm in mesh aperture towed vertically from 200 m depth to the surface at a single station (33°12′N, 133°46′E) in 1991 to 2008.

of the Kuroshio meander. For example, a clear meander of the Kuroshio was observed in 2004 and 2005 and a reduction of zooplankton biomass was observed especially during the high biomass season (March and April) in 2004 in the western area (Fig. KU-17). On the other hand, high biomass in April and May were observed in 2004 in the eastern area, and the importance of April has been sustained since 2004 (Fig. KU-18). Large peaks in zooplankton volume (>60 mm³·m⁻³) were observed during spring (February to April) before 2004, while the spring peaks were low (<40 mm³·m⁻³) after 2004. Late in the year (August to December) relatively high volumes (>20 mm3·m⁻³) were observed since 2004 although the volume was usually <20 mm³·m⁻³ before 2004 (Fig. KU-19). This implies that seasonal variation of zooplankton biomass has become obscure in recent years. It seems that the seasonal variability of zooplankton has been changing since 1998. Mechanisms causing variation of zooplankton biomass are not fully understood but data to date imply that physical conditions, not only wind or temperature but also the meander of the Kuroshio, are important in this region.

# 5.0 Fishes and Invertebrates

*(Oozeki, Takasuka, Kubota)*

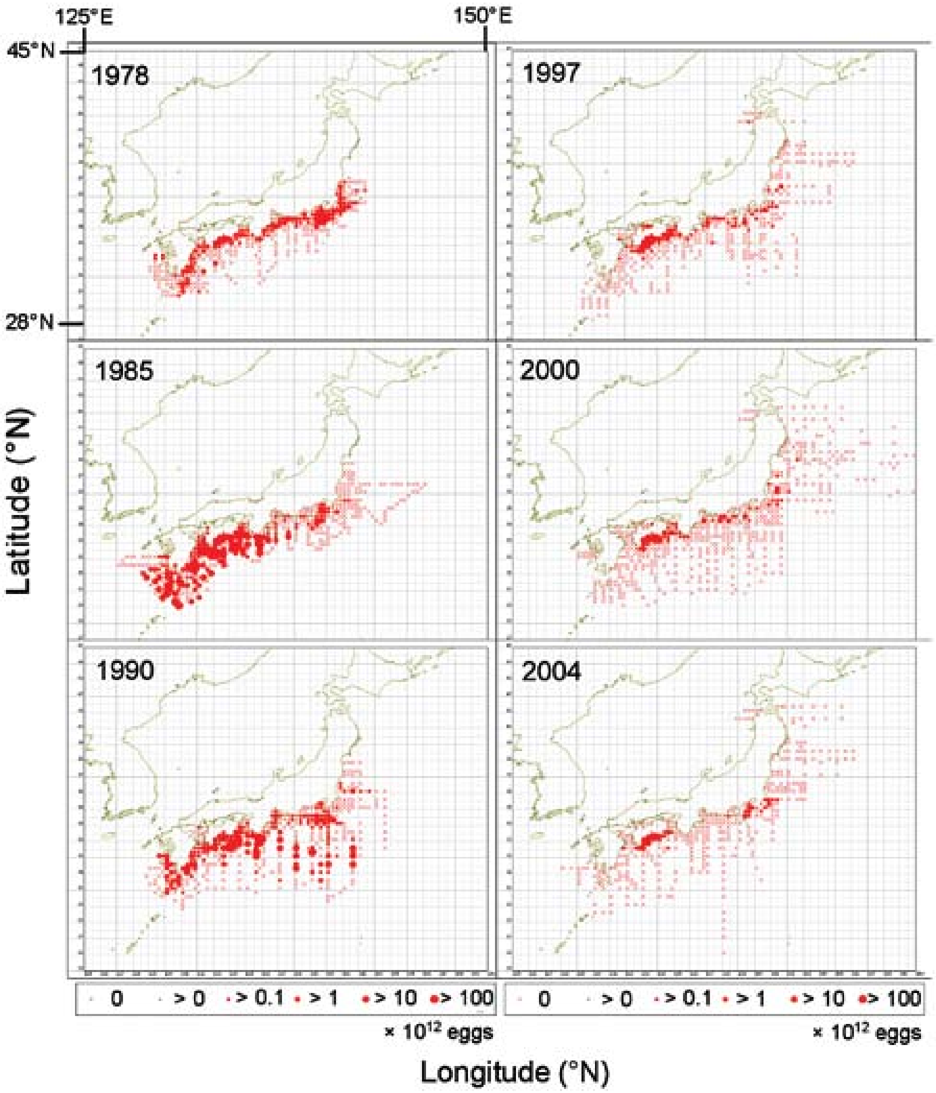
The Kuroshio system plays an important role in reproduction, dispersal, and migration of pelagic fish species including squid. Small pelagic fish species which are distributed off the Pacific coast of Japan include the Japanese sardine, Japanese anchovy, chub mackerel (*Scomber japonicus*), spotted mackerel (*Scomber australasicus*), round herring (*Etrumeus teres*), jack mackerel (*Trachurus japonicus*), Pacific saury and Japanese common squid (*Todarodes pacificus*). They utilize the Kuroshio system as a spawning ground and as the mechanism for dispersing the larval and juvenile stages from southern to northern areas of the western North Pacific. These animals migrate northward through the Kuroshio-Oyashio transition region to the Oyashio region where they are caught in fisheries. In the Kuroshio system, skipjack tuna (*Katsuwonus pelamis*), blue shark (*Prionace glauca*) and neon flying squid (*Ommastrephes bartrami*) are important predators on small pelagic fishes. Top predators such as whales and seals also feed on these small pelagic fishes in the Kuroshio Extension region.

Spatial and temporal variability of spawning habitat are composites of environmental forcing factors, spawning stock biomass, and vital parameters of spawning fish (e.g. temperature preference and food requirement). Reproductive and survival strategies are expected to be tightly linked to habitat use, extent of spawning, and responses to environments. Such biological characteristics can differ even among co-occurring congeners. For example, temperature and salinity diagrams discriminated spawning habitats of small pelagic fishes in the Kuroshio system (Oozeki et al. 2007a). As well, recent studies from the other regions showed that biological factors such as chlorophyll$_a$ concentration also serve as determinants of spawning habitat (Reiss et al. 2008). Small pelagic fishes tend to exhibit offshore expansion and inshore contraction in spawning habitat and distribution area depending on their stock size, but the habitat occupation strategy could differ between the anchovy and sardine (Barange et al. 2009). Judging from the information on spawning grounds and distributions, recent physical and biological conditions seem to favor the species which are known to be abundant during warm-sea-surface periods (Japanese anchovy, Japanese common squid, and Pacific saury) and do not seem to favor the species which are known to be abundant during cool-sea-surface periods (Japanese sardine). Further studies of species-specific responses to environmental factors and the decadal-scale shifts in spawning habitats associated with physical and biological environments would promote understanding of mechanisms linking environmental conditions to spawning ground formation, and allow discussion of recent trends in the context of ecosystem changes. The general dynamics and recent status of the spawning grounds are described below for the major small pelagic fish species in the Kuroshio system.

## 5.1 Japanese sardine

*(Sardinops melanostictus)*

The Japanese sardine is distributed off the Pacific coast of Japan (the Pacific stock) and its range fluctuates depending on stock size (Checkley et al. 2009). Biomass has been very low during the last decade (Anonymous 2009; Checkley et al. 2009). Accordingly, distribution and spawning areas have shrunk and egg abundance has been at a low level during recent years. In general, the eastern boundary of sardine distribution has been considered to be ca. 155°E longitude during low-biomass periods. However, recent studies revealed that the northern limit of migration was offshore of north Kuril Island (46°N 165°E) and that the eastern boundary was extended beyond 180° even during the low-biomass period (Kawabata et al. 2008a; Anonymous 2009). The southern and western boundaries were 29°N and 129°30'E, respectively. The southern boundary of distribution coincided with that of the spawning grounds. Spawning grounds of the Pacific stock were located in the coastal areas from 31°N 131°E to 41°N 142°E and mainly around Tosa Bay from 32°N 132°E to 33°N 135°E during the low-biomass periods of 1997-2004 (Fig. KU-21) (Mori et al. 1988; Kikuchi and Konishi 1990; Ishida and Kikuchi 1992; Zenitani et al. 1995; Kubota et al. 1999; Oozeki et al. 2007a). The sum of the total annual egg production of the Pacific stock over all the areas off the Pacific coast of Japan was low, from $38\times10^{12}$ to $152\times10^{12}$ eggs, during the period from 2005 to 2007 and the main spawning ground was located in a limited area around Tosa Bay during that period. Spawning occurs from October to May and juveniles are transported by and migrate to the Kuroshio and Kuroshio Extension currents beyond 170°E in spring. Feeding grounds are typically located in the Oyashio and Kuroshio-Oyashio

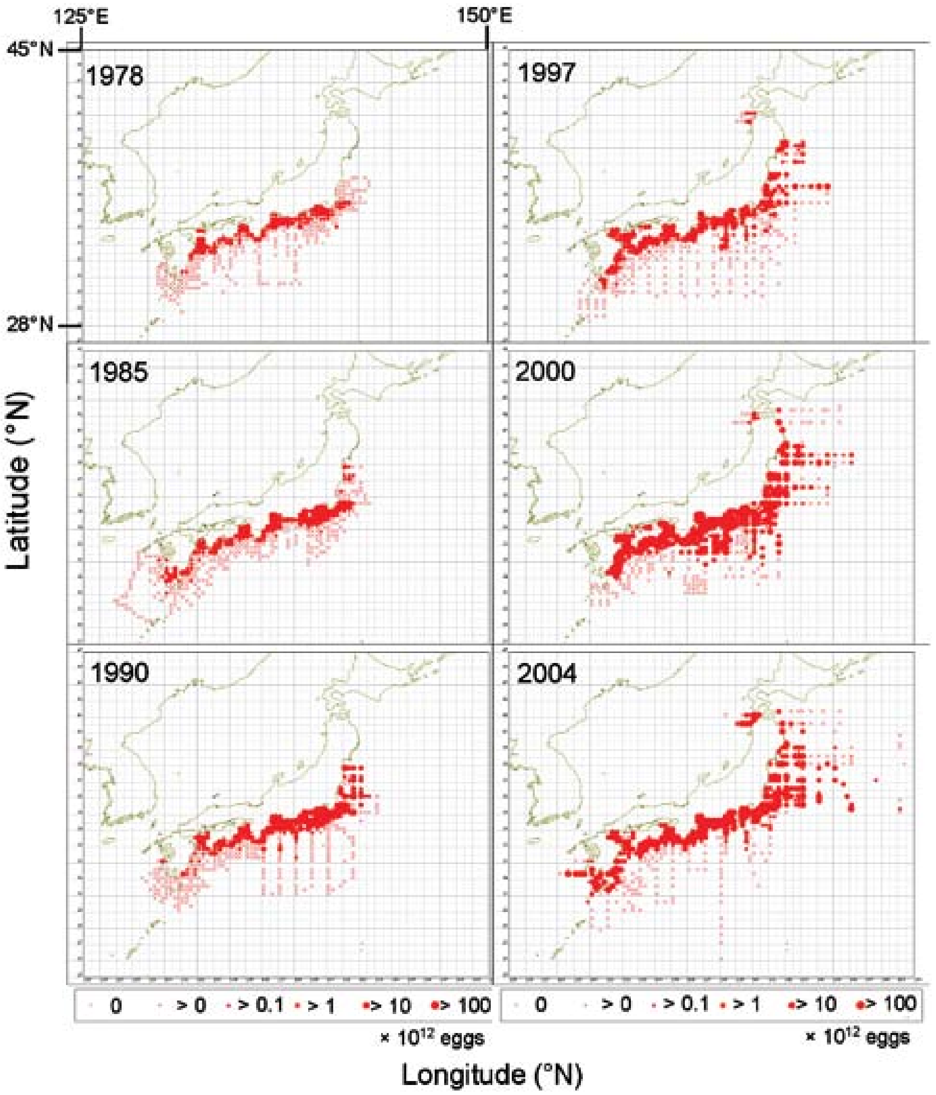


[Figure KU-21] Total egg production (eggs per year per 15′×15′ square) of Japanese sardine *Sardinops melanostictus* from 1978 to 2004. The data were collected from fish egg and larval fish research coordinated by the Fisheries Agency of Japan (Anon. 2006-2008; Anon. 2009).

Transition regions, from 42°N 144°E to 45°N 55°E, in summer and autumn. Adult fish migrate southward to their spawning grounds in late autumn and winter. Young of the year fish tend to be retained in the middle of their spawning migration path offshore of the Joban area (35-37°N 141-143°E).

## 5.2 Japanese anchovy *(Engraulis japonicus)*

The Japanese anchovy is distributed off the Pacific coast of Japan with an eastern boundary of ca. 155°E during low-biomass periods and beyond 180°E during high-biomass periods (Anonymous 2009). The Pacific stock of anchovy has been at a high-biomass level during the past decade, and thus the distribution and spawning areas are currently expansive. The southwestern boundary was observed around 29°N 129°E and the northern limit of its migration area corresponded to the offshore area of north Kuril Island, 46°N 165°E (Kawabata et al. 2008a). Spawning grounds of the Pacific stock were located in coastal areas from 32°N 131°E to 38°N 142°E during the low-biomass periods in 1978 and 1985 (Fig. KU-22) (Mori et al. 1988; Kikuchi and Konishi 1990; Ishida and Kikuchi 1992; Zenitani et al. 1995; Kubota et al. 1999; Oozeki et al. 2007a). During the high-biomass periods,

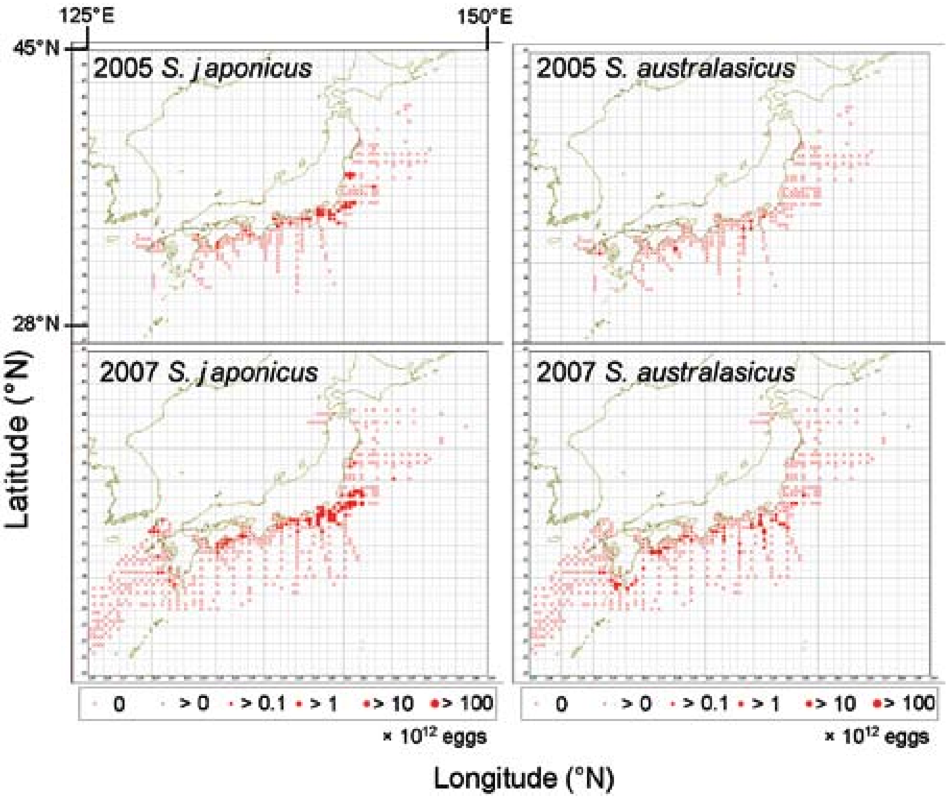


[Figure KU-22] Total egg production (eggs per year per 15′×15′ square) of Japanese anchovy (*Engraulis japonicus*) from 1978 to 2004. The data were collected from fish egg and larval fish research coordinated by the Fisheries Agency of Japan (Anon. 2006-2008; Anon. 2009).

spawning was observed not only in the inshore areas off the Pacific coast but also in the offshore areas beyond the Kuroshio axis, from 29°N 130°E to 43°N 155°E and also in the Kuroshio-Oyashio transition region (1990-2004 see Fig. KU-22). Active spawning in the coastal area of the Kuroshio-Oyashio transition region has continued from 2005 to 2008 and total annual egg production ranged from $10,000\times10^{12}$ to $12,100\times10^{12}$ eggs during 2005 to 2007. Spawning occurs from February to October and juveniles are transported by the Kuroshio and Kuroshio Extension currents beyond 170°E longitude in spring. Feeding grounds are typically located in the Oyashio and Kuroshio-Oyashio transition regions, from 42°N 144°E to 45°N 155°E, in summer and autumn. Adult fish migrate southward to the spawning grounds in late autumn. Young of the year fish tend to be retained in the middle of their spawning migration path (35-37°N 141-143°E).

### 5.3 Chub mackerel *(Scomber japonicus)*

The chub mackerel is widely distributed from the waters off Kyushu Island to the Pacific coast of northeastern Japan. Chub mackerel migrate seasonally along the Pacific coast of Japan from Kyushu to Hokkaido and feed on larvae and juveniles of small pelagic fishes during their migration.

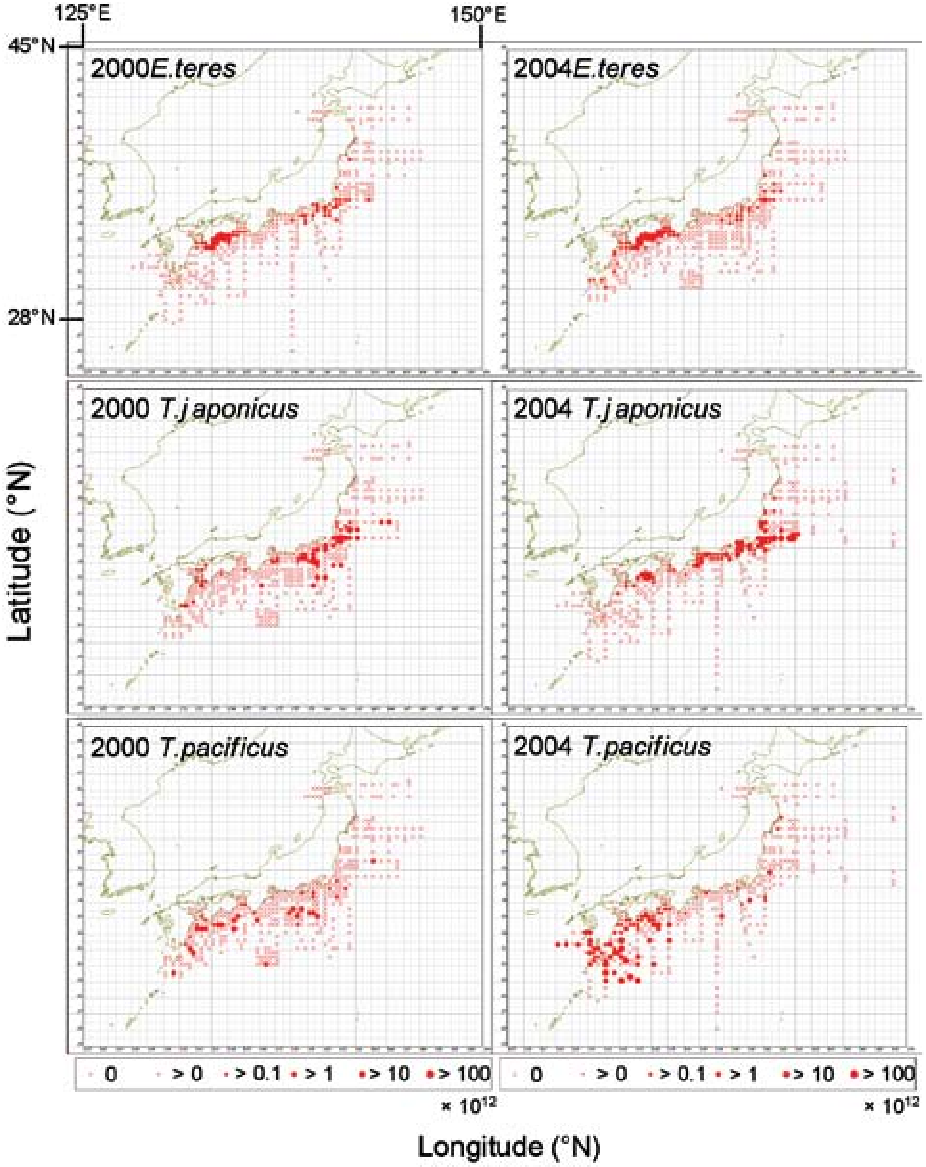


[Figure KU-23] Total egg production (eggs per year per 15′×15′ square) of chub mackerel (*Scomber japonicus*) and spotted mackerel (*Scomber australasicus*) in 2005 and 2007. The data were collected from fish egg and larval fish research coordinated by the Fisheries Agency of Japan (Anon. 2006-2008; Anon. 2009).

Spawning occurs from March to July in the waters mainly around the Izu Islands, near central Japan (Fig. KU-23) (Watanabe 1970; Usami 1973; Murayama et al. 1995; Watanabe et al. 1999; Anonymous 2006-2008). Total annual egg production ranged from $38×10^{12}$ to $280×10^{12}$ eggs during 2005 to 2007. After spawning, adults and their offspring migrate northeast and are distributed throughout the feeding ground in the Kuroshio-Oyashio transition area and in the Oyashio (Odate 1961; Kawasaki 1966; Watanabe 1970; Watanabe and Nishida 2002). In autumn, juveniles and adults migrate south to the Joban area. Juveniles usually overwinter in the coastal waters off Joban, and mature fish migrate farther south to the spawning grounds around the Izu Islands (Watanabe 1970; Usami 1973).

## 5.4 Spotted mackerel *(Scomber australasicus)*

The spotted mackerel is distributed in relatively warm waters compared to chub mackerel. Although spotted mackerel were confined to the Kuroshio system as their northern limit until the 1980s, their distribution areas have expanded up to 43°N along the Pacific coast of Hokkaido in recent years (Anonymous 2009; Kawabata et al. 2008b). The one-year old fish are mainly distributed in the Oyashio and Kuroshio-Oyashio Transition regions from 37°N to 45°N and 142°E to 170°E in summer and autumn. Recent developments in the taxonomy of mackerel eggs (Meguro 2008) have allowed the spawning grounds of chub mackerel and spotted mackerel to be separated. The spawning ground of chub mackerel has a range from 30°N to 37°N during recent years, although their major spawning ground is thought to be located in the East China Sea (Fig. KU-23). The main spawning ground has shifted from the southern area of Japan to the coastal area of the Boso peninsula and around the Izu Islands. Total annual egg production ranged from $4×10^{12}$ to $64×10^{12}$ eggs during 2005 to 2007.



[Figure KU-24] Total egg production (eggs per year per 15′×15′ square) of round herring (*Etrumeus teres*), and larval densities of jack mackerel (*Trachurus japonicus*) (yolk-sac larvae) and Japanese common squid (*Todarodes pacificus*) (rhynchoteuthion paralarva) in 2000 and 2004. The data were collected from fish egg and larval fish research coordinated by the Fisheries Agency of Japan (Anon. 2006-2008).

## 5.5 Round herring *(Etrumeus teres)*

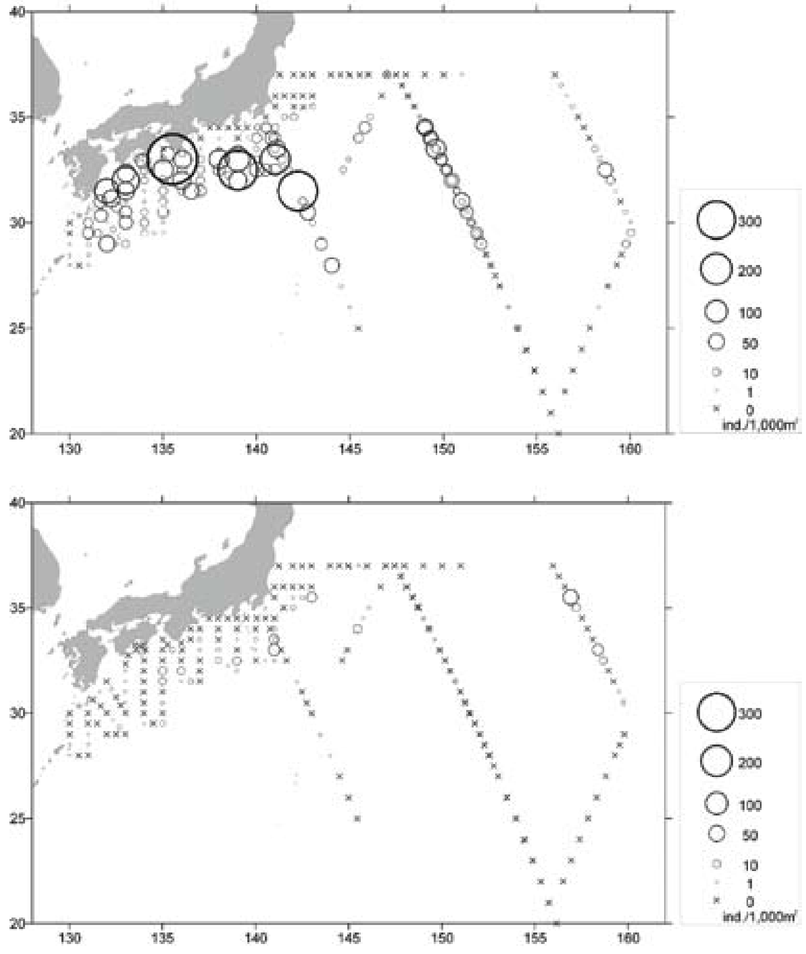
Round herring are distributed mainly along the southern Pacific coast of Japan with their northern boundary at 38°30'N. The population size of Pacific round herring is stable compared to Japanese sardine and anchovy (Anonymous 2009). The distribution areas of the Pacific stock roughly correspond to the spawning grounds, and the southwestern boundary of their habitat was observed around 29°N 129°30'E, which coincided with the southern boundary of the spawning ground (Fig. KU-24). The main spawning grounds were in the coastal areas of Tosa Bay from 32°30'N 132°30'E to 33°30'N 135°E (Mori et al. 1988; Kikuchi and Konishi 1990; Ishida and Kikuchi 1992; Zenitani et al. 1995; Kubota et al. 1999). Total annual egg production ranged narrowly from $130\times10^{12}$ to $177\times10^{12}$ eggs during 2005 to 2007.

## 5.6 Japanese common squid *(Todarodes pacificus)*

Common squid around Japan are distinguished as either a winter spawning population or an autumn spawning population, although some spawning activities are observed all year round. The abundance of common squid has been relatively high during the last decade and their spawning grounds are currently broadly distributed. The spawning ground of the winter population is thought to be located in the East China Sea as rhynchoteuthion paralarvae are widely observed from February to May along the Kuroshio Current (Fig. KU-24) (Anonymous 2009). The paralarvae are transported to northern areas by the Kuroshio and juveniles are widely observed in the Kuroshio-Oyashio transition region. The distribution of immature adults extends to the southern coast of Hokkaido Island on the Pacific side. Mature adults can migrate westward via Soya Strait or Tsugaru Strait toward their spawning grounds.

## 5.7 Pacific saury *(Cololabis saira)*

Pacific saury is a widely distributed pelagic species in the northwestern Pacific. Spawning extends from autumn to late spring from the Kuroshio to the Kuroshio-Oyashio transition regions. Survival after hatching controls recruitment in autumn and spring in the transitional waters. High growth rates lead to low mortality in the Kuroshio waters in the winter spawning season (Watanabe et al. 2003). The spawning ground of Pacific saury has expanded offshore from the Kuroshio Axis to 32°N 160°E as their southern and eastern limit (Fig. KU-25) (Oozeki et al. 2007b) and the juveniles of Pacific saury utilize the clockwise current in the Kuroshio recirculation region to come back to the Kuroshio system, and then migrate northward to reach their feeding ground from the coast of Hokkaido to the offshore area of north Kuril Island (46°N 165°E) from spring to summer.



[Figure KU-25] Distributions of larval and juvenile Pacific saury *Cololabis saira* in 2004. Larvae (upper panel) and juveniles (lower panel) are classified by 25 mm in knob length. The data were collected from egg and larvae of Pacific saury research coordinated by the Fisheries Agency of Japan (Oozeki et al. 2007b).

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# Yellow and East China Seas

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# highlights

- The Yellow Sea and East China Sea have undergone drastic changes in the past decades as witnessed by species shifts, increasing outbreaks of HABs, and jellyfish blooms. More recently, macroalgal blooms appeared in the western coastal areas of the Yellow Sea and East China Sea (Liu et al. 2009). These and other changes indicate the ecosystem structure is rapidly shifting.

- There is clear evidence of ongoing eutrophication in the Yellow Sea from the record of organic deposition in sediments, increases in biomass and abundance of the benthos during the past decade, and the appearance of an hypoxic area.

- Warming of the ocean surface waters has occurred since the mid- to late 1980s, with a parallel increasing trend in mesozooplankton abundance. The mechanism of this linkage and a possible interaction with eutrophication is unclear.

- Changjiang River discharge has been reduced with an accompanying impact on ecosystem productivity and structure in the vicinity of the river mouth. An impact on a larger scale on the shelf area is not yet evident.

- In the Yellow Sea, nitrogen:phosphorus and nitrogen:silicon ratios have been increasing basin-wide for the past three decades.

- The most prominent pressures to the ecosystem in the past decades were overfishing, eutrophication and disturbances in the freshwater budget.

- A recent survey indicates that the volume of the Yellow Sea Bottom Cold Water is reduced.

- A complicated network of pressures, anthropogenic as well as natural, is at work in these ecosystems with an anticipation of even more changes in near future. These changes are expected to have a significant impact on the resource utilization of the Yellow Sea and East China Sea.

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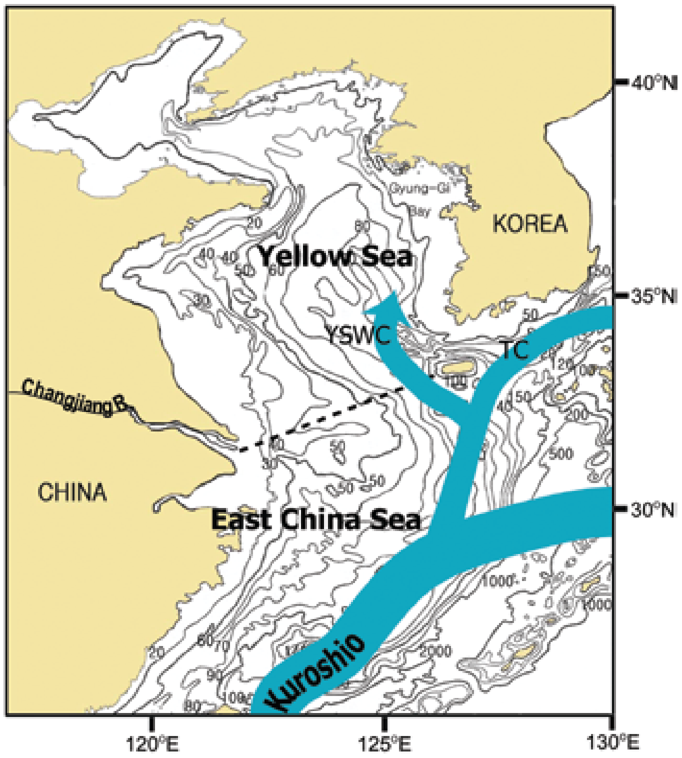
# Introduction

The Yellow Sea is a shallow marginal sea in the western North Pacific with a surface area of 380,000 km² and an average depth of 44 m (Fig. YS-1).

It is broadly connected with the East China Sea to the south and contains a semi-enclosed gulf in the north, the Bohai Sea. The region is one of the more densely populated in the world with human populations organized as the Peoples Republic of China, Democratic People's Republic of Korea, and the Republic of Korea, two of which are PICES member nations.

The surface circulation in the region has three main currents: Kuroshio, Tsushima and the Yellow Sea Warm Current (YSWC). The Kuroshio enters the East China Sea through the strait between Taiwan and Yonakunijima Island (the easternmost of the Ryukyu Islands) and flows northeastward along the shelf slope before branching into Tsushima Strait. The YSWC flows into the Yellow Sea after separating from the Tsushima Current west of Jeju Island. There are varying opinions regarding the origins of the Tsushima Current and YSWC (Beardsley et al. 1985; Lie, H.-J. 2002; Ichikawa and Beardsley 2002).



[Figure YS-1] Geography, bathymetry and major currents of the Yellow Sea and East China Sea. YSWC=Yellow Sea Warm Current. TC=Tsushima Current.

The Yellow Sea is characterized by a diversity of marine habitats due to its jagged coastline and the many islands scattered around the shallow sea. Intertidal flats are the most significant type of coastal habitat. Several different types can be found, such mudflats, salt marshes, sand flats with gravel beaches, sand dunes or eelgrass beds, and mixed flats. These habitats support important food resources and an ecological niche for a diversity of organisms. They also provide feeding, wintering and summering grounds for migratory birds. The shallow coastal areas, encompassing more than 1,000 islands, also show high productivity and provide good nursery and fishing grounds.

The Yellow Sea and East China Sea are very productive, supplying a large portion of the protein to human diets in the surrounding nations. The primary productivity of these seas has been estimated to be in the range of 150-200 $gC \cdot m^{-2} \cdot yr^{-1}$. Approximately 1,600 species were reported from marine and coastal habitats in the Korean part of the Yellow Sea, including 400 phytoplankton, 300 marine macroalgae, 50 halophytes, 500 marine invertebrates, and some 389 vertebrate species (Kim and Khang 2000). Among them, 166 zooplankton and 276 fish have been reported as resident species in the Yellow Sea. Approximately 100 commercial species have been identified in the region, comprising demersal fish (66%), pelagic fish (18%), cephalopods (7%), and crustaceans (7%).

However, various human activities threaten the region. The Yellow Sea and East China Sea are among those facing all conceivable stresses, whether natural or anthropogenic. The coastal regions of the Yellow Sea are densely populated, with approximately 600 million humans living in the region, and most of their by-products drain into the Yellow Sea. There is clear evidence of eutrophication. Artificial jetties and dams have interfered with local circulation and freshwater inputs into the sea. Overfishing has changed the trophic structure which cascades down the food web. Warming is evident. All in all, significant changes in the ecosystem are anticipated and there have been many signs. This chapter provides a review of marine ecosystem variability, with special attention to the period from 2003-2008, hereafter, the *focus period*.

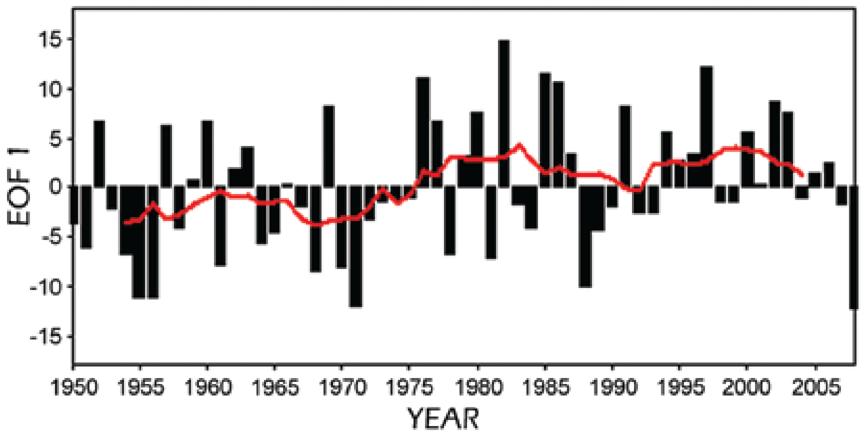
## 2.0 Atmosphere and hydrology

### 2.1 Wind and pressure

The Yellow Sea/East China Sea region is located where the Siberian High and the Subtropical Pacific Low collide to produce cold-dry winters and warm-wet summers. North and northwest winds in the autumn and winter are strong, with maximum speeds reaching 10 $m \cdot s^{-1}$. In the spring and summer, monsoon winds reverse the direction and become weaker. Typhoons develop in the western Subtropical Pacific bringing heavy rains in the summer and autumn. On average, about nine typhoons pass the region every year.

Winter sea level pressure (SLP) in the North Pacific from 1950 to 2008 shows that the western North Pacific is in a high pressure state since 1976 (Fig. YS-2). The leading EOF explains 41.8% of the variance with positive loading in western North Pacific. Although in 2007 and 2008, the anomaly shifted to negative, it is too early to tell whether this is a trend.

[Figure YS-2] Time series of the 1st EOF (explaining 41.8% of the variance) scores of SLP for Dec-Jan-Feb during 1950-2008 in the North Pacific (bounded by 110°E-120°W and 20°N-70°N). This pattern is positively loaded throughout the western North Pacific.

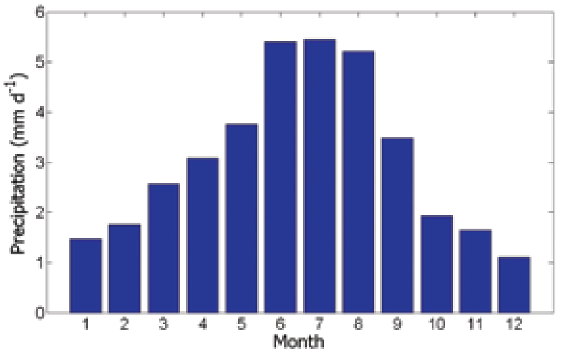


## 2.2 Precipitation and hydrology

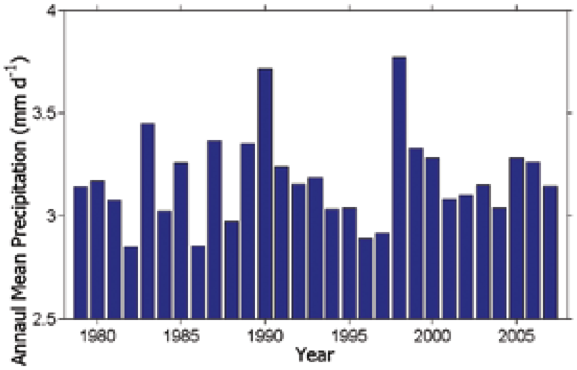
The precipitation pattern over the Yellow Sea and East China Sea shows a typical Northeast Asian monsoon pattern according to the NOAA/Climate Prediction Center Merged Analysis of Precipitation (CMAP) http://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cmap.html. The region has dry winters with the annual precipitation minimum (1.1 $\text{mm}\cdot\text{d}^{-1}$) in December and wet summers with the maximum precipitation (5.5 $\text{mm}\cdot\text{d}^{-1}$) occurring in July for the period 1979-2007 (Fig. YS-3). During the same period, there was no discernable long-term trend (Fig. YS-4). The maximum rainfall in recent years occurred during the flood year of 1998. There was no difference in annual average rainfall during the focus period (to 2007 only) from the previous period.

Fourteen rivers drain into the Yellow and East China seas, with a total discharge of >$10^{12}$ $\text{m}^3\cdot\text{y}^{-1}$ (Hong et al. 2003). Of these, the Changjiang River has the largest discharge (895 x $10^9\cdot\text{m}^3\cdot\text{y}^{-1}$) onto the shelf of the East China Sea. Interannual variation of satellite chlorophyll$_a$ on the shelf of the East China Sea from 1998 to 2006 was closely related to the Changjiang River discharge (Kim et al. 2009). During the summer monsoon salinity drops by as much as 6 psu. Such abrupt events have devastating effects on aquaculture and on some parts of the adjacent ecosystem.

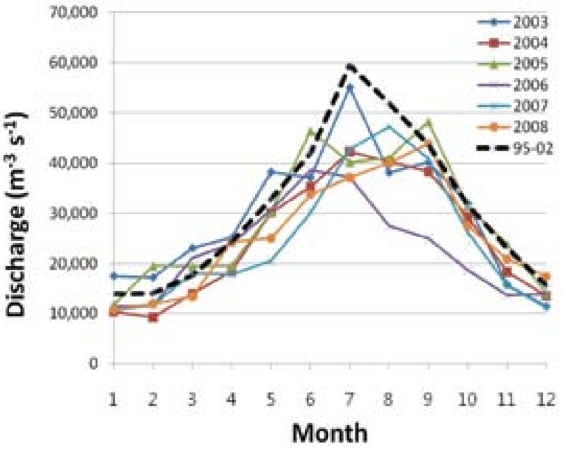
The first phase of Three Gorges Dam (TGD) construction was completed and impoundment began in June 2003, so the focus period of this report corresponds to the first six years of water impoundment. Records show lower discharges compared to the average of 1995-2002 period. Peak discharge occurred in different months (Fig. YS-5): June (2006), July (2003), August (2007) and September (2008). Average annual discharge decreased by 16.9% from 1995-2002 to 2003-2008 (Fig. YS-6). The reduction could influence the adjacent ecosystem by changing the supply of nutrients, sediment, and transparency. In fact, some recent studies showed that such changes occurred immediately after June 2003 when water impoundment started. The sediment loading was reduced by about 55% at the Datong hydrological station after June 2003 and the Si:N ratio in the vicinity of Changjiang River mouth changed from 1.5 in 1998 to 0.4 in 2004 (see Section 3.2.2) (Gong et al. 2006). The microbial community structure and microbial diversity also changed after 2 months of water storage operation (Jiao et al. 2007).



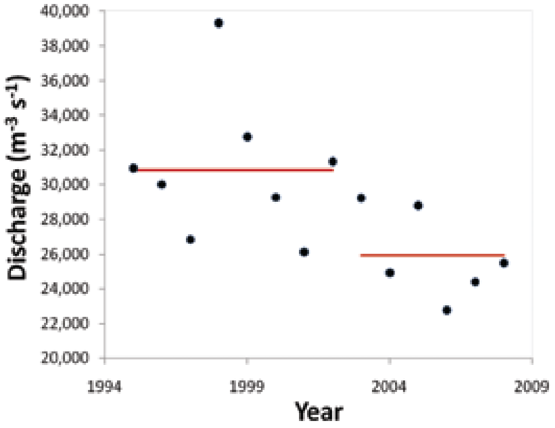
[Figure YS-3] Monthly precipitation over the Yellow Sea and East China Sea area averaged for 1979-2007. The pattern shows a typical northeastern Asian monsoon pattern of dry winters and wet summers. CMAP data are used.



[Figure YS-4] Annual average precipitation over the Yellow Sea and East China Sea area. CMAP data are used.



[Figure YS-5] Monthly discharge of the Changjiang River measured at Datong station (600 km upstream of the East China Sea). Broken line denotes the average for the period from 1995 to 2002.

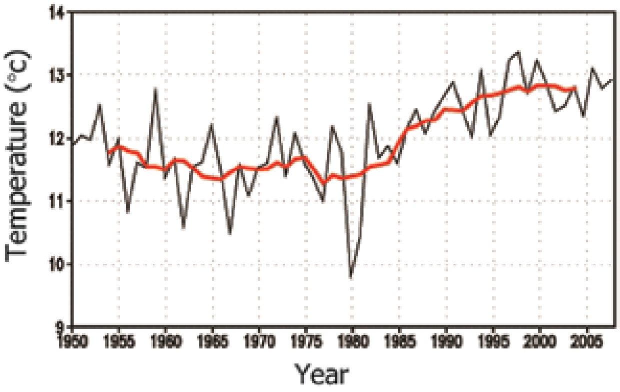


[Figure YS-6] Annual average discharge of the Changjiang River measured at Datong station. The discharge decreased after the impoundment of water began by TGD in June 2003.

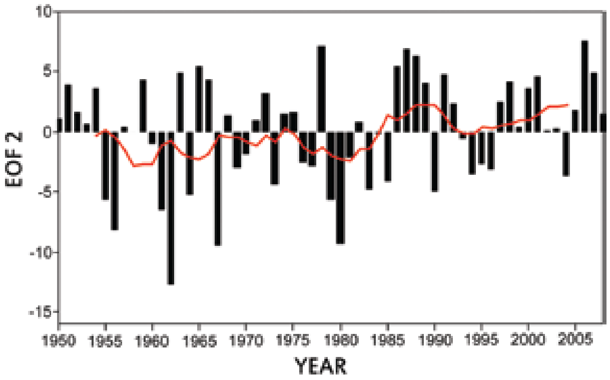
# 3.0 Physical and Chemical Ocean

## 3.1 Hydrography

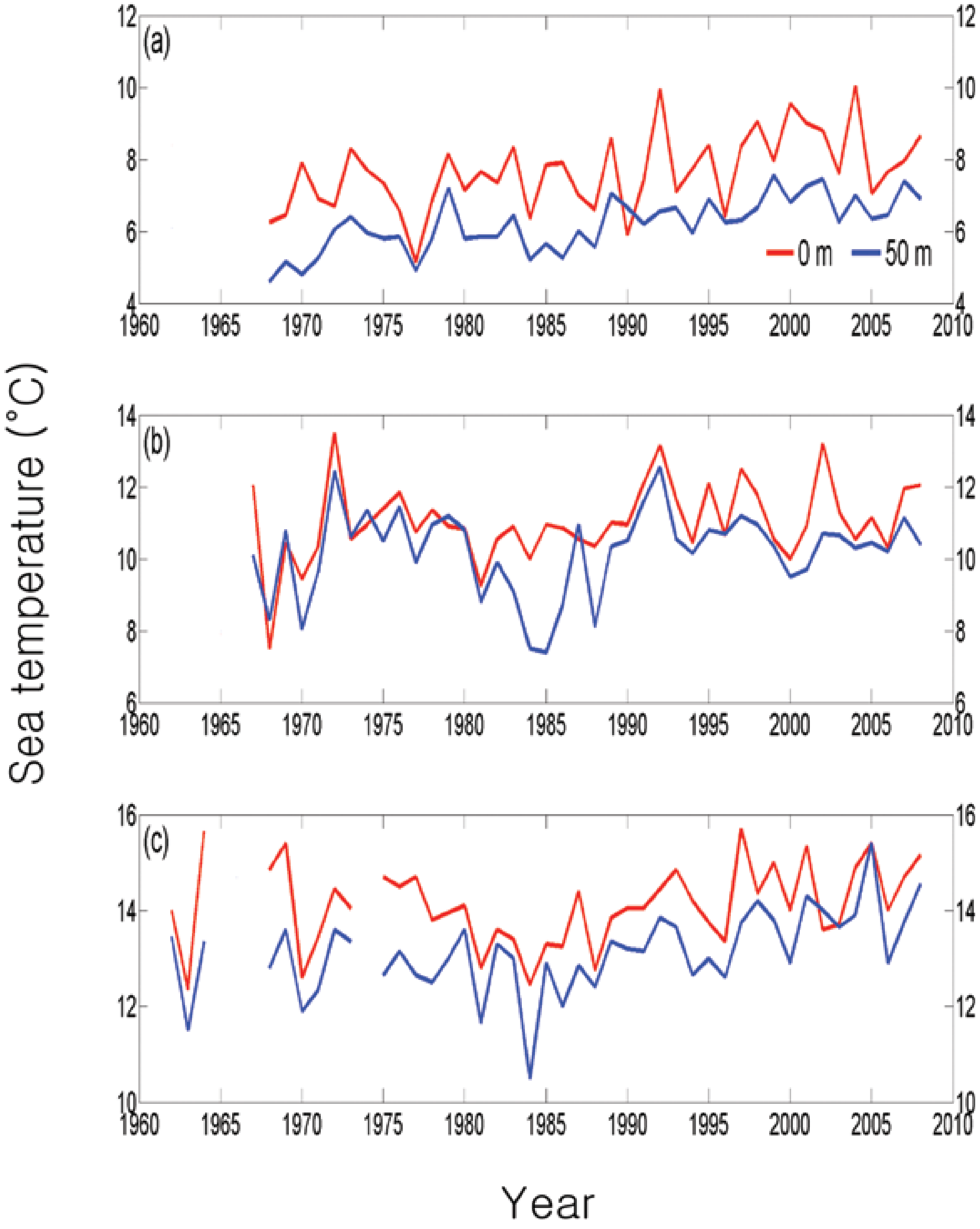
The most striking feature in the region (25°N-40°N, 118°E-127°E) is how its surface waters have warmed during boreal winter since the mid-1980s (Fig. YS-7). The long-term trend of SST in the Yellow Sea and East China Sea shows two distinctive periods from 1950 to 2008 (Yeh 2009). The first was a cooler period up to the middle 1980s, followed by a shift to a warm period (Fig. YS-7). EOF analysis shows the warming trend is most conspicuous on the shelf area of the East China Sea and in the central Yellow Sea. There is a phase shift in the temporal pattern of EOF1 based on SST from negative to positive around 1985. Recent warming in the region seems to be associated with large-scale atmospheric variability over the North Pacific basin. The 2nd EOF (explaining 19.6% of the variance) of sea level pressure (SLP) over the North Pacific, which describes the North Pacific Oscillation (NPO, Rogers 1981), shows a shift from low pressure to higher pressure in the middle of 1980s (Fig. YS-8). The correlation coefficient between the moving-averaged SST in the Yellow and East China seas and the moving-averaged principal component time series of SLP over the North Pacific was 0.79. This suggests that the circulation anomalies and thermal advection associated with NPO-like SLP variability play a role in warming the mean SST in the Yellow and East China seas during recent decades. The water temperature in April at the surface and 50 m shows a warming shift after the mid-1980s in the central Yellow Sea and Tsushima Current region (Fig. YS-9). However, on the shelf of the northern East China Sea, the trend is less clear.



[Figure YS-7] The trend of SST (Hadley Center) in Dec-Jan-Feb from 1950 to 2008 in the Yellow Sea and East China Sea region (25°N-40°N, 118°E-127°E). A warming trend is evident after the mid-1980s. The thick line indicates a nine-year moving average.



[Figure YS-8] Time series of the 2nd EOF scores of SLP for Dec-Jan-Feb from 1950 to 2008 in the North Pacific (bounded by 110°E-120°W and 20°N-70°N). The 2nd EOF explains 19.6% of the variance and the positively loaded in the southern half of the study area. The trend shows a shift from low pressure to high pressure after the mid-1980s. The line indicates a nine-year moving average. The correlation coefficient between this moving average and the SST moving average in Figure YS-7 is 0.79.



[Figure YS-9] The long-term trend of the temperature in April at the surface and 50 m in: (a) central Yellow Sea, (b) shelf of northern East China Sea, and (c) Tsushima Current area. The data were taken bimonthly at the stations of Korea Oceanographic Data Center (http://kodc.nfrdi.re.kr/page?id=eng_index).

## 3.2 Water properties

### 3.2.1 Oxygen and pH

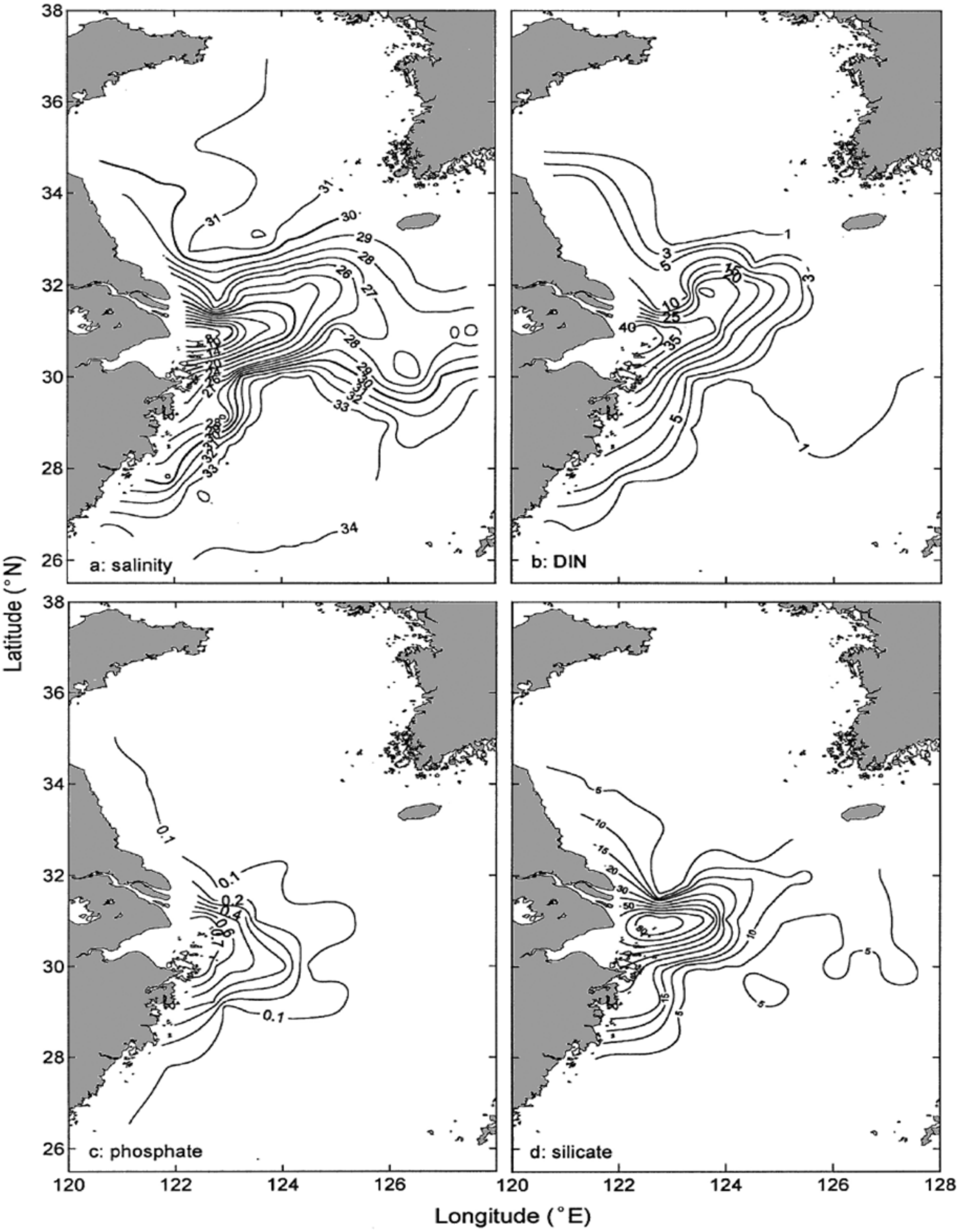
The dissolved oxygen (DO) concentration in the central part of the Yellow Sea was found in the range from 6.40 $mg \cdot l^{-1}$ to 7.81 $mg \cdot l^{-1}$. An average of 9.07 $mg \cdot l^{-1}$ was obtained from a basin-wide cruise carried out in the Yellow Sea in October 2003 (KCJRG 2004). A survey in August 2008 found that oxygen concentrations ranged from < 2.0 $mg \cdot l^{-1}$ to > 5.0 $mg \cdot l^{-1}$ in the bottom layer of the basin (UNDP/GEF 2010). Except for the station in the vicinity of the Changjiang river mouth, the oxygen concentration was >2.0 $mg \cdot l^{-1}$ in most regions. One of the largest coastal low-oxygen areas in the world occurs in the vicinity of the Changjiang River mouth (Chen et al. 2007). In August 2003, the area of DO concentrations <2-3 $mg \cdot l^{-1}$ covered >12,000 $km^2$. Hypoxia occurs near the Changjiang River mouth due to strong stratification and high primary production (Rabouille et al. 2008). The basin-wide survey in October 2003 also showed that pH values ranged from 7.63 to 8.17 with an average of 8.02 (KCJRG 2004). The pH is slightly higher on the surface than it is at a depth of 50 m.

### 3.2.2 Nutrients

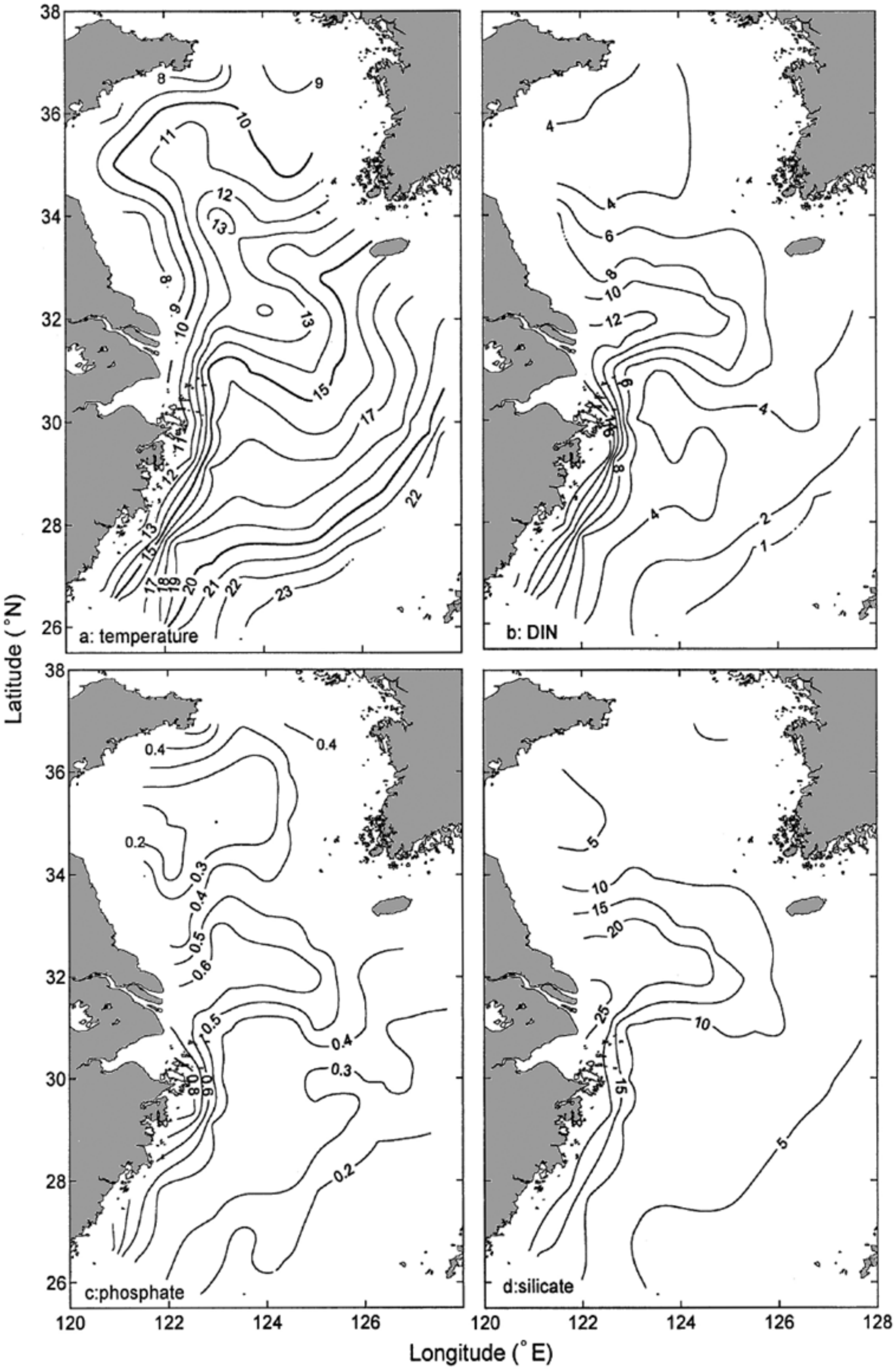
Nutrient concentrations that were measured in the summer of 1998 and the winter of 1999 show some of the characteristics of the Yellow Sea and East China Sea (Wang et al. 2003; Fig. YS-10, YS-11). In summer, most regions of the Yellow Sea were stratified and surface nutrient concentrations were very low. In the southern region, however, discharge from the Changjiang River created a strong south-north nutrient gradient. One of the biggest floods occurred in 1998 when the discharge was 30% greater than the average and the discharge during the summer flood (June 25 to the end of August) accounted for about one-third of the annual total (Wang et al. 2003). Discharge of nitrate in 1998 was $103 \times 10^9$ $moles \cdot y^{-1}$ which was more than twice the 1980-1990 average. High nutrient water covered a substantial area of the coastal Yellow Sea and northern East China Sea shelf. In January 1999, nutrients in the central Yellow Sea increased due to vertical mixing (Fig. YS-11). The area encompassed by the Changjiang River discharge was smaller in 1999 than what had occurred during the previous summer flood. A survey of the western Yellow Sea in January-February 2007 found that a similar pattern was observed (Fu et al. 2009). In some shallow coastal areas in the western Yellow Sea, $chlorophyll_a$ concentrations were high and nitrate concentrations were low indicating that biological production was active in these areas. Another basin-wide survey of the Yellow Sea in February 2008 found that nitrate concentration ranged from 4.05-11.8 μM and was higher on the eastern side (UNDP/GEF 2010). Phosphate concentrations were in the range 0.26-1.53 μM with higher values in the southeastern region. Silicate concentrations were in the range 8.16-14.5 μM with higher values in the center of the basin.

Nutrient ratios in the basin are among the best documented examples of change. Nitrate increased continuously from 1984-2000, while phosphate decreased after 1994 and silicate decreased after 1980 (Fig. YS-12). The net effect was an increase in N:P and N:Si ratios (Lin et al. 2005). The basin-scale impact of this change in nutrients on the Yellow Sea ecosystem is not clear yet.

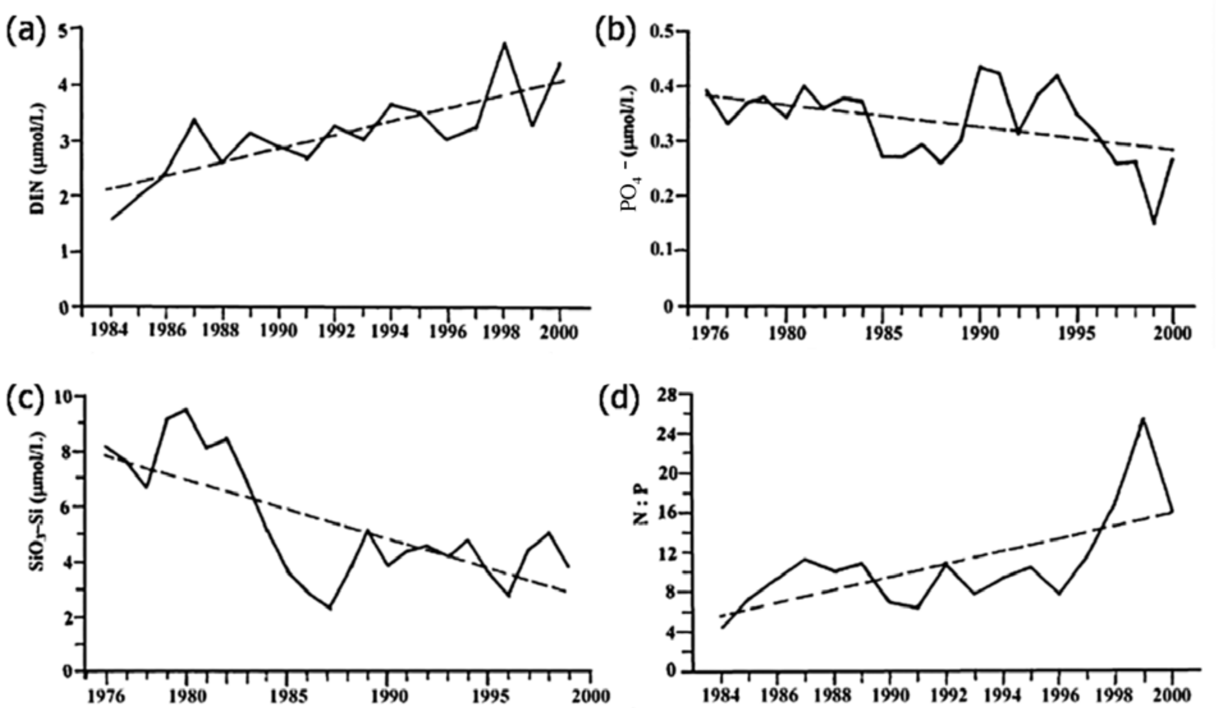
The Changjiang River is a major source of nutrients in the East China Sea. Nitrate loadings from the river have increased about threefold in 40 years (Zhou et al. 2008; Fig. YS-13). At the same time, the dissolved silicate flux has decreased since the 1950s because it is consumed in 162 large reservoirs (48,000 dams in total) in the Changjiang River basin (Li et al. 2007; Gao and Wang 2008). Sediment discharge also plays an important role in supplying nutrients, silicate in particular, to the East China Sea. The amount of sediment discharged depends on precipitation, erosion, sediment trapping by reservoirs, sediment extraction, and other factors (Chen et al. 2008). The amount of sediment discharged has been decreasing continuously since 1986. Therefore even before the construction of the TGD, N:Si and P:Si increased significantly and the result was a shift in the phytoplankton community composition toward non-siliceous species after the 1980s. The area of potential P limitation of phytoplankton growth expanded after 2003 and potential Si limitation appeared in 2005 and 2006 (Chai et al. 2009).



[Figure YS-10] Surface distribution of salinity and horizontal distributions of Dissolved Inorganic Nitrate (DIN), phosphate and silicate (all in μM) in the upper water of the YS and the ECS in August 1998 (adapted from Wang et al. 2003).



[Figure YS-11] Surface distribution of temperature and horizontal distributions of Dissolved Inorganic Nitrate (DIN), phosphate and silicate (all in μM) in the upper water of the YS and the ECS in January 1999 (adapted from Wang et al. 2003).



[Figure YS-12] Long-term trend of the nutrients along a transect across 36°N in the Yellow Sea. (a) Dissolved Inorganic Nitrate (DIN), (b) phosphates, (c) silicates, (d) N:P ratio. Modified from Lin et al. (2005).

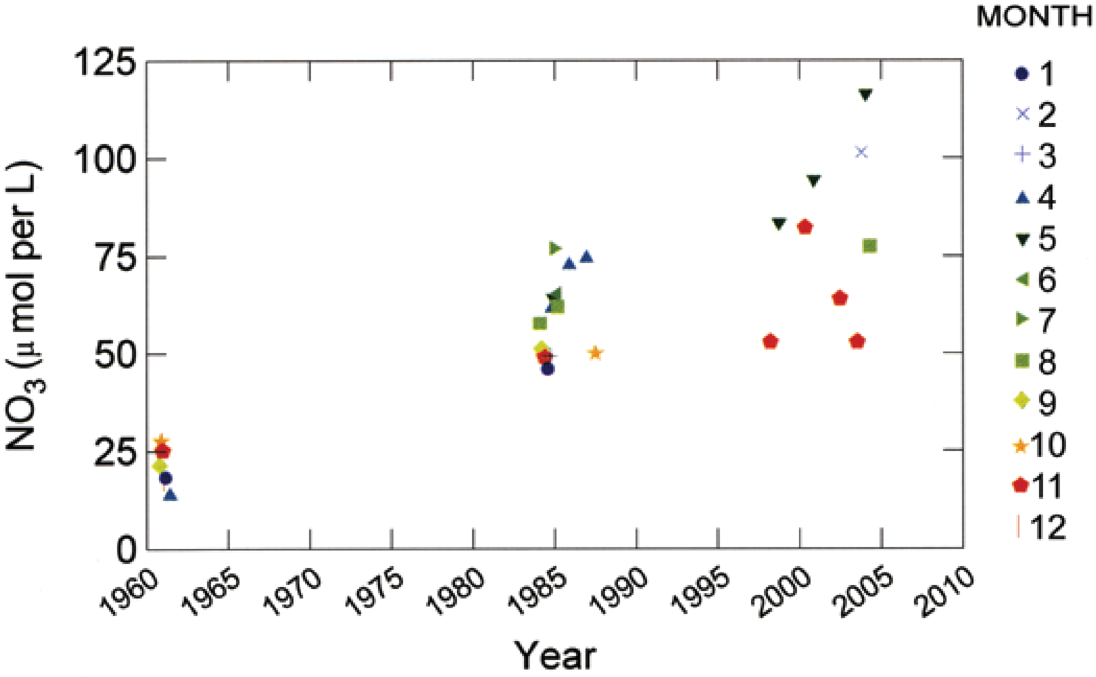
### 3.2.3 Organic sedimentation

Over the last century, total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP) have an increasing trend in the Yellow Sea. Likewise, C:N, C:P and N:P molar ratios also have significant increases. This generally coincides with the end of World War II and the beginning of the modern socio-economic developments of the surrounding lands. The decreases of TOC and TN in the sediment during the period from 1960 through the 1970s may be a reflection of a colder climate and overfishing in the region, whereas the stabilization of TP in the last 30 years is possibly associated with restricting the use of P in detergents (Fig. YS-14).

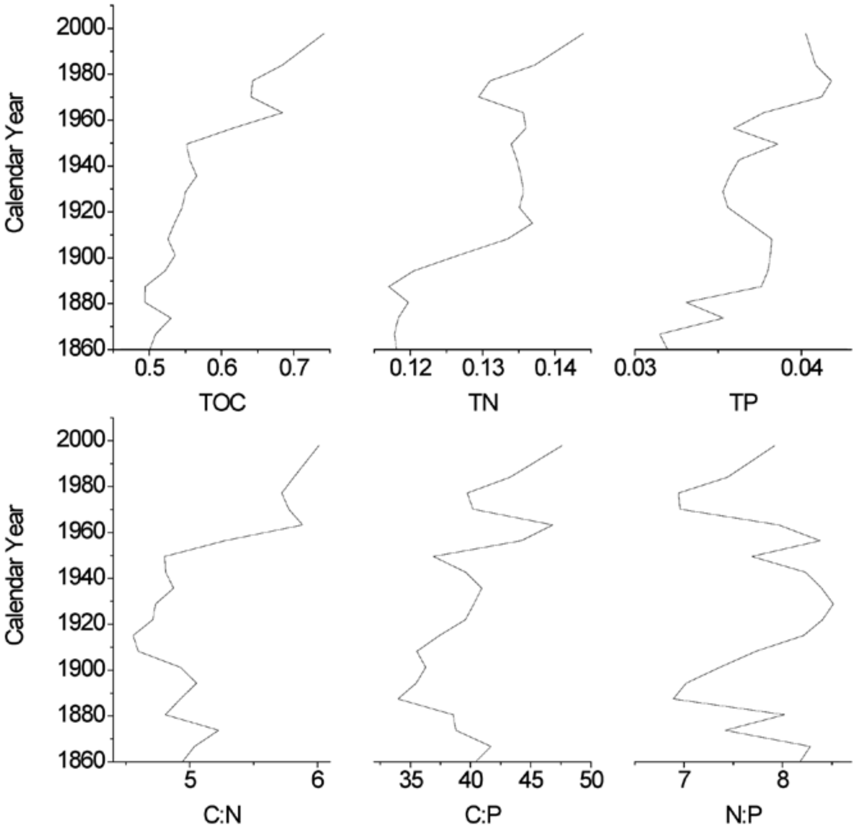
### 3.2.4 Contaminants

Sixteen polycyclic aromatic hydrocarbons (PAHs) and 28 polychlorinated biphenyls (PCBs) were measured in a core sample from the middle of the southern Yellow Sea in October, 2004 (Zhang et al. 2009). The chronology suggests that usage of PAHs had peaks from 1938-1944 and 1956-1962. The concentrations of these organic pollutants were lower than known ecologically effective values. In another study comparing various nearshore environments in the early 2000s, PCB residues in the sediments of some rivers and estuaries show that China's northeast and southern regions were more seriously polluted (Songhua River and Dalian Bay) than other areas. Jiaozhou Bay and the Pearl Estuary had relatively high PCB levels in organisms (Xing et al. 2005).

Trace metals (Al, Fe, Cu, Mn, Ni, Pb, Zn) in surface sediments of the shelf region near the Changjiang River mouth were generally lower than expected (Fang et al. 2009). Surface sediments of the inner shelf of the East China Sea were mildly contaminated by trace metals whereas higher concentrations of trace metals were found in Hangzhou Bay and along the inner shelf of the East China Sea. Trace metal contamination did not extend to the middle and outer shelves of the East China Sea (Fang et al. 2009).



[Figure YS-13] Long-term variation of nitrate concentration at the mouth of the Changjiang River, by month and year when a sample was collected. Data collected during the 1960s are courtesy of Dr. Hongkan Gu.



[Figure YS-14] Element chronographs of the Yellow Sea sediment (35°N 123.5°E): total organic carbon (TOC), nitrogen (TN), phosphorus (TP) content (w/w%) and their molar ratios.

# 4.0 Phytoplankton

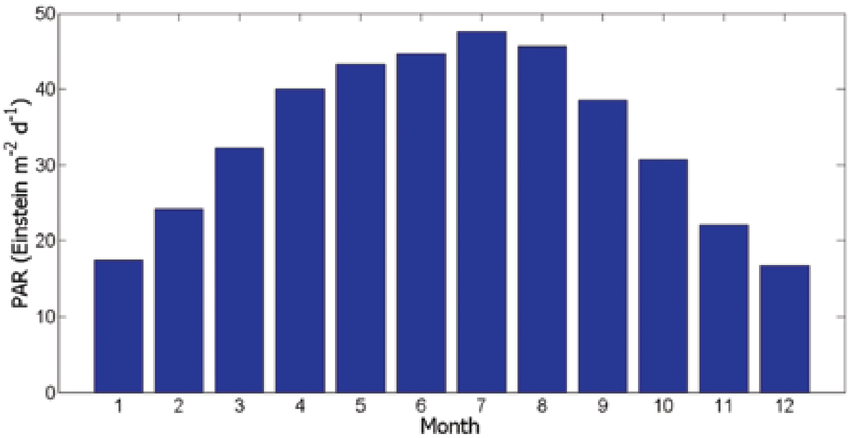
## 4.1 Light

Photosynthetically Active Radiation (PAR) at the sea surface over the Yellow Sea and East China Sea region was estimated from SeaWiFS data for the period 1998-2007. Monthly averages ranged from 16.8 $\mathrm{E \cdot m^{-2} \cdot d^{-1}}$ in December to 47.6 $\mathrm{E \cdot m^{-2} \cdot d^{-1}}$ in July (Fig. YS-15) and interannual variation was <5.5%. The minimum annual average PAR was 32.6 $\mathrm{E \cdot m^{-2} \cdot d^{-1}}$ in 1998 and the maximum was 34.4 $\mathrm{E \cdot m^{-2} \cdot d^{-1}}$ in 2004 (Fig. YS-16).

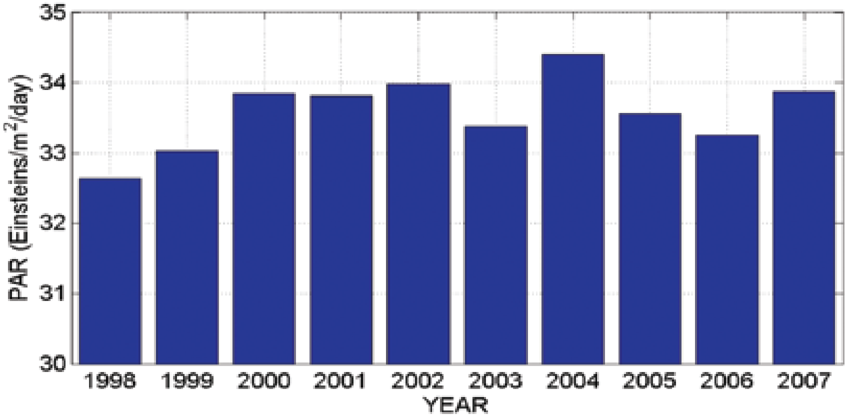
## 4.2 Phytoplankton

Seasonal phytoplankton blooms are known to occur in the Yellow Sea but there are few time series to show the interannual variation in the timing and intensity of the blooms. The current limitation the ocean colour analysis for accurate retrieval of chlorophyll delays such data availability. Compiled *in situ* records show that there are great variations in the phytoplankton biomass and primary productivity in the Yellow Sea depending on the area and time. For example, the primary productivity ranged from 11.8 to 3175 $\mathrm{mgC \cdot m^{-2} \cdot d^{-1}}$ (Yoo and Shin 1995; Cho et al. 1994; Kang et al. 1992; Choi et al. 1988; Park 2000).

In open waters of the Yellow Sea where the water column is seasonally stratified at shallow depths, seasonal blooms develop in spring and autumn. Qualitative analysis of ocean colour data from the Coastal Zone Color Scanner indicates that seasonal blooms occur in April and October. A bi-monthly survey of the eastern half of the Yellow Sea in 1986 showed that mean $\text{chlorophyll}_a$ was 1.5 $\mathrm{mg \cdot m^{-3}}$ from 12 stations in April (0.4-3.3 $\mathrm{mg \cdot m^{-3}}$) while in October, the mean was 0.97 $\mathrm{mg \cdot m^{-3}}$ (range: 0.7-1.2 $\mathrm{mg \cdot m^{-3}}$) (Choi et al. 1988). The mean values were 0.70, 0.66, and 0.4 $\mathrm{mg \cdot m^{-3}}$, in June, August and December, respectively, showing a clear bimodal seasonal pattern. Seasonal cycles were also observed in some of the shallow tidally-mixed areas. There, timing of blooms varied depending on local conditions. In Gyung-Gi Bay (see Fig. YS-1 for location), the spring bloom occurred in March and the autumn bloom



[Figure YS-15] Monthly averages of PAR in the Yellow Sea and East China Sea from 1998 to 2007.



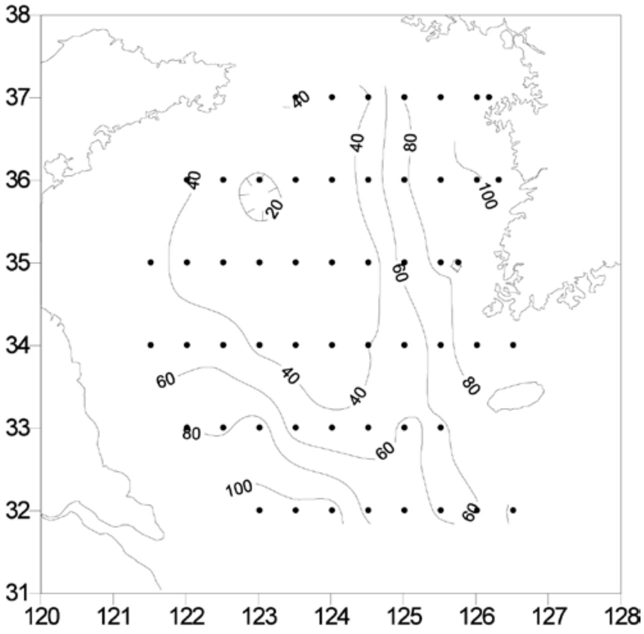
[Figure YS-16] Annual averages of PAR in the Yellow Sea and East China Sea from 1998 to 2007.

early in September. Freshwater discharge probably played an important role in this area (Song 1999). Chlorophyll$_a$ was high throughout the year (1.3-22.6 mg·m$^{-3}$). In the Saemangeum area where jetties were built recently, no particular seasonal cycle can be identified. In these areas, chlorophyll$_a$ was also high throughout the year (0.9-6.9 mg·m$^{-3}$).

A bi-monthly survey in the eastern half of the Yellow Sea in 1987 found 394 species of phytoplankton during the year (Han and Choi 1991). More than 90% of these were diatoms and dinoflagellates and the proportion of dinoflagellates increased in stratified water. Biomass and abundance of phytoplankton were typically high in coastal areas and near the Changjiang River mouth but lower in the central areas (UNDP/GEF 2007). Species diversity also showed a similar pattern (Fig. YS-17). In the summer of 2008, chlorophyll$_a$ concentrations varied from 0.13 mg·m$^{-3}$ to 6.69 mg·m$^{-3}$ with an average of 1.24 mg·m$^{-3}$ (microplankton; 29%, nanoplankton; 12%, picoplankton; 59%) (UNDP/GEF 2010). In the northern part of the Yellow Sea, *Chaetoceros* spp., cryptomonads, *Paralia sulcata*, *Karenia mikimotoi*, and *Navicula* spp. were the dominant species. The total number of species there was 110, among which 73 species were diatoms and 29 were dinoflagellates. In the southern part of the Yellow Sea, nanoflagellates, cryptomonads, and *Prorocentrum* spp. were the dominant species. The daily primary production during this study was in the range 121 mgC·m$^{-2}$·d$^{-1}$ to 1,204.7 mgC·m$^{-2}$·d$^{-1}$ with an average of 592.8 mgC·m$^{-2}$·d$^{-1}$ (UNDP/GEF 2010). Because of the high spatial and temporal variability, it is difficult to compare these results with previous studies.

In the tidally mixed zone, turbidity is very high and light could be a major limiting factor for phytoplankton growth. I$_k$ was as low as 10-12 μE·m$^{-2}$·s$^{-1}$ in a mixed coastal area in the winter (Yoo and Shin 1995). Tyco-pelagic species such as *Paralia sulcata* are dominant and diatoms are abundant. Species diversity is usually high throughout the year with a less conspicuous seasonal pattern.

The 1986 survey found that primary production was highest in June (1,391 mgC·m$^{-2}$·d$^{-1}$) with an estimate of the annual production at 141 gC·m$^{-2}$·yr$^{-1}$. A basin-scale estimate of annual production would be higher since the shallow mixed zone has higher production. During late spring and summer, a subsurface chlorophyll maximum (SCM) layer forms near the shallow thermocline (10-30 m) and production at the SCM was substantial, contributing 17.7-30.1% of the depth-integrated production in June 2000 (Park 2000). Continuous measurements by a towed profiler show that the SCM depth tends to increase towards the center of the basin. Daily primary production estimated from satellite data for the period from 1998 to 2003 was 835.6 mgC·m$^{-2}$·d$^{-1}$ for May and 672.3 mgC·m$^{-2}$·d$^{-1}$ for September (Son et al. 2005). Chlorophyll$_a$ was higher in coastal waters but primary production was higher in the central region because



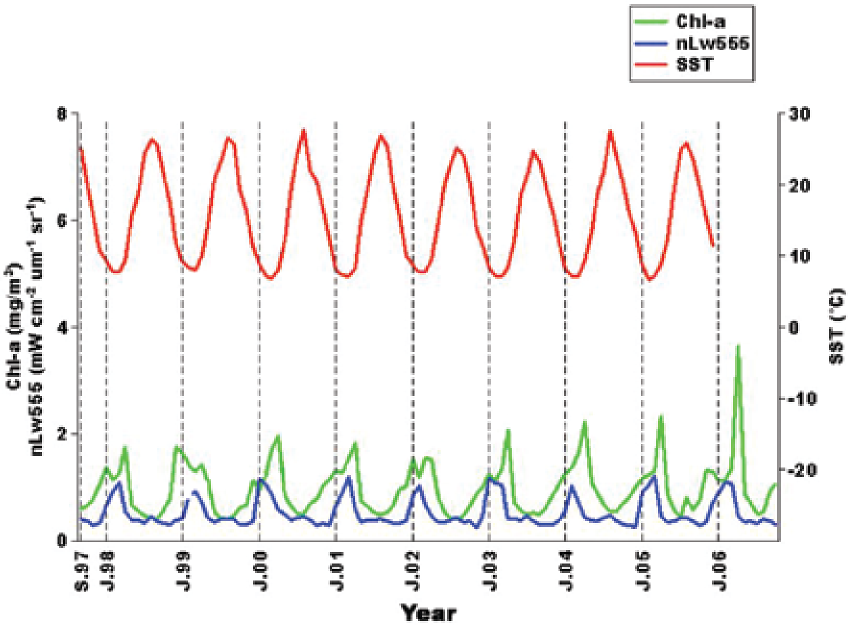
[Figure YS-17] Distribution of phytoplankton species numbers in the Yellow Sea, September 1992 (J.-H. Noh, unpublished data).

of lower turbidity. There are few data to indicate interannual variation or trends. Comparing satellite ocean colour data for 1979-1984 with 1998-2002 showed that chlorophyll$_a$ increased in most of the Yellow Sea and East China Sea. However, as two different satellites were used for the comparison, it is not clear how much of the difference was due to different sensors (Son et al. 2005). From 1997 to 2006, SeaWiFS chlorophyll$_a$ in the central area of the Yellow Sea increased after 2002 (Fig. YS-18) but the cause of this increase is not clear and there was no parallel trend in SST.

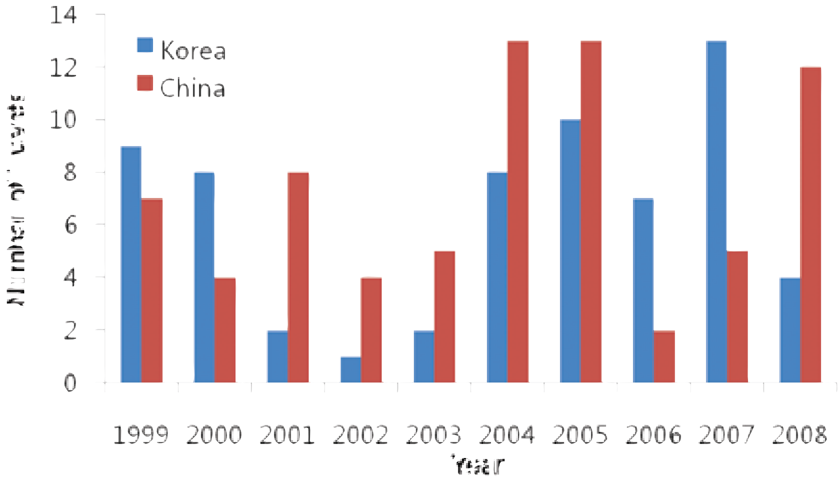
While phytoplankton in the open waters of the Yellow Sea show a typical mid-latitude bimodal seasonal cycle, the phytoplankton on the East China Sea shelf have another peak that is related to fresh water discharge from the Changjiang River in summer. Unlike the shelf waters, the Kuroshio region (Fig. YS-1) on the continental slope of the East China Sea has low chlorophyll$_a$ throughout the year (0.1-0.3 $mg \cdot m^{-3}$) and a damped seasonal cycle with only one peak in early spring. Phosphate and chlorophyll$_a$ in the upper 200 m of Kuroshio area decreased by 0.011 μM and 0.013 $mg \cdot m^{-3}$ per decade, respectively, from 1973 to 2004 and the increase of temperature in this area was faster than the global mean warming (Aoyama et al. 2008).

Red tides are common off the Chinese and Korean coasts and are related to the eutrophication of the Yellow Sea and East China Sea (Zhou et al. 2008; Tang et al. 2006). During the 1980s, algal blooms (defined by cell density) in both Chinese and Korean waters increased and reached a peak in 1990s but since then, the number of algal blooms leveled off (UNDP/GEF 2007). In both the Korean and Chinese coasts of the Yellow Sea, the number of algal blooms did not differ between the period from 1999-2003 versus the period from 2004-2008 (Fig. YS-19). Likewise, the number of algal blooms on the Korean coast of the East China Sea does not have a trend (Fig. YS-20).

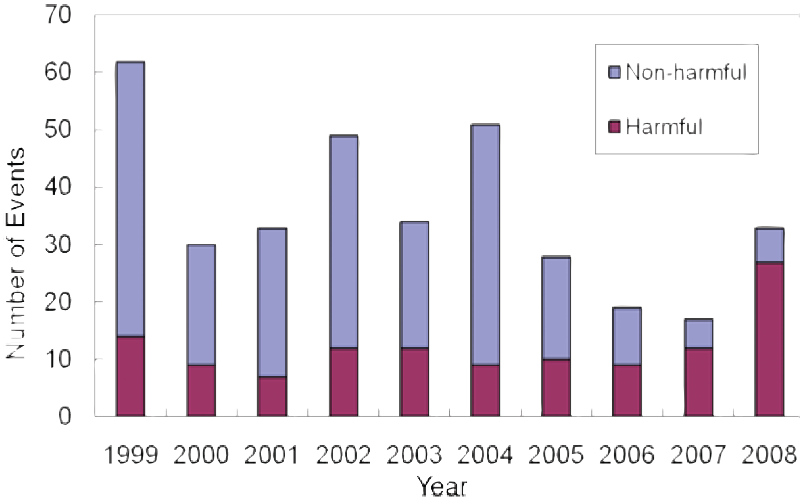
The species of dinoflagellates that cause HABs in Korean waters have changed. From 1999 to 2003, the major species were *Cochlodinium polykrikoides* (26% of blooms), *Prorocentrum minimum* and *P. dentatum* (25%), *Heterocapsa akashiwo* (16%), *Akashiwo saguinea* (7%), *Noctiluca scintillans* (5%), and *Ceratium* spp. (5%). From 2004 to 2008, the major species were *C. polykrikoides* (34%), *Prorocentrum minimum* and *P. dentatum* (13%), *N. scintillans* (12%), *H. akashiwo* (8%), *Chattonella* spp. (7%), *A. saguinea* (5%), and *G. polygramma* (5%). While *Prorocentrum* spp., *H. akashiwo*, and *Ceratium* spp. decreased, *N.scintillans*, *Chattonella* spp., and *G. polygramma* increased. In the Yellow Sea, *Chattonella* spp. increased from 0% to 27% and *N. scintillans* from 20% to 31%. *C. polykrikoides* decreased from 10% to 0% and *H. akashiwo* from 15% to 0%. Along the southern coast of Korea (northern East China Sea), *Gonyaulax polygramma* increased from 0% to 6%, *Chattonella* spp. from 0 to 3%, and *C. polykrikoides* 28% to 43%. However, *Prorocentrum* spp. decreased from 26 to 16%, and *Ceratium* spp. 5% to 0%.



[Figure YS-18] Changes in the satellite chlorophyll$_a$ in the central region of the Yellow Sea. nLw555 indicates the influence of suspended sediments. Chlorophyll$_a$ increased after 2002 while there was no change in SST and nLw555.



[Figure YS-19] Frequency of algal blooms along the Chinese and Korean coasts in the Yellow Sea during 1999-2008.

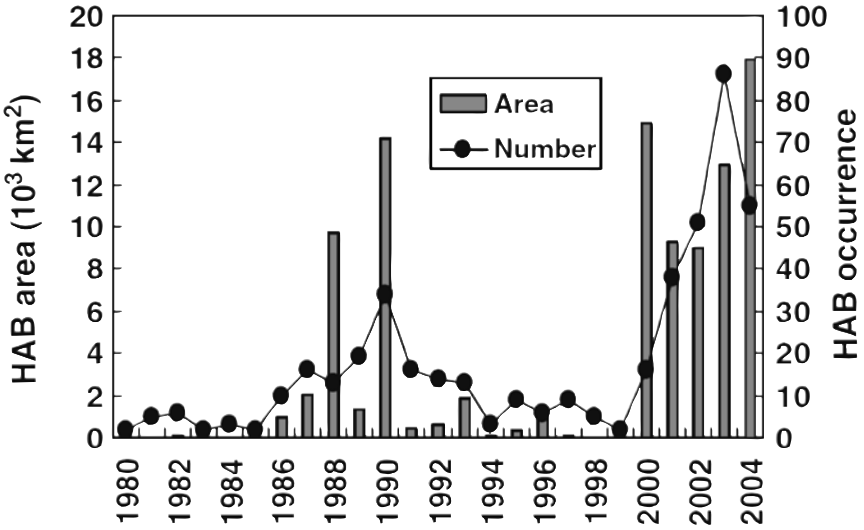


[Figure YS-20] Number of algal bloom events in the southern coast of Korea (East China Sea) during 1999-2008.

To summarize, *C. polykrikoides*, *P. minimum*, *P. dentatum*, *H. akashiwo*, *A. saguinea*, *N. scintillans*, *Ceratium* spp. and *S. costatum* were major HAB causative species throughout Korean waters from 1999 to 2008. *Chattonella* spp. (Yellow Sea) and *G. polygramma* (East China Sea) have been newly emerging HAB species in the past five years.

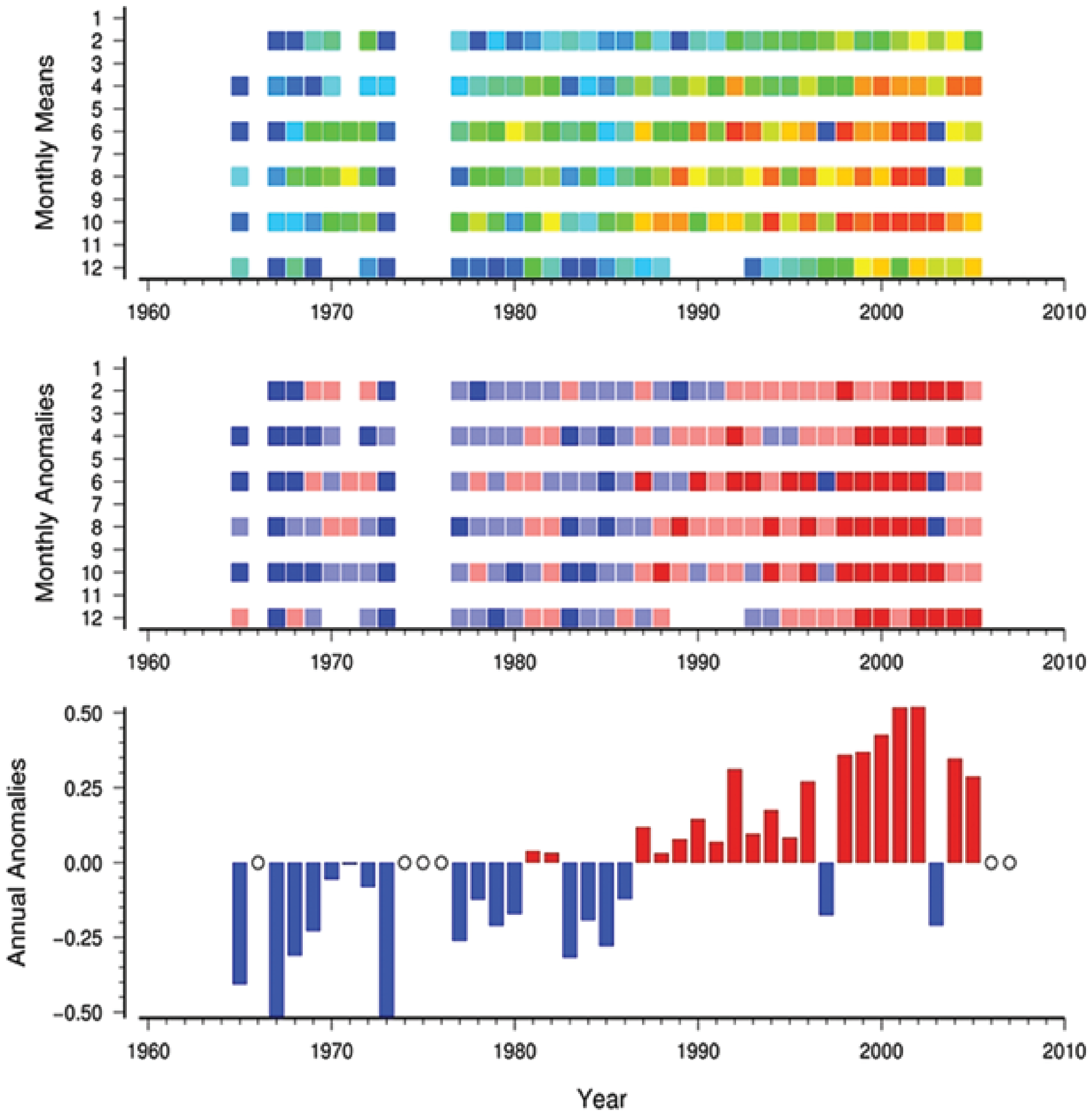
HAB occurrences are more extensive and more frequent in Chinese coastal waters of the East China Sea (Tang et al. 2006; Fig. YS-21). The frequency increased drastically after 2000 reaching almost 90 times a year by 2004. HAB events were most frequent near the Changjiang River mouth, where eutrophication is the most severe in China (http://www.soa.gov.cn/chichao/index.html). In addition to anthropogenic eutrophication, upwelling provides nutrients to the Chinese coastal region in the East China Sea (Tang et al. 2002). During the past decades, there was a shift in seasonal occurrence and causative organisms in the vicinity of the Changjiang River mouth. Before the 1980s, HABs occurred most frequently in autumn. During the 1980s, they were most frequent in July-August. After the 1990s, HAB events occurred most frequently in May. During the 1980s, *Noctiluca scintillans* was the major causative organism, however, since 2000, *Prorocentrum dentatum* became the major HAB species. It was not reported as a causative species before 2000. This shift of dominant species may be a result of increased N:Si or N:P ratio (Chai et al. 2009; Tang et al. 2006).

[Figure YS-21] Number and area of HAB occurrences in the Chinese coastal areas on the southern East China Sea shelf including the Changjiang River vicinity during 1980-2004. Adapted from Tang et al. (2006).



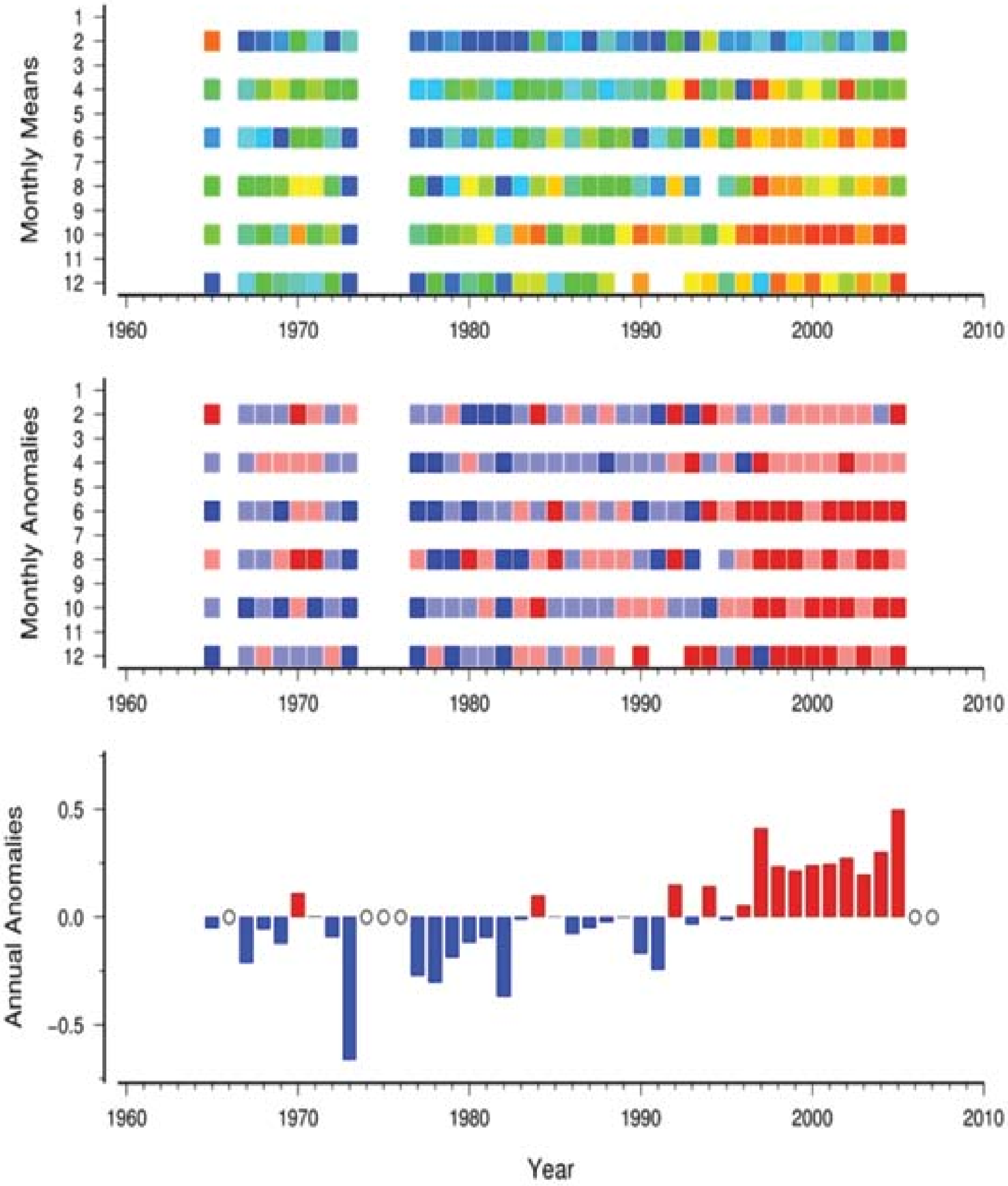
## 5.0 Zooplankton

Bimonthly mesozooplankton samples have been taken in Korean waters for decades, and there is some evidence of long-term change. Beginning in the late 1980s in the eastern Yellow Sea and in the early 1990s in the northern East China Sea, zooplankton biomass showed an increasing trend which reached its peak in the early 2000s (Figs. YS-22, YS-23). Although the mechanisms responsible for the change are not yet understood, the trends are parallel to changes observed in SST (Fig. YS-8). Annual anomalies of zooplankton biomass in the eastern Yellow Sea shifted generally from negative to positive values in the late 1980s. After 1987, anomalies became positive except for 1998 and 2004. Biomass anomalies were higher from 1999 to 2006 than from 1988-1997 (Kang et al. 2009; Fig. YS-22). Seasonal variation of zooplankton biomass anomalies was generally lowest in winter (February and December) and highest in late spring/autumn (June-October).

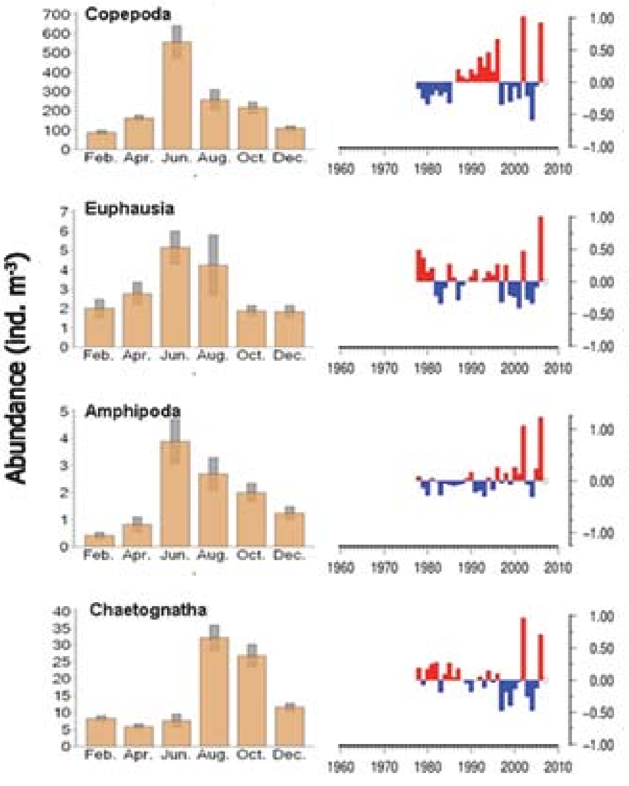


[Figure YS-22] Standardized (SCOR-WG 125) time series of monthly zooplankton biomass (ln[mg·m⁻³]) in the eastern Yellow Sea. Small circles indicate missing data. See Kang et al. (2009) for further details of the analysis.

Annual mean abundance anomalies in the eastern Yellow Sea showed a similar trend among copepods, euphausiids and chaetognaths (Fig. YS-24). Copepods and euphausiids showed a slight upward trend after the late 1980s, but switched to a downward trend after the mid-1990s, especially in 1997. Chaetognaths also showed a downward trend after the mid-1990s but there were high positive values observed in 2002 and 2006. In contrast to the other three groups, anomalies of amphipod abundance increased slightly after the early 1990s with two high values in 2002 and 2006. Bimonthly mean densities of four zooplankton groups, copepods, euphausiids, amphipods and chaetognaths showed seasonal variation (Fig. YS-24). Densities of copepods, euphausiids and amphipods were highest in June, while chaetognath density was highest in August.



[Figure YS-23] Standardized (SCOR-WG 125) time series of monthly zooplankton biomass (ln[mg·m⁻³]) in the northern East China Sea. Small circles indicate missing data. See Kang et al. (2009) for further details of the analysis.

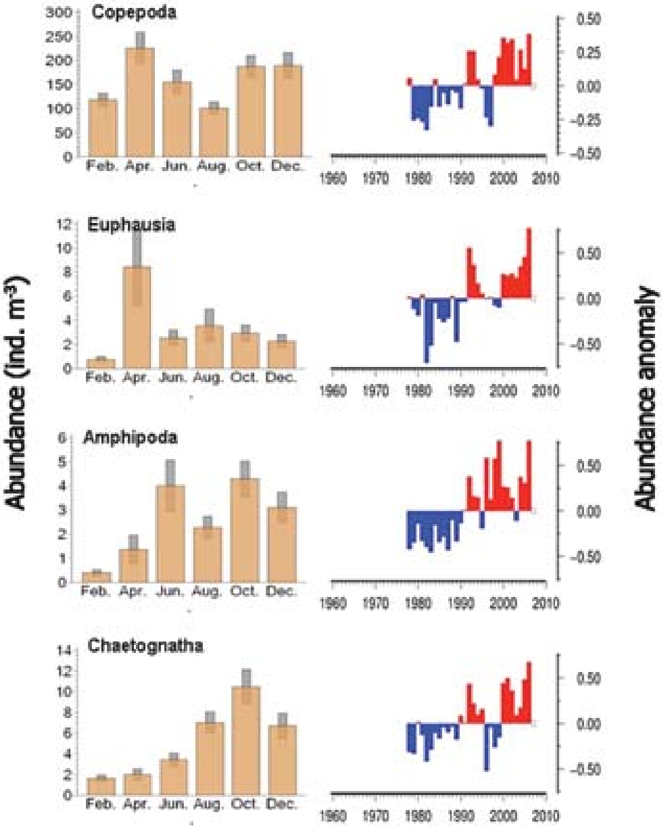


[Figure YS-24] Seasonal and interannual comparison of copepods, euphausiids, amphipods and chaetognaths in the eastern Yellow Sea.

Annual mean anomalies of zooplankton biomass in the northern East China Sea shifted from negative to positive values in the early 1990s, except for 1994 and 1996 (Fig. YS-23). Biomass increased abruptly after 1998 and maintained a high value through 2006. Bimonthly mean biomass of total zooplankton was generally lowest in February and highest in June/October while high values were observed mainly in October and December after the late 1980s. After the mid-1990s, the peak biomass occurred in June and August.

Annual mean abundance anomalies in the northern East China Sea were similar among copepods, euphausiids and chaetognaths, but the amphipod trends were distinctive (Fig. YS-25). The abundance of copepods, euphausiids and chaetognaths increased after the early 1990s, but anomalies were negative during the mid-1990s with a peak around 1997. The abundance of amphipods increased after the early 1990s despite the negative anomalies in 1995 and 2003. In bimonthly mean densities of the four zooplankton groups, copepods and euphausiids had peaks in April, October and December (Fig. YS-25), while amphipods peaked in June and October and chaetognaths in October.

A detailed analysis of bimonthly samples from the Yellow Sea from 1997 to 1999 showed that copepods made up 70.1% of the total zooplankton biomass, on average (Lim et al. 2003). The remainder was comprised of dinoflagellates (5.78%, mostly *Noctiluca*), Cladocera (5.42%), Chordata (5.26%) and Chaetognatha (5.19%). The proportion of copepods was highest from late autumn through early spring because the biomass of other groups increased from late spring and remained high until late autumn. Among the copepods, *Calanus sinicus*, *Paracalanus* sp., *Oithona atlantica*, and *Corycaeus affinis* were dominant through all seasons and occurred in most areas, comprising 75.6% of the total copepod biomass. Total zooplankton biomass was highest in June and October. There was a year to



[Figure YS-25] Seasonal and interannual comparison of copepods, euphausiids, amphipods and chaetognaths in the northern East China Sea.

year variation in the pattern. For example, in 1997 and 1998, the biomass was highest in June, while in 1999, the biomass was highest in October. Seasonal fluctuation was higher in the northern and neritic environments.

In the Yellow Sea copepods account for 70~90% by number of total zooplankton but there are seasonal and areal variations (Kang and Lee 1991; Rebstock and Kang 2003). *Calanus sinicus* is the most important large calanoid species in the Yellow and East China seas (Chen 1964). *Paracalanus* spp. and *Acartia* spp. are small neritic species that are important in the coastal areas of China and Korea. Apart from copepods, *Sagitta crassa*, *Euphausia pacifica* were also dominant (Tang 1989). Oceanic, warm water species were rare but found episodically in the Yellow Sea. Zooplankton biomass was highest in the southern area off the Changjiang River estuary (UNDP/GEF 2010; OSTI & IOCAS 1998). In general, zooplankton biomass was higher in the coastal waters than in central waters. Unlike in the northern East China Sea, where zooplankton abundance showed two peaks annually, the zooplankton abundance has one seasonal peak in the eastern Yellow Sea. For copepods, amphipods, and euphausiids the peak occurs in June, while chaetognaths have a peak in October (Kang 2008).

In the northern East China Sea, copepods account for >90% by number of total zooplankton. In contrast to the Yellow Sea, many oceanic, warm-water copepods are common and important components of the zooplankton biomass (Kang and Hong 1995). Zooplankton biomass has episodic peaks in the northern East China Sea when warm water species are transported by the Tsushima Warm Current. This phenomenon indirectly or directly influences fisheries.

A conspicuous feature of the zooplankton community in recent years is the occurrence of blooms of the large scyphomedusa, *Nemopilema nomurai* (giant jellyfish) in the East China Sea (Anonymous 2004). An unusual bloom was first observed in 2000 with the largest bloom occurring in 2003. Ocean currents carried the jellyfish northward into adjacent seas causing serious problems for fishermen (and beach bathers). Jellyfish observed in Korean waters are the giant *Nemopilema nomurai*, medium-sized *Aurelia aurita*, big and venomous *Cyanea capillata* and *Dactylometra quinquecirrha* (*Chrysaora quinquecirrha*). The highly venomous *Physalia physalis* and *Carybdea rastonii* are also reported occasionally. *N. nomurai* is the biggest jellyfish occurring in Korean waters with bell size of about 2 m and weight of 150 kg. Outbreaks of these were reported by Japanese fishermen in 1920, 1958, 1995, and 2002. The causes of the blooms and their interannual fluctuation are unknown. Several factors such as increasing sea temperature, overfishing, and marine pollution have been suggested as causal factors or at least mediators.

Giant jellyfish have occurred in the region in large numbers since 2003. The average densities off the southern Korean peninsula were 177, 7, 83, and 9 inds.·ha$^{-2}$ in August 2005, 2006, 2007 and 2008, respectively. The cosmopolitan jellyfish species, *A. aurita*, has been superabundant in Korean waters since the late 1990s. Along with giant jellyfish, *A. aurita* causes significant damage to fisheries. In 2006, *C. capillata* began appearing from the end of spring to the end of autumn in the southern offshore areas. Since then, its areal distribution has expanded and the duration of its seasonal appearance is prolonged. *D. quinquecirrha* has appeared mainly in the eastern and southern parts of the Korean peninsula. Its occurrence seems related to the cold water mass in those areas.

## 6.0 Fishes and Invertebrates

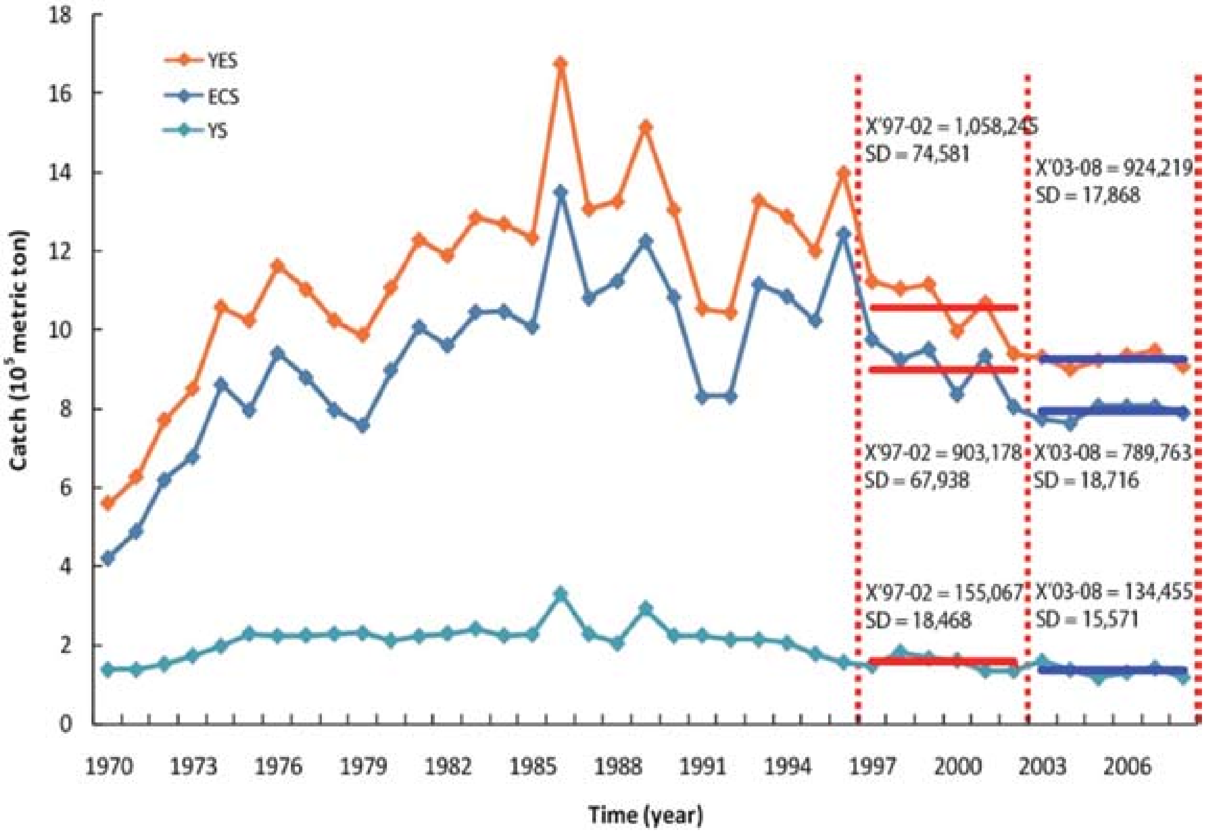
The Yellow Sea is the location of multispecies, multinational fisheries and is one of the most intensively exploited areas in the world. Although many fisheries resources are utilized commonly by neighboring countries, there are few joint scientific and management activities. A total of 276 species have been identified on the Korean side of the Yellow Sea, and approximately 100 species including cephalopods and crustaceans have been utilized as resources. Over 90% of these species are warm or warm-temperate water species. Many share a typical migration pattern with spawning in the coastal areas during the spring, and overwintering in the southern Yellow Sea and the northern East China Sea. Currently, about 30 species are commercially targeted. The abundance of most species is relatively low and only ~20 species exceed 10,000 t in annual catch. A small group of species (Table YS-1) accounts for 40 to 60% of the annual catch in the Yellow Sea and East China Sea. The biomass of demersal species such as small yellow croaker, hairtail, large yellow croaker, flatfish, and Pacific cod declined by more than 40% as the fishing effort increased threefold from the early 1960s to the early 1980s (Zhang and Kim 1999).

Scientific surveys of the Chinese side found 149 and 177 species during bottom surveys in autumn 2000 and spring 2001, respectively. They found that biomass in autumn was higher than in spring. The biomass of pelagic species was higher than that of demersal fish especially in autumn, but the reverse was true in spring. Bottom trawl surveys in Korean waters found 134 demersal species in the summer of 1967 but only 51 species were found in the 1980/81 survey revealing a 62% reduction in the number of species. Of the 15 most abundant species in the 1980/81 survey, 8 were not found in a list of the 20 most abundant species in the 1967 survey (Zhang and Kim 1999).

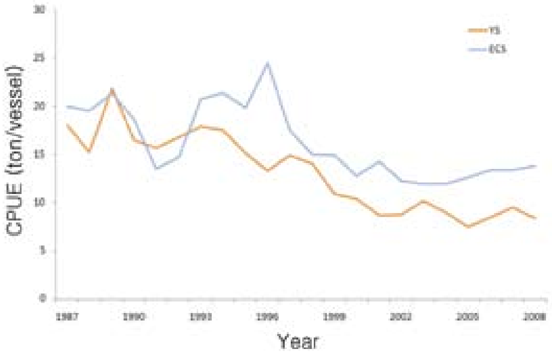
The total catch by Korean fisheries in the Yellow Sea has decreased gradually since its peak in the mid-1980s (Fig. YS-27). Likewise, CPUE has gradually decreased since its peak in the late 1980s (Yellow Sea) and the mid-1990s (East China Sea) (Fig. YS-28). In the long-term, semi-demersal fishes have been replaced by small pelagic fishes and as a consequence, the mean trophic level has been decreasing for the past three decades (Fig. YS-29, YS-30, YS-31 and YS-32). The mean annual catch decreased from 1,058,245 t in 1997-2002 to 924,219 t during the focus period. Fluctuations have decreased and the annual catch became stable during the focus period. The decline in catch from the Yellow Sea was less than from the East China Sea, and fluctuations were proportionately lower in the Yellow Sea than in the East China Sea.

[Table YS-1] Major commercial species in the Yellow Sea and the East China Sea

| Common Name | Species |
|---|---|
| Demersal and semi-demersal fishes | |
| Small yellow croaker | *Pseudosciaena polyactis* |
| Hairtail | *Trichiurus lepturus* |
| Filefish | *Stephanolepis cirrhifer* |
| Pomfret | *Pampus argenteus* |
| Corvenias | *Collichthys niveatus* |
| Large yellow croaker | *Pseudosciaena crocea* |
| White croaker | *Argyrosomus argentatus* |
| Brown croaker | *Miichths miiuy* |
| Roundnose flounder | *Eopsetta grigorjewi* |
| Bastard halibut | *Paralichthys olivaceus* |
| Common seabass | *Epinephelus septemfasciatus* |
| Pacific cod | *Gadus macrocephalus* |
| Puffers | *Tetraodontidae* |
| Sharptoothed eel | *Muraenesox cinereus* |
| Red seabream | *Pagrus major* |
| Sea-devil | *Lophiomus setigerus* |
| Bigeyed herring | *Herklotsichthys zunasi* |
| Rockfish | *Sebastes inermis* |
| Flathead | *Platycephalus indicus* |
| Skateray | *Raja kenojei* |
| Pelagic fishes | |
| Anchovy | *Engraulis japonica* |
| Sardine | *Sardinops melanostictus* |
| Pacific herring | *Clupea pallasii* |
| Common mackerel | *Scomber japonicus* |
| Horse mackerel | *Trachurus japonicus* |
| Spanish mackerel | *Scomberomorus niphonius* |
| Shellfish | |
| Cuttlefish | *Sepia esculenta* |
| Blue crab | *Portunus trituberculatus* |
| Large shrimp | *Penaeus orientalis* |
| Common squid | *Todarodes pacificus* |



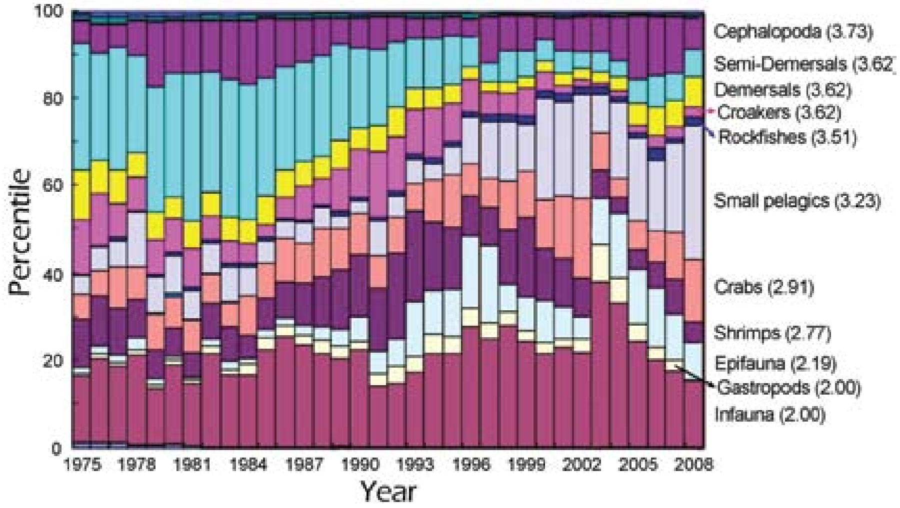
[Figure YS-27] Long-term trend in the catch by Korean fisheries in the Yellow Sea (YS), East China Sea (ECS) and the sum of the two seas (YES).



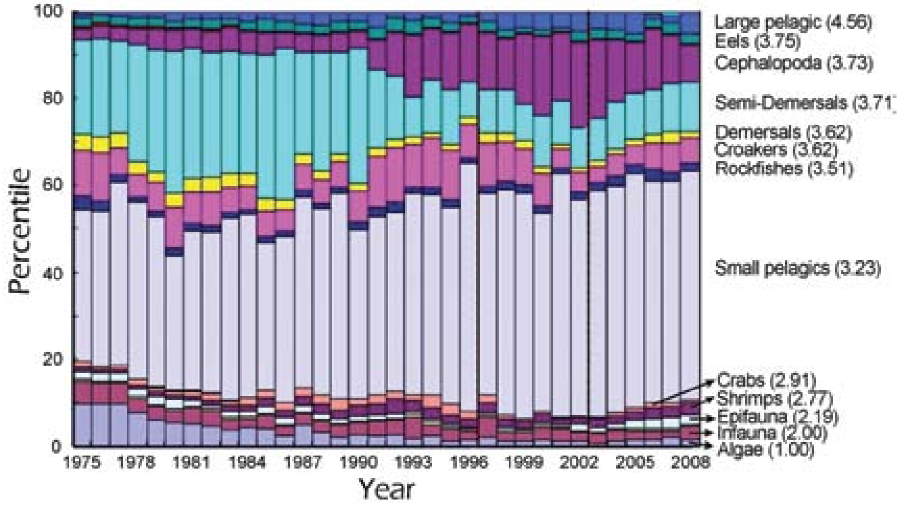
[Figure YS-28] Long-term trend of effort by Korean fisheries in the Yellow Sea (YS) and the East China Sea (ECS).

The catch composition in major fisheries changed during the focus period. In the Yellow Sea, the proportion of anchovy increased from 15.5% to 21.6% while that of common squid increased from 2.8% to 8.3% between 1997-2002 and 2003-2008 (Fig. YS-33). The proportion of flatfishes also increased from 0.8% to 3.2% during the same periods, while the catches of blue crab and shrimps declined. As a result, the mean trophic level in the catch increased from 3.24 to 3.34. In the East China Sea, the proportion of anchovy increased from 25.4% to 28.9% and that of Spanish mackerel increased from 2.5% to 4.3% between the two periods (Fig. YS-34). However, unlike the Yellow Sea, the proportion of common squid decreased from 13.2% to 11.1% while the catches of other species remained more or less the same. Therefore, the mean trophic level was similar between the two periods.

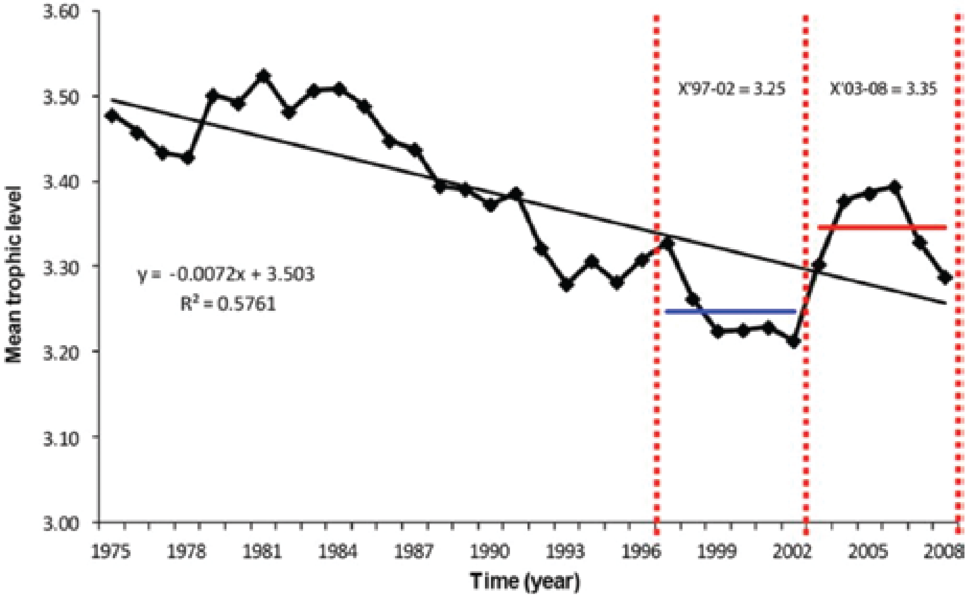
Of the six major species caught in Korean fisheries in the Yellow Sea and the East China Sea, the CPUEs of common mackerel and anchovy were relatively stable during the recent decade, but with some fluctuations (Fig. YS-35). The CPUE of common squid increased until 2003 and then decreased afterward. The CPUE of hairtail has a declining trend while that of small yellow croaker has an increasing trend (Fig. YS-35).



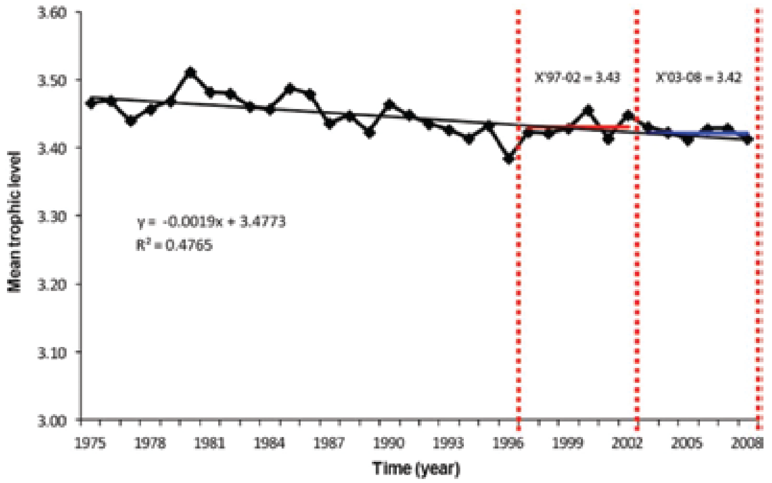
[Figure YS-29] Changes in the major Korean fisheries species in the Yellow Sea. The numbers in the parentheses are estimated trophic level.



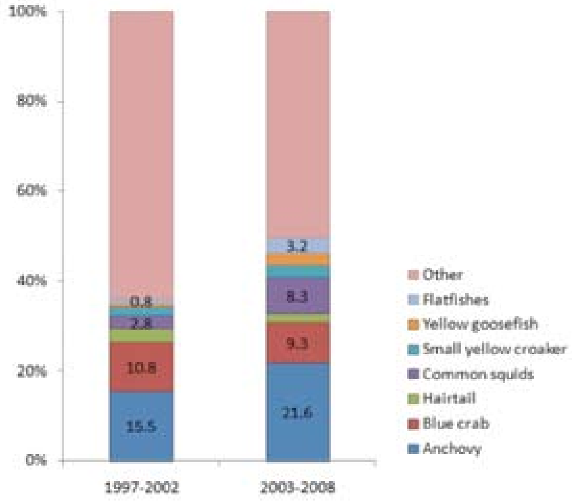
[Figure YS-30] Changes in the major fisheries species in the East China Sea. The numbers in the parentheses are estimated trophic level.



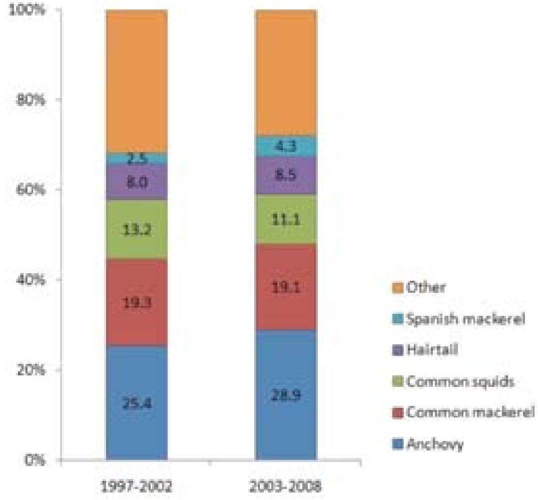
[Figure YS-31] Mean trophic level of the fisheries catch in the Yellow Sea. It increased in 2003-2008 period due to increased catch of demersals and cephalopods.



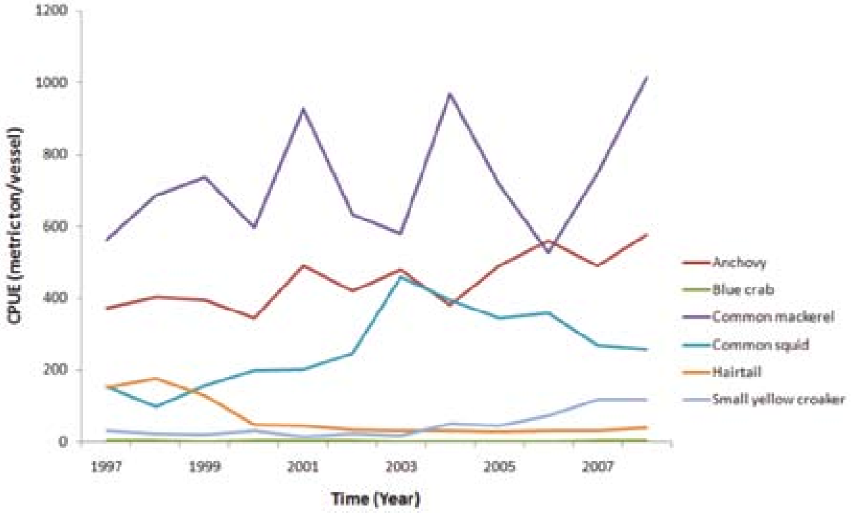
[Figure YS-32] Mean trophic level of the fisheries catch in the East China Sea. Although it has decreased in the long term, it is similar in 1997-2002 and 2003-2008.



[Figure YS-33] Proportion of species in Korean fisheries in the Yellow Sea. Anchovy and common squid increased in large proportions.



[Figure YS-34] Proportion of species in Korean fisheries in the East China Sea. The proportions largely did not change.



[Figure YS-35] CPUE (catch/vessel) of species in Korean fisheries in the Yellow Sea and the East China Sea.

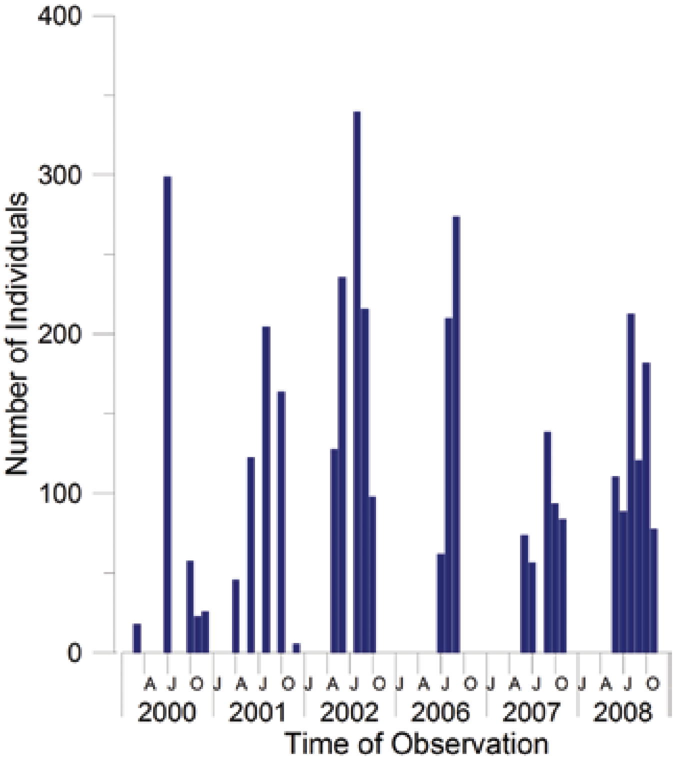
## 7.0 Marine Birds and Mammals

### 7.1 Pinnipeds

Larga seals, *Phoca larga*, inhabit many coastal areas of the Yellow Sea. Since the 1960s, populations have been decreasing due to heavy catch and habitat destruction and only small groups can now be found. Larga seals are designated as protected animals in both Korea and China. For the past nine years, surveys of larga seals have occurred on Bakryoung-Do, an island in the northern Yellow Sea that is a major habitat for the larga seals. A maximum of 343 individuals was observed in 2002 (Fig. YS-36). The number of individuals was 139 in 2007 and 210 in 2008. Whether this indicates a reduction in the population size is not clear and further monitoring is necessary.

### 7.2 Cetaceans

A total of 16 cetacean species have been recorded. Amongst them, fin whale (*Balaenoptera physalus*), Minke whale (*B. acutrostrata*), killer whale (*Orcinus orca*), Blainville's beaked whale (*Mesoplodon densirostris*), and finless porpoise (*Neophocaena phocaenoides*) have commonly been observed. Catching whales was banned in Korea in 1986 and some of the whale populations have increased. In the Changjiang River estuary, two endangered migratory freshwater cetaceans can be found, baiji (*Lipotes vexillifer*) and finless porpoise. The former, listed as a critically endangered species in IUCN Red Book, lives only in China (The Yellow Sea Ecoregion Initiative 2001). In Korean waters, finless porpoises are typically observed in nearshore areas while Minke whales are observed in offshore areas. Surveys in Korean coastal waters of the Yellow Sea show that the number of Minke whales was reduced from 1,685 in 2001 to 733 in 2008, although this may not be statistically significant (Table YS-2).



[Figure YS-36] Census of spotted seal (*Phoca larga*) around Bak-ryoung island in 2000 to 2002 and 2006 to 2008.

[Table YS-2] Abundance of Minke whale in Yellow Sea in 2001-2008.

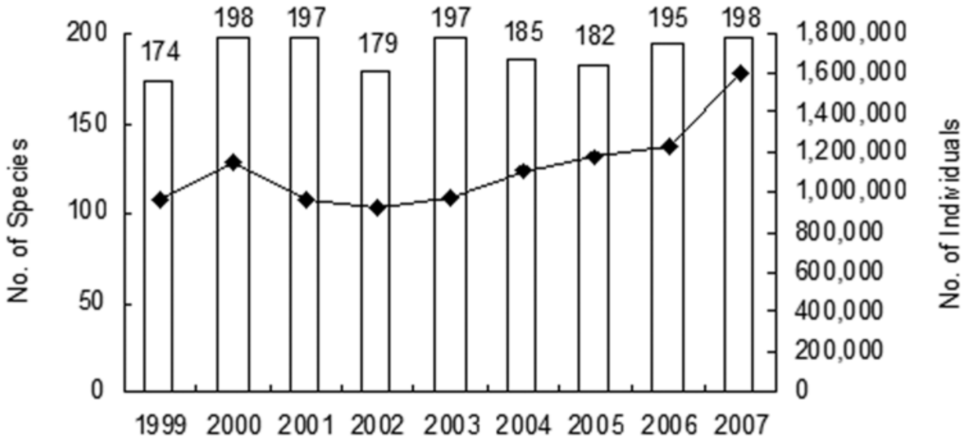
| Year | Survey effort (n. mile) | Number of Observation (No.) | Abundance (No.) | 95% CI | |
|---|---|---|---|---|---|
| | | | | Lower | Upper |
| 2001 | 811 | 28 | 1,685 | 1,042 | 2,726 |
| 2004 | 1,787 | 18 | 1,287 | 385 | 4,303 |
| 2008 | 1,407 | 18 | 733 | 327 | 1,646 |

## 7.3 Seabirds

The intertidal areas and coastal wetlands of the Yellow Sea support >2 million shorebirds during their northward migration; about 40% of the all migratory shorebirds in the East Asian-Australasian Flyway (Barter 2002). A total of 36 shorebird species have been found to occur in internationally important numbers at one or more sites in the Yellow Sea, representing 60% of the migratory shorebird species occurring in the flyway. Two of the species are classified as globally threatened, the spotted greenshank, *Tringa guttifer*, and the spoon-billed sandpiper, *Eurynorhynchus pygmeus*, whilst two are near-threatened, the eastern curlew *Numenius madagascariensis* and Asian dowitcher *Limnodromus semipalmatus*. While the South Korean coastline has been well surveyed, only about one-third of the Chinese coasts have been surveyed and little is known from North Korea.

In Korea, water birds of islands/islets, coastal wetlands/tidal flats, and the seas include 167 species in 16 families: the Anatidae, Gruida, Rallida, Scolopacida, Rostratulidae, Jacanidae, Charadriidae, Glareolidae, Laridae, Podicipedidae, Phalacrocoracidae, Ardeidae, Threskiornithidae, Pelecanidae, Ciconiidae, and Gaviidae. In addition, some of the marine birds that inhabit the shorelines include the Procellaridae, Diomedeidae, Hydrobatidae, Fregatidae and Laridae (Stercorariini and Alcinae). The number of species of waterbirds for the entire Korean peninsula is approximately 176 (the total number of species counts is 430), including those mentioned above (167 species) and several other observed waterbirds, representing approximately 40.9% of all bird species in Korea. The Korean peninsula is an attractive area for waterbirds, as reflected by the relatively high percentage of waterbirds compared to the global percentage of waterbird species (8.6% of total bird species of the world).

Since 1999, an annual national census of wintering birds has occurred at 128 inland and coastal wetlands/tidal flat sites. These reports include the abundance of wintering birds in river watersheds, artificial lakes formed after reclamation, coastal wetlands/tidal flats (excluding inland wetlands), and freshwater lakes. The number of species from 1999-2007 was rather stable, varying between 174-198 (Fig. YS-37). The number of individuals increased steadily after 2003.



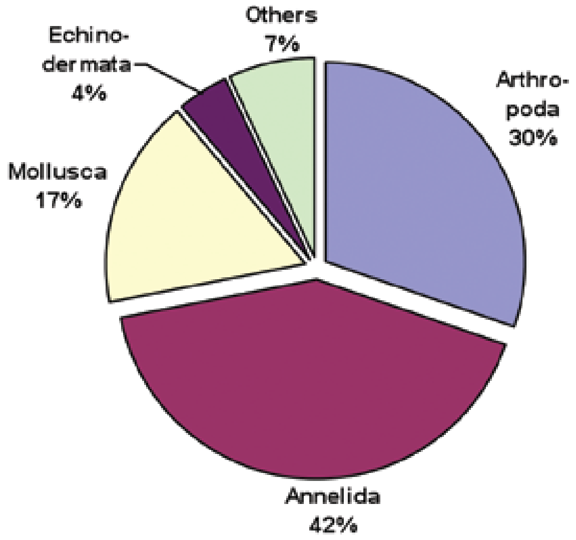
[Figure YS-37] Annual fluctuation in the number of species and individuals of wintering populations of water birds in South Korea.

# 8.0 Benthos

## 8.1 Zoobenthos

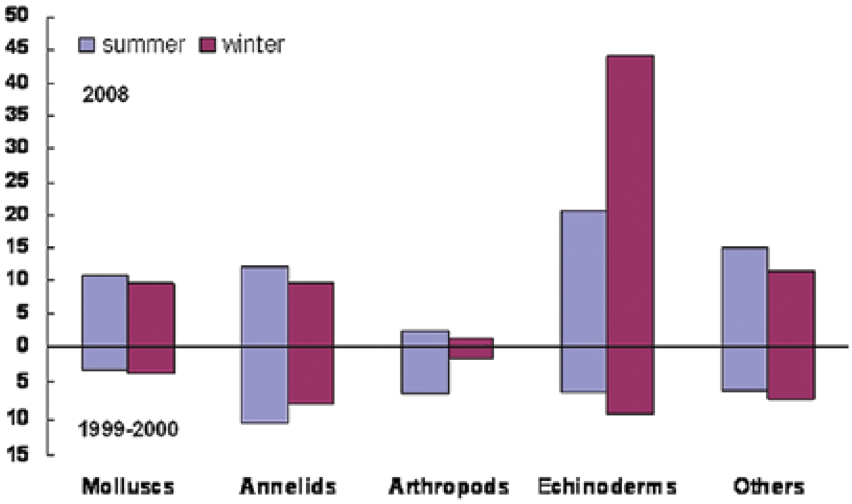
Approximately 50 years ago, the biomass of zoobenthos was higher in the northern Yellow Sea than in the central and southern regions (Liu 1963). The seasonal maximum of 49.68 g·m$^{-2}$ occurred in the spring, and seasonal means were 39.14 g·m$^{-2}$ in winter, 38.05 g·m$^{-2}$ in autumn, and 37.85 g·m$^{-2}$ in summer. In the central and southern Yellow Sea, the mean biomass was 19.71 g·m$^{-2}$ where the maximum value 27.36 g·m$^{-2}$, also occurred in the spring. In other seasons, mean biomass did not vary significantly, ranging from 17.29 g·m$^{-2}$ in summer, 16.39 g·m$^{-2}$ in autumn and 16.38 g·m$^{-2}$ in winter. Mollusks accounted for >55% of the total biomass while the remainder was made up of echinoderms (20%), polychaetes (15%), and crustaceans (10%). The remaining taxa accounted for about 5% of total biomass. Along the Korean coast, benthic biomass was higher, in the range from 79.44 to 171.6 g·m$^{-2}$ (UNDP/GEF 2007). Abundance ranged from 769 - 1,939 ind.·m$^{-2}$. A total of about 500 species has been reported comprising 135 mollusks, 148 arthropods, 87 annelids, 24 echinoderms, 34 cnidarians, and 7 poriferan species (UNDP/GEF 2007). Such differences are at least partly related to different sampling methods and strategies.

Recent surveys of the central Yellow Sea in winter and summer of 2008 (UNDP/GEF 2010) found ~360 species of macrobenthos with the following taxonomic composition: Annelida (42%), Arthropoda (30%), Mollusca (17%), Echinodermata (4%) and 7% distributed among the Coelenterata, Urochordata, Plathyhelminthes, Nemertinea, Nematoda, Echiura, Sipuncula, Ectoprocta (Bryozoa), Branchiopoda and Osteichthyes (Fig. YS-38). The benthic environment in the central region of the Yellow Sea maintains stable low temperature throughout the year due to Yellow Sea Cold Water Mass. This makes the benthic fauna relatively consistent through the seasons: ca. 38% of all identified species occurred both in winter and summer. *Ophiura sarsii* and *Eudorella pacifica* were the most dominant ones throughout the seasons.

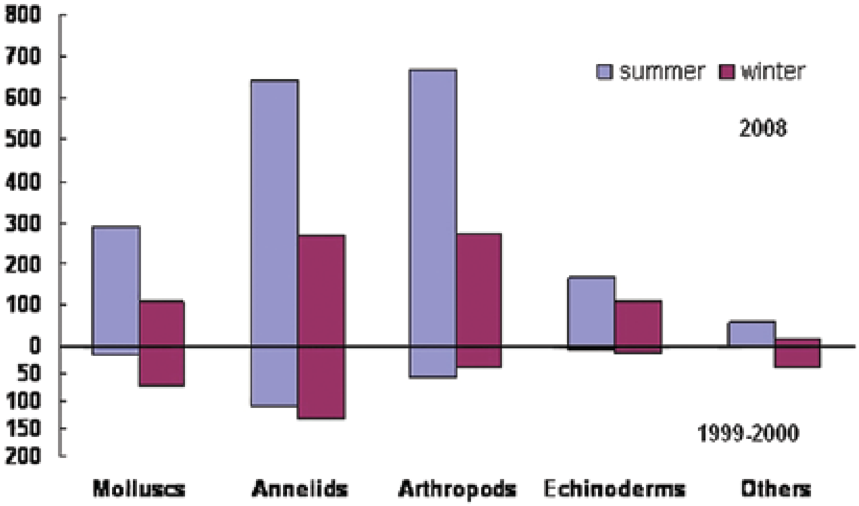


[Figure YS-38] Macrobenthos in the central Yellow Sea: total species composition in winter and summer 2008.

Average seasonal biomass was higher than what was found ten years ago (Li 2003), and this was due mainly to increases of echinoderm and mollusk biomasses (Fig. YS-39). This suggests increased food availability possibly associated with eutrophication (bottom-up effect) and/or a decline in fish abundance (top-down effect). In 2008, the average biomass in summer (60.65 g·m$^{-2}$) was lower than that in winter (76.06 g·m$^{-2}$), although by taxonomic group the averages were generally higher in summer except for the larger sea urchins whose biomass was higher in winter. Echinoderms accounted for the highest proportion (~47%) of the total biomass, followed by annelids (16%), mollusks (15%), arthropods (3%) and the remaining species (19%). Arthropods had higher biomass in the area south of 34°N than in the north, whereas echinoderm biomass is higher north of 34°N. Annelid biomass is more evenly distributed, mollusks present higher biomass between 122.5°E and 124°E, other remaining species occurs with higher biomass along two transects 124°E and 34°N.



[Figure YS-39] Comparison of macrobenthos biomass (g·m$^{-2}$) in the central Yellow Sea in 1999-2000 and 2008.



[Figure YS-40] Comparison of macrobenthos abundance (ind.·m$^{-2}$) in the central Yellow Sea in 1999-2000 and 2008.

Seasonal mean abundance was higher than what was measured 10 years ago (UNDP/GEF 2010), especially for arthropods, annelids, mollusks and echinoderms (Fig. YS-40). In 2008, abundance in summer (1824 ind.·m$^{-2}$) was higher than what was found in winter (774 ind.·m$^{-2}$). Arthropods accounted for the highest proportion of the total abundance (~36%), followed by annelids (35%), mollusks (15%), echinoderms (11%) and the remaining species (3%). Total abundance generally increases from lower levels in the northwest to higher levels in the southeast parts of the Yellow Sea. Both annelids and mollusks were more abundant in the area south of 34°N, whereas echinoderms are more abundant north of 34°N. Arthropods had the highest abundance south of 33.5°N, lower between 36°N and 36.5°N and lowest 33.5-36°N. Other remaining species are abundant in the south, southwest and northwest margins.

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