Marine Ecosystems of the North Pacific Ocean 2003-2008

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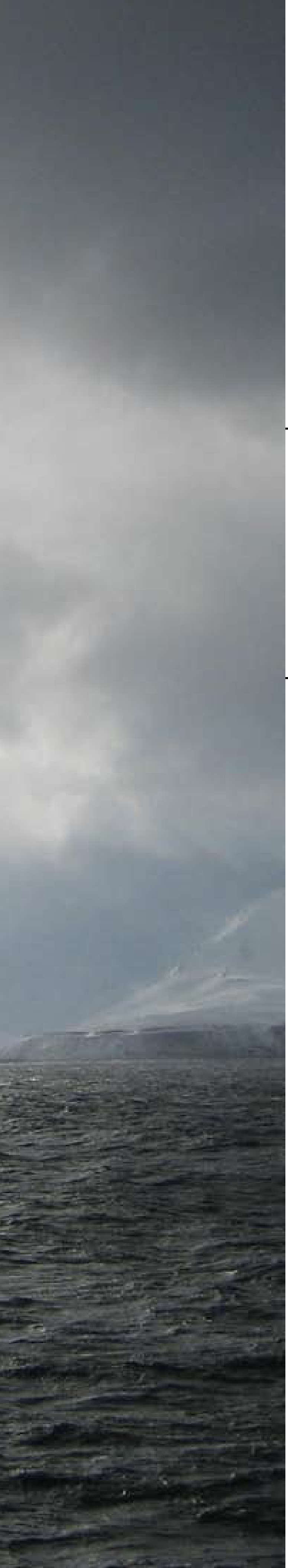

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North Pacific Synthesis

Citation:

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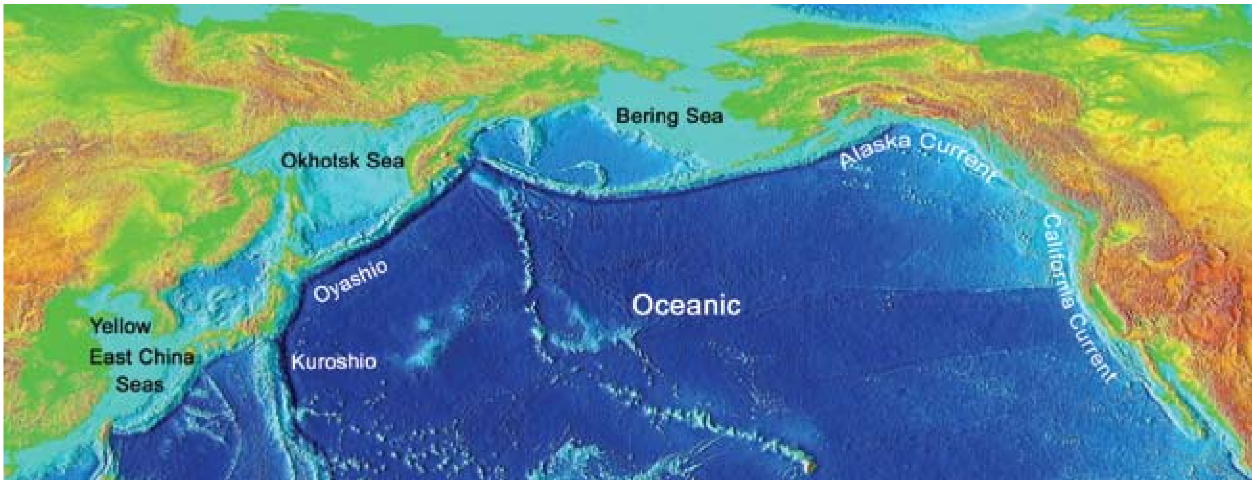
highlights

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.

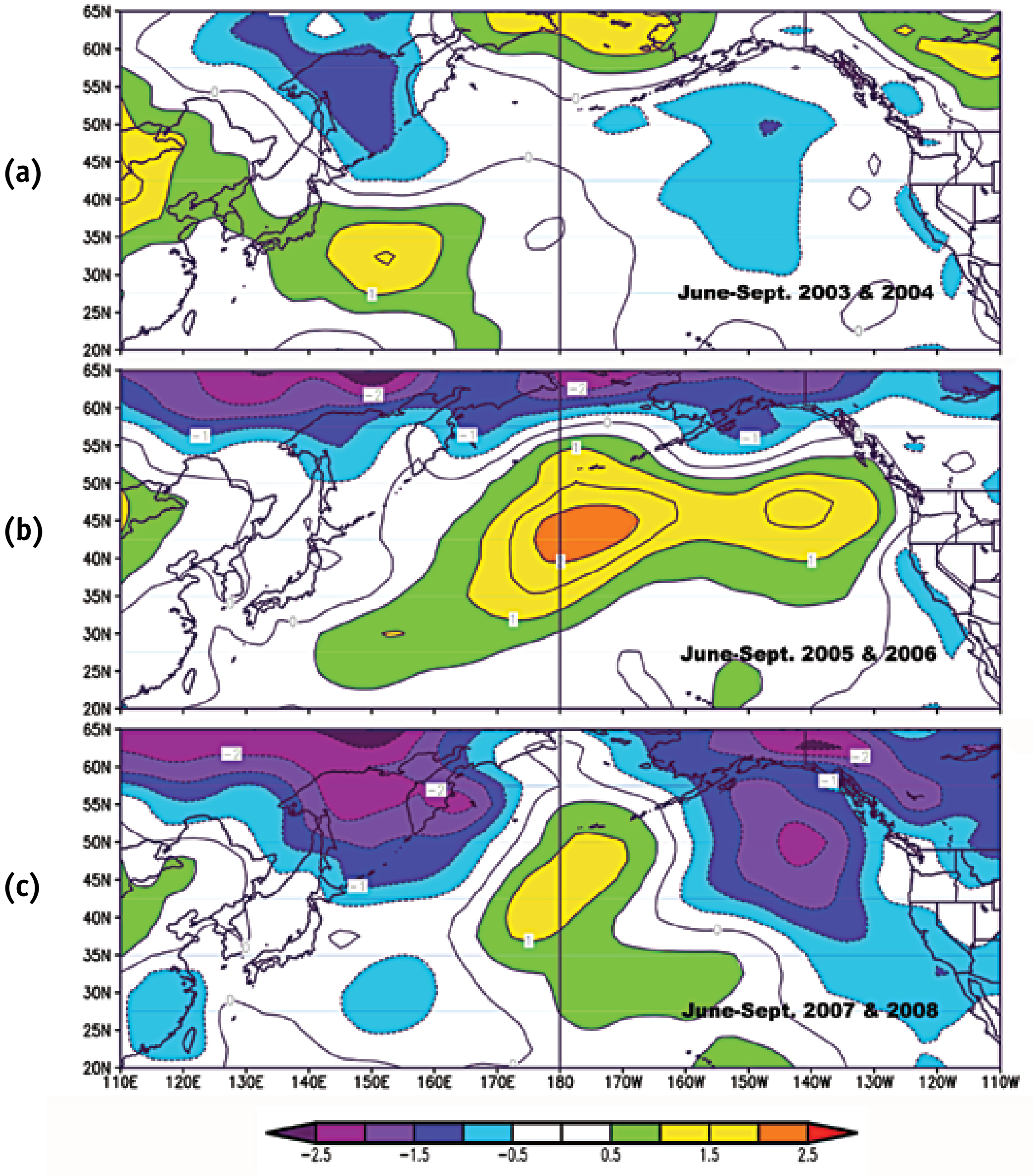
2.0 Climate *(Bond)*

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

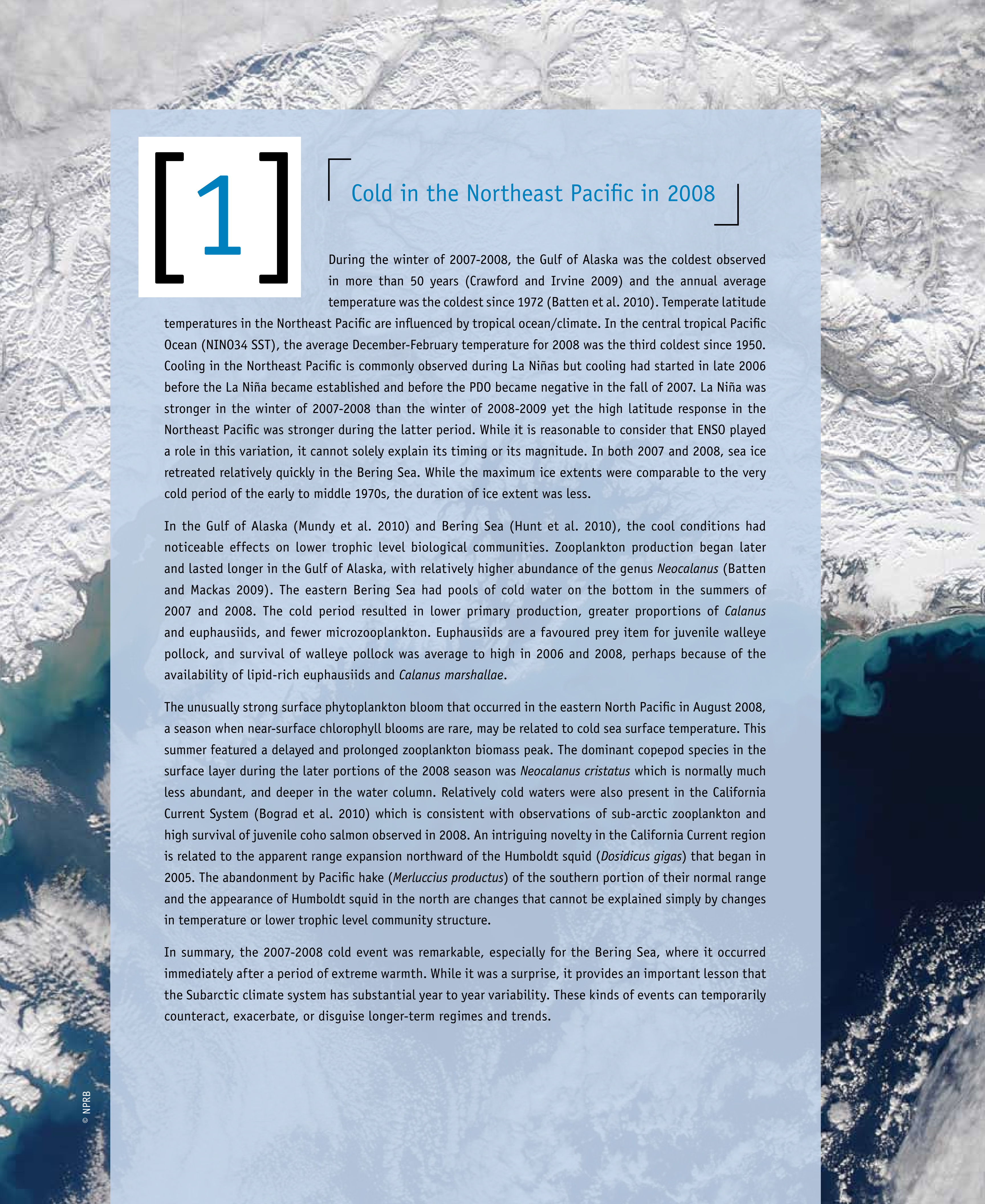


[Figure S-2] Average summer SLP anomalies (hPa) from June to September in (a, upper) 2003-2004, (b, middle) 2005-2006, and (c, lower) 2007-2008. Figures are courtesy of NOAA/ESRL Physical Sciences Division from NCEP/NCAR re-analysis data. The climatology used to compute the anomalies is 1968-1996.

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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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).

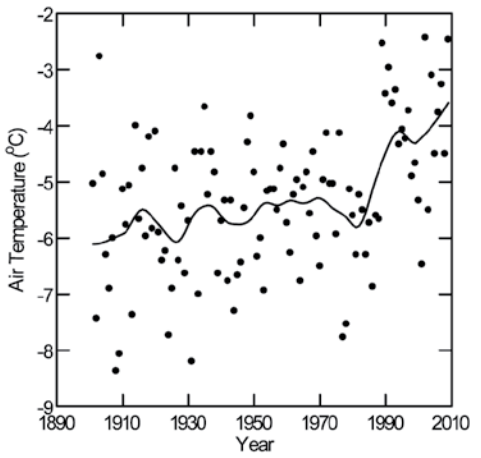
2.4 Disentangling climate variability

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.

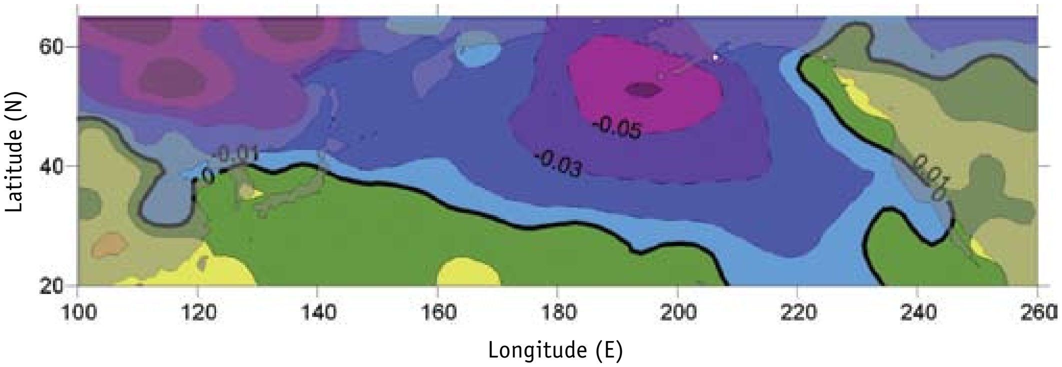
[2]

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).

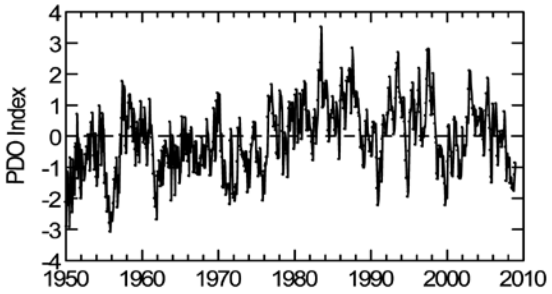
3.0 Physical Ocean *(Foreman)*

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.

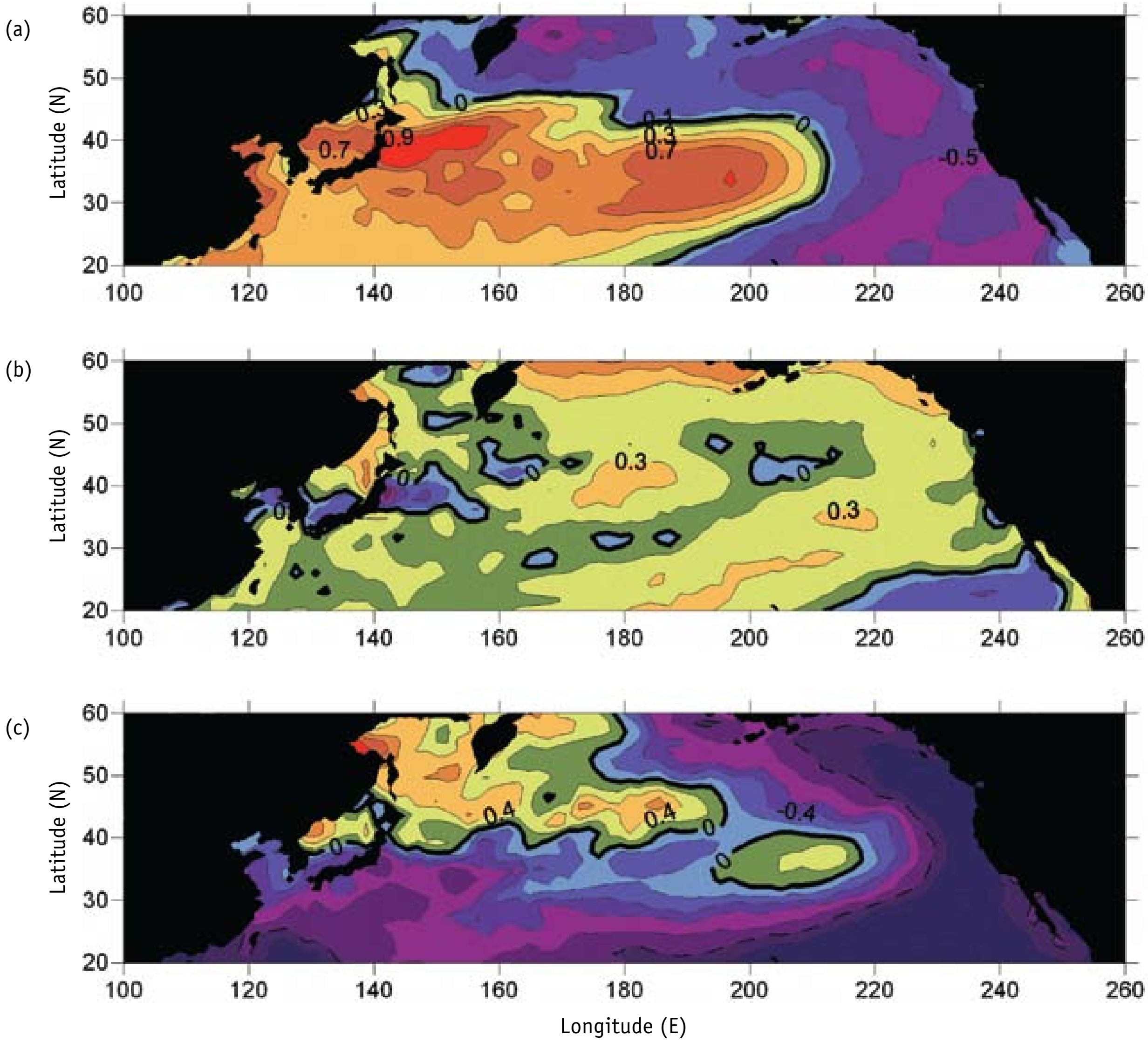
Temperature is a key water property that affects ecosystem productivity throughout the North Pacific and with the exception of the Kuroshio whose temperatures remained relatively constant over the focus period, there were significant temperature variations in all other regions. In the Oceanic region, 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

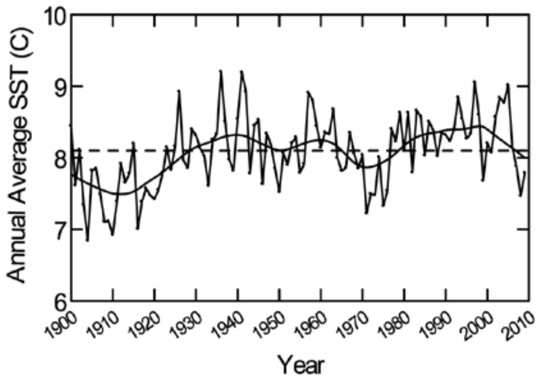


[Figure S-5] Monthly values of the Pacific Decadal Oscillation Index, 1950-2009.



[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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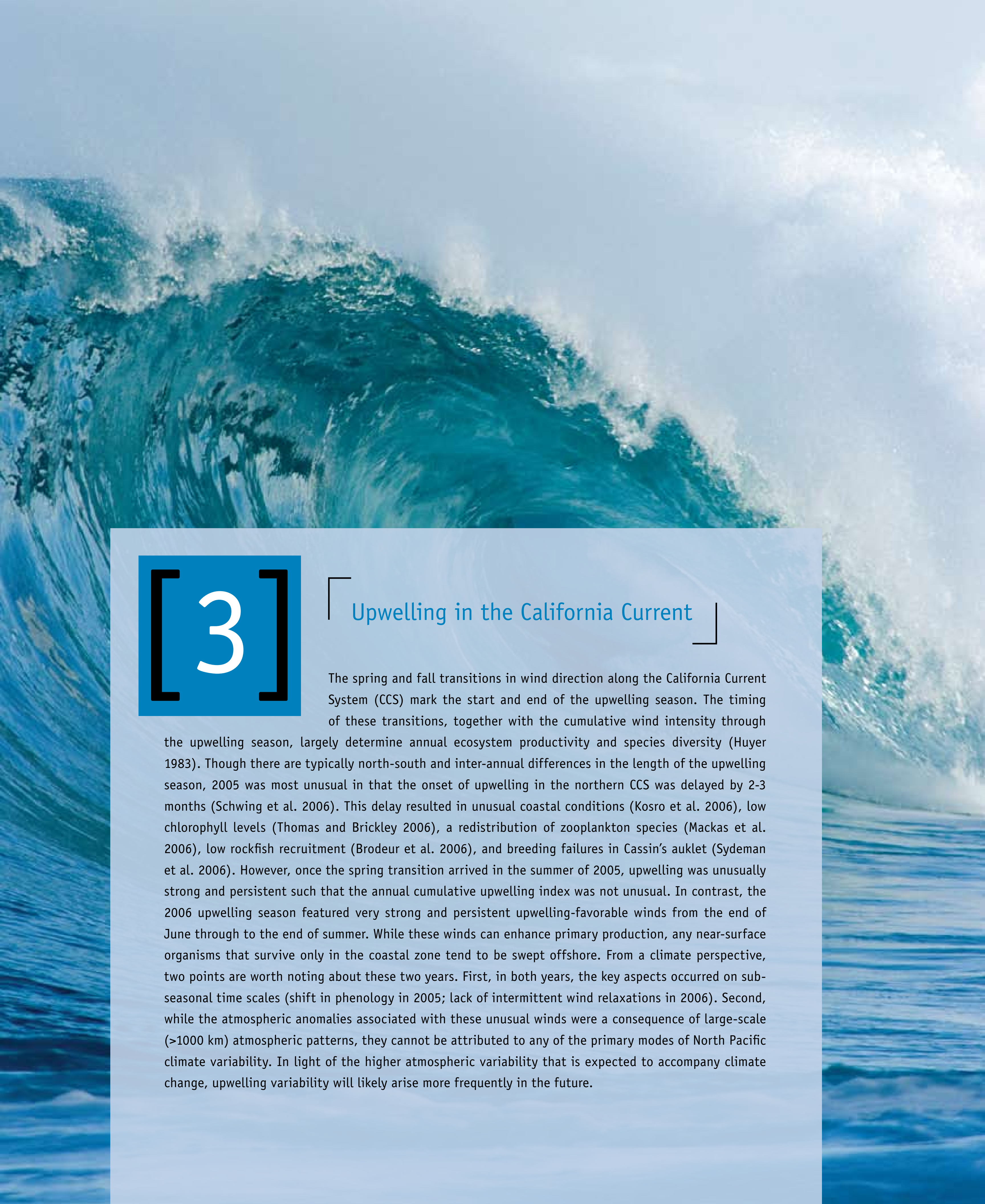
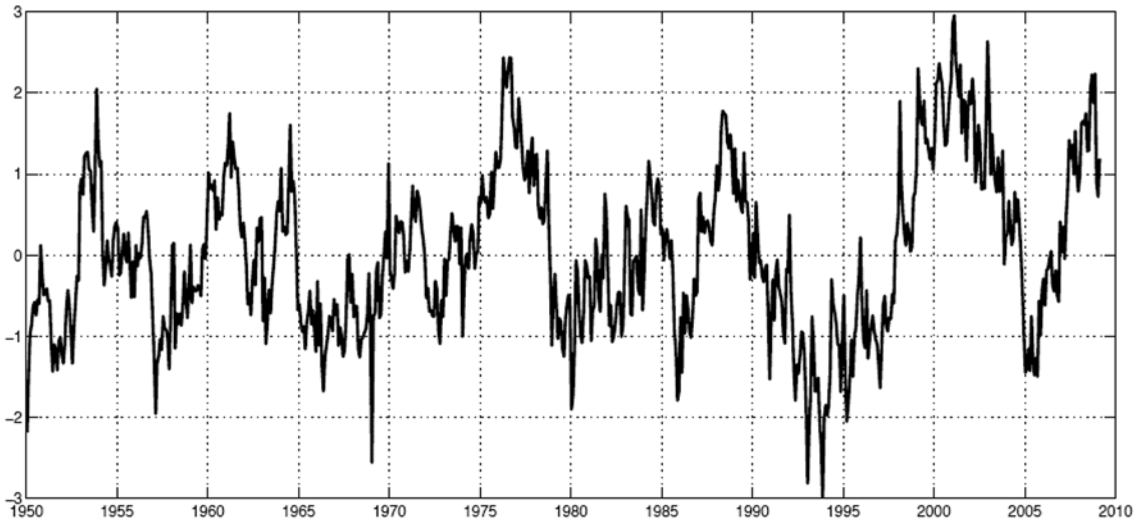


[3]

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.

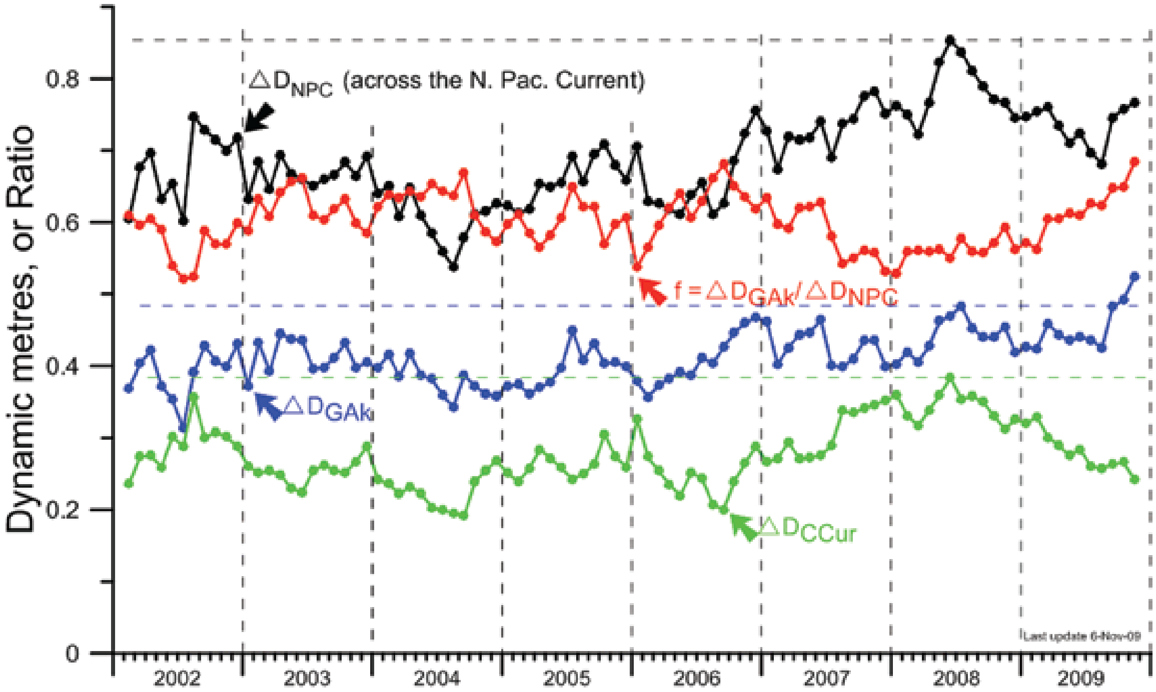


[Figure S-8] North Pacific Gyre Oscillation index (updated from Di Lorenzo et al. 2008).

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.

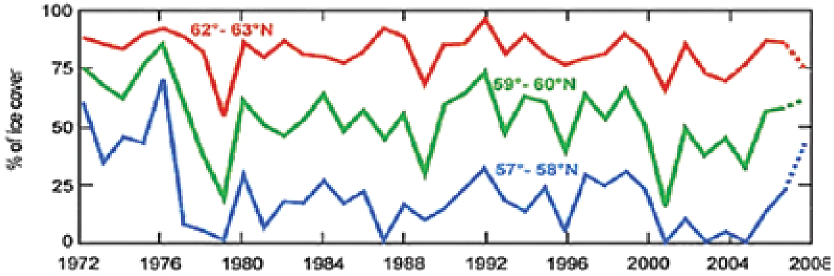
The establishment of the international Argo profiling float program in 2002 initiated an era of ocean sampling at finer spatial and temporal resolutions than was previously possible and permitted more complete time series of ocean temperatures, salinities and their derived quantities. Using Argo-based 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.



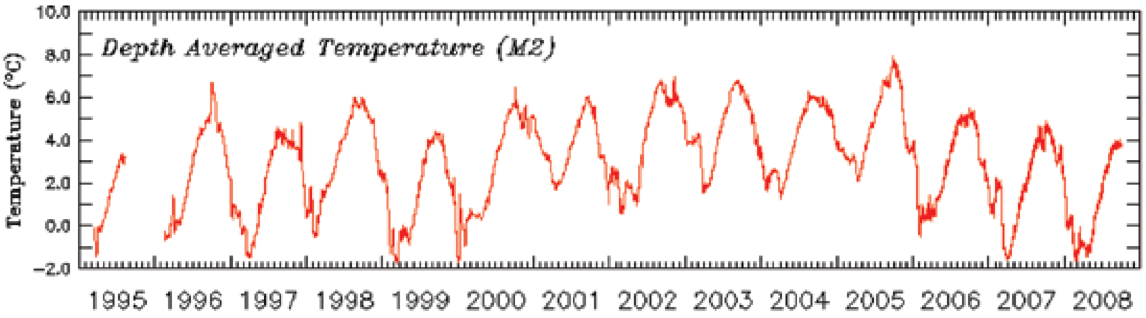
[Figure S-9] Indices of the relative strengths of the North Pacific Current (NPC), Alaska Current (GAk) and California Current (CCur) (updated from Freeland et al. 2006). ΔD= difference in dynamic heights across each current. f=ratio of dynamic height differences in the two boundary currents.

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.

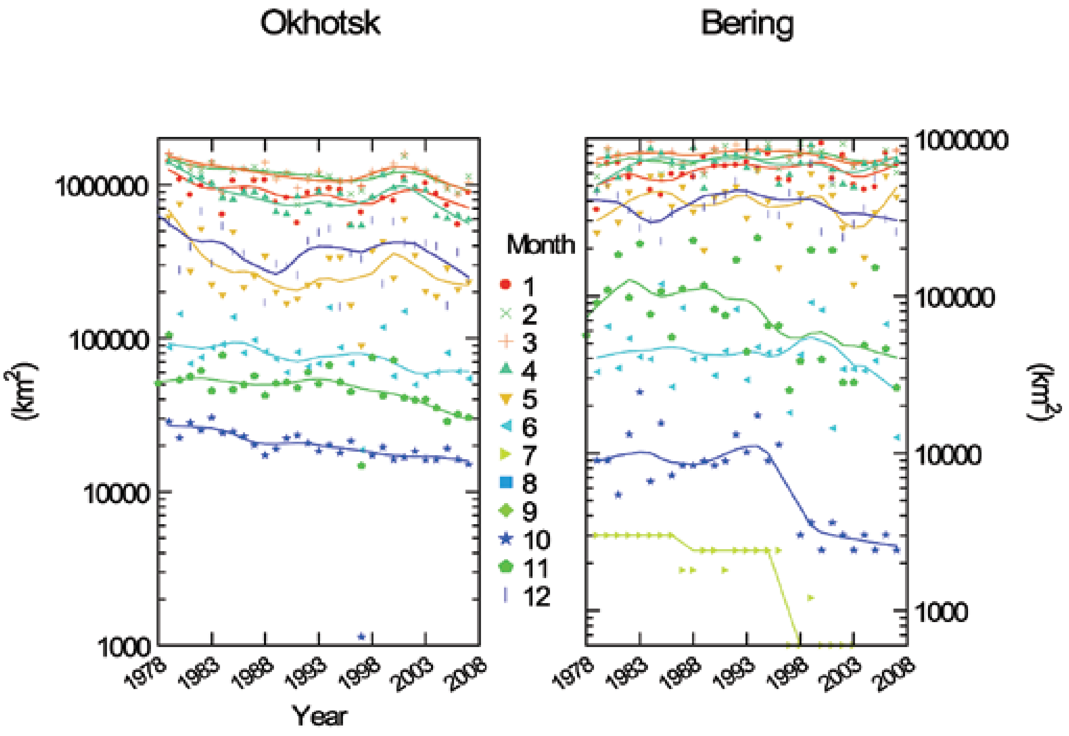
3.4 Sea ice

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.

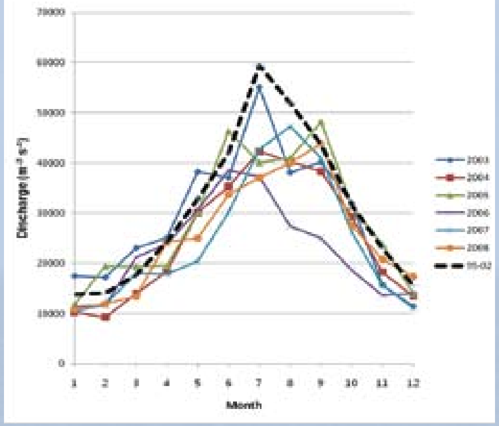
[4]

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.

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.



[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.

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.

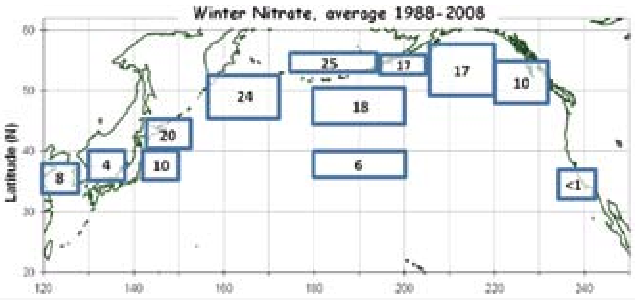
An emerging concern for the surface ocean is its exposure to increasing atmospheric carbon dioxide levels. Oceans are a major sink for CO_2 so, as more fossil fuels are combusted, more of this acid-producing gas dissolves into the upper ocean. Also, the interior ocean can become more acidic as oxygen 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.

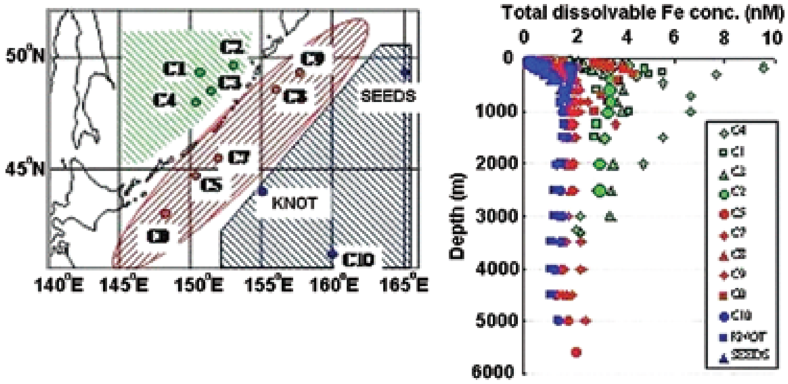
4.1 Nutrients

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.



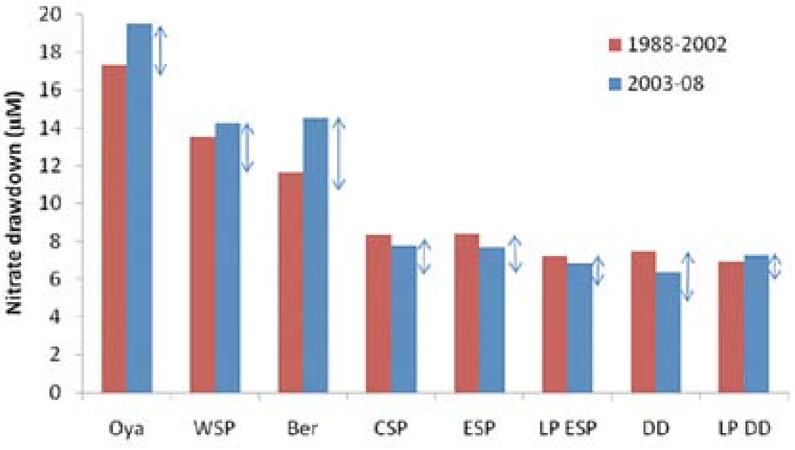
[Figure S-15] Vertical profiles of total dissolvable iron around the Kuril Island. Green symbols indicate the data from the Sea of Okhotsk, red symbols indicate the data from the Oyashio region and blue symbols indicate the data from oceanic regions of the western Subarctic Pacific (SEEDS Project Stations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

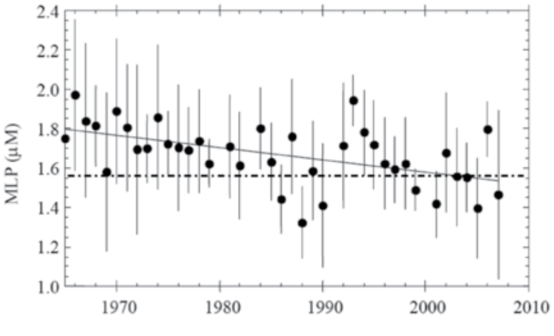
increased mixing towards the 2006 peak of the lunar nodal cycle has increased winter nutrient supply to waters along the Aleutian and Kuril Islands, as was proposed by Yasuda et al. (2006). Overall, diminished nutrients in the surface ocean might be expected since stratification is generally strengthening 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 σ_θ 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 σ_θ 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 σ_θ 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

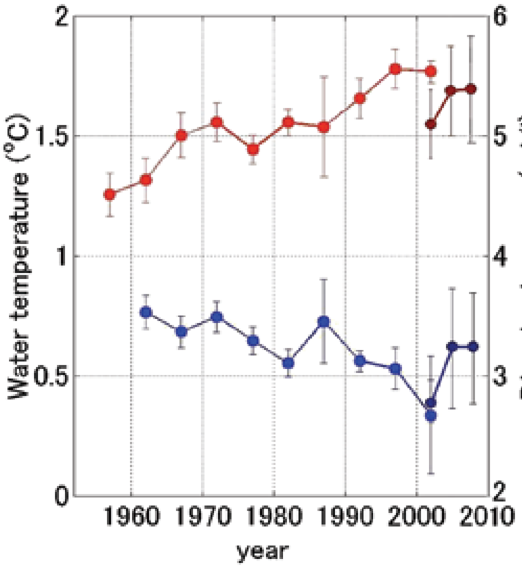


[Figure S-17] Mixed layer phosphate (MLP) in the Oyashio region off northern Japan; vertical bars indicate ±1 standard deviation.

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 σ_θ 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 $3\ \mathrm{m \cdot y^{-1}}$ 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.

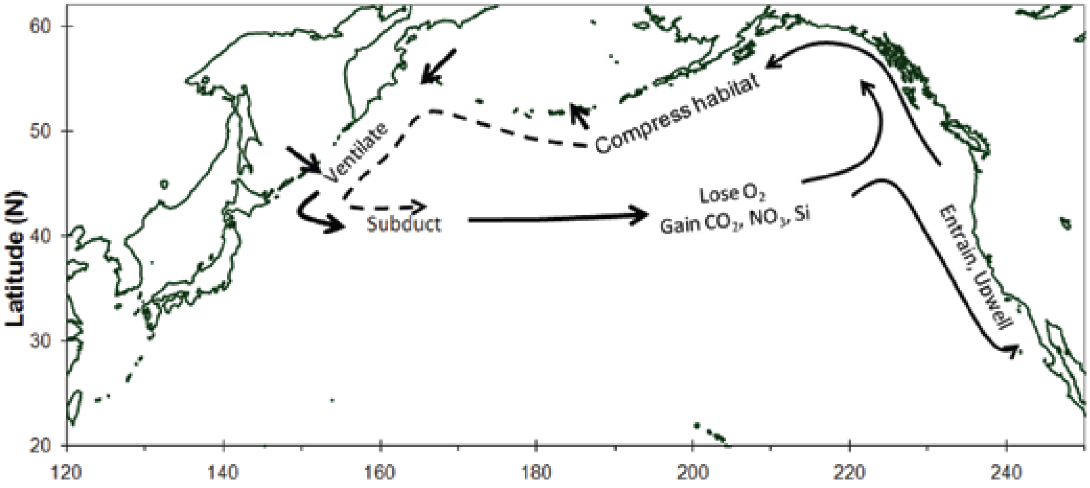


[Figure S-18] Time series of temperature (red line) and dissolved oxygen (blue line) of the intermediate water in the Sea of Okhotsk at 27.0 σ_θ, corresponding to approximately 250-550 m depth, during the past 50 years. Additions for 2002, 2005, and 2008 indicate mean and 95% confidence interval calculated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



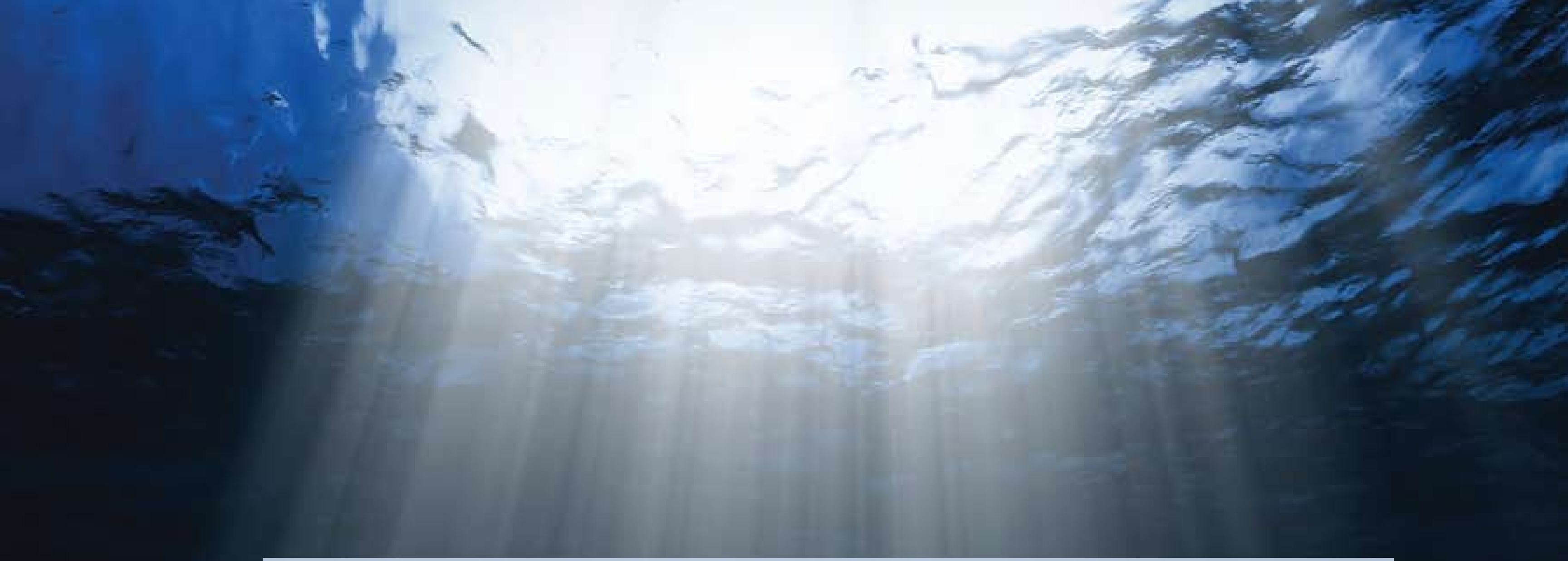
[Figure S-19] The formation and transport of ventilated waters from the Asian coast, across the Pacific towards the coast of North America. En route, waters lose oxygen and gain carbon dioxide plus nutrients as organic detritus is consumed. These waters can then be transported onto the continental shelf 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 $m \cdot y^{-1}$ 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)*

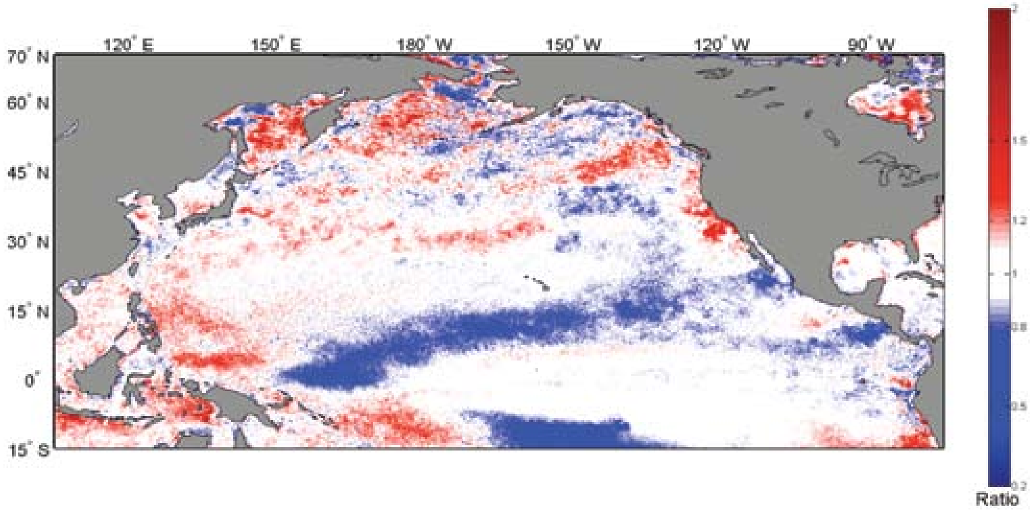
5.1.1 Basin-wide changes in satellite chlorophyll

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.

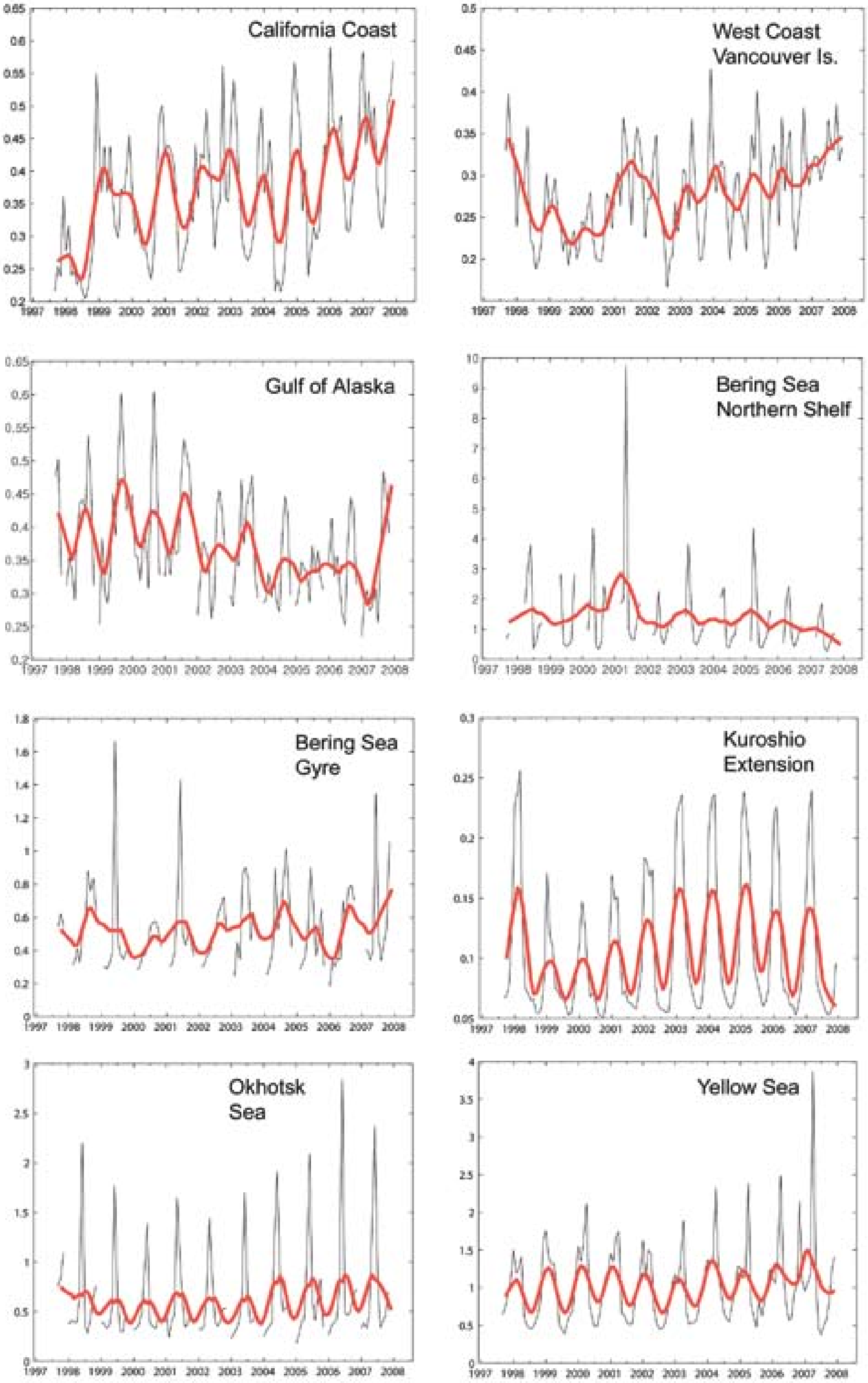
Time series of mean monthly chlorophyll$_a$ concentrations were extracted from the regions where chlorophyll$_a$ increased or decreased by more than 20% (Fig. S-20). In the California Current region, chlorophyll$_a$ increased after 2004 (Fig. S-21). On the west coast of Vancouver Island, chlorophyll$_a$ 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$_a$ (≤ 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).

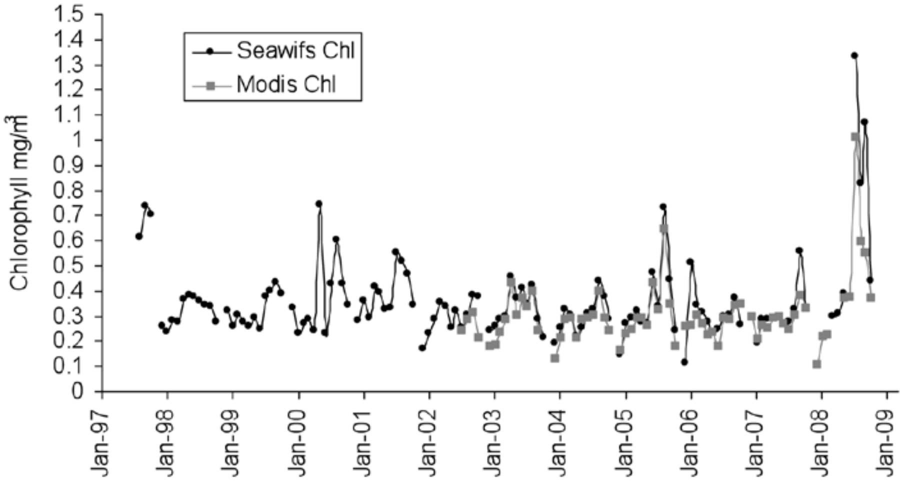
In the Sea of Okhotsk, Amur River discharge and ice dynamics tend to control phytoplankton dynamics. The discharge of large amounts of silicate and iron enhances biological production, especially by diatoms, in the East Sakhalin Current (Andreev and Pavlova 2010). In 2003 and 2008, chlorophyll$_a$ concentrations 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.

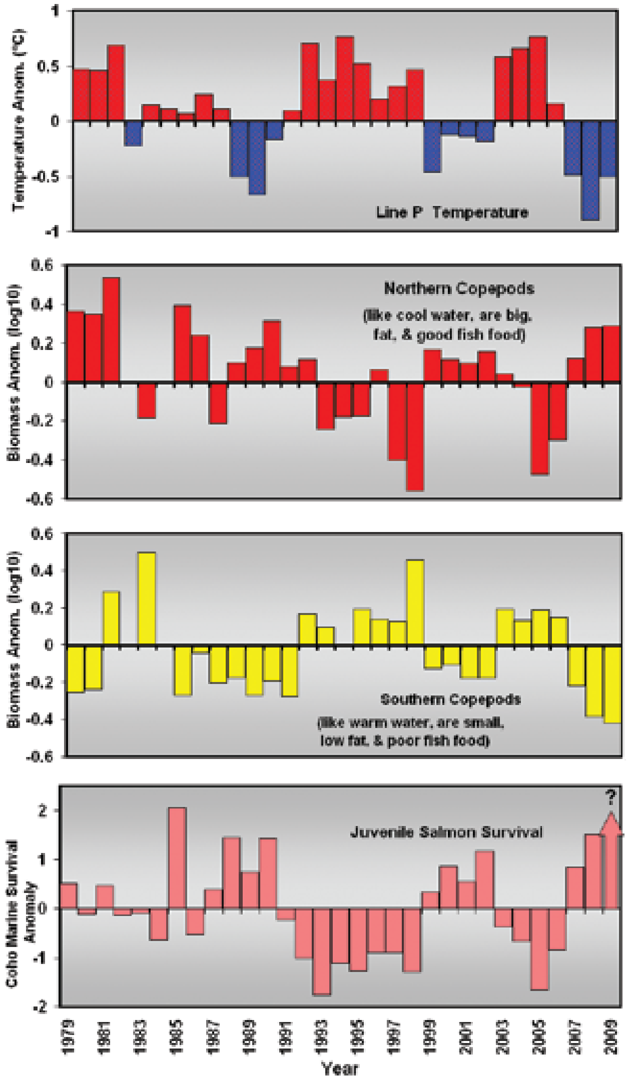
5.2.2 Oceanic North Pacific

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).

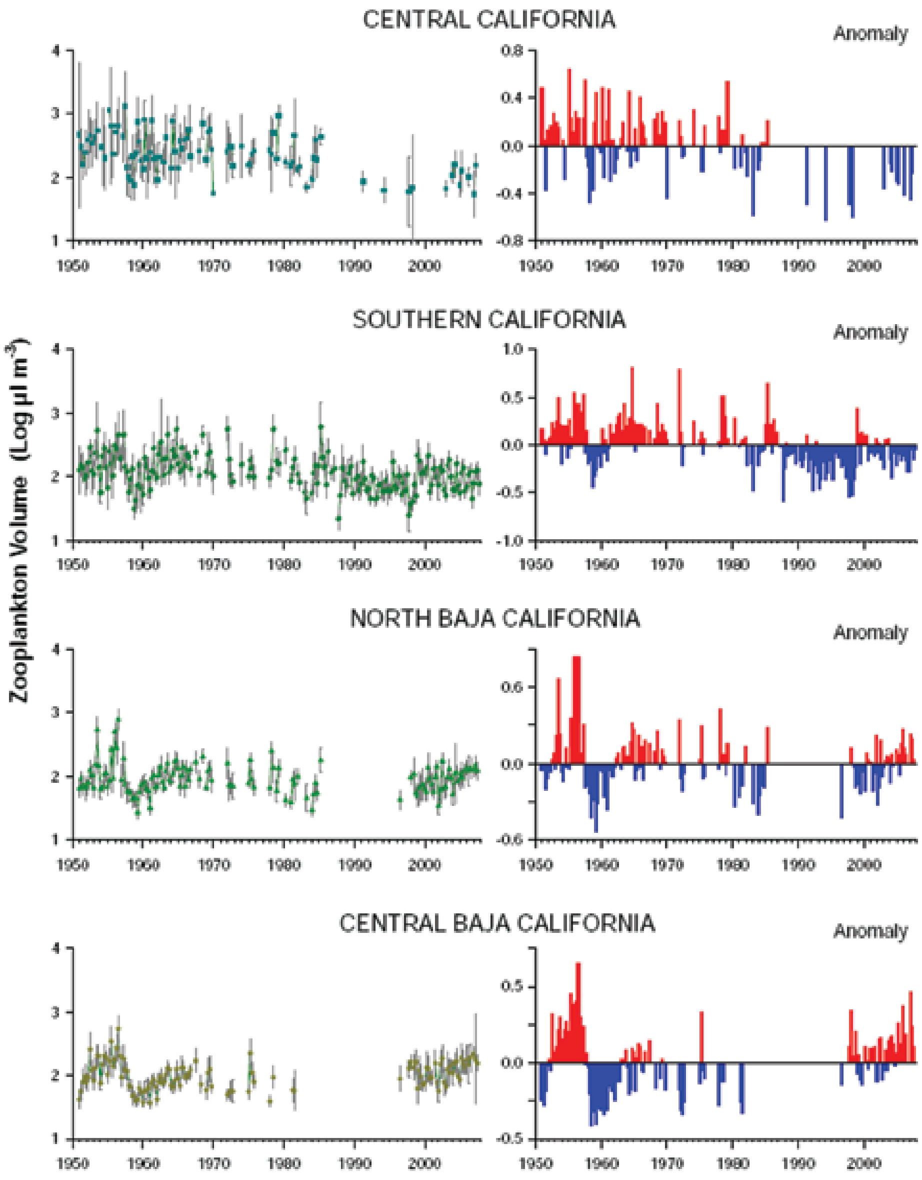
5.2.4 Northwest Pacific

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).

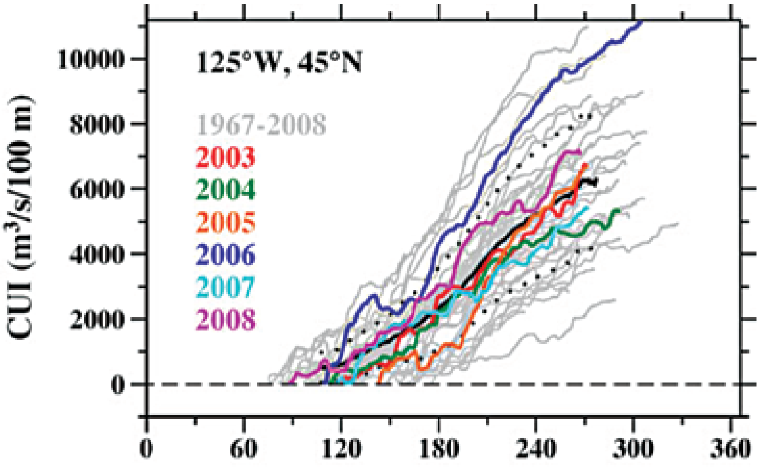
5.2.5 Ice cover and large zooplankton

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).

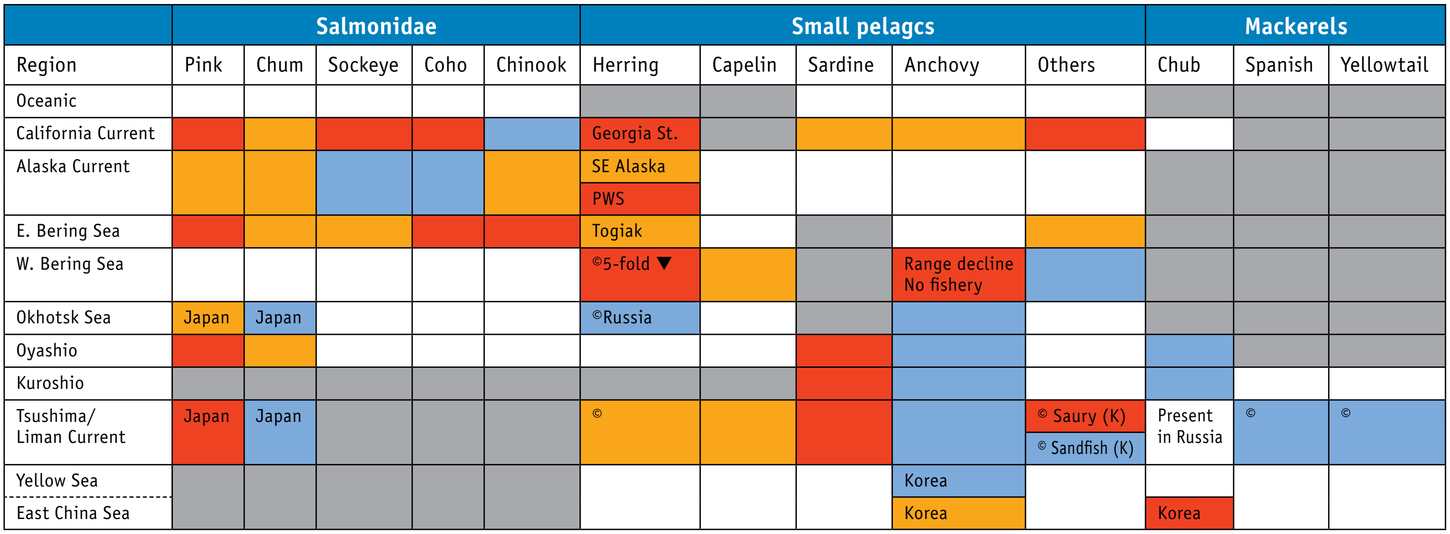
Along the west coast of Japan, increased catches and an expansion of the northern range of yellowtail (*Seriola quinqueradiata*) and Spanish mackerel (*Scomberomorus niphonius*) were apparent. In addition to increasing water temperatures in the Yellow Sea and East China Sea, eutrophication, blooms of 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

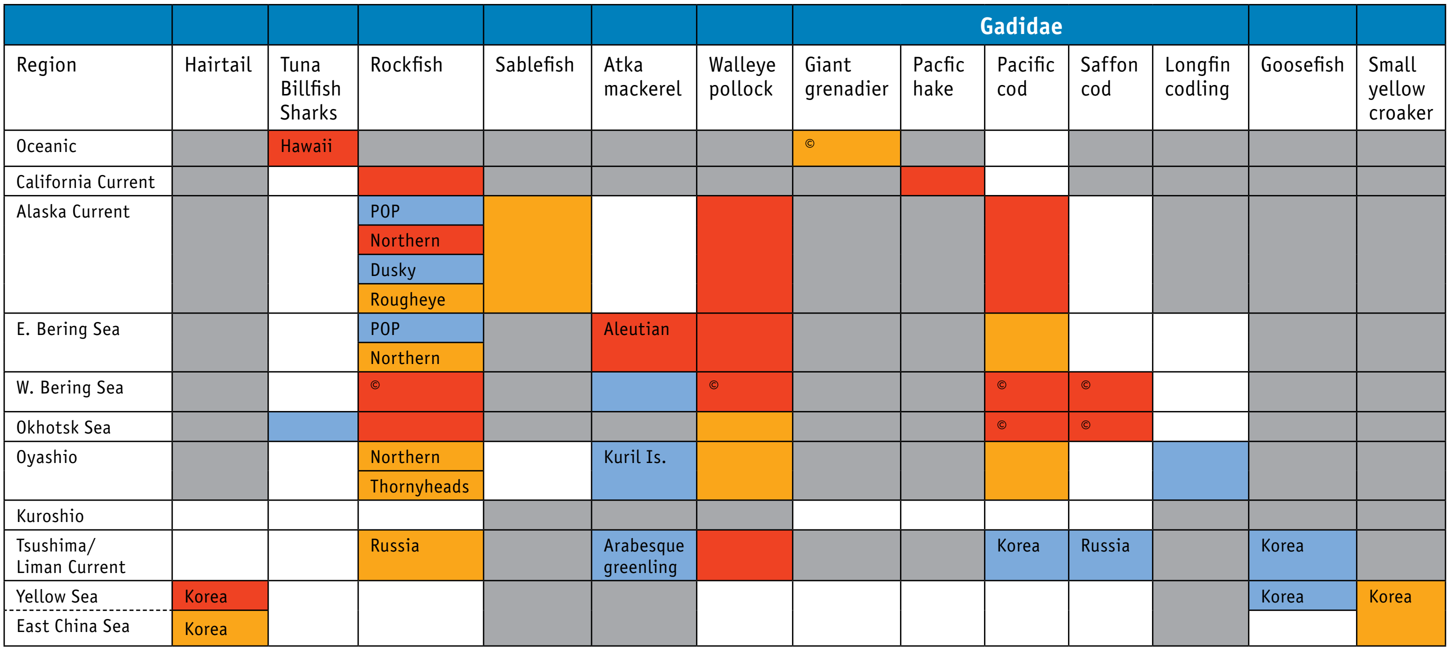
To examine these phenomenon across the entire North Pacific, long time series of abundance (or commercial catch) were examined using species that are commonly found in most regions of the North Pacific.

6.2.1 Pacific salmon

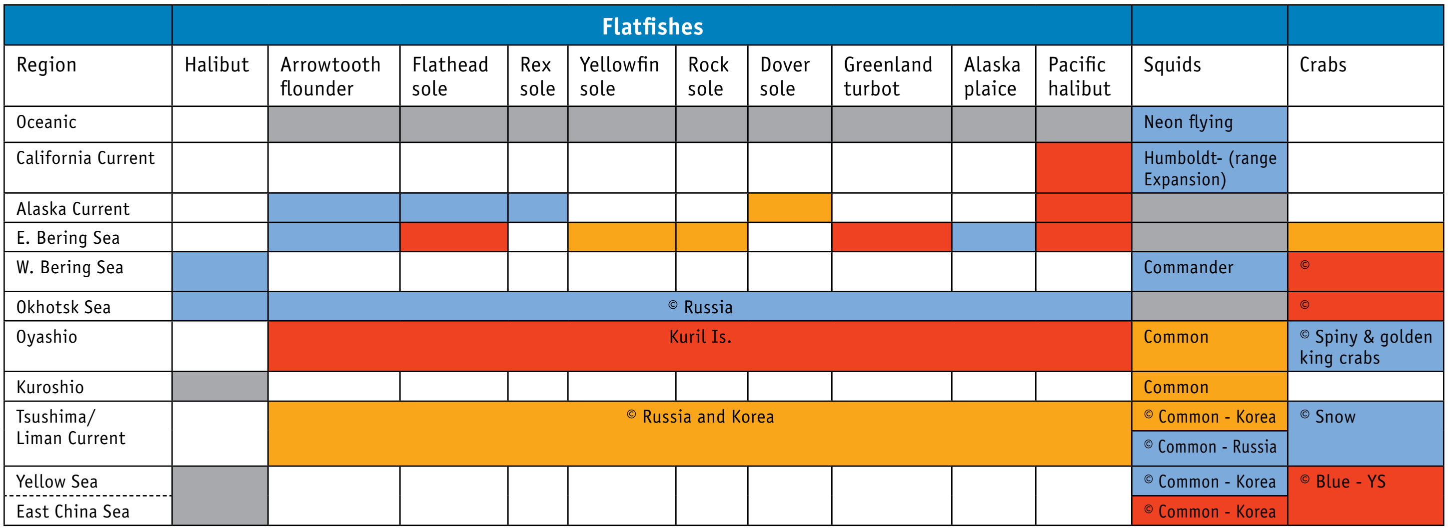
Aggregate commercial catches of Pacific salmon in the North Pacific during the focus period were the highest ever recorded (Fig. S-26, Irvine et al. 2009). Exceptional total catch during the focus period was a result of fisheries for pink salmon (*O. gorbuscha*) and chum salmon (*O. keta*) in Asia. There, 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.



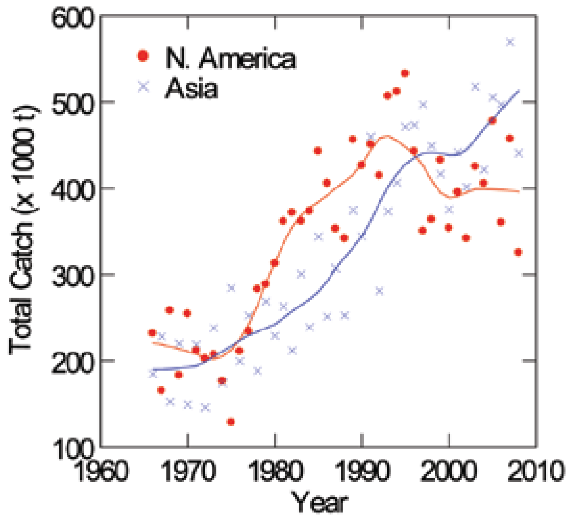
	Salmonidae					Small pelagcs					Mackerels		
Region	Pink	Chum	Sockeye	Coho	Chinook	Herring	Capelin	Sardine	Anchovy	Others	Chub	Spanish	Yellowtail
Oceanic						▨	▨				▨	▨	▨
California Current	🟥	🟧	🟥	🟥	🟦	🟥 Georgia St.	▨	🟧	🟧	🟥		▨	▨
Alaska Current	🟧	🟧	🟦	🟦	🟧	🟧 SE Alaska 🟥 PWS					▨	▨	▨
E. Bering Sea	🟥	🟧	🟧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



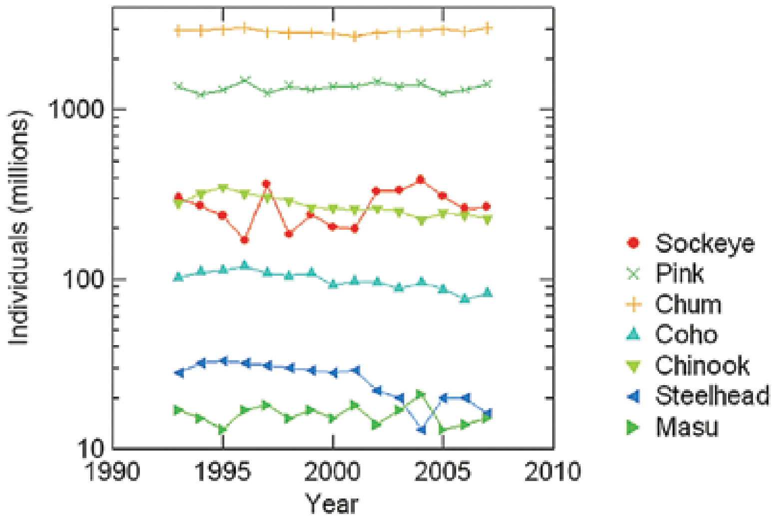
							Gadidae						
Region	Hairtail	Tuna Billfish Sharks	Rockfish	Sablefish	Atka mackerel	Walleye pollock	Giant grenadier	Pacfic hake	Pacific cod	Saffon cod	Longfin codling	Goosefish	Small yellow croaker
Oceanic	▨	🟥 Hawaii	▨	▨	▨	▨	🟧 ©	▨		▨	▨	▨	▨
California Current	▨		🟥	▨	▨	▨	▨	🟥		▨	▨	▨	▨
Alaska Current	▨		🟦 POP 🟥 Northern 🟦 Dusky 🟧 Rougheye	🟧		🟥	▨	▨	🟥		▨	▨	▨
E. Bering Sea	▨		🟦 POP 🟧 Northern	▨	🟥 Aleutian	🟥	▨	▨	🟧			▨	▨
W. Bering Sea	▨		🟥 ©	▨	🟦	🟥 ©	▨	▨	🟥 ©	🟥 ©		▨	▨
Okhotsk Sea	▨	🟦	🟥	▨	▨	🟧	▨	▨	🟥 ©	🟥 ©		▨	▨
Oyashio	▨		🟧 Northern 🟧 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 🟦 © 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).

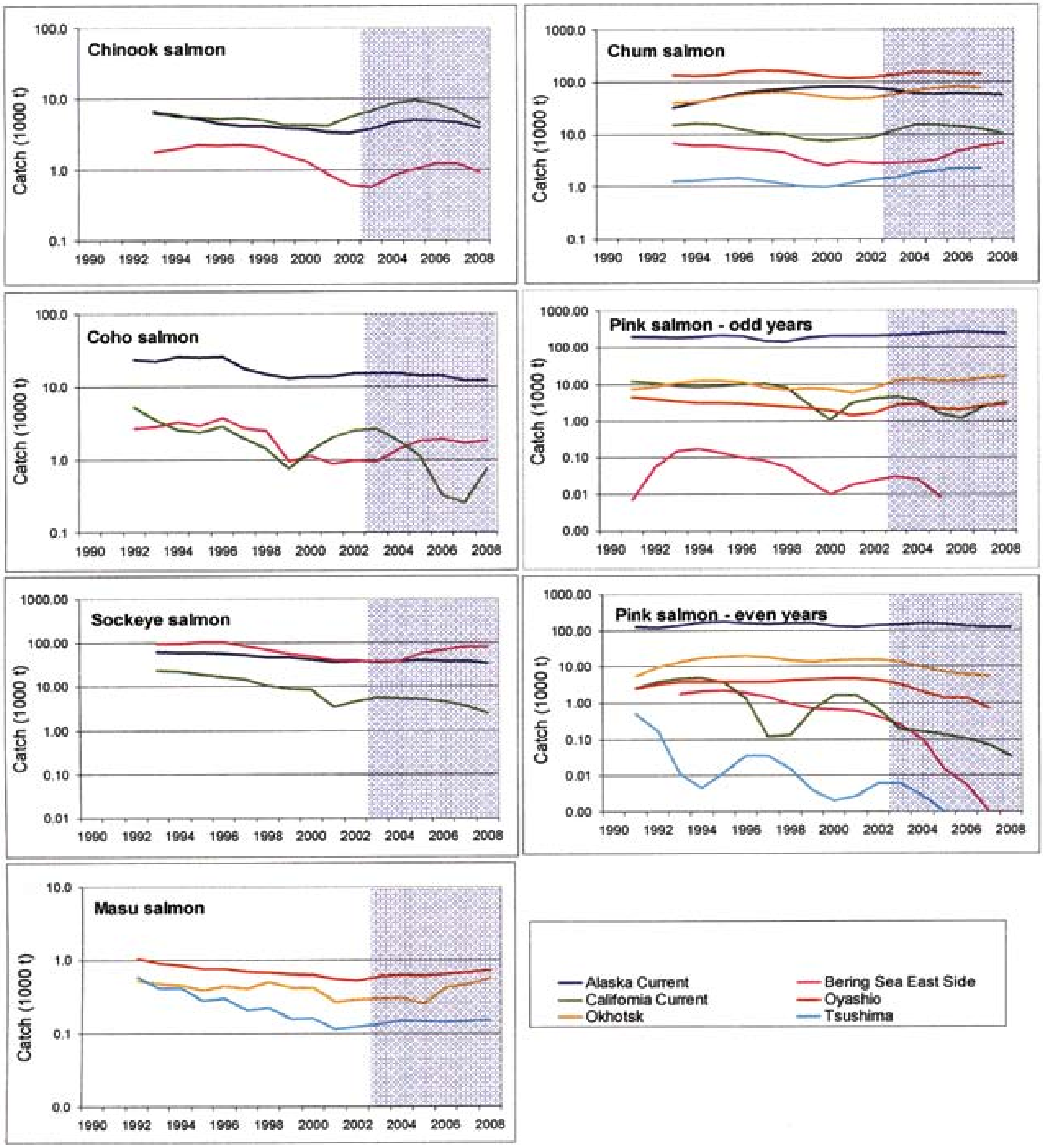


[Figure S-27] Numbers of salmon by species released by all hatcheries in the North Pacific during 1993-2007. The average during the focus period (2003-2007 only) was ~5.0 billion annually (Data source: NPAFC, see Irvine et al. 2009).

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.



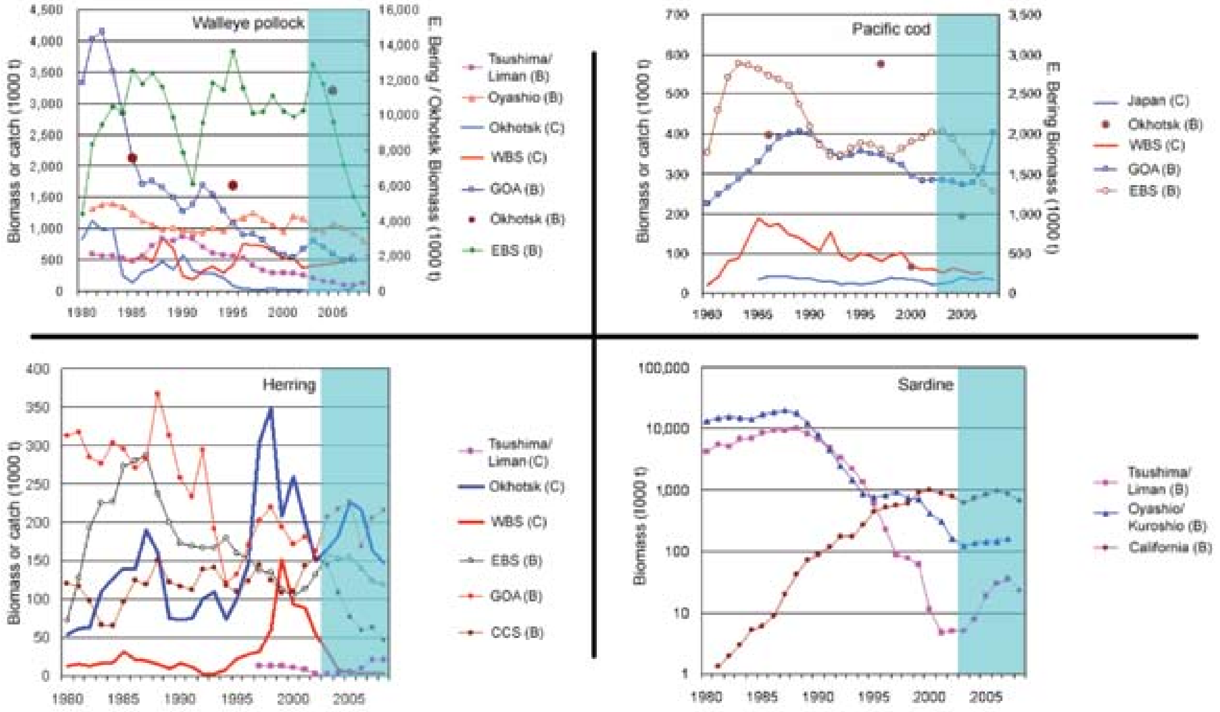
[Figure S-28] Year-to-year variations in catch of Pacific salmon species by oceanic region. Russian catches are excluded because they could not be partitioned into the regions of interest. Running averages are plotted (final year of 4-year moving window for sockeye, chinook, and chum salmon, 3 year for 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.



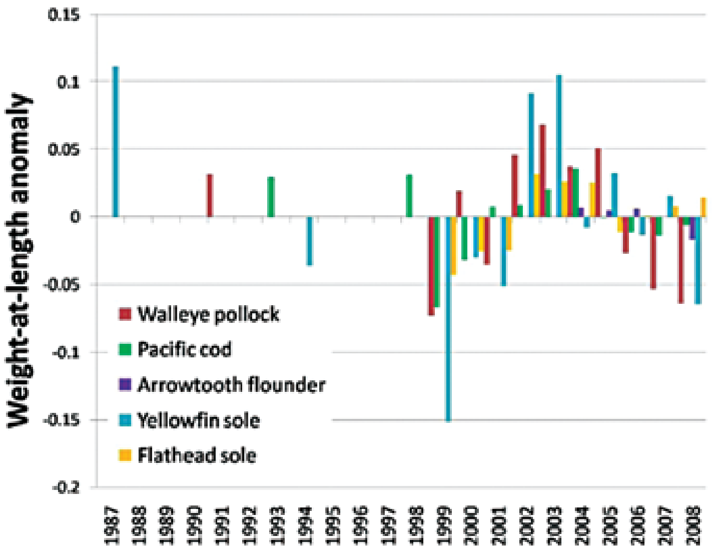
[Figure S-29] Year-to-year variations in biomass (B) or catch (C) of selected non-salmonid fishes by region CCS=California Current region, EBS=eastern Bering Sea, GOA=Gulf of Alaska, WBS=western Bering Sea. EBS herring biomass is Togiak herring; GOA herring biomass includes Prince William Sound, Southeast 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).

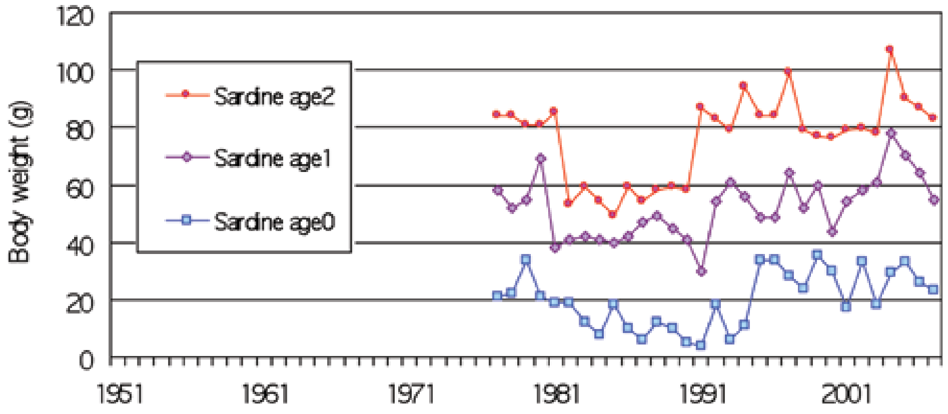
(J. Cleary, Fisheries and Oceans Canada, pers. comm.). Eastern Bering Sea herring biomass has been below the long-term average and decreased in the last five years (Buck 2008). Western Bering Sea herring catch has been variable but perhaps became stable during 2002-2004. Herring catch in the Russian 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

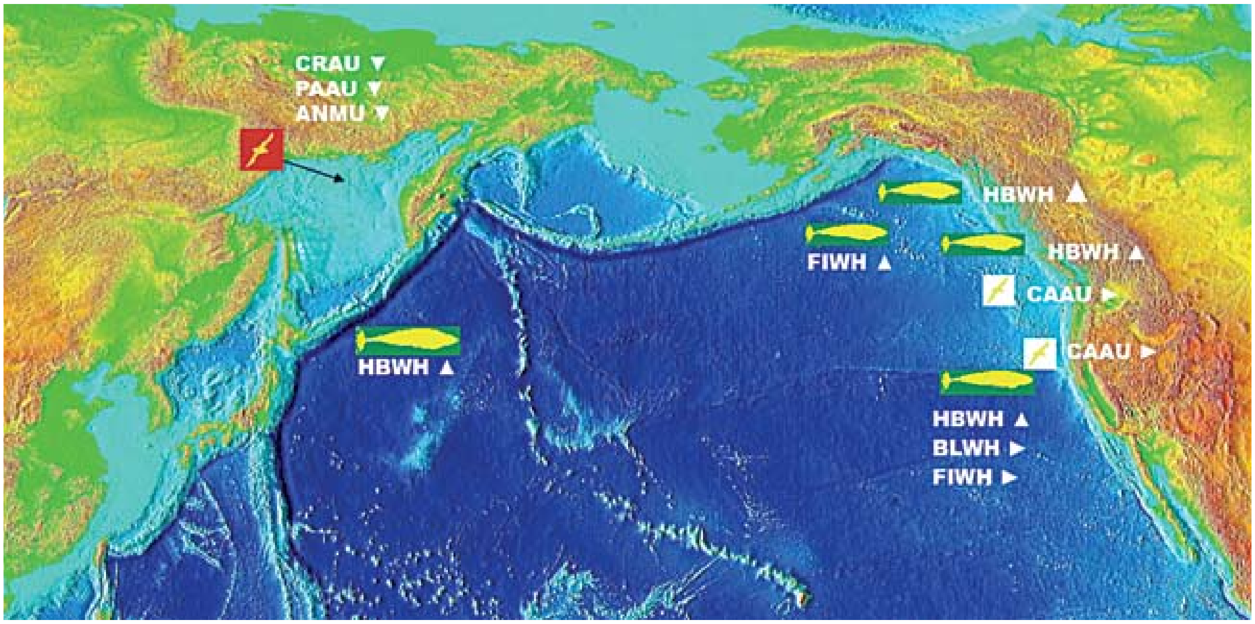
Location	Species	Metric	Dates Used	Trend	Reference
St. Paul Is., E Bering	Black-legged kittiwake	Population trend	1999 - 2008	No trend	Dragoo, pers. comm.
St. Paul Is., E. Bering	Common murre	Population trend	1999 - 2008	No trend	Dragoo, pers. comm.
St. George Is., E. Bering	Black-legged kittiwake	Population 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

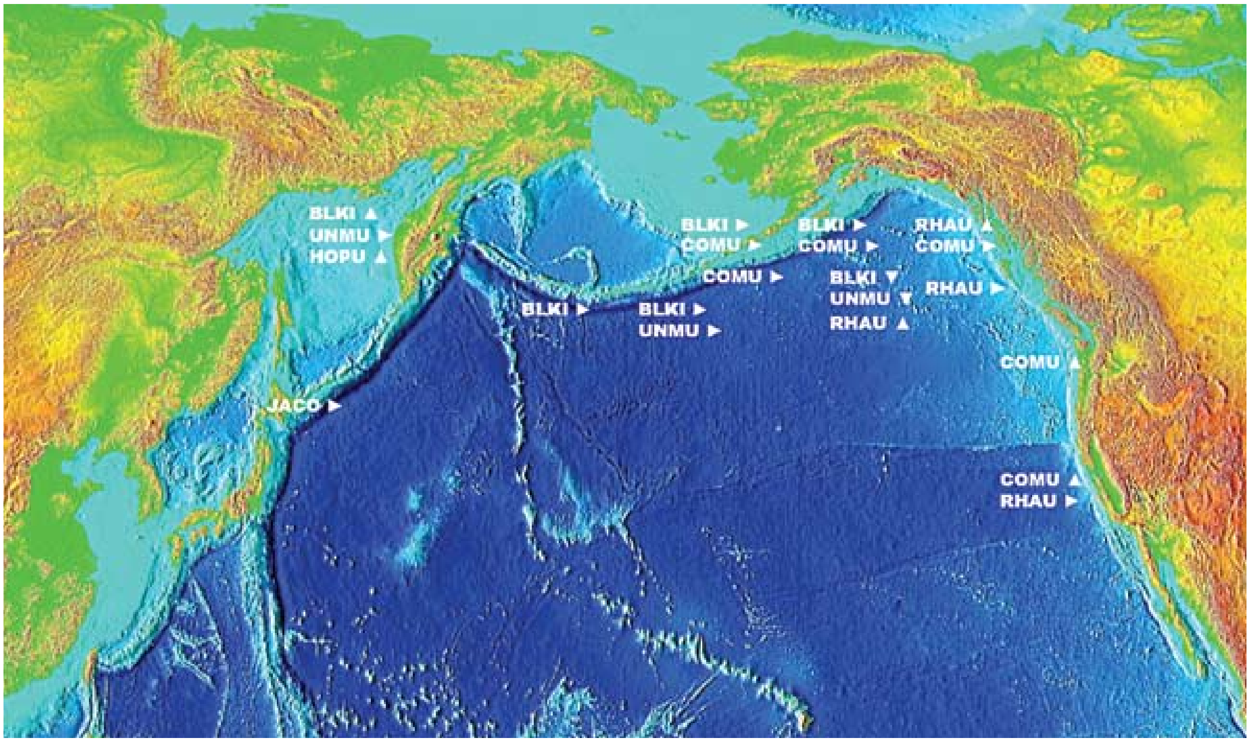
Location	Species	Metric	Dates Used	Trend	Reference
E. Kamchatka	Steller sea lion	Non-pup count	2001 – 2008	No trend	Burkanov et al. 2009
Commander Islands	Steller sea lion	Non-pup count	2000 - 2008	No trend	Burkanov et al. 2009
Commander Islands	Northern fur seal	Pup production	1972 - 76 vs. 2002 - 06	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).

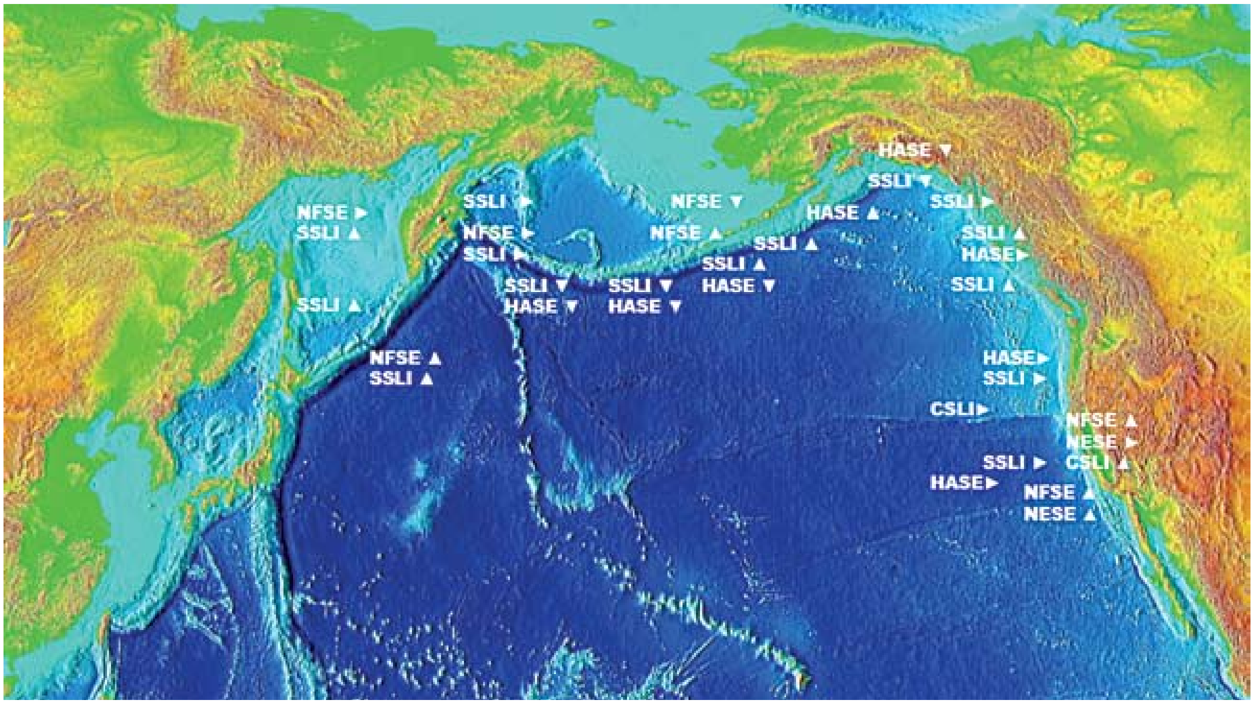
Moving northward and westward from the British Columbia coast to southeast Alaska and the Gulf of Alaska, an increasing number of piscivorous species show a shift from increasing population trends to either no trend or a decreasing trend (Table S-3a). For example, Steller sea lion populations have positive 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

References

Abraham, C.L., Sydeman, W.J. 2004. Ocean climate, euphausiids, and auklet nesting: Inter-annual trends and variation in phenology, diet and growth of a planktivorous seabird, *Ptychoramphus aleuticus*. Marine Ecology Progress Series 274: 235-250.

Aguilar-Islas, A.M., Rember, R.D., Mordy, C.W., Wu, J. 2008. Sea ice-derived dissolved iron and its potential influence on the spring algal bloom in the Bering Sea. Geophysical Research Letters 35: L24601, doi:10.1029/2008GL035736.

Ainley, D.G., Sydeman, W.J., Norton, J. 1995. Upper trophic level predators indicate interannual negative and positive anomalies in the California Current food web. Marine Ecology Progress Series 118: 79-89.

Allen, B.M., Angliss, R.P. (eds.). 2009. Draft Alaska Marine Mammal Stock Assessments 2009 (draft of 5/29/2009). National Marine Mammal Laboratory, Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115.

Andreev, A.V., Golugova, E.Yu., Kharitonov, S.P., Zubakin, V.A. In Press. Abundance of seabird colonies on Talan Island: The twenty-year trend. Vestnik DVNC, SVKNI, Magadan, Russia.

Andreev, A.G., Pavlova, G.Y. 2010. Okhotsk Sea, pp. 394-406, *In* Liu, K.-K., Atkinson, L., Quiñones, R., and Talaue-McManus, L. (eds.), Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis, Global Change - The IGBP Series, Springer, Berlin.

Aydin, K., Gaichas, S., Ortiz, I., Kinzey, D., Friday, N. 2007. A comparison of the Bering Sea, Gulf of Alaska, and Aleutian Islands large marine ecosystems through food web modeling. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-AFSC-178, 298 p.

Batten, S.D., Mackas, D.L. 2009. Shortened duration of the annual *Neocalanus plumchrus* biomass peak in the Northeast Pacific. Marine Ecology Progress Series 393: 189-198.

Batten, S., Chen, X., Flint, E.N., Freeland, H.J., Holmes, J., Howell, E., Ichii, T., Kaeriyama, M., Landry, M., Lunsford, C., Mackas, D.L., Mate, B., Matsuda, K., McKinnell, S.M., Miller, L., Morgan, K., Peña, A., Polovina, J.J., Robert, M., Seki, M.P., Sydeman, W., Thompson, S.A., Whitney, F., Woodworth, P., Yamaguchi, A. 2010. Status and trends of the North Pacific oceanic region, 2003-2008, pp. 56-105 In S.M. McKinnell and M.J. Dagg. [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

Baumgartner, T., Durazo, R., Lavaniegos, B., Gaxiola, G., Gomez, J., Garcia, J. 2008. Ten years of change from IMECOCAL observations in the southern region of the California Current Ecosystem. GLOBEC International Newsletter 14(2): 43-54.

Beamish, R.J. (ed.) 2009. Impacts of climate and climate change on the key species in the fisheries in the North Pacific. PICES Science Report No. 35, 217 p.

Benowitz-Fredericks, Z.M., Shultz, M.T., Kitaysky, A.S. 2008. Stress hormones suggest opposite trends of food availability for planktivorous and piscivorous seabirds in two years. Deep-Sea Research II 55: 1868-1876.

Benson, A.J., McFarlane, G.A., Allen, S.E., Dower, J.F. 2002. Changes in Pacific hake (*Merluccius productus*) migration patterns and juvenile growth related to the 1989 regime shift. Canadian Journal of Fisheries and Aquatic Sciences 59: 1969-1979.

Bertram, D.F., Mackas, D.L., McKinnell, S.M. 2001. The seasonal cycle revisited: interannual variation and ecosystem consequences. Progress in Oceanography 49: 283–307.

Bograd, S.J., Castro, C.G., Di Lorenzo, E., Palacios, D.M., Bailey, H., Gilly, W., Chavez, F.P. 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. Geophysical Research Letters 35: L12607, doi:10.1029/2008GL034185.

Bograd, S.J., Sydeman, W.J., Barlow, J., Booth, A., Brodeur, R.D., Calambokidis, J., Chavez, F., Crawford, W.R., Di Lorenzo, E., Durazo, R., Emmett, R., Field, J. Gaxiola-Castro, G., Gilly, W., Goericke, R., Hildebrand, J., Irvine, J.E., Kahru, M., Koslow, J.A., Lavaniegos, B., Lowry, M. Mackas, D.L., Manzano-Sarabia, M. McKinnell, S.M., Mitchell, B.G., Munger, L., Perry, R.I., Peterson, W.T., Ralston, S., Schweigert, J., Suntsov, A., Tanasichuk, R., Thomas, A.C., Whitney, F. 2010. Status and trends of the California Current region, 2003-2008, pp. 106-141 In S.M. McKinnell and M.J. Dagg. [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

Brodeur, R.D., Ralston, S., Emmett, R.L., Trudel, M., Auth, T.D., Phillips, A.J. 2006. Anomalous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005. Geophysical Research Letters 33: L22S08, doi:10.1029/2006GL026614.

Brodie, E.C., Gulland, F.M.D., Greig, D.J., Hunter, M., Jaakola, J., St Leger, J., Keighfield, T.A., van Dolah, F.M. 2006. Domoic acid causes reproductive failure in California sea lions (*Zalophus californianus*). Marine Mammal Science 22: 700-707.

Buck, G. 2008. Togiak herring population trends. *In* Ecosystem Considerations for 2009. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports, North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Burkanov, V., Andrews, R., Calkins, D., Altukhov, K., Vetrtyankin, V., Waite, J. 2009. Update on Steller sea lion (*Eumetopias jubatus*) surveys in Russia, 2006-2008. Poster presented at the 2009 Alaska Marine Science Symposium. Available at : ftp://ftp.afsc.noaa.gov/posters/pBurkanov07_ssl-surveys.pdf

Byrd, G.V., Schmutz, J.A., Renner, H.M. 2008. Contrasting population trends of piscivorous seabirds in the Pribilof Islands: A 30-year perspective. Deep-Sea Research II 55: 1846-1855.

Calambokidis, J. 2009. Abundance estimates of humpback and blue whales off the US West Coast based on mark-recapture of photo-identified individuals through 2008. Cascadia Research, 218½ W 4th Ave., Olympia, WA 98501. Document PSRG-2009-07.

Caretta, J.V., Forney, K.A., Lowry, M.S., Barlow, J., Baker, J., Johnston, D., Hanson, B., Muto, M.M., Lynch, D., Carswell, L. 2009. U.S. Pacific Marine Mammal Stock Assessments: 2009. NOAA Technical Memorandum NMFS, NOAA-TM-NMFS-SWFSC-434.

Chan, F., Barth, J.A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W.T., Menge, B.A. 2008. Emergence of anoxia in the California Current Large Marine Ecosystem. Science 319: 920.

Chavez, F.P., Ryan, J., Lluch-Cota, S.E., Ñiquen C., M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299: 217. doi 10.1126/science.1075880

Chelton, D.A., Bernal, P.A., McGowan, J.R. 1982. Large-scale interannual physical and biological interaction in the California Current. Journal of Marine Research 40: 1095-1125.

Chiba, S., Hirawake, T., Ishizaki, S., Ito, S., Kamiya, H., Kaeriyama, M., Kuwata, A., Midorikawa, T., Minobe, S., Okamoto, S., Okazaki, Y., Ono, T., Saito, H., Saitoh, S., Sasano, D., Tadokoro, K., Takahashi, K., Takatani, Y., Watanabe, Y., Watanabe, Y.W., Watanuki, Y., Yamamura, O., Yamashita, N., Yatsu, A. 2010. Status and trends of the Oyashio region, 2003-2008, pp. 300-329 In S.M. McKinnell & M.J. Dagg [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication No. 4, 393 p.

Coyle, K.O., Pinchuk, A.I., Eisner, L.B., Napp, J.M. 2008. Zooplankton species composition, abundance and biomass on the eastern Bering Sea shelf during summer: the potential role of water column stability and nutrients in structuring the zooplankton community. Deep-Sea Research II 55: 1775-1791.

Crawford, W., Irvine, J. 2009. State of the Northeast Pacific into early 2009. PICES Press 17(2): 28-29.

Crawford, W.R., Brickley, P.J., Thomas, A.C. 2007. Mesoscale eddies dominate surface phytoplankton in northern Gulf of Alaska. Progress in Oceanography 75: 287-303.

Cushing, D.H. 1975. Marine Ecology and Fisheries. Cambridge University Press, Cambridge, 278 p.

DeMaster, D.P., Trites, A.W., Clapham, P., Mizroch, S., Wade, P., Small, R.J., Ver Hoef, J. 2006. The sequential megafaunal collapse hypothesis: Testing with existing data. Progress in Oceanography 68: 329-342.

DeMaster, D. 2009. Letter to Douglas Mecum, Director, Alaska Region and Kaja Brix and Lisa Rotterman, Alaska Region Protected Resources, Subject: Aerial survey of Steller Sea lions in Alaska, June-July 2009 and Update on the status of the western stock in Alaska.

Deutsch, C., Emerson, S., Thompson, L. 2005. Fingerprints of climate change in North Pacific oxygen. Geophysical Research Letters 32: L16604, doi:10.1029/2005GL023190.

DFO (Department of Fisheries and Oceans, Canada). 2008. Population assessment: Steller sea lion (*Eumentopias jubatus*). DFO Canadian Science Advice Secretariat Advisory Report 2008/047.

Di Lorenzo, E., Schneider, N., Cobb, K.M., Chhak, K., Franks, P.J.S., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchister, E., Powell, T.M., Rivere, P. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophysical Research Letters 35: L08607, doi:10.1029/2007GL032838.

Di Lorenzo E., Fiechter, J., Schneider, N., Bracco, A., Miller A.J., Franks P.J.S., Bograd S.J., Moore, A.M., Thomas, A., Crawford, W., Peña, A., Herman, A. 2009. Nutrient and salinity decadal variations in the central and eastern North Pacific. Geophysical Research Letters 36: doi:10.1029/2009GL038261.

Dragoo, D. 2010. Personal Communication. Alaska Maritime National Wildlife Refuge, 95 Sterling Highway, Suite 1, Homer, AK 99603-7472.

Drobysheva, S.S. 1967. The role of specific composition in the formation of the Barents Sea euphausiid abundance. Trudy PINRO. Vyp.20: 195–204 (in Russian).

Drobysheva, S.S. 1994. The Barents Sea euphausiids and their role in the formation of fishing biological production. Murmansk: PINRO Press, 1994. 139 p. (in Russian).

Feely, R.A., Sabine, C.L., Lee, K., Millero, F.J., Lamb, M.F., Greeley, D., Bullister, J.L., Key, R.M., Peng, T.-H., Kozyr, A., Ono, T., Wong, C.S. 2002. *In situ* calcium carbonate dissolution in the Pacific Ocean. Global Biogeochemical Cycles 16: doi:10.1029/2002GB001866.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D., Hales, B. 2008. Evidence of upwelling of corrosive "acidified" water onto the continental shelf. Science 320: 1490-1492.

Ford, J.K.B., Rambeau, A.L., Abernethy, R.M., Boogaards, M.D., Nichol, L.M., Spaven, L.D. 2009. An assessment of the potential for recovery of humpback whales off the Pacific coast of Canada. DFO Canadian Science Advisory Secretariat Research Document 2009/015, 33 p.

Foreman, M.G.G., Cummins, P.F., Cherniawsky, J.Y., Stabeno, P. 2006. Tidal energy in the Bering Sea. Journal of Marine Research 64: 797-818.

Freeland, H.J., Denman, K., Wong, C.S., Whitney, F., Jacques, R. 1997. Evidence of change in the mixed winter layer in the Northeast Pacific Ocean. Deep-Sea Research I 44: 2117-2129.

Freeland, H.J. 2006. How much water from the North Pacific Current finds its way into the Gulf of Alaska? Atmosphere-Ocean 44: 321-330.

Glebova, S.Yu. 2006. Influence of atmospheric circulation above the far-eastern region on character of iciness change in the Okhotsk and Bering Seas. Meteorologiya i Gydrologiya 12: 54-60 (in Russian).

Goldstein, T., Zabka, T.S., DeLong. R.L., Wheeler, E.A., Ylitalo, G., Bargu, S., Silver, M., Leighfield, T., Van Dolah, F., Langlois, G., Sidor, I., Dunn, J.L., Frances, M., Gulland, D. 2009. The role of domoic acid in abortion and premature parturition of California sea lions (*Zalophus californianus*) on San Miguel Island, California. Journal of Wildlife Diseases 45: 91-108.

Hare, S.R., Mantua, N.J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47: 103-145.

Hebert, K., Dressel, S. 2009. Southeastern Alaska herring. *In* Ecosystem Considerations for 2010. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Hipfner, M. 2010. Personal Communication. Canadian Wildlife Service, Pacific and Yukon Region, RR#1 5421 Robertson Road, Delta, B.C. V4K 3N2

Hiroi, O. 1998. Historical trends of salmon fisheries and stock condition in Japan. North Pacific Anadromous Fish Commission Bulletin 1: 23-27.

Honda, M., Yamazaki, K., Nakamura, H., Takeuchi, K. 1999. Dynamic and thermodynamic characteristics of atmospheric response to anomalous sea-ice extent in the Sea of Okhotsk. Journal of Climate 12: 3347-3358.

Hooff, R.C., Peterson, W.T. 2006. Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. Limnology and Oceanography 51: 2042-2051.

Hunt, G.L, Jr., Allen, B.M., Angliss, R.P., Baker, T., Bond, N., Buck,G., Byrd, G.V., Coyle, K.O., Devol, A., Eggers, D.M., Eisner, L.,Feely, R., Fitzgerald, S., Fritz, L.W. Gritsay, E.V., Ladd, C., Lewis, W., Mathis, J., Mordy, C.W., Mueter, F., Napp, J., Sherr, E., Shull, D., Stabeno, P., Stepanenko, M.A., Strom, S., Whitledge, T.E. 2010. Status and trends of the Bering Sea region, 2003-2008, pp. 196-267 In S.M. McKinnell and M.J. Dagg [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008.PICES Special Publication 4, 393 p.

Hunt, G.L., Stabeno, P., Walters, G., Sinclair, E., Brodeur, R.D., Napp, J.M., Bond, N.A. 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep-Sea Research II 49: 5821-5853.

Hunt, G.L., Jr., Stabeno, P.J., Strom, S., Napp, J.M. 2008. Patterns of spatial and temporal variation in the marine ecosystem of the southeastern Bering Sea, with special reference to the Pribilof Domain. Deep-Sea Research II 55: 1919-1944.

Huyer, A. 1983. Coastal upwelling in the California Current system. Progress in Oceanography 12: 259-284.

Ianelli, J.N., Barbeaux, S., Honkalehto, T., Kotwicki, S., Aydin, K., Williamson, N. 2009. Assessment of the walleye pollock stock in the Eastern Bering Sea. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Iida, T., Saitoh, S.-I. 2007. Temporal and spatial variability of chlorophyll concentrations in the Bering Sea using empirical orthogonal function (EOF) analysis of remote sensing data. Progress in Oceanography 54: 2657-2671.

Iles, T.D., Sinclair, M. 1982. Atlantic herring: stock discreteness and abundance. Science 215:627-633.

Irvine, J.R., Fukuwaka, M., Kaga, T., Park, J.H., Seong, K.B., Kang, S., Karpenko, V., Klovach, N., Bartlett, H., Volk, E. 2009. Pacific salmon status and abundance trends. NPAFC Document 1199, Rev. 1., 153 pp.

IUCN (International Union for Conservation of Nature). 2009. IUCN Red List of Threatened Species. Version 2009.2. <www.iucnredlist.org>. Downloaded on 28 January 2010.

Johnson, W.K., Miller, L.A., Sutherland, N.E., Wong, C.S. 2005. Iron transport by mesoscale Haida eddies in the Gulf of Alaska. Deep-Sea Research II 52: 933-953.

Kaeriyama, M. 1998. Dynamics of chum salmon, *Oncorhynchus keta*, populations released from Hokkaido, Japan. North Pacific Anadromous Fish Commission Bulletin 1: 90-102.

Kaeriyama, M., Seo, H., Kudo, H. 2009. Trends in run size and carrying capacity of Pacific salmon in the North Pacific Ocean. NPAFC Bulletin 5: 293–302.

Kaev, A.M., Ignatiev, Y.I. 2007. Hatchery production of salmon in Sakhalin. Rybnoye Khoziaystvo (Fisheries) 6: 57-60.

Kahru, M., Mitchell, B.G. 2008. Ocean color reveals increased blooms in various parts of the World. EOS Transactions of the American Geophysical Union 89(18): 170.

Kahru, M., Kudela, R., Manzano-Sarabia, M., Mitchell, B.G. 2009. Trends in primary production in the California Current detected with satellite data. Journal of Geophysical Research 114: C02004, doi:10.1029/2008JC004979.

Kitaysky, A.S., Golubova, E.G. 2000. Climate change causes contrasting trends in reproductive performance of planktivorous and piscivorous alcids. Journal of Animal Ecology 69: 248-262.

Kosro, P.M., Peterson, W.T., Hickey, B.M., Shearman, R.K. Pierce, S.D. 2006. Physical versus biological spring transition: 2005. Geophysical Research Letters 33: L22S03, doi:10.1029/2006GL027072.

Lavaniegos, B.E. 2009. Influence of a multiyear event of low salinity on the zooplankton from Mexican eco-regions of the California Current. Progress in Oceanography 83: 369-375.

Lee, D.E., Nur, N., Sydeman, W.J. 2007. Climate and demography of the planktivorous Cassin's auklet *Ptychoramphus aleuticus* off northern California: implications for population change. Journal of Animal Ecology 76: 337-347.

Lee, C.S., Seong, K.B., Lee, C.H. 2007. History and status of the chum salmon enhancement program in Korea. Journal of the Korean Society of Oceanography 12: 73-80.

Li, M., Xu, K., Watanabe, M., Chen, Z. 2007. Long-term variations in dissolved silicate, nitrogen and phosphorous flux from the Yangtze River into the East China Sea and impacts on estuarine ecosystem. Estuarine, Coastal and Shelf Science 71: 3-12.

Longhurst, A. 1985. The structure and evolution of zooplankton communities. Progress in Oceanography 15: 1-35.

Mackas, D.L., Peterson, W.T., Ohman, M.D., Lavaniegos, B.E. 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005. Geophysical Research Letters, doi:10.1029/2006GL027930.

Mackas, D.L., Batten, S., Trudel, M. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. Progress in Oceanography 75: 223-252.

Markus, T., Stroeve, J.C., Miller, J. 2009. Recent changes in Arctic sea ice melt onset, freezeup, and melt season length. Journal of Geophysical Research 114: C12024, doi:10.1029/2009JC005436, 2009

Marty, G.D., Quinn, II, T.J., Carpenter, G., Meyers, T.R., Willits, N.H. 2003. Role of disease in abundance of a Pacific herring (*Clupea pallasi*) population. Canadian Journal of Fisheries and Aquatic Sciences 60: 1258-1265.

Marty, G.D., Quinn, T.J., II, Miller, S.A., Meyers, T.R., Moffitt, S.D. 2004. Effect of disease on recovery of Pacific herring in Prince William Sound, Alaska. Exxon Valdez Oil Spill Restoration Project Final Report (Restoration Project 030462), University of California, Davis, CA.

McKinnell, S.M., Crawford, W.R. 2007. The 18.6-year lunar nodal cycle and surface temperature variability in the Northeast Pacific. Journal of Geophysical Research 112: C02002, 10.1029/2006JC003671.

Meehl, G.A., Arblaster, J.M., Branstator, G., van Loon, H. 2008. A coupled air-sea response mechanism to solar forcing in the Pacific region. Journal of Climate 21: 2883-2897.

Miller, A.J., Cayan, D.R., White, W.B. 1998. A westward-intensified decadal change in the North Pacific thermocline and gyre-scale circulation. Journal of Climate 11: 3112-3127.

Moffitt, S. 2008. Prince William Sound herring. *In* Ecosystem Considerations for 2009. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Moss, J.H., Farley Jr., E.V., Feldman, A.M., Ianelli, J.N. 2009. Spatial distribution, energetic status, and food habits of Eastern Bering Sea age-0 walleye pollock. Transactions of the American Fisheries Society 138: 497-505.

Mueter, F.J., Ladd, C., Palmer, M.C., Norcross, B.L. 2006. Bottom-up and top-down controls of walleye pollock (*Theragra chalcogramma*) on the Eastern Bering Sea shelf. Progress in Oceanography 68 :52-183.

Mueter, F.J., Litzow, M.A. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. Ecological Applications 18: 309-320.

Mueter, F.J., Litzow, M.A., Lauth, R. 2009. Spatial distribution of groundfish stocks in the Bering Sea. *In* Ecosystem Considerations for 2009. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Mundy, P.R., Allen, D.M., Boldt, J.L., Bond, N.A., Dressel, S., Farley Jr., E.V., Hanselman, D.H., Heifetz, J., Hopcroft, R.R., Janout, M.A., Ladd, C., Lam, R.C., Livingston, P.A., Lunsford, C.R., Mathis, J.T., Mueter, F.J., Rooper, C.N., Sarkar, N., Shotwell, S.A.K., Sturdevant, M.V., Thomas, A.C., Weingartner, T.J., Woodby, D. 2010. Status and trends of the Alaska Current region, 2003-2008, pp 142-195 In S.M. McKinnell and M.J. Dagg [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

Mustapha, M.A., Saitoh, S.-I. 2008. Observations of sea ice interannual variations and spring bloom occurrences at the Japanese scallop farming area in the Okhotsk Sea using satellite imageries. Estuarine, Coastal and Shelf Science 77: 577-588, doi:10.1016/j.ecss.2007.10.021.

Nakamura, H., Sampe, T., Tanimoto, Y., Shimpo, A. 2004. Observed associations among storm tracks, jet streams and midlatitude oceanic fronts, pp. 329–346, *In* Wang, C., Xie, S.-P., Carton, J.A. (eds.), Earth's Climate: The Ocean–Atmosphere Interaction, Geophysical Monograph 147, American Geophysical Union, Washington, DC.

Nicol, S., Endo, Y.1997. Krill fisheries of the world. FAO Fisheries Technical Paper No. 367, FAO, Rome, 100 p.

Nishioka, J., Ono, T., Saito, H., Nakatsuka, T. and Takeda, S., Yoshimura, T., Suzuki, K., Kuma, K., Nakabayashi, S., Tsumune, D., Mitsudera, H., Johnson, W.K., Tsuda, A. 2007. Iron supply to the western subarctic Pacific: Importance of iron export from the Sea of Okhotsk. Journal of Geophysical Research 112: C10012, doi:10.1029/2006JC004055.

Norcross, B.L., Brown, E.D., Foy, R.J., Frandsen, M., Gay, S.M., Kline Jr., T.C., Mason, D.M., Patrick, E.V., Paul, A.J., Stokesbury, K.D.E. 2001. A synthesis of the life history and ecology of juvenile Pacific herring in Prince William Sound, Alaska. Fisheries Oceanography 10(Suppl. 1): 42-57.

Norris, J.R. 1998. Low cloud type over the ocean from surface observations. Part II: Geographical and seasonal variations. Journal of Climate 11: 383-403.

Olesiuk, P.F. 2009. Preliminary assessment of the recovery potential of northern fur seals (*Callorhinus ursinus*) in British Columbia. DFO Canadian Science Advisory Secretariat Research Document 2007/076.

Osafune, S., Yasuda, I. 2006. Bidecadal variability in the intermediate waters of the northwestern subarctic Pacific and the Okhotsk Sea in relation to 18.6-year period nodal tidal cycle. Journal of Geophysical Research 111: C05007, doi:10.1029/2005JC003277.

Parrish, J.K., Bond, N., Nevins, H., Mantua, N., Loeffel, R., Peterson, W.T., Harvey, J.T. 2007. Beached birds and physical forcing in the California Current System. Marine Ecology Progress Series 352: 275-288.

Piatt, J.F., Harding, A.M.A., Shultz, M., Speckman, S.G., van Pelt, T.I., Drew, G.S., Kettle, A.B. 2007. Seabirds as an indicator of marine food supplies: Cairns revisited. Marine Ecology Progress Series 352: 221-234.

PICES. 2004. Marine ecosystems of the North Pacific. PICES Special Publication No. 1, 280p.

Peterson, W.T., Schwing, F.B. 2003. A new climate regime in Northeast Pacific ecosystems. Geophysical Research Letters 30: 1896, doi:10.1029/2003GL017528.

Polovina, J.J., Howell, E.A., Abecassis, M. 2008. Ocean's least productive waters are expanding. Geophysical Research Letters 35: L03618, doi:10.1029/2007GL031745.

Radchenko, V.I., Dulepova, E.P., Figurkin, A.L., Katugin, O.N., Ohshima, K., Nishioka, J. McKinnell, S.M., Tsoy, A.T. 2010. Status and trends of the Sea of Okhotsk region, 2003-2008, pp. 268-299 In S.M. McKinnell and M.J. Dagg. [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

Raven, J.A., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., Watson, A. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. Royal Society, London, UK, 68 p.

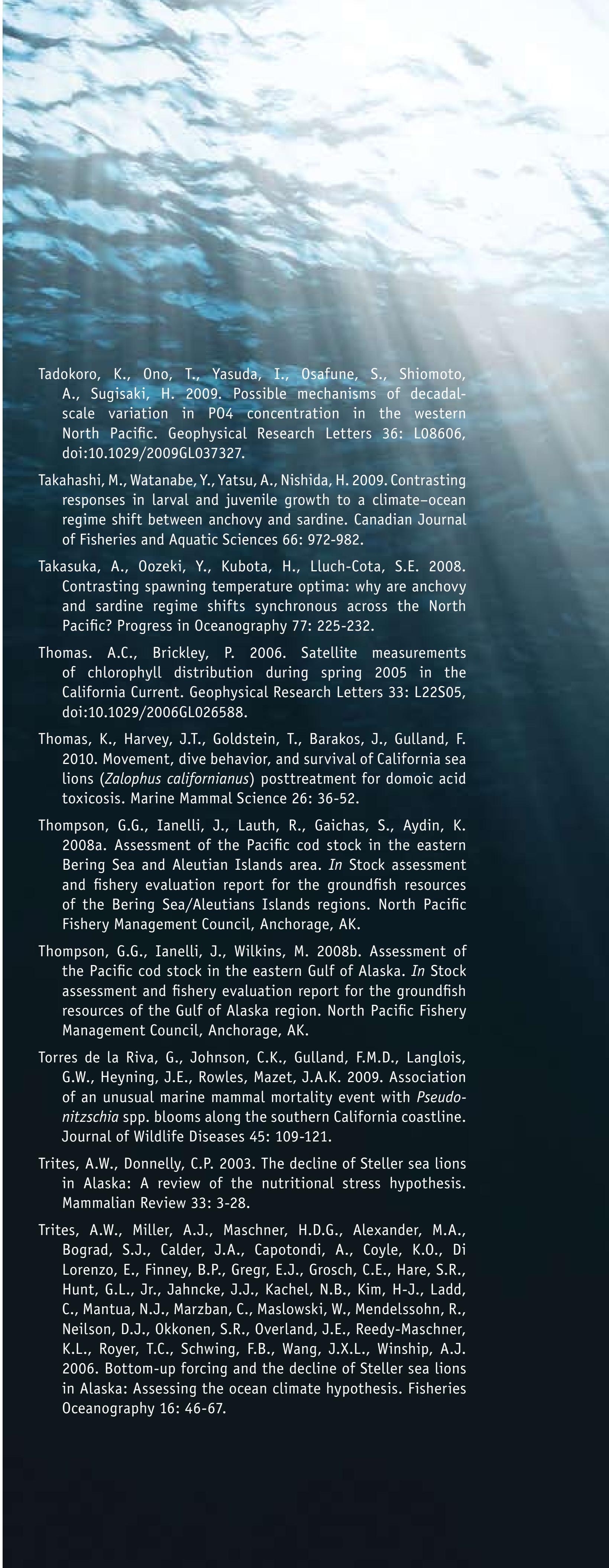
Ream, R.R., Sterling, J.T., Loughlin, T.R. 2005. Oceanographic features related to northern fur seal migratory movements. Deep-Sea Research II 52: 823-843.

Rodionov, S.N., Bond, N.A., Overland, J.E. 2007. The Aleutian Low, storm tracks, and winter climate variability in the Bering Sea. Deep-Sea Research II 54: 2560-2577.

Rooper, C.N. 2008. Distribution of rockfish species along environmental gradients in Gulf of Alaska and Aleutian Islands bottom trawl surveys. *In* Ecosystem Considerations for 2009. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Royer, T.C. 1993. High-latitude oceanic variability associated with the 18.6-year nodal tide. Journal of Geophysical Research 98: 4639–4644.

Saito, T., Nagasawa, K. 2009. Regional synchrony in return rates of chum salmon (*Oncorhynchus keta*) in Japan in relation to coastal temperature and size at release. Fisheries Research 95: 14-27.



Scholin, C.A., Gulland, F., Doucette, G.J., Benson, S., Busman, M., Chavez, F.P., Cordarok, J., DeLong, R., DeVogelaere, A., Harvey, J., Haulena, M., Lefebvre, K., Lipscomb, T., Loscutoff, S., Lowenstine, L.J., Marin III, R., Miller, P.E., McLellan, W.A., Moeller, P.D.R., Powell, C.L., Rowlesk, T., Silvagni, P., Silver, M., Spraker, T., Trainer, V., Van Dolah, F.M. 2000. Mortality of sea lions along the central California coast linked to a toxic diatom bloom. Nature 403: 80-84.

Schweigert, J.F., Hay, D.E., Therriault, T.W., Thompson, M., Haegele, C.W. 2009a. Recruitment forecasting using indices of young-of-the year Pacific herring (*Clupea pallasi*) abundance in the Strait of Georgia (BC). ICES Journal of Marine Science 66: 1681-1687.

Schweigert, J., Christensen, L.B., Haist, V. 2009b. Stock assessments for British Columbia herring in 2008 and forecasts of the potential catch in 2009. Canadian Science Advisory Secretariat, 2009/019, 66 p.

Shuntov, V.P., Temnykh, O.S. 2009. Current status and tendencies in the dynamics of biota of the Bering Sea macroecosystem. North Pacific Anadromous Fish Commission Bulletin 5: 321–331.

Slater, L., Byrd, G.V. 2009. Status, trends, and patterns of covariation of breeding seabirds at St. Lazaria Island, Southeast Alaska, 1994-2006. Journal of Biogeography 36: 465-475.

Small, R.J., Boveng, P.L., Byrd, G.V., Withrow, D.E. 2008. Harbor seal population decline in the Aleutian Archipelago. Marine Mammal Science 24: 845-863.

Spencer, P.D. 2008. Density-independent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. Fisheries Oceanography 17: 396-410.

Springer, A.M., Estes, J.A., van Vliet, G.B., Williams, T.M., Doak, D.F., Danner, E.M., Forney, K.A., Pfister, B. 2003. Sequential megafaunal collapse in the North Pacific Ocean: An ongoing legacy of industrial whaling? Proceedings of the National Academy of Sciences USA 100: 12,223-12,228.

Sugisaki, H., Nonaka, M., Ishizaki, S., Hidaka, K., Kameda, T., Hirota, Y., Oozeki, Y., Kubota, H., Takasuka, A. 2010. Status and trends of the Kuroshio region, 2003-2008, pp 330-359 In S.M. McKinnell and M.J. Dagg [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

Schwing, F.B., Bond, N.N., Bograd, S.J., Mitchell, T., Alexander, M.A., Mantua, N. 2006. Delayed coastal upwelling along the U.S. west coast in 2005: A historical perspective. Geophysical Research Letters 33: L22S01, doi.10.1029/2006GL026911.

Sydeman, W.J., Bradley, R.W., Warzybok, P., Abraham, C.L., Jahncke, J., Hyrenback, K.D., Kousky, V., Hipfner, J.M., Ohman, M.D. 2006. Planktivorous auklet (*Ptychoramphus aleuticus*) responses to the anomaly of 2005 in the California Current. Geophysical Research Letters 33: L22S09, doi:/10.1029/2006GL026736.

Tadokoro, K., Ono, T., Yasuda, I., Osafune, S., Shiomoto, A., Sugisaki, H. 2009. Possible mechanisms of decadal-scale variation in PO4 concentration in the western North Pacific. Geophysical Research Letters 36: L08606, doi:10.1029/2009GL037327.

Takahashi, M., Watanabe, Y., Yatsu, A., Nishida, H. 2009. Contrasting responses in larval and juvenile growth to a climate–ocean regime shift between anchovy and sardine. Canadian Journal of Fisheries and Aquatic Sciences 66: 972-982.

Takasuka, A., Oozeki, Y., Kubota, H., Lluch-Cota, S.E. 2008. Contrasting spawning temperature optima: why are anchovy and sardine regime shifts synchronous across the North Pacific? Progress in Oceanography 77: 225-232.

Thomas. A.C., Brickley, P. 2006. Satellite measurements of chlorophyll distribution during spring 2005 in the California Current. Geophysical Research Letters 33: L22S05, doi:10.1029/2006GL026588.

Thomas, K., Harvey, J.T., Goldstein, T., Barakos, J., Gulland, F. 2010. Movement, dive behavior, and survival of California sea lions (*Zalophus californianus*) posttreatment for domoic acid toxicosis. Marine Mammal Science 26: 36-52.

Thompson, G.G., Ianelli, J., Lauth, R., Gaichas, S., Aydin, K. 2008a. Assessment of the Pacific cod stock in the eastern Bering Sea and Aleutian Islands area. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutians Islands regions. North Pacific Fishery Management Council, Anchorage, AK.

Thompson, G.G., Ianelli, J., Wilkins, M. 2008b. Assessment of the Pacific cod stock in the eastern Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska region. North Pacific Fishery Management Council, Anchorage, AK.

Torres de la Riva, G., Johnson, C.K., Gulland, F.M.D., Langlois, G.W., Heyning, J.E., Rowles, Mazet, J.A.K. 2009. Association of an unusual marine mammal mortality event with *Pseudo-nitzschia* spp. blooms along the southern California coastline. Journal of Wildlife Diseases 45: 109-121.

Trites, A.W., Donnelly, C.P. 2003. The decline of Steller sea lions in Alaska: A review of the nutritional stress hypothesis. Mammalian Review 33: 3-28.

Trites, A.W., Miller, A.J., Maschner, H.D.G., Alexander, M.A., Bograd, S.J., Calder, J.A., Capotondi, A., Coyle, K.O., Di Lorenzo, E., Finney, B.P., Gregr, E.J., Grosch, C.E., Hare, S.R., Hunt, G.L., Jr., Jahncke, J.J., Kachel, N.B., Kim, H-J., Ladd, C., Mantua, N.J., Marzban, C., Maslowski, W., Mendelssohn, R., Neilson, D.J., Okkonen, S.R., Overland, J.E., Reedy-Maschner, K.L., Royer, T.C., Schwing, F.B., Wang, J.X.L., Winship, A.J. 2006. Bottom-up forcing and the decline of Steller sea lions in Alaska: Assessing the ocean climate hypothesis. Fisheries Oceanography 16: 46-67.

Trudel, M., Welch, D.W., Morris, J., Farley, E., Murphy, J. 2005. Influence of marine feeding area on lipid accumulation in juvenile coho salmon. North Pacific Anadromous Fish Commission Bulletin 6: 94-95.

Turner, R.E., Qureshi, N., Rabalais, N.N., Dortch, Q., Justic, D., Shaw, R.F., Cope, J. 1998. Fluctuating silicate:nitrate ratios and coastal plankton food webs. Proceedings of the National Academy of Sciences USA 95: 13,048-13,051.

Wade, P.R., Hoef, J.M.V., DeMaster, D.P. 2009. Mammal-eating killer whales and their prey-trend data for pinnipeds and sea otters in the North Pacific Ocean do not support the sequential megafaunal collapse hypothesis. Marine Mammal Science 25: 737-747.

Wallace, J.M., Gutzler, D.S. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere Winter. Monthly Weather Review 109: 784-812.

Warzybok, P. 2010. Personal communication, PRBO Conservation Science, Marine Ecology Division, 3820 Cypress Drive #11, Petaluma, CA 94954.

Watanabe, Y.W., Nishioka, J., Shigemitsu, M., Mimura, A., Nakatsuka, T. 2009. Influence of riverine alkalinity on carbonate species in the Okhotsk Sea. Geophysical Research Letters 36: L15606, doi:10.1029/2009GL038520.

Watanuki, Y. 2010. Personal Communication. Graduate School of Hokkaido University, 041-8611 Hakodate, Minatocho 3-1-1, Japan.

Wespestad, V.G., Fritz, L.W., Ingraham, W.J., Megrey, B.A. 2000. On the relationships between cannibalism, climate variability, physical transport, and recruitment success of Bering Sea walleye pollock. ICES Journal of Marine Science 57: 272-278.

Whitney, F.A., Freeland, H.J. 1999. Variability in upper-ocean water properties in the NE Pacific Ocean. Deep-Sea Research II 46: 2351-2370.

Whitney, F.A., Crawford, W.R., Harrison, P.J. 2005. Physical processes that enhance nutrient transport and primary productivity in the coastal and open ocean of the subarctic NE Pacific. Deep-Sea Research 52: 681-706.

Whitney, F.A., Freeland, H.J., Robert, M. 2007. Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. Progress in Oceanography 75: 179-199.

Williams, E.H., Quinn II, T.J. 2000. Pacific herring, *Clupea pallasi*, recruitment in the Bering Sea and north-east Pacific Ocean, II: relationships to environmental variables and implications for forecasting. Fisheries Oceanography 9: 300-315.

Wing, B.L. 2005. Unusual invertebrates and fish observed in the Gulf of Alaska, 2004–2005. PICES Press 14(2): 26-28.

Wolf, S.G., Sydeman, W.J., Hipfner, J.M., Abraham, C.L., Tershy, B.R., Croll, D.A. 2009. Range-wide reproductive consequences of ocean climate variability for the seabird Cassin's Auklet. Ecology 90: 742-753.

Wong, C.S., Waser, N.D., Nojiri, Y., Johnson, W.K., Whitney, F.A., Page, J.S.C., Zeng, J. 2002. Seasonal and interannual variability in the distribution of surface nutrients and dissolved inorganic carbon in the northern North Pacific: influence of El Niño. Journal of Oceanography 58: 227-243.

Wootton, J.T., Pfister, C.A., Forester, J.D. 2008. Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. Proceedings of the National Academy of Sciences USA 105: 18,848-18,853.

Yasuda, I., Osafune, S., Tatebe, H. 2006. Possible explanation linking 18.6-year period nodal tidal cycle with bi-decadal variations of ocean and climate in the North Pacific. Geophysical Research Letters 33: L08606, doi:10.1029/2005GL025237.

Yatsu, A., Aydin, K.Y., King, J.R., McFarlane, G.A., Chiba, S., Tadokoro, K., Kaeriyama, M., Watanabe,Y. 2008. Elucidating dynamic responses of North Pacific fish populations to climatic forcing: Influence of life-history strategy. Progress in Oceanography 77: 252-268.

Yatsu, A., Kaeriyama, M. 2005. Linkages between coastal and open-ocean habitats and dynamics of Japanese stocks of chum salmon and Japanese sardine. Deep-Sea Research II 52: 727-737.

Yoo, S., Bae, S., Choi, J.-K., Choi, S., Ishizaka, J., Lee, J.B., Lee, Y.-J., Li, R., Kang, Y.-S., Kim, H.-c., Lee, C., Park, J., Wang, Z., Wen, Q., Yeh, S.-W., Yoon, W.-D., Yeon, I., Zhang, C.-I., Zhang, X., Zhu, M. 2010. Status and trends in the Yellow Sea and East China Sea region, pp. 360-393 In S.M. McKinnell and M.J. Dagg. [Eds.] Marine Ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4, 393 p.

Yoo, S., Batchelder, H.B., Peterson, W.T., Sydeman, W.J. 2008. Seasonal, interannual and event scale variation in North Pacific ecosystems. Progress in Oceanography 77: 155-181, doi:10.1016/j.pocean.2008.03.013.