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Bering Sea

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highlights

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

- Walleye pollock recruitment may be adversely affected by unusually warm conditions; strong year-classes failed to emerge in the warm years of 2002-2005 despite a declining biomass of pollock. Possibly, there were strong year-classes in the cold years of 2006 and 2008. In the cold years of 2006-2008, age-0 pollock were in good condition and energy-rich, though not as abundant as they were in the warmer years, when they were less energy-rich.

- Age-0 pollock consumed mostly small crustacean zooplankton and smaller pollock in the warmer years, and neither *C. marshallae* nor *T. raschii* were important dietary components. In the cold years, their diets were dominated by *C. marshallae* and euphausiids, and there was less cannibalism.

- Comparison of fisheries statistics between the eastern and western Bering Sea showed that, overall, the aggregated catches of all major fisheries tended to be positive, suggesting that the two sides of the Bering Sea were responding similarly to shared climate forcing.

- Both size-at-age and weight-at-length of groundfish tended to be above the long term mean in the warmer years, and below the mean in the cold years.

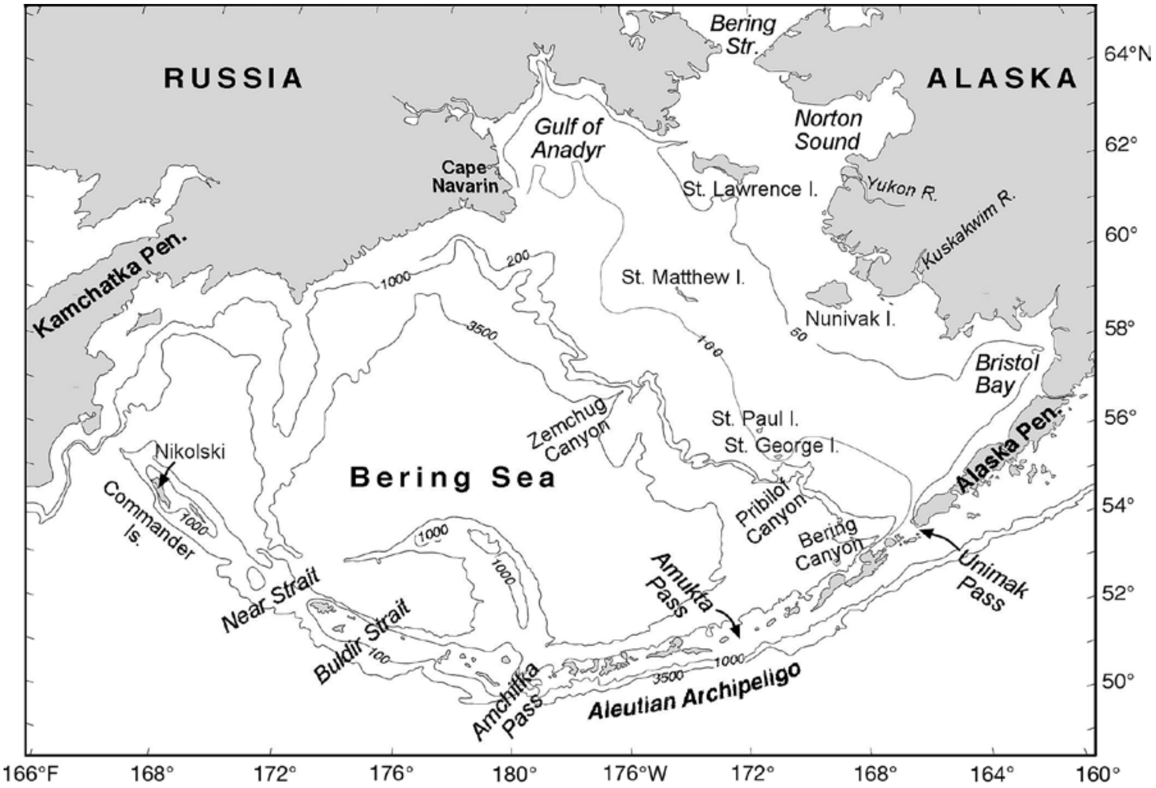
- Catches of crabs in the eastern and western Bering Sea declined after the early 1990s (eastern Bering Sea) or the late 1990s (western Bering Sea), but catches began to increase on both sides of the Bering Sea after 2004. The biomass of both red king crab and snow crab have increased in the eastern Bering Sea, although snow crab catches remain low due to conservative catch limits.

- Catches of Pacific herring on both sides of the Bering Sea have been stable since 2001, whereas the Togiak stock in the eastern Bering Sea has declined.

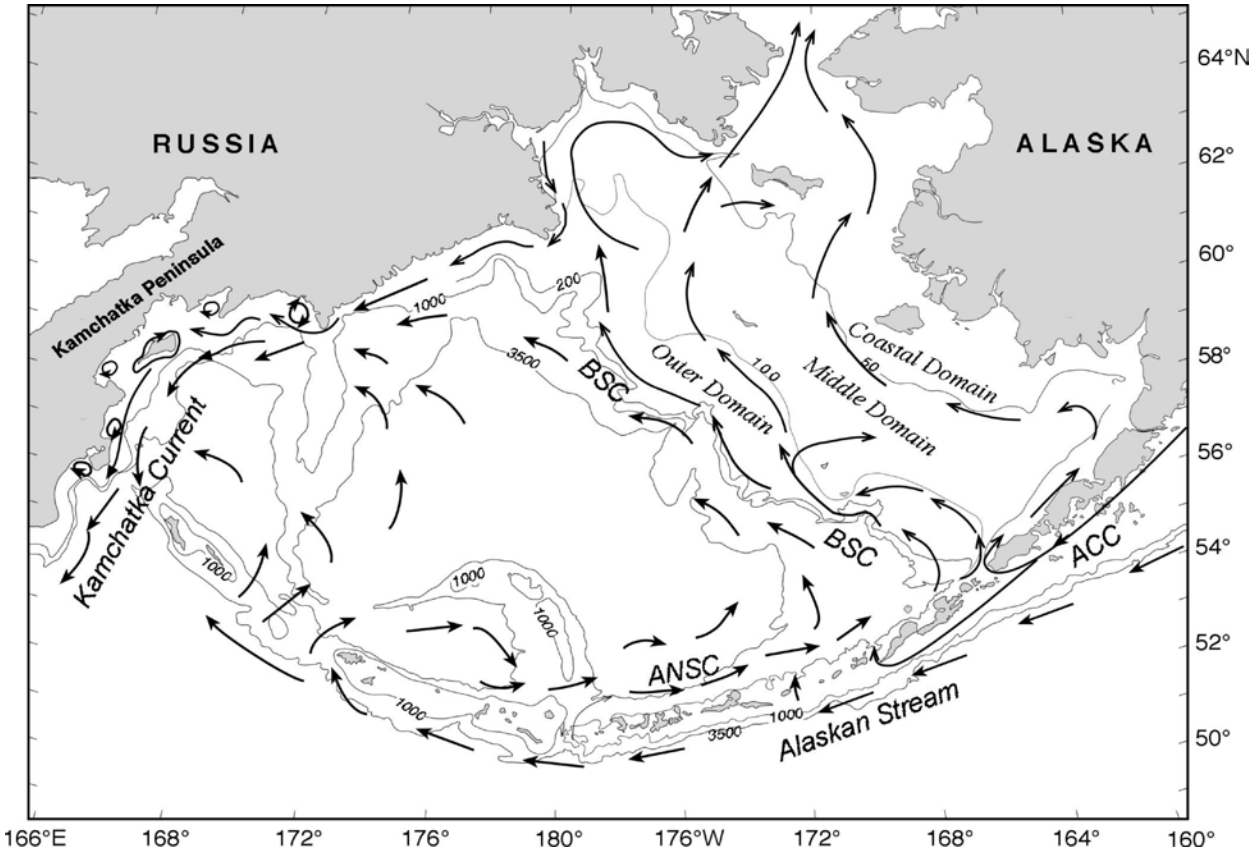
- Catches of salmon in both the eastern and western Bering Sea were above average and dominated by pink and chum salmon in the western Bering Sea and sockeye salmon in the eastern Bering Sea. In both the eastern and western Bering Sea, the catches of chinook salmon are in decline when compared to catches from the mid-1960s to the early 1990s.

Introduction

The Bering Sea is a semi-enclosed Subarctic sea that connects the North Pacific and Arctic Oceans. It is bounded by Bering Strait to the north and the Aleutian archipelago to the south, and lies between 52° and 66°N, and 162°E and 157°W. The Bering Sea consists of a deep central basin, a northwestern shelf in the Gulf of Anadyr that reaches south along the Kamchatka Peninsula, and a broad eastern shelf that stretches from the Alaska Peninsula to Russia and the Bering Strait (Fig. BS-1). The Bering Sea area covers almost 3×10^6 km^2 and is divided almost equally between waters >200 m deep and shelf waters <200 m in depth (ACIA 2005). The 500 km-wide eastern continental shelf is about 1,200 km from north to south, and encompasses about 40% of the Bering Sea.



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



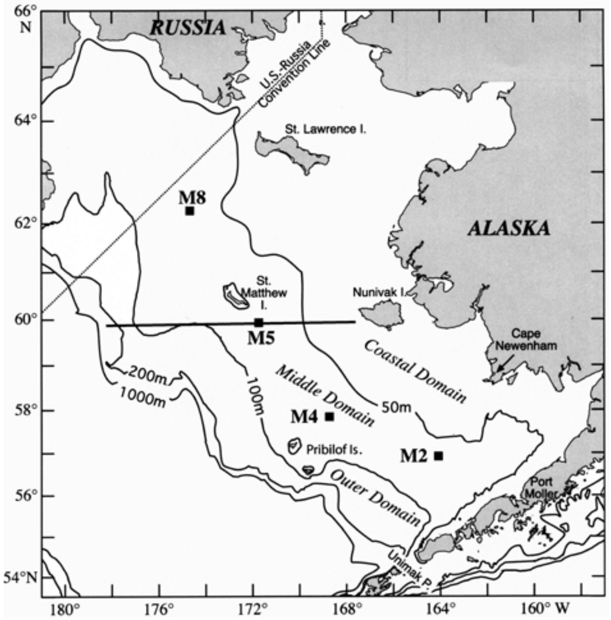
[Figure BS-2] Schematic diagram of the major currents in the Bering Sea. BSC – Bering Slope Current; ACC- Alaska Coastal Current; ANSC- Aleutian North Slope Current. Modified from Stabeno et al. 1999a, courtesy of N. Kachel, NOAA Pacific Marine Environmental Laboratory, Seattle, WA.

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

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

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

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

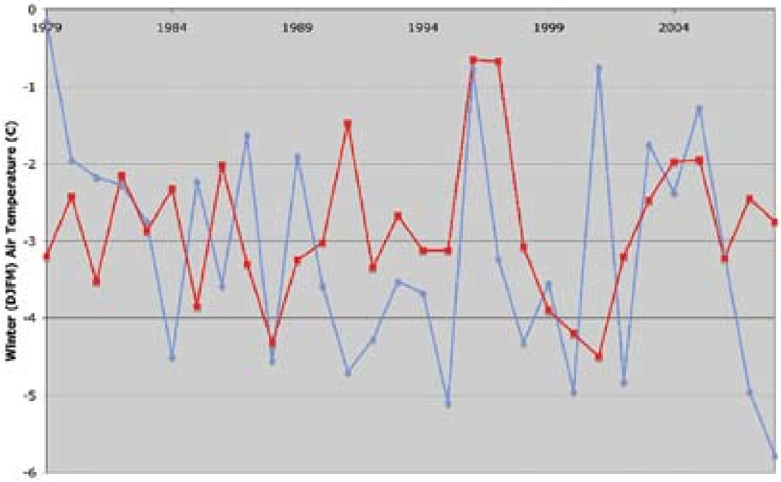


[Figure BS-3] Southeastern Bering Sea shelf showing isobaths, domains and the location of NOAA's biophysical Moorings M2, M4, M5, and M8. Horizontal line through M5 is the MN line of the BEST / BSIERP Program. Map courtesy of N. Kachel, NOAA Pacific Marine Environmental Laboratory, Seattle, WA.

2.0 Atmosphere *(Bond)*

2.1 Temperature

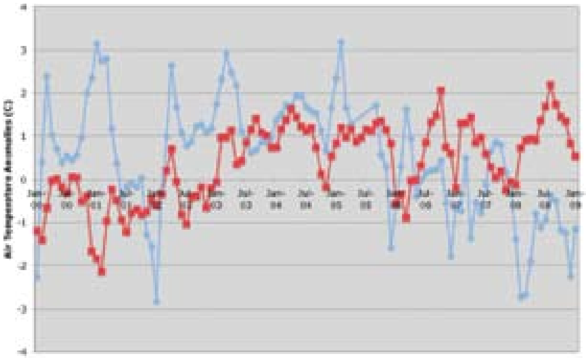
Context for the recent weather of the Bering Sea is provided by Figure BS-4, which portrays seasonal mean winter (December-March) air temperatures observed along the western Bering Sea coast at Nikolski (55.2°N 166.0°E) and on the eastern Bering Sea shelf at St. Paul Island (57.2°N 170.2°W) for the period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



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

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

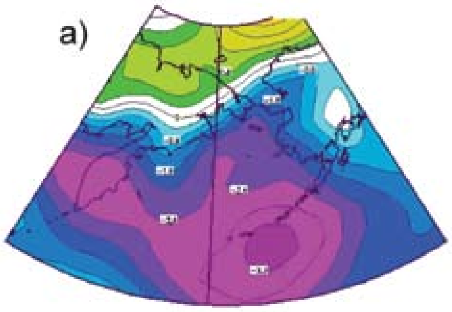
A more detailed perspective on the weather of the Bering Sea over the last few years is offered by the 3-month running mean temperature anomalies (referenced to means for 1971-2000) at Nikolski and St. Paul (Fig. BS-5). Note that Nikolski tends to experience considerably greater season-to-season persistence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



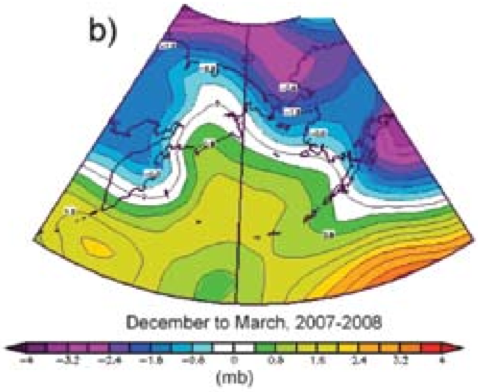
[Figure BS-5] Air temperature anomalies (°C) at Nikolski (red) and St. Paul (blue). Values are three-month running means referenced to a base period of 1971-2000.

2.2 Sea level pressure

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



December to March, 2003-2005

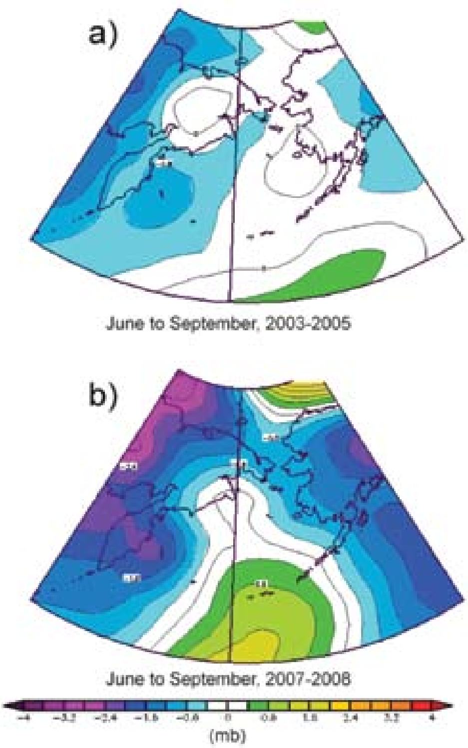


December to March, 2007-2008

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

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

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



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

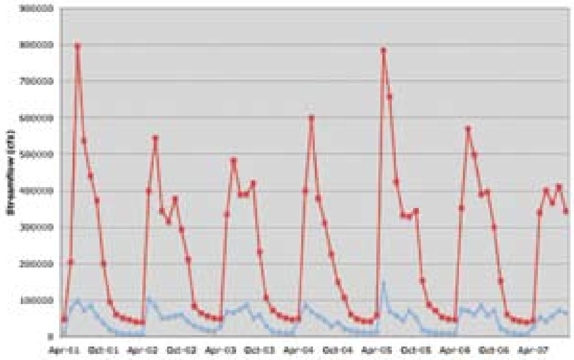
[Table BS-1] Summer cloudiness and wind mixing. The cloud fractions are averages for June through September of each year, and for a western region of 55-60°N, 165-175°E, and an eastern region of 55-60°N, 170-160°W. The source of these data is the NCEP Real-time Marine Data. The wind mixing index is for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

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

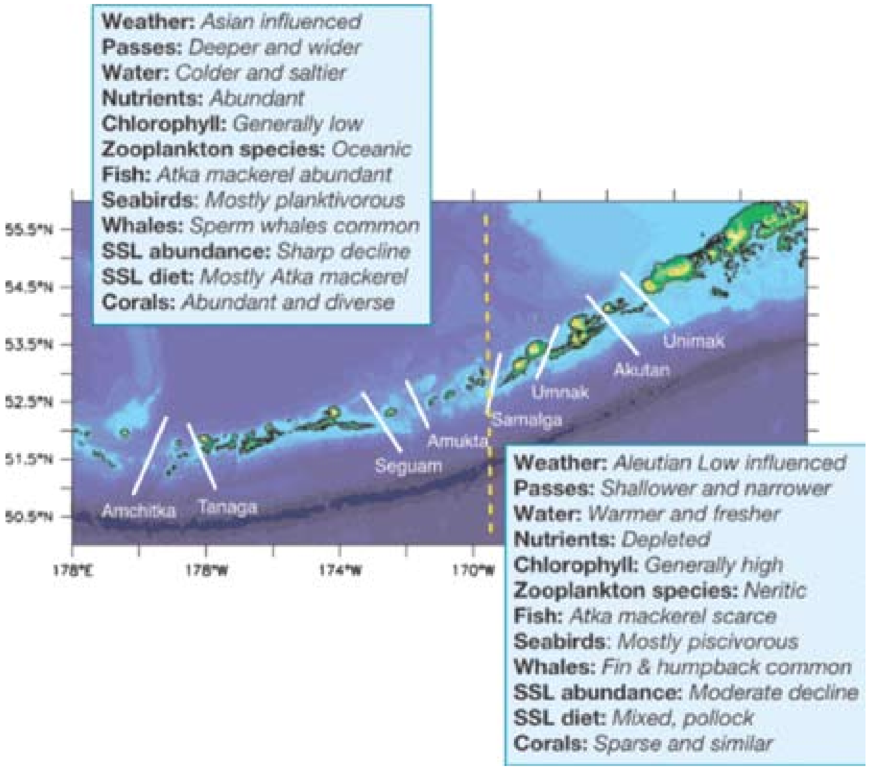
in the western region, with relatively cloudy conditions tending to coincide with the relatively calm (reduced wind mixing) warm seasons of 2004, 2005 and 2007 for the eastern Bering Sea.

2.3 River inputs

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



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



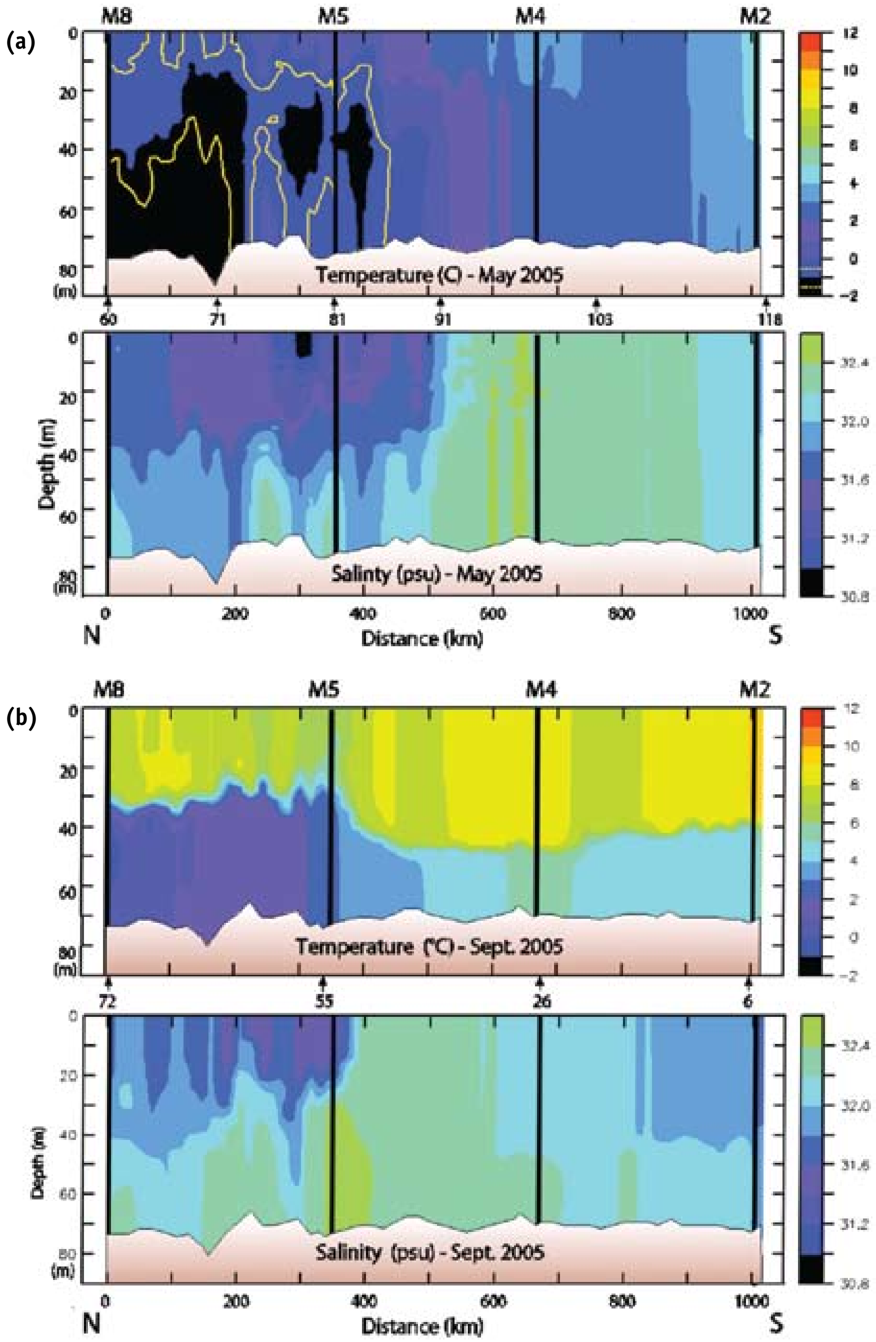
[Figure BS-9] Many Aleutian marine environmental attributes change in the vicinity of Samalga Pass, suggesting that the marine ecosystem of the archipelago may be differentiated into multiple, ecologically distinct regions. Future examination of status and trends in the Aleutians may require separate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

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

3.1 Fluxes and currents

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

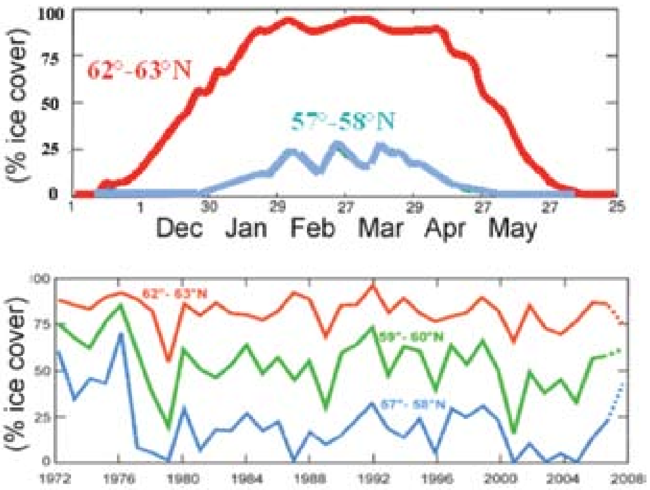
Just as transport through the Aleutian passes influences the water properties in the Bering Sea, northward flow through Bering Strait influences the Arctic (Woodgate 2006 et al.). There was an increase of northward transport during 2001-2005, likely a result of the weaker southward winds that occurred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



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

3.2 Hydrography and structure

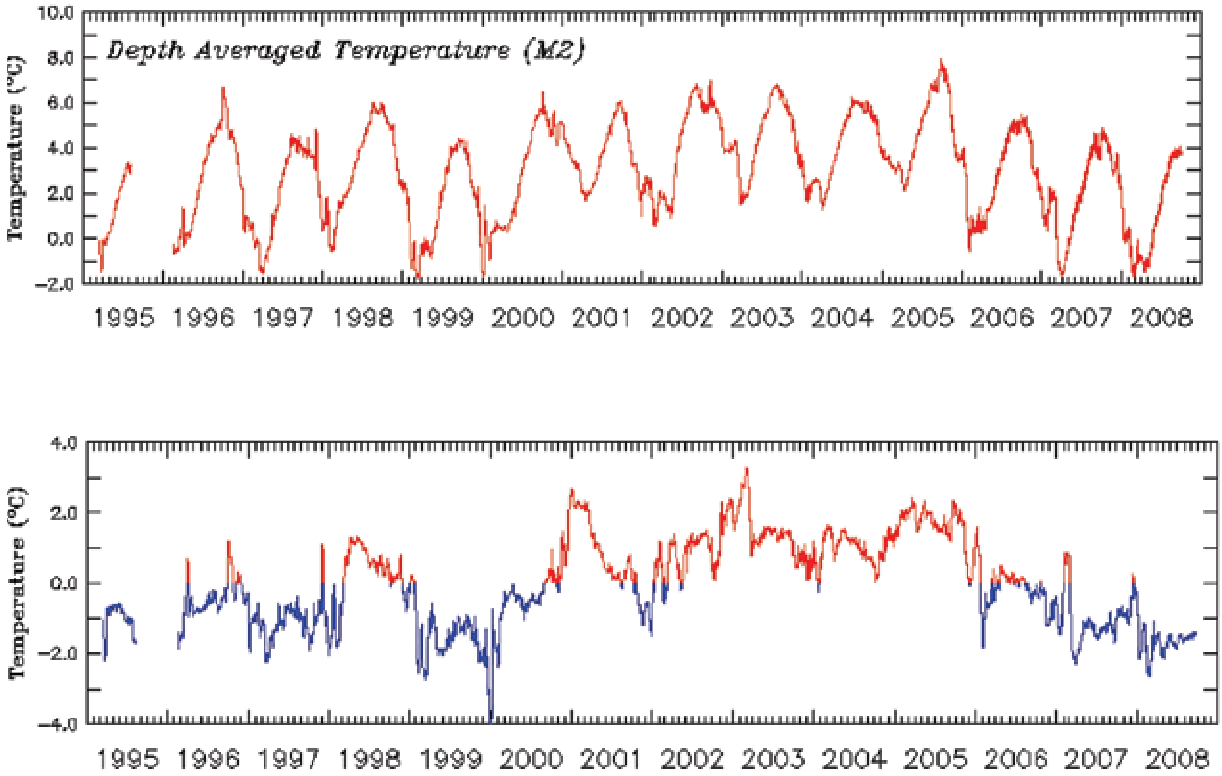
The cross-shelf variability on the eastern Bering Sea shelf has been noted by many scientists (e.g., Schumacher et al. 1979; Kinder and Schumacher 1981; Kachel et al. 2002). Described more recently is the frontal structure that forms south of St. Matthew Island during the summer (Stabeno et al. 2010).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



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

3.3 Seasonal sea ice

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



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

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

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

3.4 Variability in the cold pool

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

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

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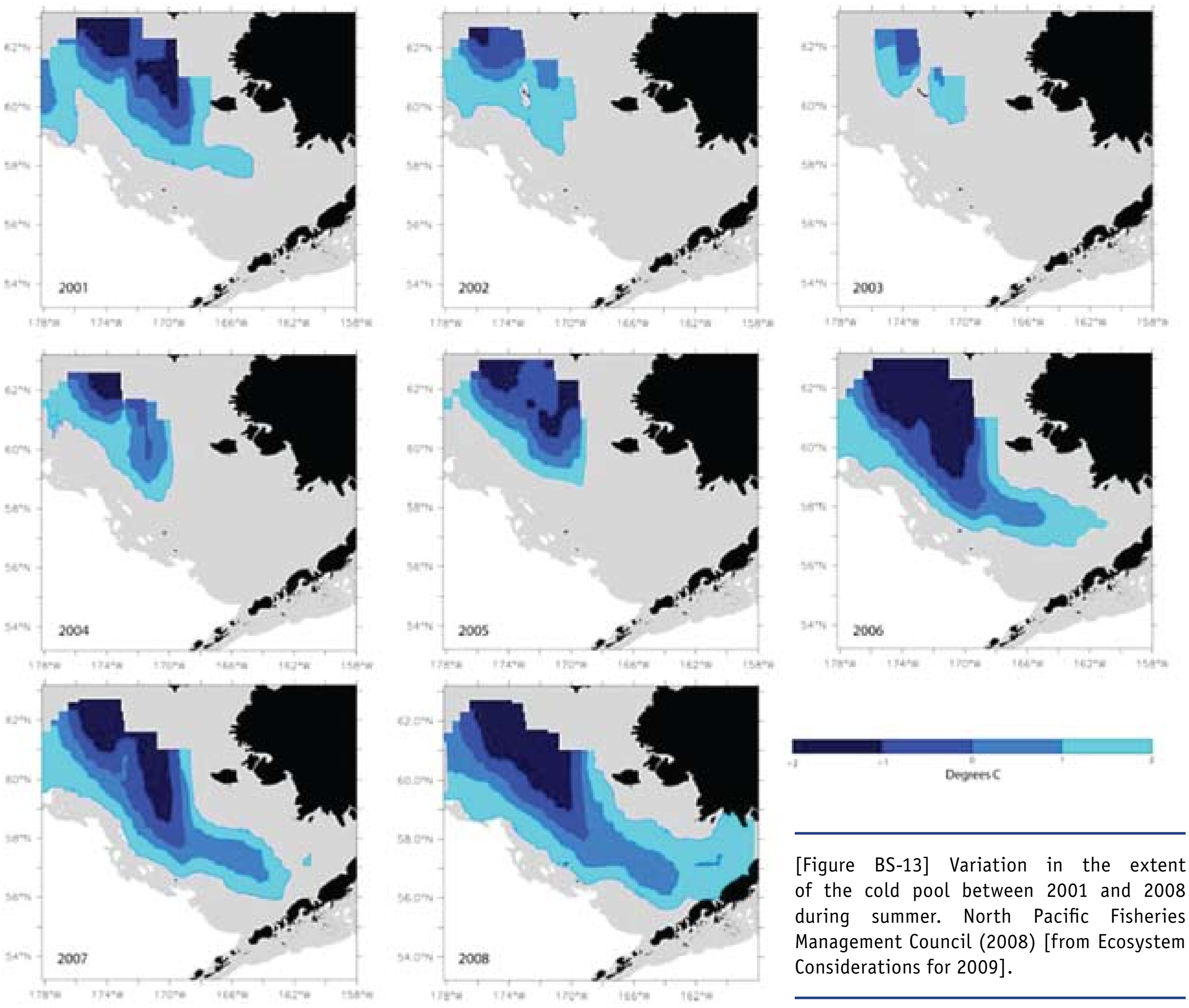
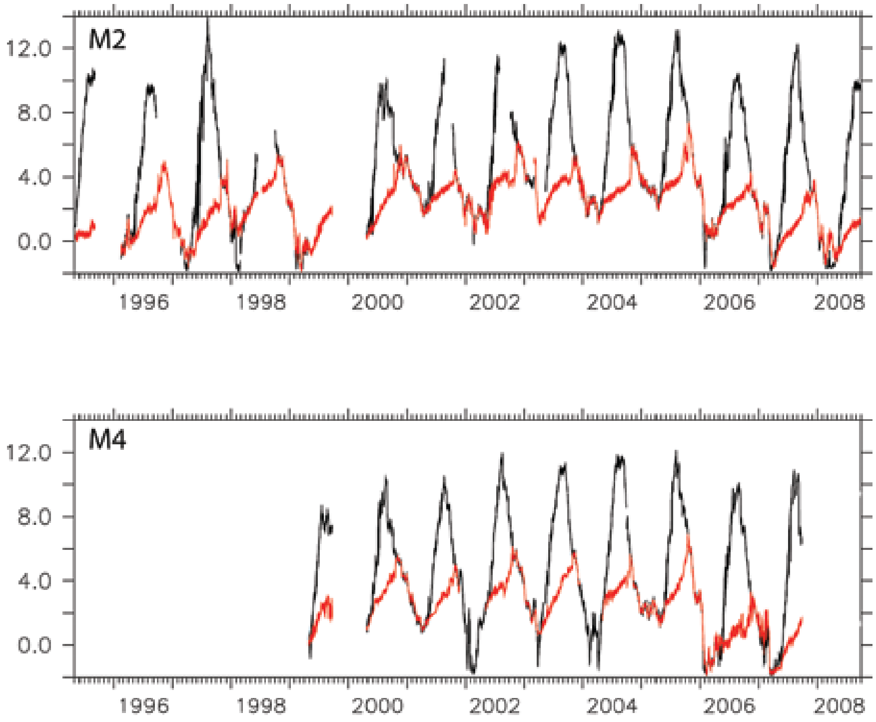


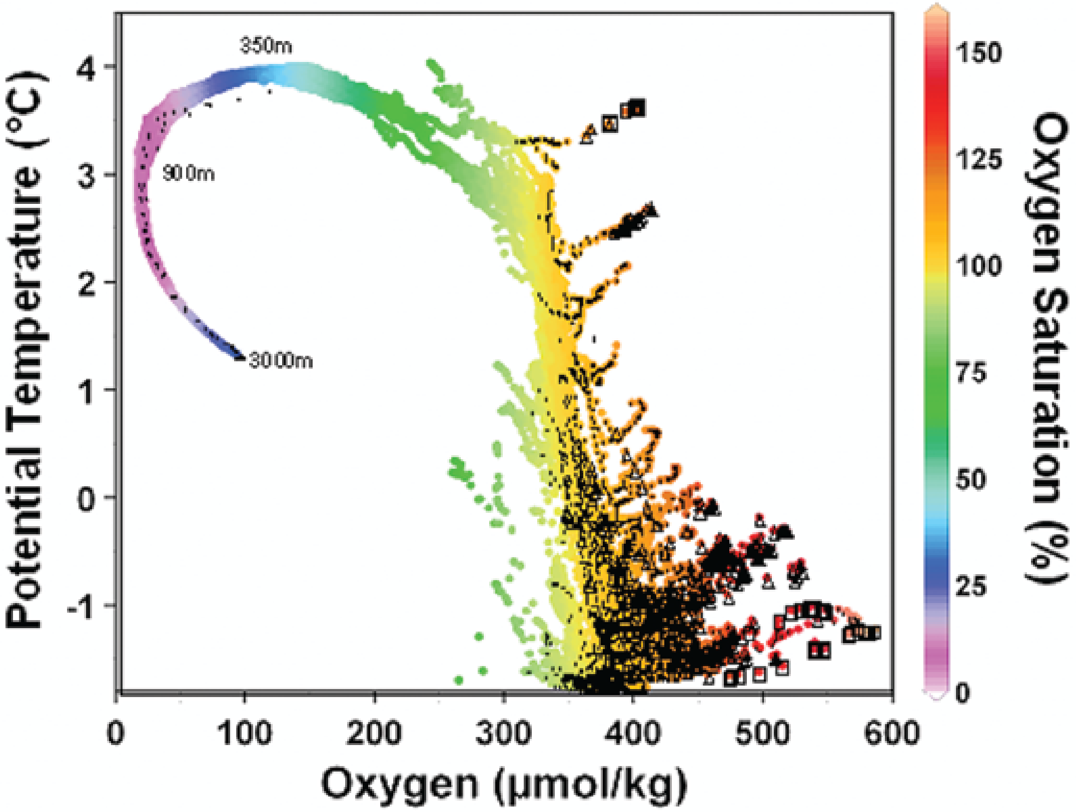
[Figure BS-13] Variation in the extent of the cold pool between 2001 and 2008 during summer. North Pacific Fisheries Management Council (2008) [from Ecosystem Considerations for 2009].

3.5 Eastern Bering Sea stratification

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



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



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

4.0 Chemical Ocean

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

4.1 Oxygen saturation

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

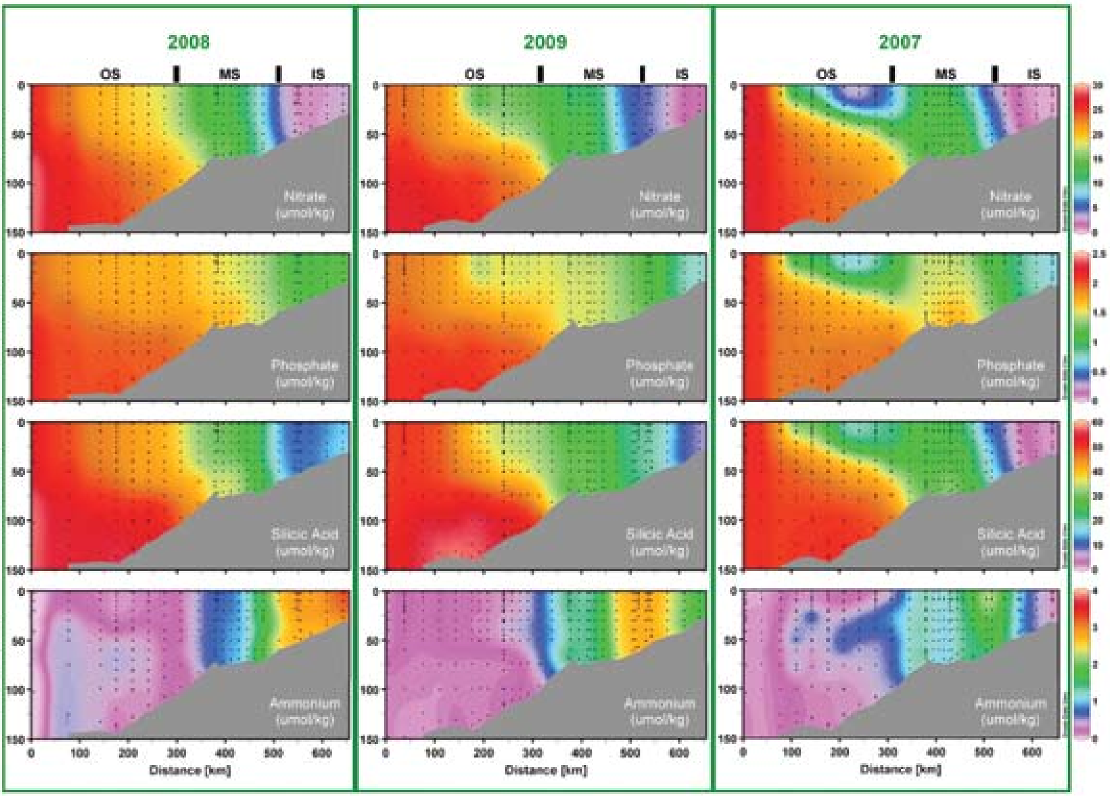
4.2 Interannual variation in seasonal nutrient dynamics on the Bering Sea Shelf

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

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

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

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



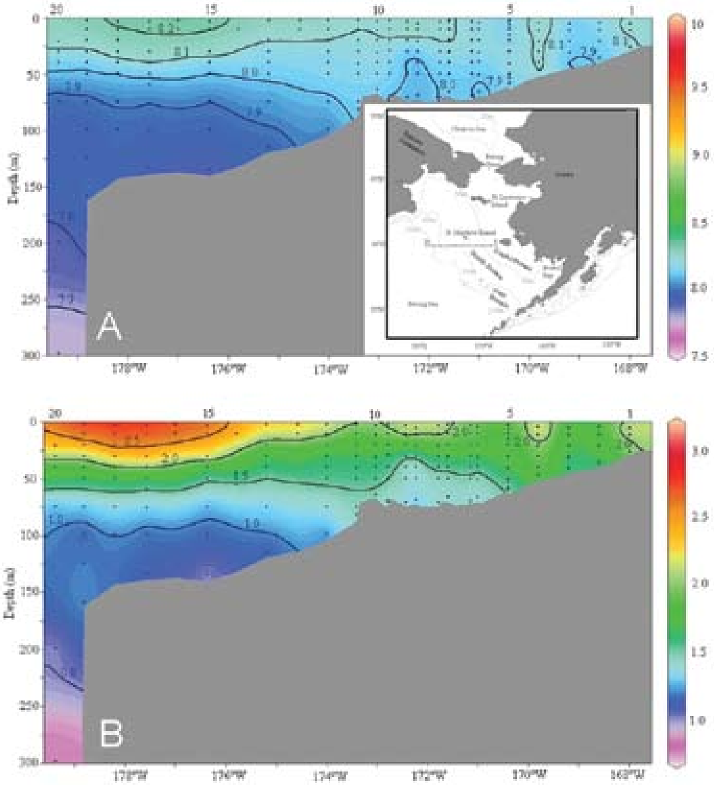
[Figure BS-16] Vertical sections of nutrients in April-May 2007-2009 along the MN line (See Fig. BS-3) in the eastern Bering Sea. Years are presented in order of decreasing nitrate. The Outer, Middle and Inner domains are indicated on the top figure for each year (OS, MS, and IS respectively). Data were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

4.3 Dissolved iron

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

4.4 Ocean acidification

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



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

5.0 Phytoplankton Biomass and Primary Production *(Eisner)*

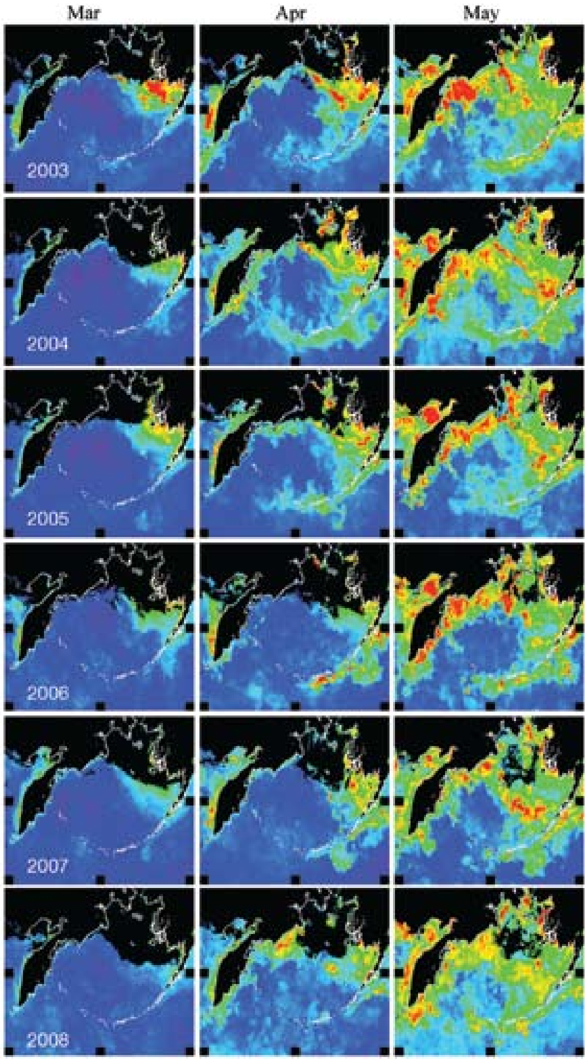
5.1 Spatial and temporal distribution of chlorophyll

5.1.1 Satellite ocean colour data

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

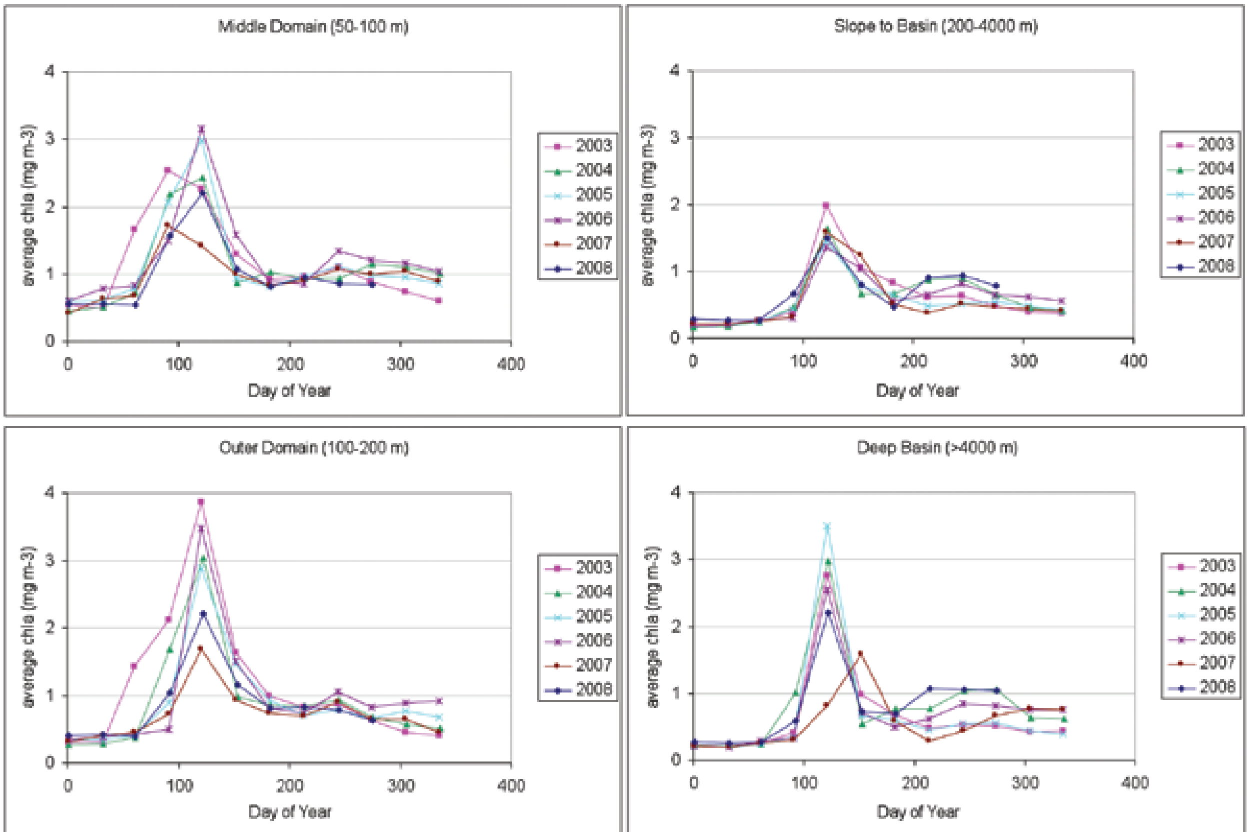
Monthly average chlorophyll$_a$ data indicate that the peak biomass was observed in May for the Middle Domain, Outer Domain, slope to basin and deep basin, with exceptions in April 2003 and 2007 for the Middle Domain, when April and May biomass was comparable, and in June 2007 for the deep basin (Fig.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

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



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

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



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

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

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

5.1.2 Mooring fluorometer data

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

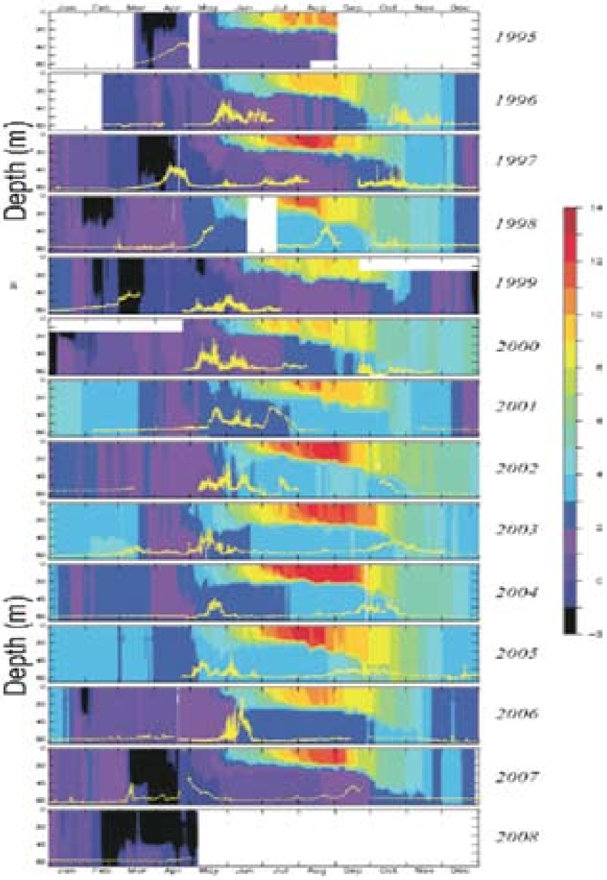
At M4, spring blooms were observed earlier than at M2 (March and April) for both warm and cold years, but peaked in May, as typically seen at M2. The sea surface temperature (SST) was often ~ 4°C when the spring bloom peak was observed at M2 (e.g. 2003-2006) (Fig. BS-20). These were all years in which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

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

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

5.1.3 Comparisons of ocean colour and mooring data

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



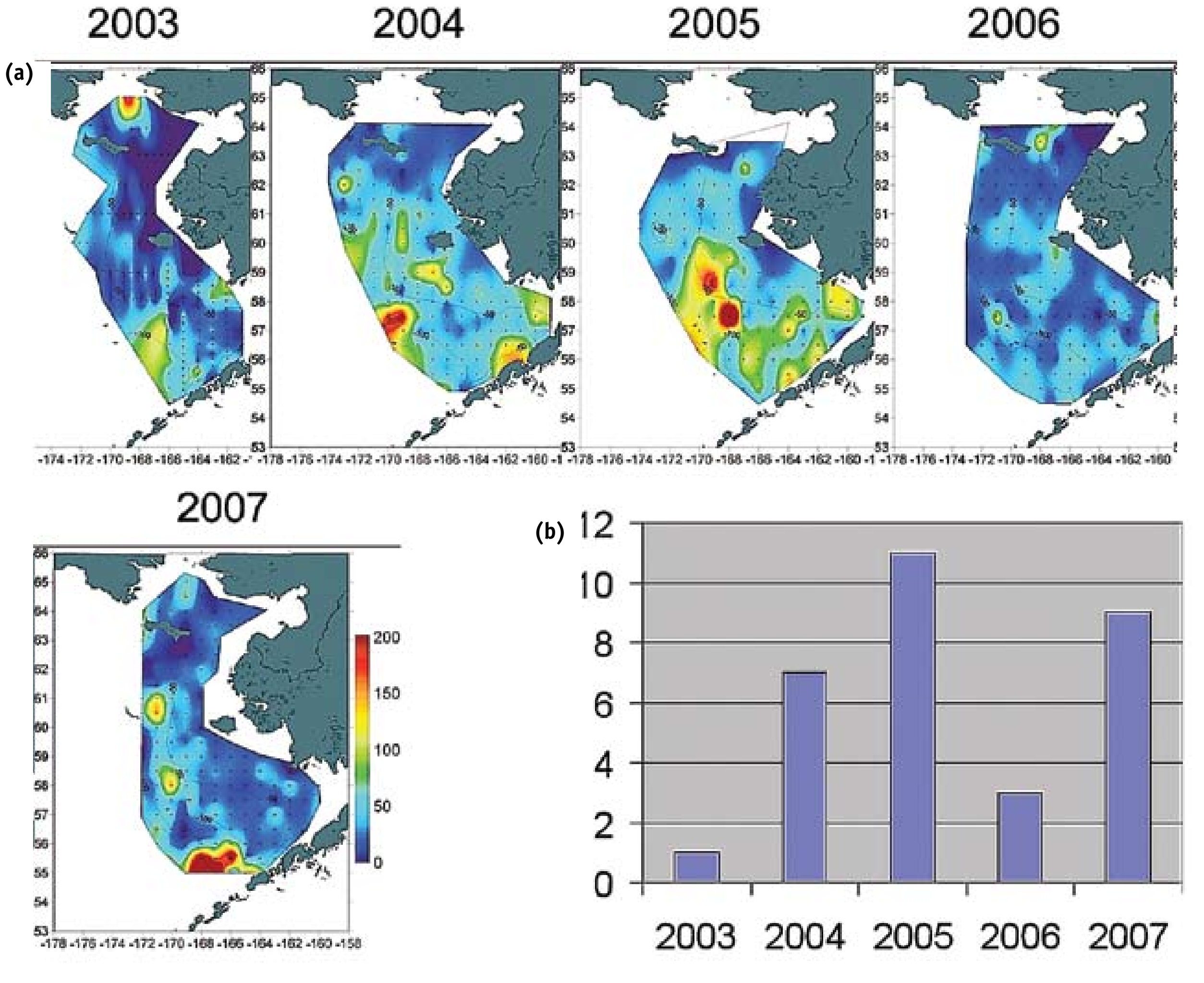
[Figure BS-20] Temperature contours overlaid with surface chlorophyll$_a$ fluorescence trace (yellow line) from mooring M2 for 1995-2008. Data courtesy of Phyllis Stabeno, EcoFOCI / PMEL/NOAA.

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

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

5.1.4 Fall chlorophyll data

Late summer/early fall integrated chlorophyll$_a$ were patchy during all years with more "hot spots" (i.e. high values) seen in 2004, 2005 and 2007, coinciding with an increase in wind events (wind speed cubed $> 0.4 \times 10^4 m^3 \cdot s^{-3}$) during August and September (Fig. BS-21). Mean integrated chlorophyll$_a$ values were high in 2004 and 2005 (warm years), low in 2006 and 2007 (cold years) and average in 2003 (warm year) (ANOM for ln transformed data, $p < 0.05$, Table BS-4). The low chlorophyll$_a$ seen in 2003 during the late summer (August to September) surveys supports the idea of a late fall bloom (started in October at M2) due to the reduced number of late summer wind events (Fig. BS-21b).



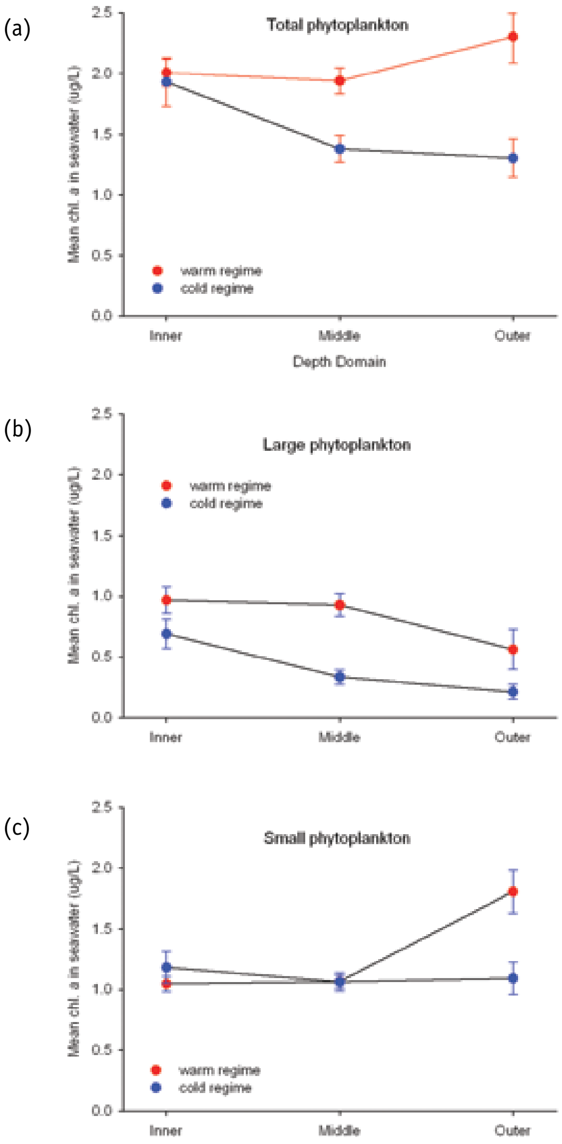
[Figure BS-21] a) Integrated water column chlorophyll$_a$ (mg·m^{-2}) from discrete chlorophyll$_a$ samples collected mid-August to early October for 2003-2007 (BASIS/ABL/AFSC/NOAA), and b) Number of wind events, defined as wind speed cubed greater than 0.4 x10^4 m^3·s^{-1}, during August and September in SE Bering Sea (near M2).

5.1.5 Surface chlorophyll

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

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

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



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

5.1.6 Surface size-fractionated chlorophyll

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

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

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

5.1.7 Net primary production

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

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

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

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

5.1.8 Conclusions

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

6.0 Microzooplankton *(Sherr, Strom)*

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

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

6.1 Biomass and seasonal cycles

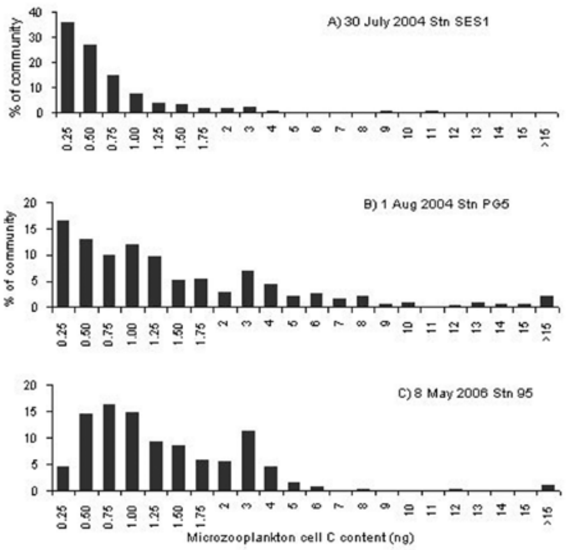
To date, data on the biomass of microzooplankton in the Bering Sea, mainly ciliates and heterotrophic dinoflagellates, are limited to early spring and mid-summer and have all been collected in the eastern Bering Sea. Overall biomass levels ranged from 2 to 178 µgC·l^{-1} (Table BS-6). Two early spring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

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

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

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

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



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

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

6.2 Growth rates

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

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

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

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

6.3 Microzooplankton as grazers of phytoplankton

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

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

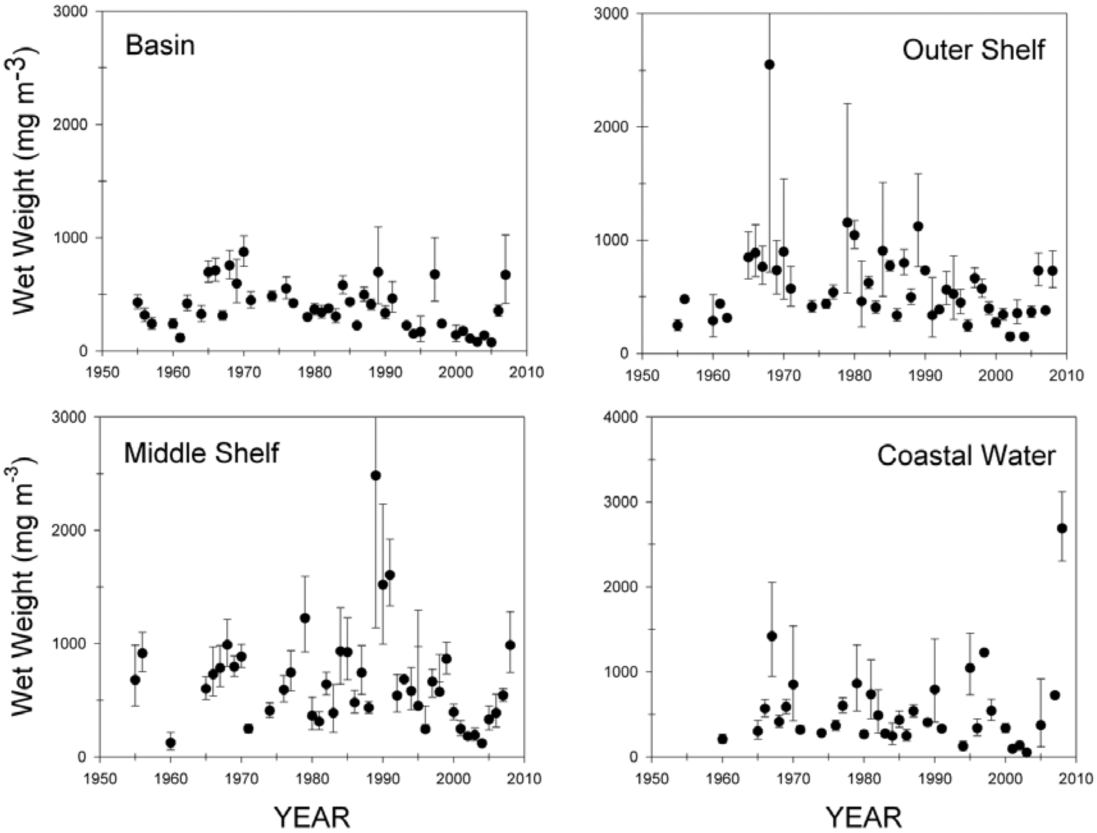
7.0 Mesozooplankton *(Napp, Coyle, Eisner)*

7.1 Total mesozooplankton biomass

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

7.2 Species composition

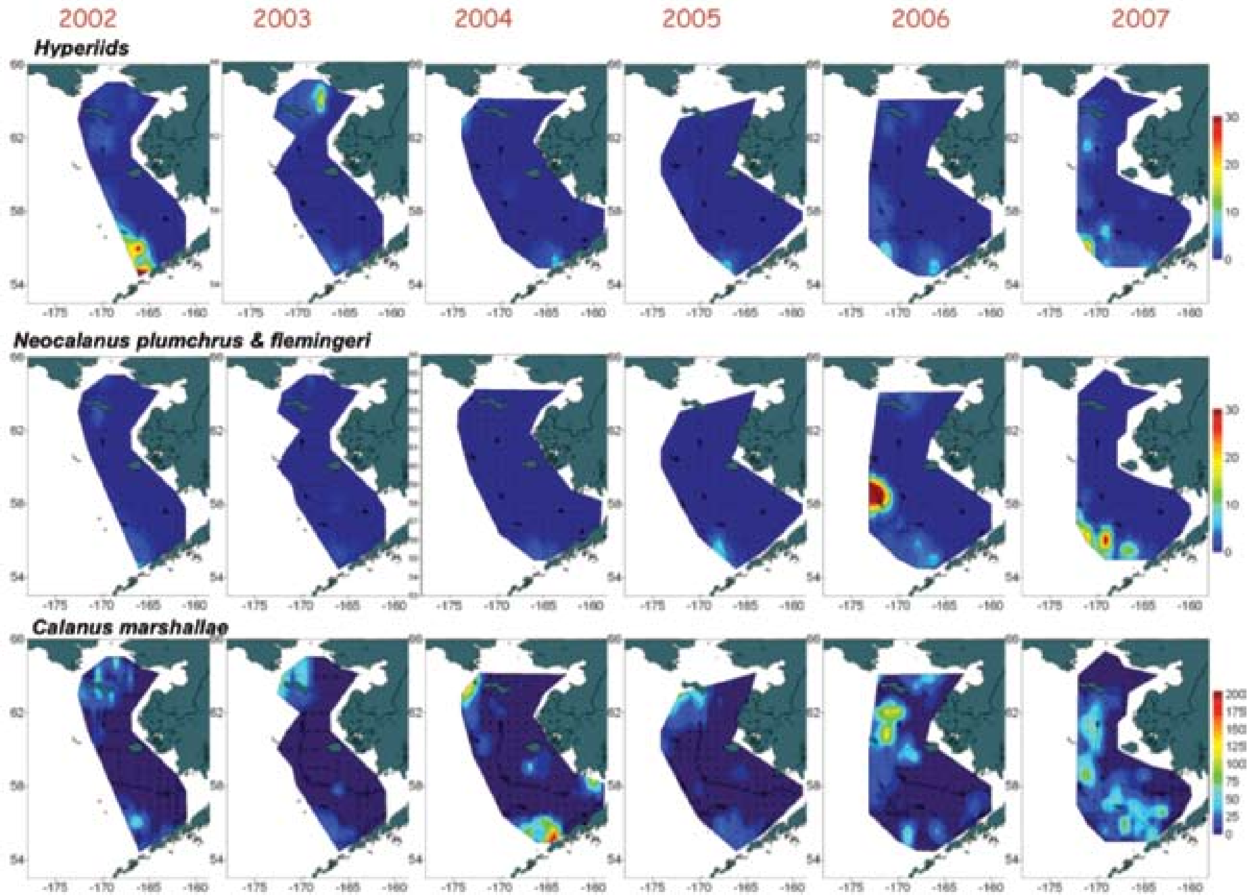
The species composition of the zooplankton community is important to the transfer of energy to higher trophic levels because of the sensitivity of predators to prey size and the timing of prey availability. The recent alternation of warm and cold years has given us limited insight into how temperature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



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

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

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

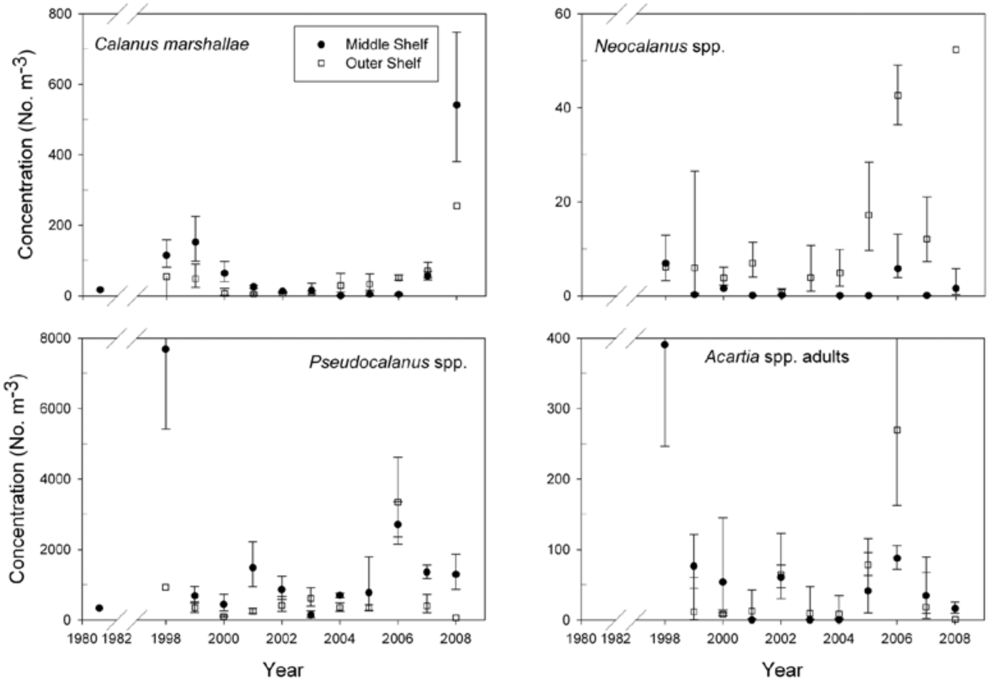


[Figure BS-25] Distribution and abundance (#·m⁻³) of large zooplankton sampled by a 505 µm mesh Bongo net in the BASIS program, 2002-2007. Figure courtesy of Lisa Eisner.

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

7.3 Interannual variations in seasonal patterns of zooplankton species abundance

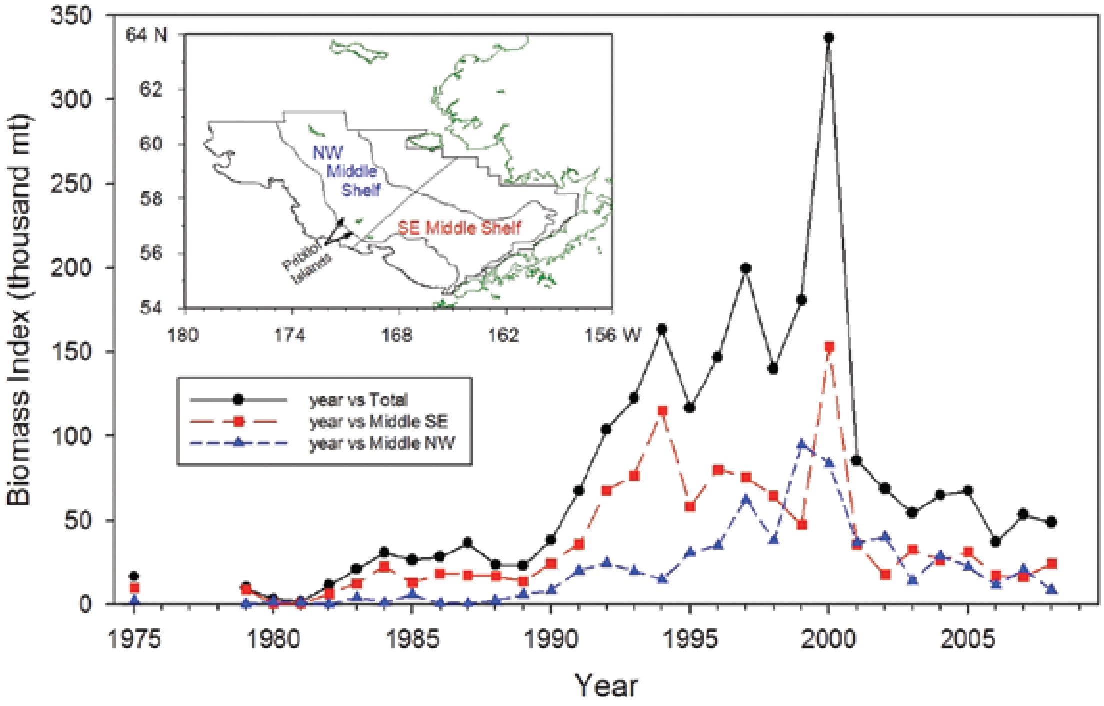
Insight has also been gained into fluctuations in species composition by comparing the results from process studies that occurred under different conditions. For example, comparison of plankton abundance and biomass between a cold year in the Inner Front Study (1999) and a warm year during the Pribilof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



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

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

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



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

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

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

7.4 Mechanisms

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

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

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

7.5 Significance

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

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

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

8.0 Fishes and Invertebrates

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

8.1 Species composition and diversity

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

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

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

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

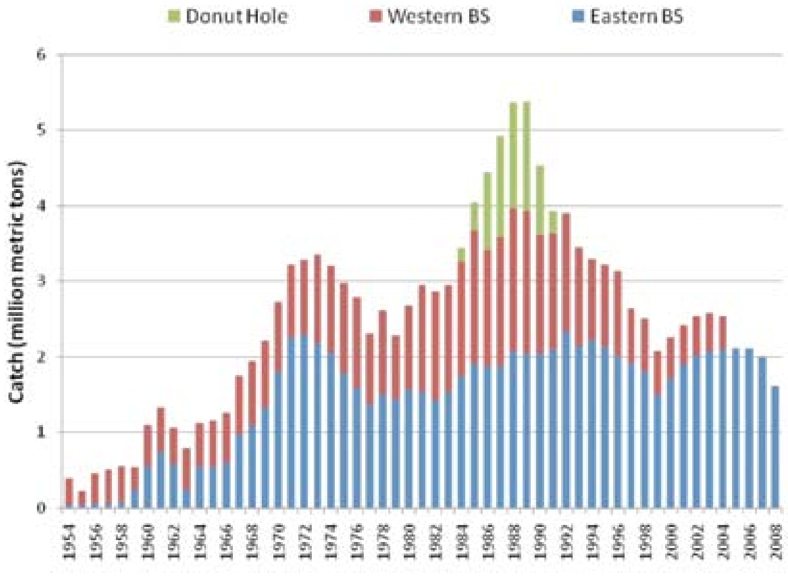
The relative abundances of different species in the Bering Sea have undergone large changes as a result of fishing as well as natural variability. Recent trends in major commercial stocks are summarized below in the context of long-term variability. Variability in forage fishes, including mesopelagic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

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

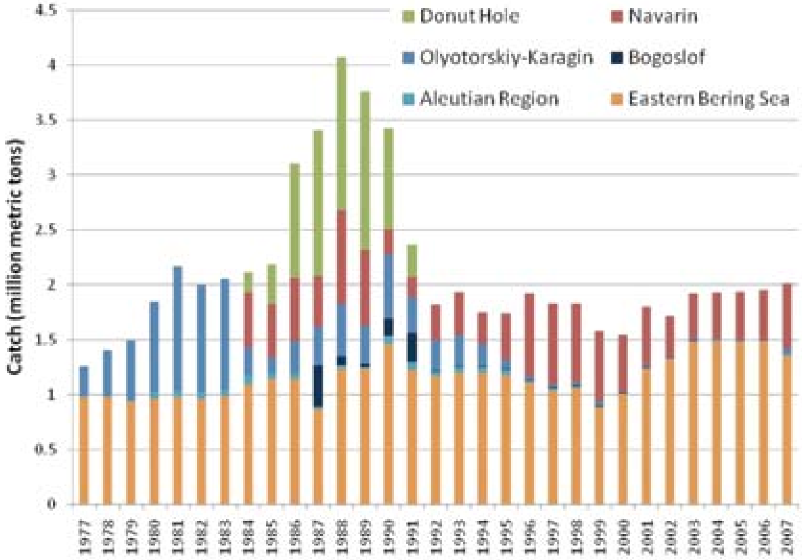
In subsequent sections catches and, where available, biomass and recruitment trends of major commercial species are summarized for three areas: the Russian Exclusive Economic Zones (EEZ) along the continental shelf and slope of the western Bering Sea, the EEZ of the United States along the eastern Bering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

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

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



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

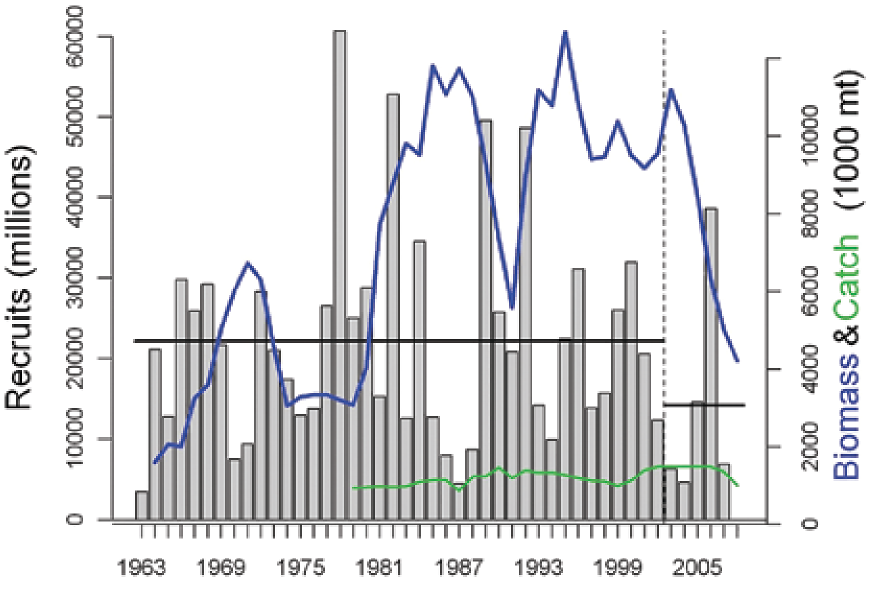


[Figure BS-29] All-nation historical catches of walleye pollock from the Bering Sea (million t), 1977-2008. Source: Report of the 13th Annual Conference of the parties to the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea.

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

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

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



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

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

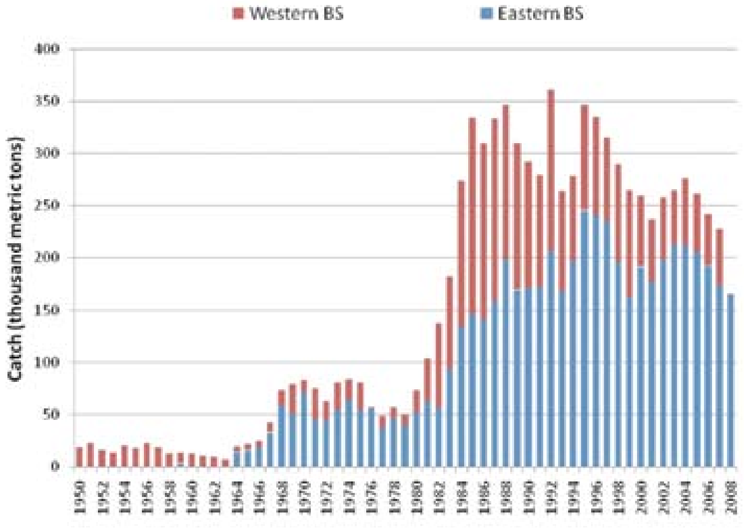
Walleye pollock increasingly shifted their distribution into the northwestern Bering Sea during the summers and falls of 2003-2008, but the reason for this behavior may have differed among years. In 2003-2006, the abundance of zooplankton in the southeastern Bering Sea was relatively low (Volkov et al.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

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

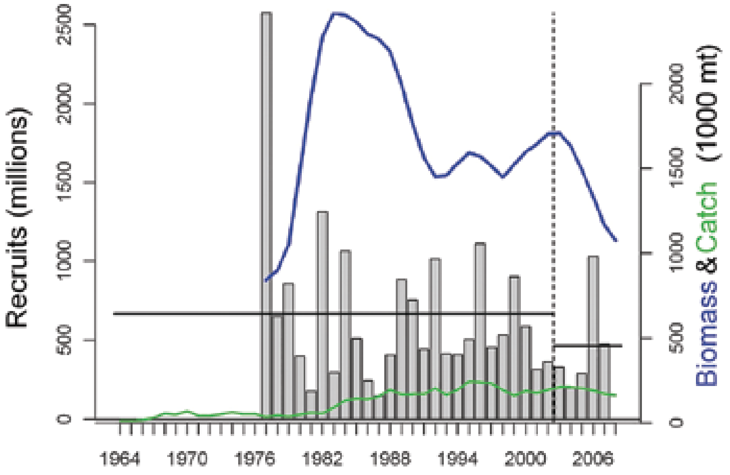
Pacific cod, a large demersal gadid, is abundant throughout the shelf and upper slope areas of the Bering Sea and Aleutian Islands, and is the target of the oldest groundfish fishery off Alaska. Catches in both the eastern and western Bering Sea increased dramatically in the 1980s. Catches since then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

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

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



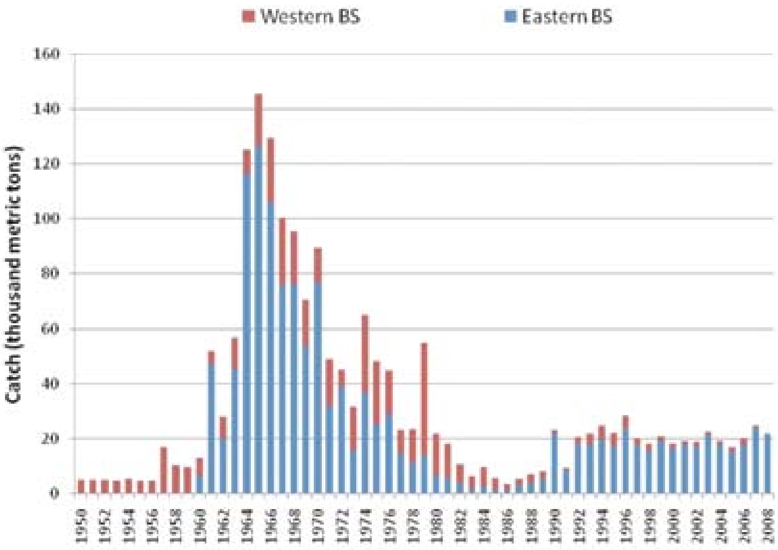
[Figure BS-31] Historical catches of Pacific cod in the Bering Sea (thousand t), 1950-2008. Sources: Eastern Bering Sea catches from NPFMC (2008); western Bering Sea catches from the United Nations Food and agricultural Organization (FAO) (http://www.fao.org/fishery/statistics/global-capture-production/en)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



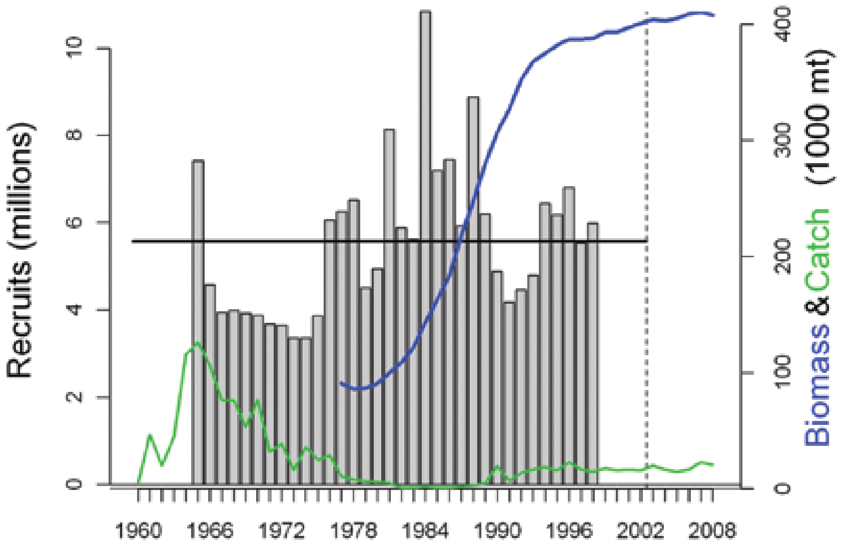
[Figure BS-32] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of Pacific cod in the eastern Bering Sea (Source: NPFMC 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different, p =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

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

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



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

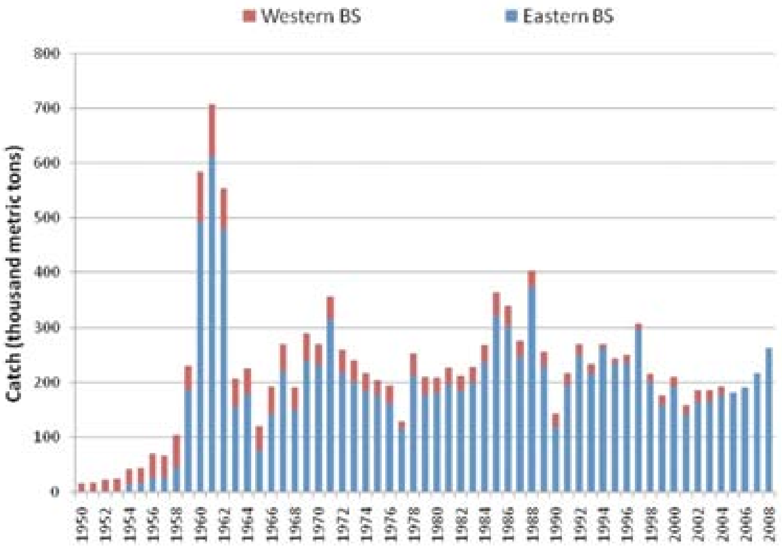


[Figure BS-34] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of Pacific ocean perch in the eastern Bering Sea (Source: NPFMC, 2008). Catches include all species that were reported and managed as part of the "POP complex" prior to 2004. Horizontal bar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

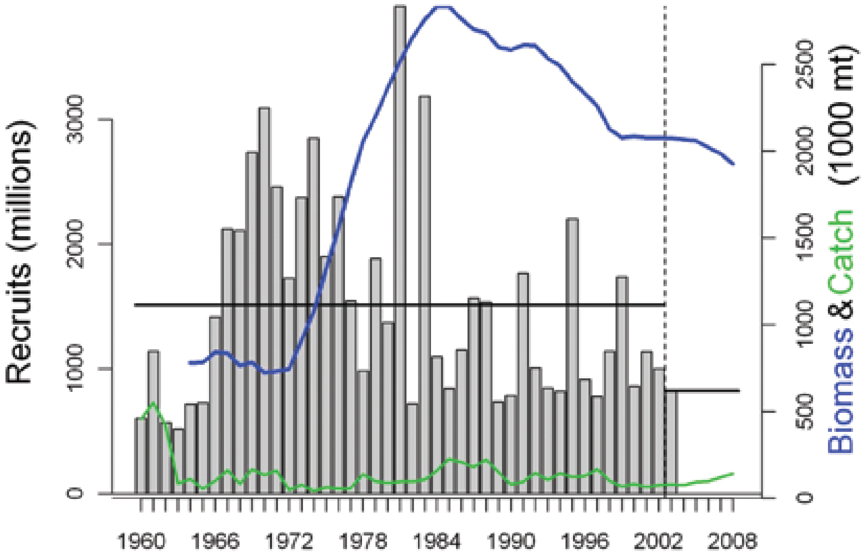
at the highest levels that have been observed over recent decades, reflecting favorable environmental conditions and conservative exploitation rates.

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

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



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

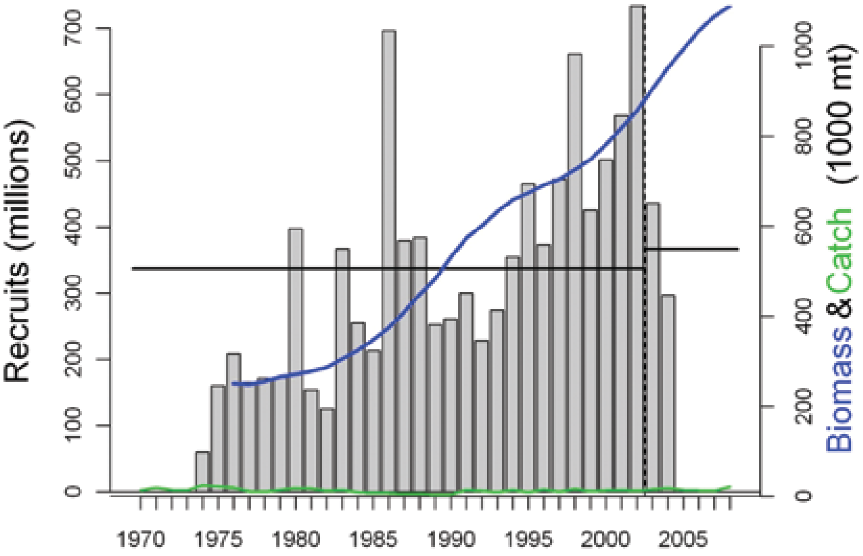


[Figure BS-36] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of yellowfin sole in the eastern Bering Sea (Source: NPFMC, 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different,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

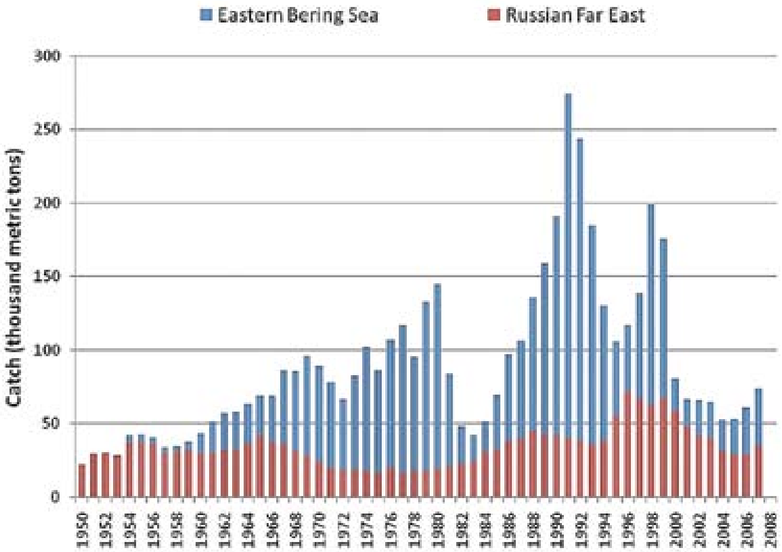
last several decades, hence changes in biomass are largely a result of recruitment variability. Of particular note is the steady increase in arrowtooth flounder biomass from 250,000 t in 1976 to over 1 million t in 2008 (Fig. BS-37). Exploitation rates are very low and arrowtooth flounder recruitment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

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

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



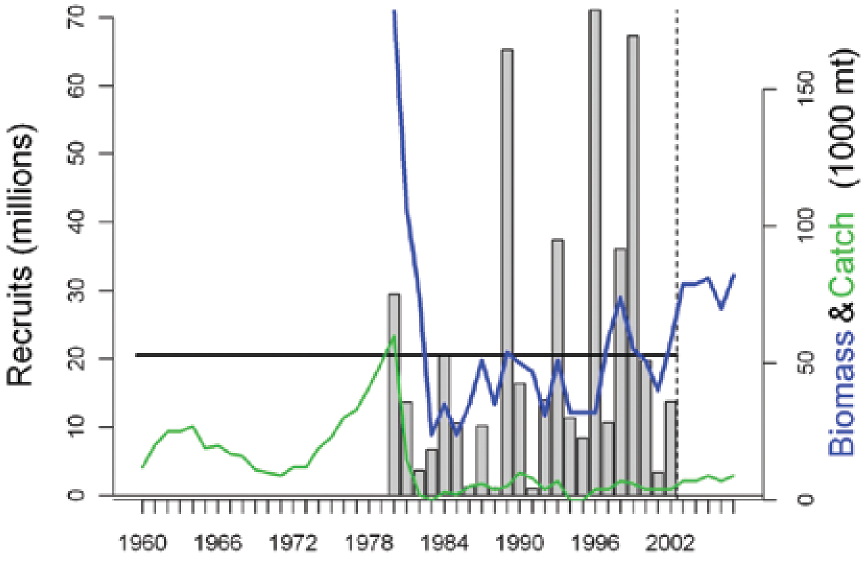
[Figure BS-37] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of arrowtooth flounder in the eastern Bering Sea (Source: NPFMC, 2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly different,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



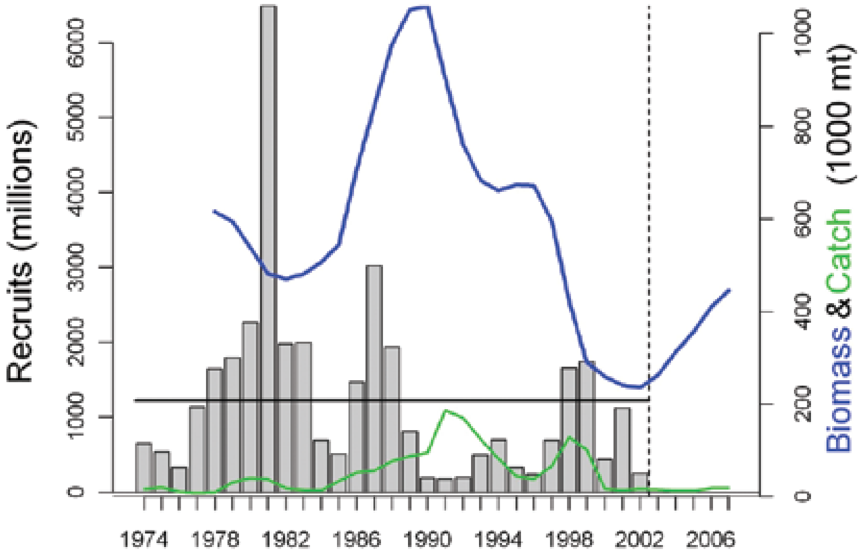
[Figure BS-38] Historical catches of all crabs in the Bering Sea (thousand t), 1950-2008. Sources: Eastern Bering Sea catches from Zheng and Siddeek (2008), Rugolo et al. (2008), and Rugolo and Turnock (2008); western Bering Sea catches from FAO consist of all crab landings reported by the Soviet Union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

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

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



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

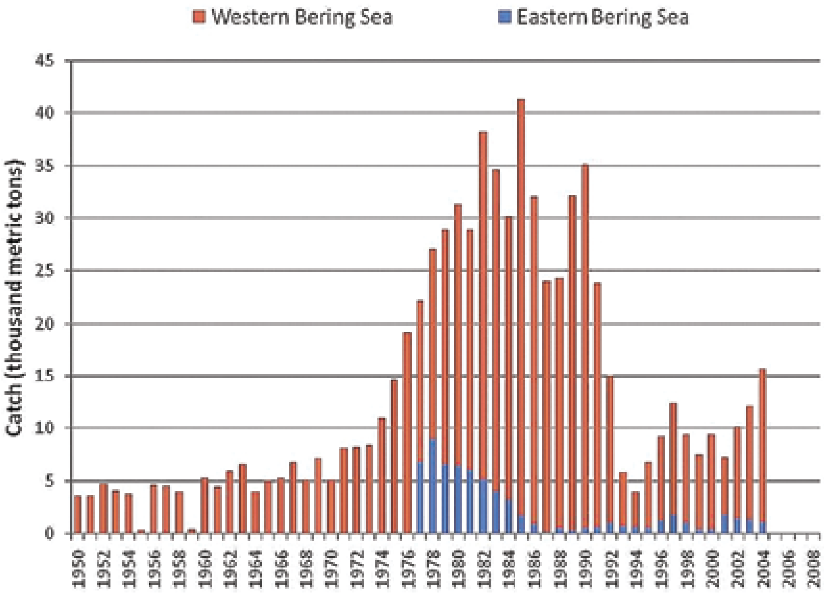


[Figure BS-40] Estimated mature biomass (blue line), fishery removals (green line) and recruitment of the 25-50 mm size class (bars) of snow crab in the eastern Bering Sea (Source: Zheng and Siddeek, 2008). Recruitment has been lagged to correspond to approximate year-class. Horizontal bar indicates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

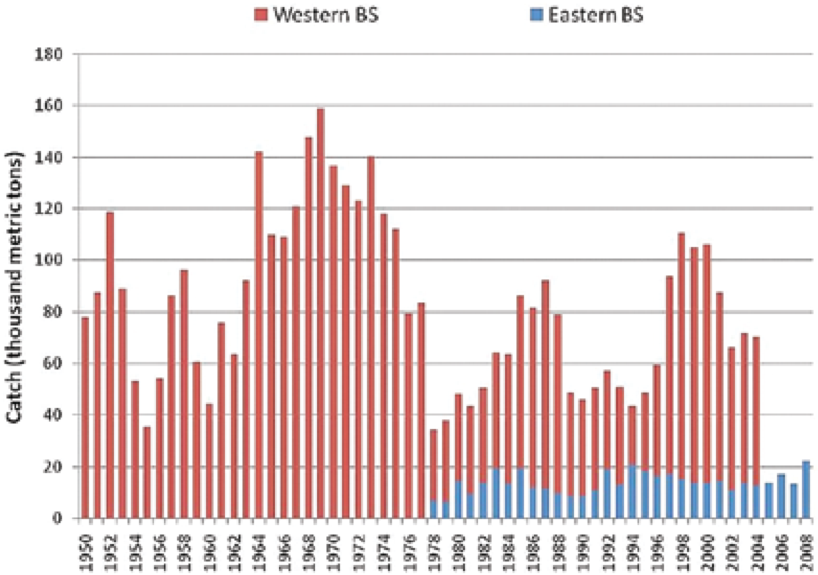
1998 and 1999. The most recent recruitment estimates, which approximately correspond to the 2000-2002 year classes, have all been below average.

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

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



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

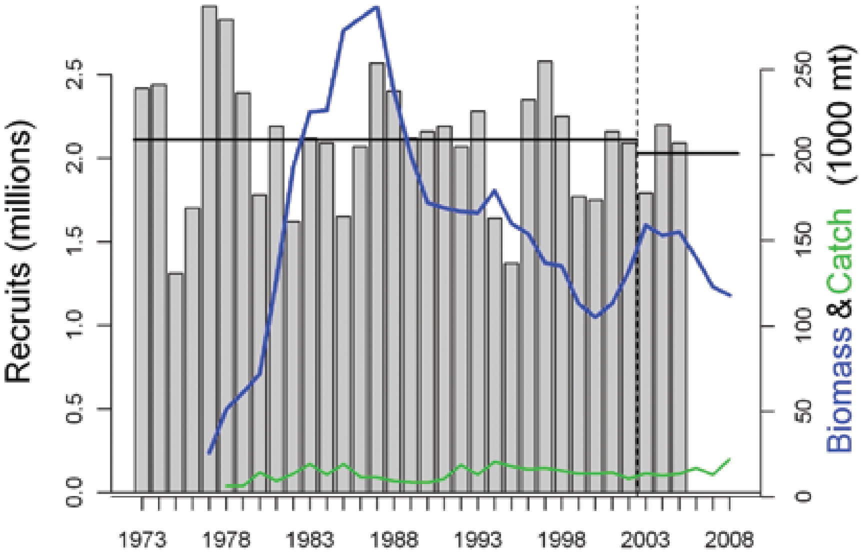


[Figure BS-42] Historical catches of Pacific herring in the Bering Sea (thousand t). Sources: Eastern Bering Sea catches from Gregory Buck (ADF&G, pers. comm.), 1978-2008; western Bering Sea catches through 2004 from the Sea Around Us Project (www.saup.org).

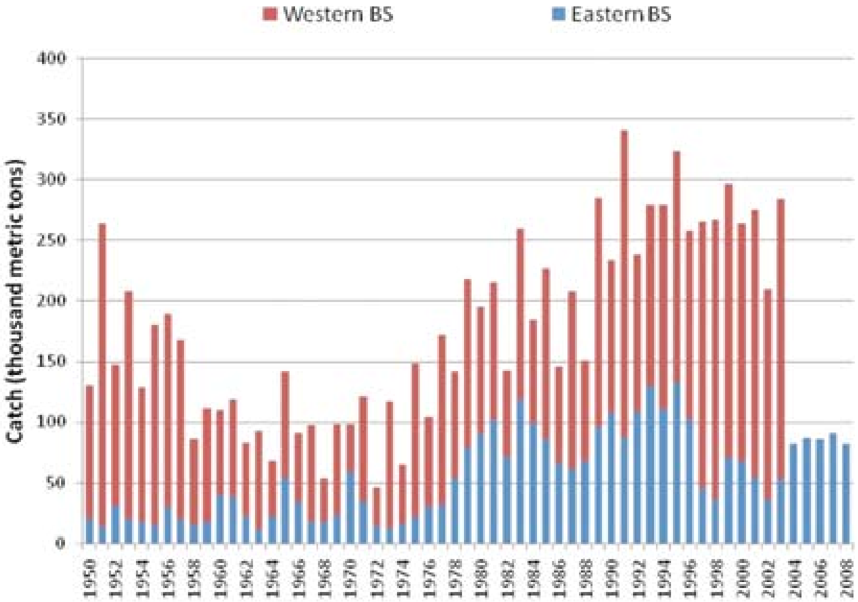
Sea have generally been under 20,000 t. Catches in the western Bering Sea have undergone cyclical fluctuations with peaks in 1952, 1969, 1987, and most recently, in 1998. In the eastern Bering Sea, the estimated biomass of the Togiak herring stock decreased from its peak of 287,000 t in 1987 to between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

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

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



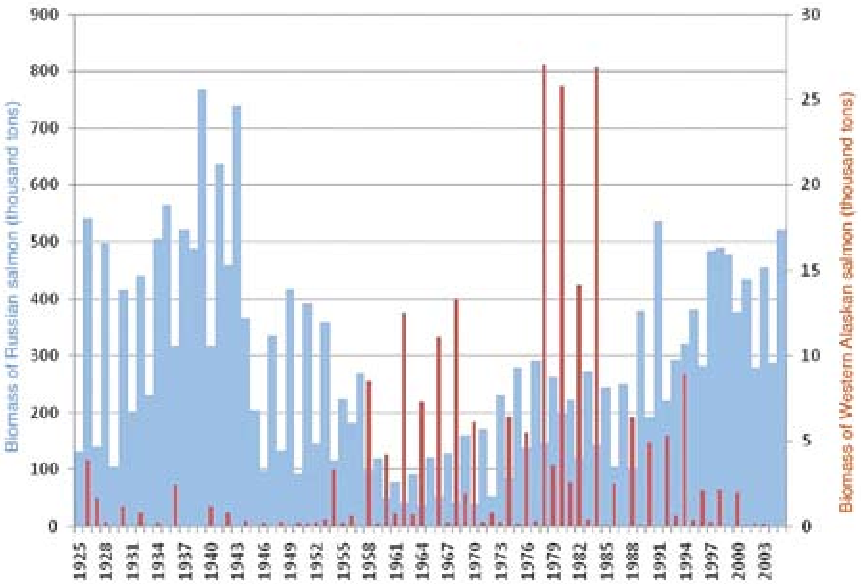
[Figure BS-43] Estimated biomass (blue line), fishery removals (green line) and recruitment by year-class (bars) of Pacific herring (Togiak stock) in the eastern Bering Sea from NPFMC (2008). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively (means not significantly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



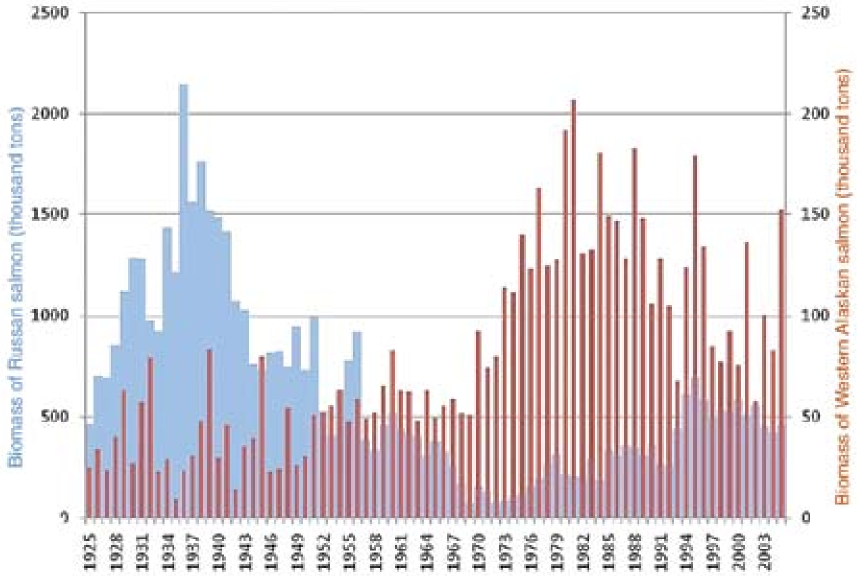
[Figure BS-44] Historical catches of all salmon species in the Bering Sea (thousand t). Source: Eggers (2010). Western Bering Sea catches include all of coastal Russia; an unknown proportion of these catches originate in the western Bering Sea. Catches of Bering Sea (western Alaska) stocks for 2006-2008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

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

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



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

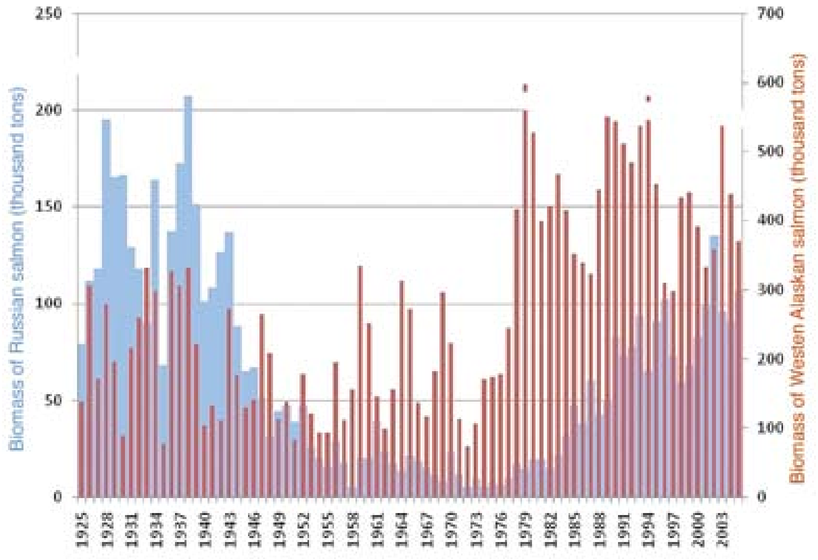


[Figure BS-46] Annual estimated biomass of western Alaska and Russian chum salmon (thousand t), 1925-2005, from Eggers (2010). Note difference in scale between the two biomass series.

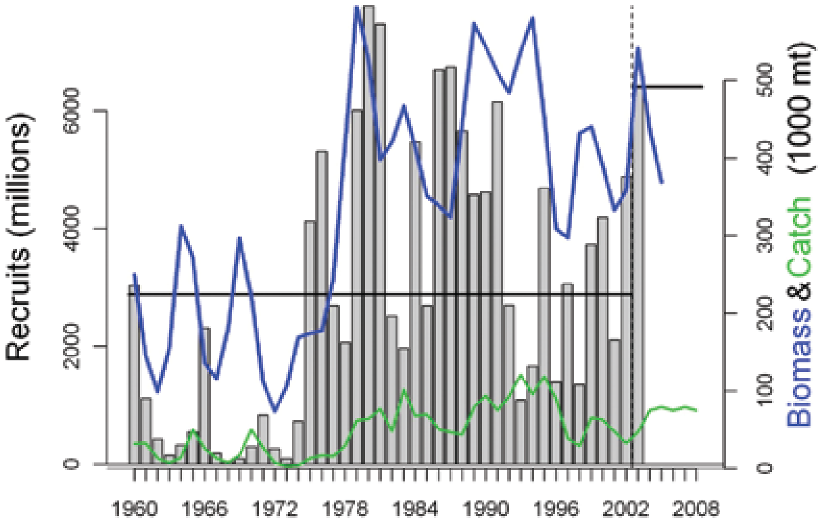
Alaska pink salmon were most abundant from the 1960s through the mid-1980s and decreased substantially after 1985. Both interannual (even/odd year) variability and long-term variability suggest a possible negative interaction between pink salmon from the east and west side of the Bering Sea (Rank correlation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

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

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



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

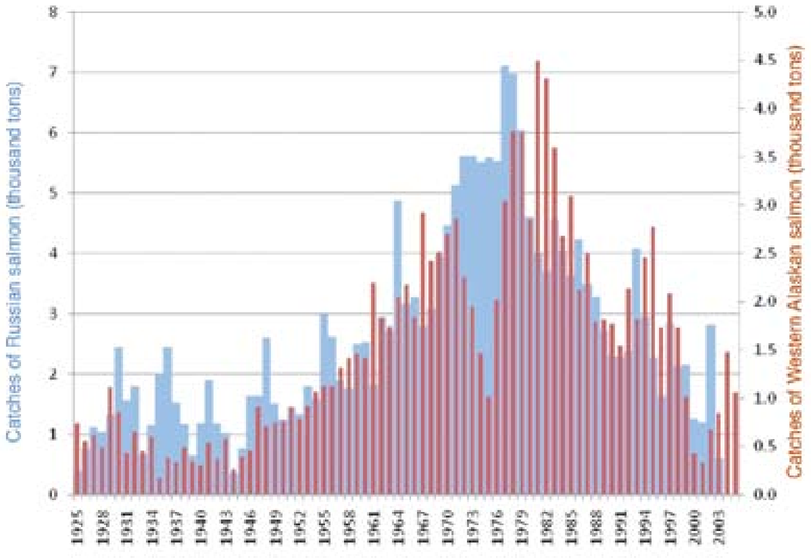


[Figure BS-48] Estimated biomass (blue line), fishery removals (green line) and total recruits by year-class (bars) of Bristol Bay sockeye salmon in the eastern Bering Sea from Eggers (2010) and Tim Baker (ADF&G, pers. comm.). Horizontal bars indicate mean recruitment prior to 2003 and since 2003, respectively.

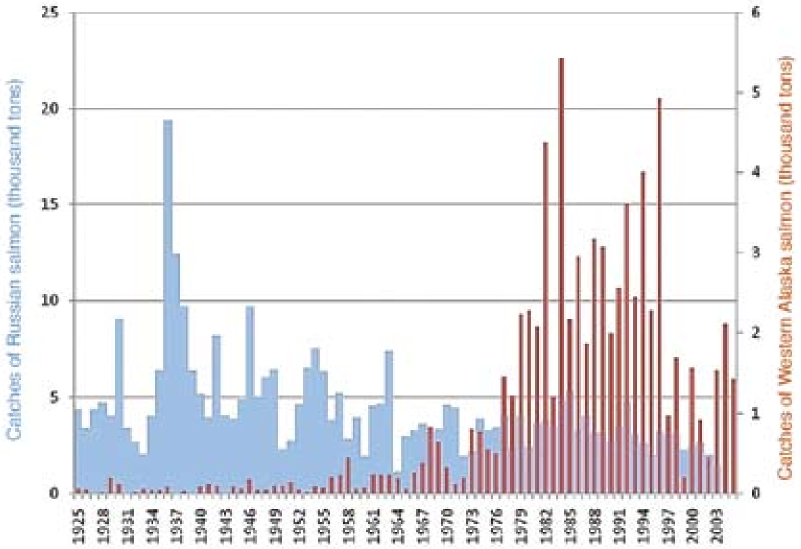
regime shift (Fig. BS-48), which was associated with an increase in marine survival and subsequent recruitment of sockeye salmon (Fig. BS-48) (Eggers, 2010). Russian sockeye salmon have been at their highest abundances in recent years since the peak abundances observed in the 1930s (Fig. BS-47), presumably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

Only catch data are available to examine long-term trends in chinook and coho salmon at the scale of the Bering Sea. Chinook salmon catches display remarkably similar trends on both sides of the Bering Sea with gradually increasing catches from the 1940s to a peak in the 1970s and gradually declining catches since then to very low levels in recent years (r = 0.732, p = 0.061 when adjusted for autocorrelation) (Fig. BS-49).

Coho salmon catch trends show very different patterns in Russia and western Alaska. Russian catches peaked in the mid-1930s and gradually declined since then to very low levels in recent years (Fig. BS-50). In contrast, coho salmon in western Alaska were harvested in low numbers through most of the century, but catches increased sharply after the mid-1970s, suggesting that coho salmon, like sockeye



[Figure BS-49] Annual reported catches of western Alaska and Russian chinook salmon, 1925-2005, from Eggers (2010). Note difference in scale between the two catch series. Western Alaska catches updated through 2008 with data from the Alaska Department of Fish and Game (www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmcatch.php)



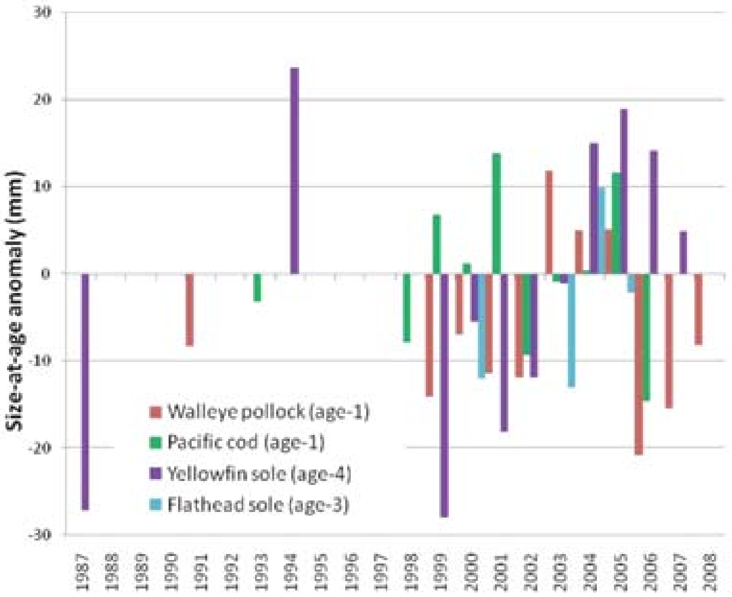
[Figure BS-50] Annual reported catches of western Alaska and Russian coho salmon, 1925-2005, from Eggers (2010). Note difference in scale between the two catch series. Western Alaska catches updated through 2008 with data from the Alaska Department of Fish and Game (www.cf.adfg.state.ak.us/geninfo/finfish/salmon/salmcatch.php)

salmon, experienced increased survival after the 1976/77 regime shift. Catches remained high through most of the 1990s but fell sharply in 1997 and have remained at low to moderate levels since then (Fig. BS-50). The sharp decline in 1997 has been observed through much of the range of coho salmon (Shaul et al. 2007).

Variability in size and condition of fish can offer insight into environmental conditions affecting fish growth and provide evidence of growth limitations resulting from density-dependent effects related to the overall carrying capacity of available habitat. For example, widespread observations suggest that salmon have been growing at a slower rate, achieving a smaller size-at-age, and maturing later in life since the pronounced increase in overall salmon biomass in the North Pacific in the mid-1970s (Bigler et al. 1996; Eggers and Irvine 2007; Helle and Hoffman 1998). These observations of density-dependent growth and maturation suggest that the capacity of the North Pacific Ocean to support salmon was approaching its limits during the period of high abundance following the 1976/77 climate regime shift. However, carrying capacity for salmon may not be constant, and the North Pacific appeared to support salmon of large body size even at high population abundances after 1995 (Helle et al. 2007).

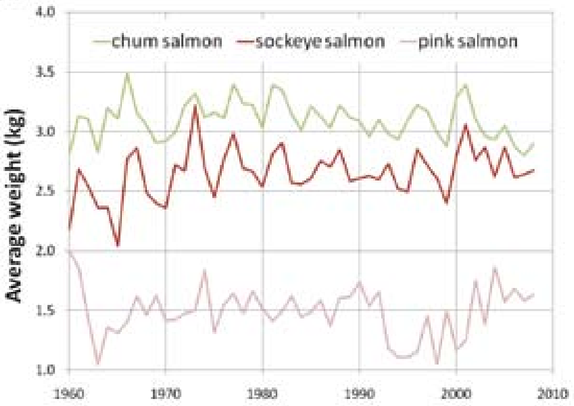
Mean size of harvested individuals is routinely measured and provides a useful measure of the growth rate of fish, which may be affected by temperature, prey availability, density-dependence, and other factors. Size-at-age anomalies were estimated for several groundfish species in the eastern Bering Sea based on samples obtained during bottom trawl surveys (Lauth and Acuna 2007). Annual size-at-age anomalies were estimated by first fitting a von Bertalanffy growth model to all available size-at-age data for a given species, then estimating annual mean deviations from the overall fit for the youngest age-class that was adequately sampled by the trawl survey. There was substantial variability in size-at-age for all species with sufficient data (Fig. BS-51), but some common patterns emerged. Most species had below average size in 1998-2002 and above average size in 2003-2005, corresponding to unusually warm conditions. Size-at-age was mostly below average during the recent cold years (2006-2008). Size-at-age-1 anomalies of walleye pollock were positively correlated with annual average bottom temperatures (r=0.74, p = 0.024), but anomalies of the other species were not. These short data series provided no evidence for a density-dependent relationship between size-at-age anomalies and biomass of the same species.

Changes in overall mean size of salmon in catches were assessed under the assumption that the age composition remains approximately constant, which is a reasonable assumption for some salmon populations when evaluating long-term trends (Helle et al. 2007). Annual mean weights of sockeye and chum salmon catches in western Alaska decreased slightly from about the mid-1970s to the late 1990s, increased in 2000/2001, and decreased again after 2001, particularly for sockeye salmon (Fig. BS-52). Average pink salmon weight was relatively stable from the 1970s through the early 1990s, was considerably lower in the mid- to late 1990s, and increased thereafter to high levels in the 2000s when catches and estimated biomass were at very low levels. These trends are consistent with those reported by Bigler et al. (1996) and Helle et al. (2007). Numerous authors have suggested a density-dependent response of size-at-age to variability in total biomass. However, the average size of sockeye, chum, and pink salmon in western Alaska was not correlated with the estimated biomass of these same populations at any lag. This may be a result of differences in age composition that can mask changes in average size. Moreover, growth anomalies during early marine life are negatively related to growth anomalies during late marine life in sockeye salmon (Ruggerone et al. 2007), hence the average size of returning salmon may be a poor indicator of variability in growth conditions.



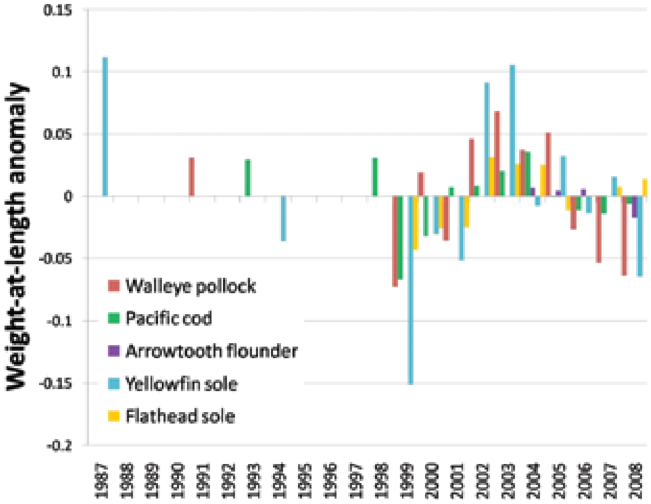
[Figure BS-51] Size-at-age anomalies for four groundfish species in the eastern Bering Sea. Anomalies were computed as deviations from von Bertalanffy growth curves for the indicated ages.

To further examine variability in growth conditions as reflected in body weight, we computed weight-at-length anomalies for several groundfish stocks in the eastern Bering Sea that had sufficient data to examine trends over at least a decade. Weight-at-length anomalies were computed by fitting linear regressions of log(weight) on log(length) by year and expressing the annual fitted values at an arbitrarily chosen small size as anomalies from the mean log(weight) at the same size estimated over all years. These weight-at-length anomalies show a strong pattern of negative anomalies in 1999-2001, changing to positive anomalies in 2002-2005, and back to mostly negative anomalies in 2006-2008 (Fig. BS-53). Weight-at-length anomalies of all five species were strongly and positively correlated with mean annual bottom temperatures on the shelf (correlations ranging from 0.62 to 0.89, except r = 0.34 for flathead sole).



[Figure BS-52] Annual average weights (kg) of harvested sockeye, pink, and chum salmon in western Alaska, 1960-2008.

To compare variability within and between the eastern and western Bering Sea, we examined commonalities and differences in biomass or catch time series. Pair-wise correlations between time series from the eastern and western Bering Sea were computed and were tested for significance using the method recommended by Pyper and Peterman (1998) to account for autocorrelation in each time series (Table BS-10). Biomass time series were used where available (walleye pollock, Pacific cod, and Pacific herring in the eastern Bering Sea; pink, chum, and sockeye salmon in both regions) and catch series otherwise. Catches of groundfish prior to 1964 were excluded to eliminate the period when many of these fisheries first developed and catches are unlikely to reflect changes in abundance.



[Figure BS-53] Weight-at-length anomalies for five groundfish species in the eastern Bering Sea. Anomalies were computed by estimating log(weight) at a given size for each year from linear regressions of log(weight) on log(length).

[Table BS-10] Correlations between the eastern and western Bering Sea based on catch or biomass series (see text) by species or aggregate group. P-values were adjusted for autocorrelation in each time series following Pyper and Peterman (1998). For walleye pollock, correlations are also shown for three subgroups (EBS: Eastern Bering Sea, Oy-K: Olyotorskiy-Karagin).

Group	Correlation	P-value
walleye pollock	0.169	0.663
EBS vs. Oy-K	-0.280	0.544
EBS vs. Navarin	0.227	0.364
Oy-K vs. Navarin	-0.181	0.502
Pacific cod	0.649	0.163
rockfish	0.240	0.429
flatfish	0.011	0.956
crab	0.053	0.858
squid	0.232	0.708
Pacific herring	0.053	0.900
pink salmon	-0.480	0.001
chum salmon	-0.550	0.201
sockeye salmon	0.112	0.774
coho salmon	-0.239	0.298
king salmon	0.732	0.061

Comparisons between regions suggest relatively weak and non-significant correlations between eastern and western Bering Sea catches of the same groups after adjusting p-values for autocorrelation in the time series (Table BS-11). The two exceptions are a significant negative correlation between pink salmon stocks and a strong positive correlation between chinook salmon stocks from both sides of the Bering Sea. In contrast, comparisons within regions resulted in a number of significant correlations that were largely positive (Table BS-11), with the exception of a significant negative correlation between flatfish catches and pink salmon biomass in the western Bering Sea. Notable positive correlations include those between pollock biomass, cod biomass, and flatfish catches in the eastern Bering Sea and between a number of salmon catch or biomass series within each region.

[Table BS-11] Significant correlations among species or aggregate groups within the eastern and western Bering Sea, respectively. P-values were adjusted for autocorrelation in each time series following Pyper and Peterman (1998).

Comparison	Correlation	P-value
Eastern Bering Sea		
pollock vs. cod	0.778	0.039
pollock vs. herring	0.702	0.035
pollock vs. flatfish	0.454	0.023
herring vs. flatfish	0.596	0.025
squid vs. pink salmon	0.565	0.035
coho vs. pink salmon	0.418	0.047
coho vs. chum salmon	0.730	0.040
coho vs. sockeye salmon	0.679	0.044
chinook vs. pink salmon	0.460	0.021
Western Bering Sea		
Navarin pollock vs. herring	0.536	0.032
Navarin pollock vs crab	0.521	0.022
flatfish vs. pink salmon	-0.748	0.020
sockeye vs. pink salmon	0.632	0.027
sockeye vs. chum salmon	0.752	0.051
coho vs. chum	0.605	0.006

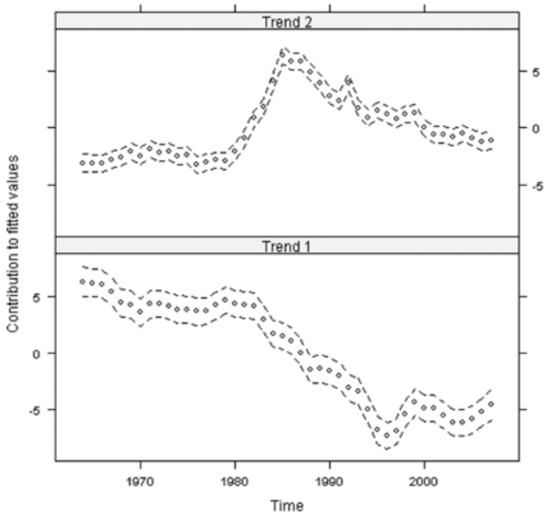
These patterns suggest that there is broad positive co-variation among catch trends within both the eastern and western Bering Sea, little or no significant covariation between the two areas for groundfish, and both positive (chinook salmon) and negative (pink, and possibly chum and coho salmon) covariation between salmon stocks spawning along the eastern and western Bering Sea margins. Although there is evidence for opposite trends in primary production between the eastern and western Bering Sea (Iida and Saitoh 2007), aggregated catches of all major fisheries for the period 1954-2004 or 1964-2004 (to remove influence of developing fisheries) tend to be positively correlated (r = 0.64, p = 0.12 and r = 0.36, p = 0.28, respectively).

8.3 Common trends in abundance

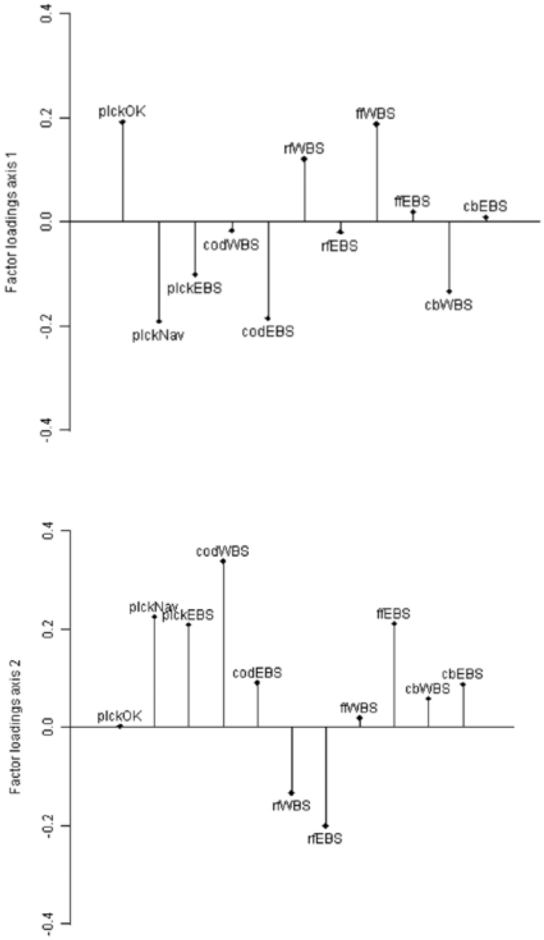
Common trends in the catch series from 1964 to 2007 were identified using Dynamic Factor Analysis (Zuur et al. 2007). The DFA model decomposes a set of time series into a small number of underlying trends plus "noise", where the noise terms may be autocorrelated over time and correlated between species. A number of different models with one, two, or three common trends were compared and the best model was chosen on the basis of the Akaike Information Criterion adjusted for small sample sizes.

8.3.1 Common trends among groundfish species

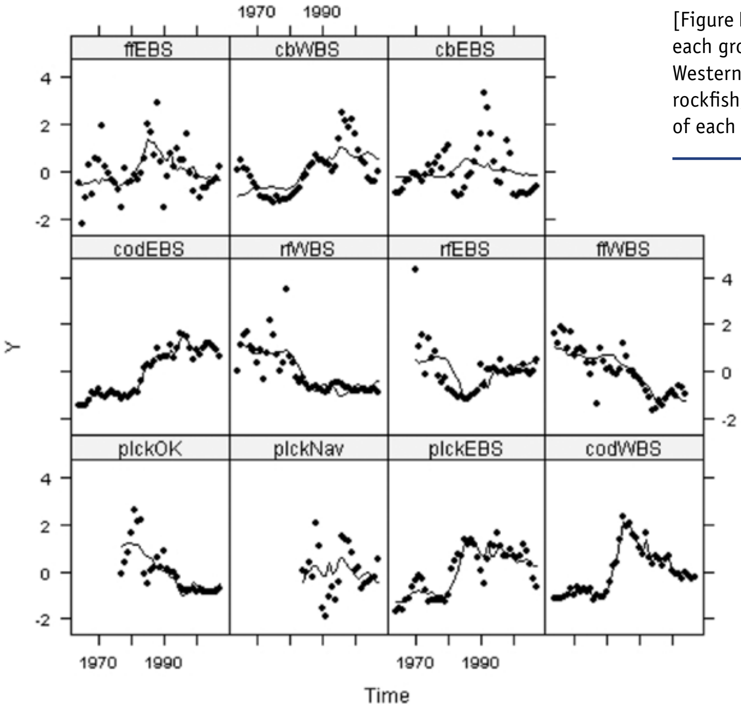
The best model to describe common trends among 11 groundfish groups (catch or biomass series) consisted of 2 common trends (Fig. BS-54) and a diagonal covariance matrix (i.e., no correlation among residual trends). These common trends suggest relatively stable catches in the 1960s and 1970s and a period of change from about 1980 to the mid-1990s (Trend 1), with a particularly sharp transition in the early 1980s (Trend 2). Figure BS-55 shows the factor loadings for each group, which indicate how strongly each group is associated with a given trend. Trend 1 was positively associated with walleye pollock catches in the Olyotorskiy-Karagin region and with rockfish and flatfish catches in the WBS, and was negatively associated with Navarin pollock, with Pacific cod and walleye pollock in the EBS, and with crab in the WBS. Trend 2 was positively associated with most groups but was negatively associated with rockfish (both EBS and WBS), reflecting a widespread increase in the abundance of a number of groundfish species in the early 1980s. Generally, the model fits were reasonably good (Fig. BS-56), although there is obvious serial correlation in the residuals that is not accounted for in the model.



[Figure BS-54] Estimated common trends that underlie the observed time series of catch or biomass of 11 groundfish species or species groups in the Bering Sea with 95% confidence interval.



[Figure BS-55] Factor loadings on catch/biomass trends 1 and 2 for each groundfish species / group (EBS = Eastern Bering Sea, WBS = Western Bering Sea, plck = walleye pollock, cod = Pacific cod, rf = rockfish, ff = flatfish, cb = crab). Loadings reflect the contribution of each catch series to the respective common trend.



[Figure BS-56] Model fits to observed groundfish catch/biomass series based on the two common underlying trends in Fig. BS-54.

8.3.2 Common trends among pelagic species

The best model to describe common trends among 14 pelagic groups (catch or biomass series) was a model with 2 common trends (Fig. BS-57), which indicate a pronounced change in catches (and catch composition) from the mid-1970s to the mid-1980s (Trend 1), as well as a continuing long-term trend starting in the early 1980s. The shift in the late 1970s and early 1980s was associated with an increase in the catches of almost all species, as evident in positive factor loadings (Fig. BS-58), except herring in the WBS and squid in the EBS, although the squid series was short and consisted of incidental catches only. Trend 2 reflects a contrast between pink, chum, and sockeye salmon in the western Bering Sea, which are positively associated with the increasing trend, and most other groups, which were negatively associated with this trend. The model fits fairly well (Fig. BS-59) and accounts for much of the variability in most of the time series.

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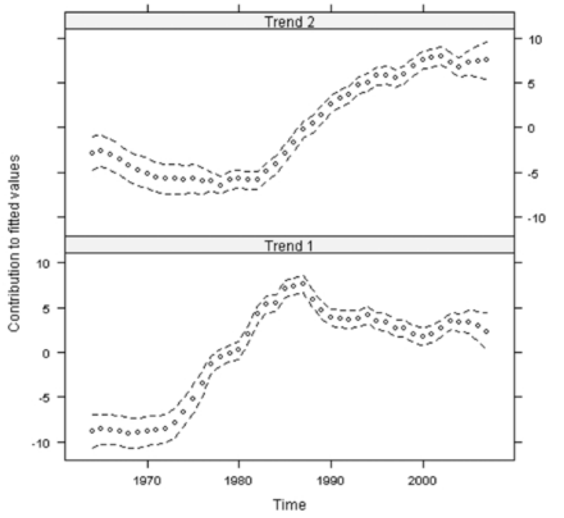
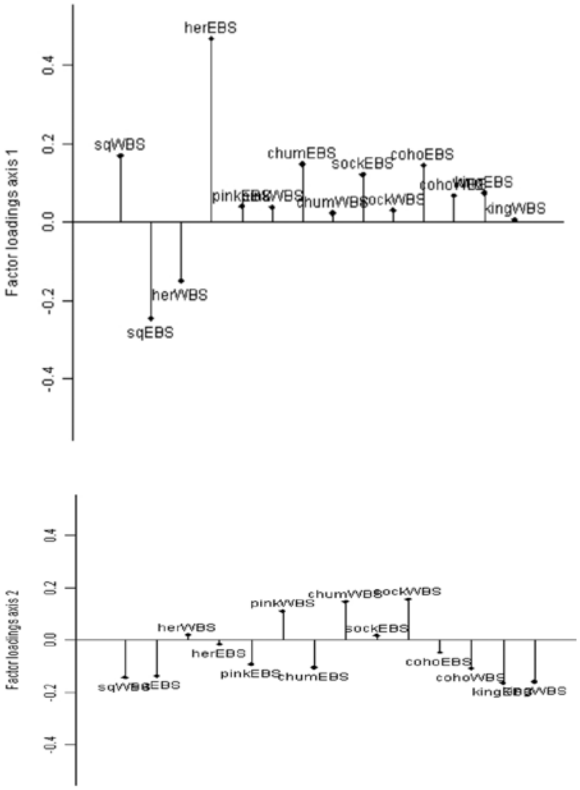
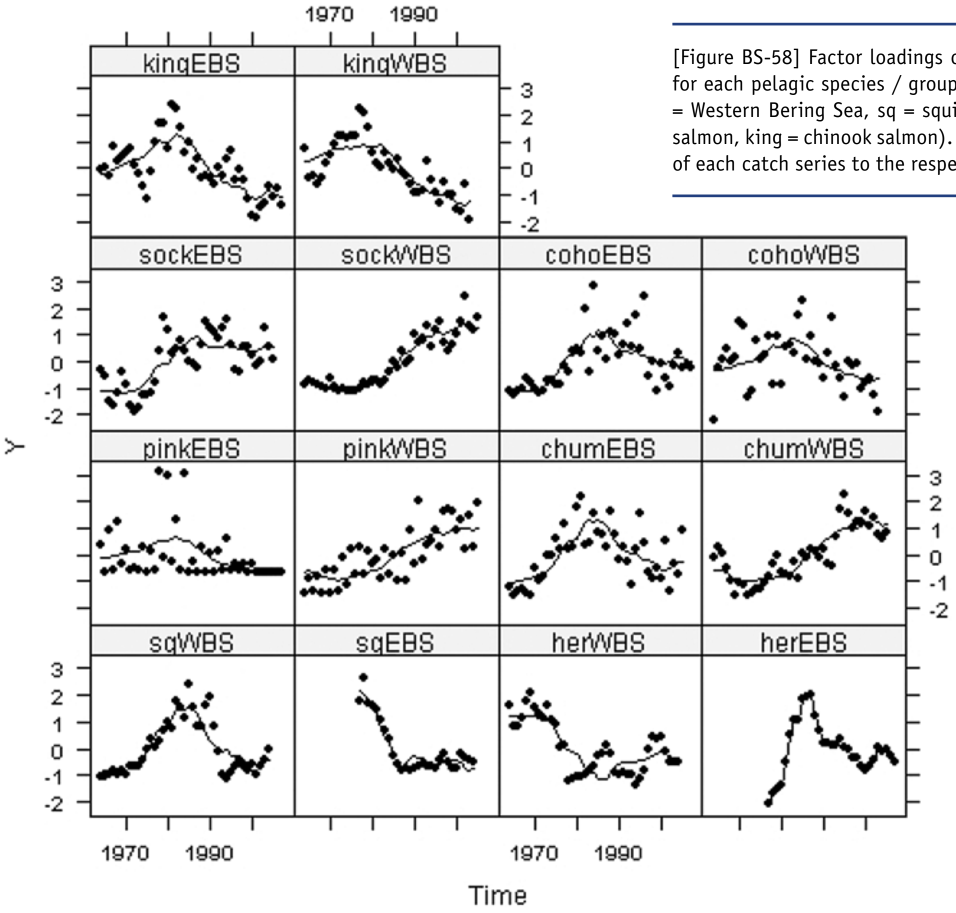


[Figure BS-57] Estimated common trends that underlie the observed time series of catch or biomass of 14 pelagic stocks in the Bering Sea with 95% confidence interval.



[Figure BS-58] Factor loadings on catch/biomass trends 1 and 2 for each pelagic species / group (EBS = Eastern Bering Sea, WBS = Western Bering Sea, sq = squid, her = herring, sock = sockeye salmon, king = chinook salmon). Loadings reflect the contribution of each catch series to the respective common trend.



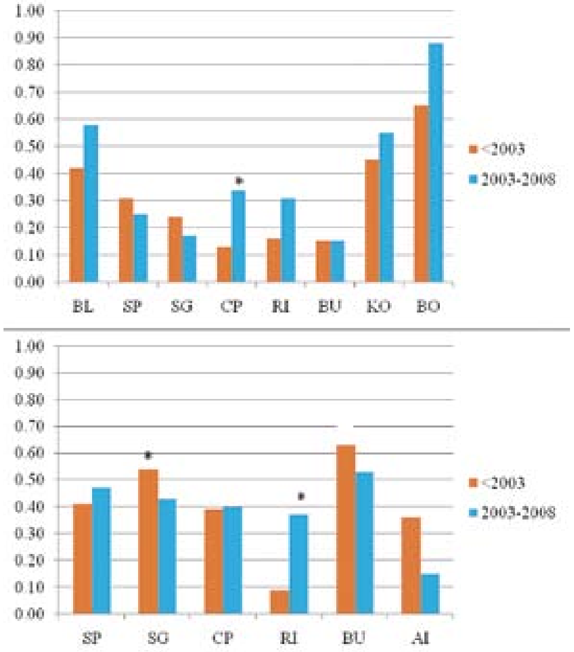
[Figure BS-59] Model fits to the observed pelagic catch/ biomass series based on the two common underlying trends in Fig. BS-57.

9.0 Marine Birds *(Byrd, Fitzgerald)*

9.1 Trends in breeding seabirds

Breeding seabirds are monitored to document patterns of change in a suite of response variables at selected colonies in the Bering Sea (see Byrd 2007), and results of monitoring are summarized in annual reports (see Dragoo et al. 2008). Kittiwakes (*Rissa* spp.) and murres (*Uria* spp.) are two of the most widespread types of nesting seabirds in the Bering Sea, and they are included in monitoring schemes at most sites. Kittiwakes and murres typically nest in dense aggregations on sea cliffs, often in mixed species colonies, and they prey primarily on small fish and large zooplankton. During the breeding season, kittiwakes, which are restricted to feeding at the sea surface, are relatively sensitive to changes in prey availability. Periodically they completely fail to produce young at some colonies, and in extreme years, adults can suffer mass mortality. Murres are deep divers and therefore are able to pursue prey at depths not available to kittiwakes. This capacity tends to buffer their response to prey shortages (i.e. shortages may reduce rates of productivity, but seldom cause complete reproductive failures or die offs in summer). Because of these differences in foraging strategies, productivity of kittiwakes varies highly among years, whereas murre productivity is less variable.

Reproductive rate is likely an interannual response variable to changes in the marine environment. Figure BS-60 compares the focus period with historic (earlier than 2003) estimates of average reproductive rates of black-legged kittiwakes (*R. tridactyla*) and common murres (*U. aalge*) at selected colonies for which multiple years of data are available in both periods. Mean estimates of productivity for kittiwakes tended to be higher during the more recent period or similar in the two periods (although the differences were statistically significant only at Cape Pierce (Fig. BS-60). Murre productivity tended to be higher during the earlier period or similar in the two periods, but like kittiwakes, few colonies showed statistically significant differences (Fig. BS-60). The Round Island colony seemed to be an exception, with significantly higher productivity since 2002 than earlier.



[Figure BS-60] Average productivity (chicks fledged/nesting pair on the y axis) of black-legged kittiwakes (above) and common murres (below) at selected colonies in the Bering Sea during 2003-2008 compared to earlier years (Various- 1975-2002, depending on colony). Location codes: BL=Bluff in Norton Sound; SP=St. Paul Island, Pribilofs; SG=St. George Island, Pribilofs; CP=Cape Pierce, Bristol Bay; Round Island, Bristol Bay; BU=Buldir Island, western Aleutians; KO= Koniuji Island, central Aleutians; BO=Bogoslof Island, eastern Aleutians, and AI=Aiktak Island, eastern Aleutians. Asterisk indicates differences are significant at the 0.1 level (t-test).

Since seabirds are typically long-lived, populations usually respond gradually to changes in rates of recruitment and productivity. Unlike reproductive success, which varies interannually in response to conditions of the marine food web, population indices are considered to be lagged responses to marine conditions. Table BS-12 summarizes recent changes in long-term trends for kittiwakes and murres. It appears that for kittiwakes, relatively recent counts of populations are either down or leveling out after a decline at most sites monitored. The exception was at St. George Island where kittiwakes have been increasing after a decline from the mid-1970s to the mid-1980s (see Byrd et al. 2008 for discussion of contrasting trends between St. George and St. Paul in the Pribilof Islands). For common murres, there appear to be either no trends or recent increases at all colonies except St. George and St. Paul Islands, the latter having been in long-term decline.

The influence of sea temperatures and other climate variables on seabirds is typically mediated through the marine food web. There is some indication that diets have shifted for some species in the Bering Sea at decadal

[Table BS-12] Comparison of long-term and recent short-term (2003-2008) population trends for kittiwakes and murres at selected colonies in the Bering Sea (data through 2005 in Dragoo et al. 2008, more recent data from E.C. Murphy—Bluff, Togiak National Wildlife Refuge files—Cape Pierce, and Alaska Maritime National Wildlife Refuge files for data from other sites).

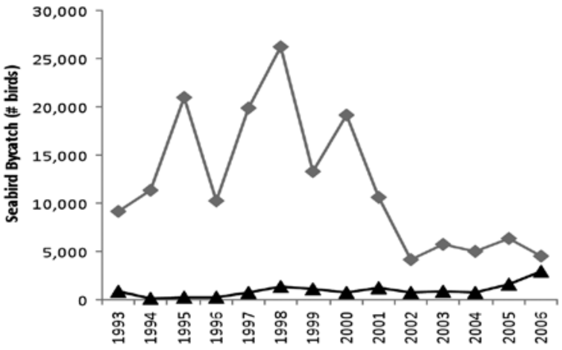
Species	Location	<2003	2003-2008	Comments
Black-legged Kittiwake	Bluff	up	down	Increase 1975-1995, then decline thereafter
	St. Paul	down	no trend	Overall decline
	St. George	down	up	Decline 1976-mid-1980s, then increase after 1989
	Cape Pierce	down	down	Uptick 2006-2007
	Buldir	up then no trend	down	Decline after 2000
Common Murre	Bluff	no trend	no trend	
	St. Paul	down	down	
	St. George	no trend	down	Downtick since 2002
	Cape Pierce	down	up	
	Buldir	up	up	
	Aiktak	down	no trend	

scales. For instance a recent comparison of diets of kittiwakes and murres in the Pribilof Islands between the mid-1970s and 2000 indicated shifts in types of prey taken by kittiwakes and murres relative to oceanographic shifts in the 1970s and 1990s (Sinclair et al. 2008).

9.2 Seabird bycatch in Alaskan groundfish fisheries *(Fitzgerald)*

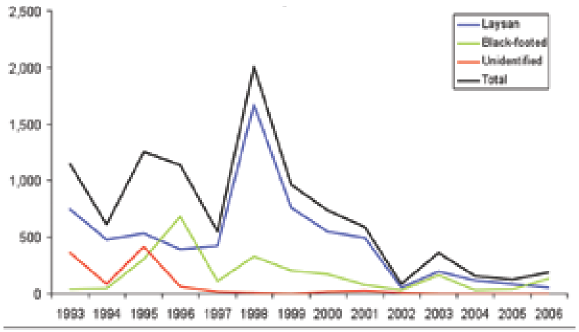
Groundfish fisheries in Alaskan waters are required to meet regulatory requirements for on-board fishery observers. These observers report on, among many things, seabird bycatch. Estimates have been produced for 1993 through 2006. Observers are able to easily see bycatch during their sampling of the catch on pot and longline gear types. Seabirds are also reported from sampling trawl vessels. However, additional mortalities are known to occur outside of the sampled catch due to interactions with various fishing gear such as third-wire or paravane cables, devices used to monitor net performance, and with the trawl warp itself. Observers are unable to collect seabird mortality data from these interactions, so estimates of the trawl fleet are biased low. No estimates are made of the Pacific halibut demersal longline fishery, which does not carry observers. The state-managed seine, troll, and gillnet fisheries are also not included in these estimates.

Seabird mortality as a result of interactions with fisheries has been at much higher rates historically (e.g., DeGange 1993) than in recent years due to cooperative conservation measures such as tori lines in long-line fisheries in both US and Russian (Artukhin et al. 2006) waters of the Bering Sea. Seabird bycatch in the pot fishery is very low, averaging 73 birds per year over 1993-2006. The bulk of seabird bycatch has traditionally occurred in the demersal longline fisheries for cod, Greenland turbot, and sablefish, while bycatch in the trawl fisheries from a suite of fisheries has been much lower (Fig. BS-61).

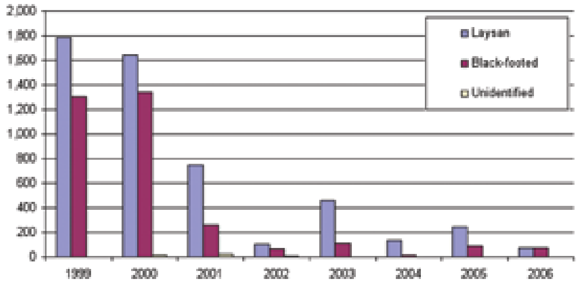


[Figure BS-61] Seabird bycatch totals for demersal longline (diamonds) and trawl (triangles) groundfish fisheries in Alaskan waters.

The large reduction in longline bycatch that occurred from 2000 through 2002 is a direct result of seabird mitigation studies conducted by Washington Sea Grant in close collaboration with the fishing industry, the U.S. Fish and Wildlife Service, and NOAA Fisheries. During the period before widespread use of streamer lines (1993 through 2000) the average annual seabird bycatch rate was 16,507. In the 5 years since streamer line use has become widespread and later required by regulation (2002-2006) the annual average bycatch of seabirds was 5,138. Traditionally, northern fulmars (*Fulmarus glacialis*) have constituted about 50% of the bycatch in Alaskan fisheries. However, with the advent of seabird mitigation gear in the longline fishery that percentage is falling while that of gulls is rising. Overall, the bycatch of birds appears to have remained at these lower levels during the 2007-2009 fishing seasons.



[Figure BS-62] Estimated albatross bycatch in demersal groundfish fisheries, 1993-2006.



[Figure BS-63] Estimated albatross bycatch in the North Pacific, 1999-2006, Hawaii and Alaska combined.

The bycatch of albatrosses in the demersal groundfish longline fishery has also been reduced substantially due to the use of seabird mitigation gear (primarily paired streamer lines) (Fig. BS-62). Similar studies, fisheries closures, and enactment of regulations requiring seabird mitigation occurred at the same time in the Hawaiian fisheries, which also provided for reduction in albatross bycatch throughout the North Pacific Ocean (Fig. BS-63).

9.3 Threatened and endangered marine birds

Spectacled eider: The nesting-pair-index on the Yukon Delta, the primary breeding area on the Bering Sea coast, indicates an overall decline since 1985 when the survey started. The index in 2003 was near its lowest level, but since then the index has been increasing. In fact, 2008 marked the "first time in the history of the survey that the recent 10-year average growth rate for spectacled eiders is significantly above 1.00 (alpha > 0.90)" (Fischer et al. 2008).

Steller's eider: Long-term aerial survey data from spring staging areas in the southeastern Bering Sea indicate a 2.6% average annual decline between 1992 and 2008, but the trend since 2002 has been relatively level albeit at a low population level (Larned 2008).

Short-tailed albatross: This endangered species continues to increase although it remains at low population levels (USFWS 2005). A recent review of observations suggests that birds concentrate in hot spots (e.g. at least 200 albatross or about 10% of the total population were observed within sight of a single fishing vessel) and therefore may be vulnerable to perturbations in these locations (Piatt et al. 2006).

10.0 Marine Mammals

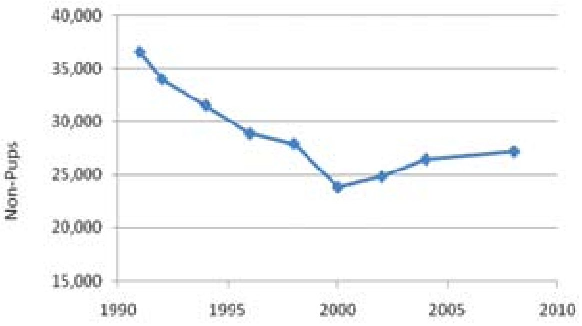
(Allen, Angliss, Fritz, Lewis)

The Bering Sea is a species-rich ecosystem that provides essential resources and habitat for over 23 species of marine mammals representing the orders Pinnipedia, Carnivora, and Cetacea (Table BS-13). These species occur in diverse habitats, including deep oceanic waters, the continental slope, and the continental shelf (Lowry et al. 1982). Marine mammal populations in the Bering Sea have been affected by both natural and anthropogenic causes. Whales in particular were impacted by commercial hunting, during which time population levels declined. Some populations, such as the Eastern North Pacific right whale, have not recovered, while others have largely recovered (e.g., North Pacific humpback and eastern gray whales). Several pinniped species, including northern fur seal, Steller sea lion, and sea otter were severely impacted by the commercial fur trade and subsequently recovered, though at present, populations of these three species are considerably below their recent highs. Investigations into the effects of global climate change on marine mammal species, especially for those species dependent on sea ice, are ongoing.

10.1 Species accounts

10.1.1 Steller sea lion

The minimum abundance estimate (n = 41,197) of Steller sea lion is based on counts of pups and non-pups on rookeries and major haulout sites in the Gulf of Alaska, Bering Sea, and Aleutian Islands. The most recent minimum abundance estimate for the Aleutian Islands / Bering Sea portion of the western stock of Steller sea lion is 20,157 (Fritz et al. 2008a,b) (Fig. BS-64). Burkanov and Loughlin (2005) estimated a total of 1,000 animals (674 non-pups and 236 pups) on the Commander Islands based on counts from 2004, a minimum estimate for the western Bering Sea.



[Figure BS-64] Trends in abundance of western Steller sea lion in Alaska from 1991-2008 based on non-pup counts.

The first counts of Steller sea lion in Alaska estimated a minimum of 140,000 animals in the Gulf of Alaska and Aleutian Islands in 1956-1960 (Merrick et al. 1987). A major population decrease in the eastern Aleutian Islands was first detected in the mid-1970s (Braham et al. 1980), with the decline spreading eastward towards Kodiak Island during the late 1970s and early 1980s, and then westward to the central and western Aleutian Islands during the early and mid-1980s (Merrick et al. 1987; Byrd 1989). There was a 40% decline at trend sites in the eastern Bering Sea from 1991-2002 (Loughlin and York 2000). Starting in 2000, counts of non-pups increased 5.5% every two years for all trend sites. The Steller sea lion population size in the eastern Bering Sea remained relatively unchanged between 2004 and 2008 and is stable or slightly declining, with considerable regional variability (Fritz et al. 2008a, b). Reasons for the regional variability are unknown.

Reliable data on Steller sea lion counts in eastern Kamchatka and the western Bering Sea only exist for the last 30 years. The numbers in both areas have declined dramatically since the early 1980s, with sea lions nearly disappearing from the western Bering Sea and a greater than five-fold decline along east Kamchatka (Burkanov et al. 2009). As of 2005, the abundance of Steller sea lion along the Asian coast was estimated at 16,000, with half of those inhabiting waters around the Kuril Islands (Burkanov and Loughlin 2005). A survey based on data from 2006-2008 indicated that the abundance has remained relatively stable, although at a low level (Burkanov et al. 2008; 2009). Pup production continued to increase at the Commander Island rookery until 1999, despite the decrease in the number of males present and the decline in overall Steller sea lion abundance in most of the western population during this period. The number of pups stabilized at approximately 220-230 per year from 2000-2008 (Burkanov et al. 2009).

[Table BS-13] Marine mammals of the Bering Sea and Aleutian Islands, status and trends. N/A = not available. Sources: Angliss and Allen, 2009; Allen and Angliss, 2010.

Species Stock	Scientific Name	Abundance	Trend in Abundance	Primary Forage Species
Pinnipeds				
Steller sea lion Western U.S. Stock	*Eumetopias jubatus*	41,197	Stable; slightly decreasing	Atka mackerel, pollock, Pacific cod
Northern fur seal Eastern Pacific Stock	*Callorhinus ursinus*	665,550	Decreasing	Pollock, gonatid squid, small schooling fish, Atka mackerel, salmon
Pacific Walrus Alaska Stock	*Odobenus rosmarus divergens*	21,610	Unknown	Mollusks, benthic invertebrates
Harbour seal Bering Sea Stock	*Phoca vitulina richardsi*	21,651	Unknown(thought to be decreasing)	Demersal fish, pelagic schooling fish, octopus, squid
Spotted seal Alaska Stock	*Phoca largha*	N/A	Unknown	Pollock, capelin, arctic cod, herring, flounder, halibut, sculpin, crabs, octopus
Bearded seal Alaska Stock	*Erignathus barbatus*	N/A	Unknown	Crabs, shrimp, mollusks, arctic and saffron cod
Ringed seal Alaska Stock	*Phoca hispida*	N/A	Unknown	Polar cod
Ribbon seal Alaska Stock	*Histriophoca fasciata*	N/A	Unknown	Pollock and Arctic cod, squid
Cetaceans				
Beluga whale Beaufort Sea Stock	*Delphinapterus leucas*	39,258	Unknown	Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans
Beluga whale E. Chukchi Sea Stock	*Delphinapterus leucas*	3,710	Unknown	Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans
Beluga whale E. Bering Sea Stock	*Delphinapterus leucas*	18,142	Unknown	Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans
Beluga whale Bristol Bay Stock	*Delphinapterus leucas*	2,877	Increasing	Salmon, Arctic cod, herring, capelin, cephalopods, crustaceans
Killer whale E. North Pacific Alaska Resident Stock	*Orcinus orca*	1,123*	Unknown	Variety of fish species
Killer whale GOA, Aleutian Islands, Bering Sea Transient Stock	*Orcinus orca*	314*	Unknown	Variety of marine mammal species

[Table BS-13 continued] Marine mammals of the Bering Sea and Aleutian Islands, status and trends. N/A = not available. Sources: Angliss and Allen, 2009; Allen and Angliss, 2010.

Species Stock	Scientific Name	Abundance	Trend in Abundance	Primary Forage Species
Cetaceans Continued				
Harbour porpoise Bering Sea Stock	*Phocoena phocoena*	48,215	Unknown	Herring, capelin, sprat, silver hake
Dall's porpoise Alaska Stock	*Phocoenoides dalli*	83,400	Unknown	Herring, pilchards, hake, squid
Pacific White-Sided Dolphin North Pacific Stock	*Lagenorhynchus obliquidens*	26,880	Unknown	Herring, anchovies, capelin, sardines, cephalopods
Sperm whale North Pacific Stock	*Physeter macrocephalus*	N/A	Unknown	Squid, octopus, demersal rays, sharks
Baird's beaked whale Alaska Stock	*Berardius bairdii*	N/A	Unknown	Squid, deep-sea fish
Cuvier's beaked whale Alaska Stock	*Ziphius cavirostris*	N/A	Unknown	Squid
Stejneger's beaked whale Alaska Stock	*Mesoplodon stejnegeri*	N/A	Unknown	Meso- and bathypelagic squid
Gray whale Eastern North Pacific Stock	*Eschrichtius robustus*	18,813	Increasing	Benthic amphipods
Humpback whale Western North Pacific Stock	*Megaptera novaeangliae*	394	Unknown	Krill, herring, capelin, sandlance
Humpback whale Central North Pacific Stock	*Megaptera novaeangliae*	4,005	Increasing	Krill, herring, capelin, sandlance
Fin whale Northeast Pacific Stock	*Balaenoptera physalus*	5,700	Unknown	Krill, herring, capelin, sandlance
Minke whale Alaska Stock	*Balaenoptera acutorostrata*	N/A	Unknown	Krill, herring, capelin, sandlance
North Pacific right whale Eastern North Pacific Stock	*Eubalaena japonica*	N/A	Unknown	Copepods, krill
Bowhead whale Western Arctic Stock	*Balaena mysticetus*	10,545	Increasing	Copepods, krill

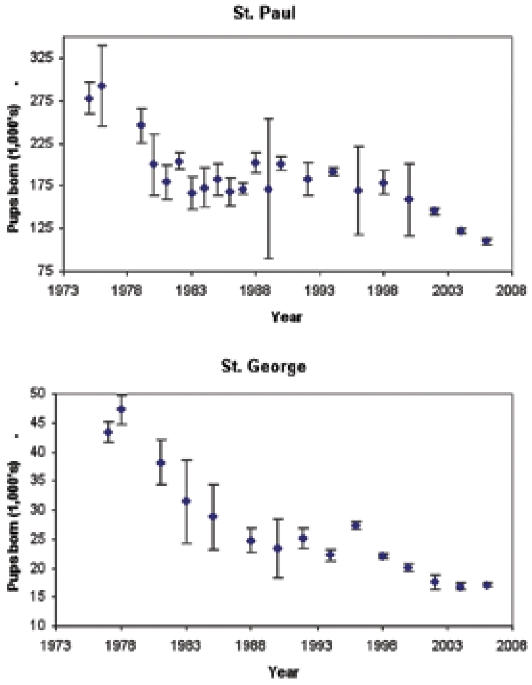
* Estimated population size based on counts of individual animals identified from photo-identification catalogs.

10.1.2 Northern fur seal

Northern fur seal ranges from southern California to the Bering Sea, and as far west as the Sea of Okhotsk and Honshu Island, Japan. Most of the population is found on the Pribilof Islands in the southern Bering Sea during the summer breeding season, although some animals remain on rookeries in Russia, on Bogoslof Island (53° 55´N 168° 2´W) in the southern Bering Sea, and on San Miguel Island off southern California (Lander and Kajimura 1982; NMFS 1993). The fur seal population has been subjected to a variety of harvest strategies, both commercial and scientific. The total population estimate in 1983 was 877,000 (Briggs and Fowler 1984). Since the cessation of commercial harvests in 1984, the overall population trend has been declining (Towell et al. 2006). Annual pup production on St. Paul Island remained stable between 1981 and 1996 (Fig. BS-65; York and Fowler 1992). However, since the mid-1990s, there has been a decline in pup production on St. Paul Island. Despite the slight increase in the number of pups born on St. George Island in 1996, there was an overall decreasing trend in births between 1996 and 1998 (Fig. BS-65). During 1998-2006, pup production declined 6.1% per year (SE = 0.45%; P< 0.01) on St. Paul Island and 3.4% per year (SE = 0.60%; P= 0.01) on St. George Island. The estimated pup production in 2006 was below the 1918 level on St. Paul Island and below the 1916 level on St. George Island (Towell et al. 2006). The most recent northern fur seal estimate for the eastern Pacific stock is 687,902 (Angliss and Allen, 2009). This estimate is based on pup counts from Sea Lion Rock (2002), the Pribilof Islands (2006), and Bogoslof Island (2007). The population is declining for unknown reasons. The northern fur seal was designated as “depleted” under the U.S. Marine Mammal Protection Act (MMPA) in 1988.

10.1.3 Phocid seals

Five species of phocid seal breed in the Bering Sea. Some of these depend upon sea ice for pupping and hauling out (ringed seal, spotted seal, ribbon seal, bearded seal), whereas others more often use beaches (harbour seals). Population trends for these species are not known, though for some estimates of present population size are becoming available (Table BS-13). For example, the current abundance estimate for the eastern Bering Sea population of harbour seals is 21,651 (Angliss and Allen 2009). In contrast, a reliable estimate of spotted seal population abundance is not available (Boveng et al. 2009). Early population estimates were in the range of 335,000-450,000 animals worldwide, with the population of the Bering Sea estimated to be 200,000-250,000 (Burns 1973). A provisional population estimate of 101,568 (SE = 17,869) spotted seals in the eastern and central Bering Sea was developed based on survey data from 2007 and 2008 (Boveng et al. 2009). Similarly, for bearded seals, early population estimates of the Bering Sea and Chukchi Sea population ranged from 250,000 to 300,000 (Popov 1976; Burns 1981). Reliable estimates of the present abundance and population trends of bearded seals are not available. Data on ribbon seals are somewhat better. Burns (1981) estimated the Bering Sea population of ribbon seals at 90,000-100,000 in the mid-1970s. Boveng et al. (2008) developed a provisional population estimate of 49,000 ribbon seals in the eastern and central Bering Sea based on aerial surveys conducted in portions of the eastern Bering Sea in 2003 (Simpkins et al. 2003), 2007 (Cameron and Boveng 2007; Moreland et al. 2008), and 2008 (Peter Boveng, unpublished). Abundance of ribbon seals in the western Bering Sea is unknown.



[Figure BS-65] (a) Estimated number of northern fur seal pups born on (a) St. Paul Island and (b) St. George Island from 1970 to 2006 (modified from Towell et al. 2006).

10.1.4 Killer whale

The killer whale (*Orcinus orca*) has been observed in all oceans and seas of the world and are found throughout most of the Bering Sea, ranging from Bristol Bay, Alaska, along the Aleutian and Commander Islands to Kamchatka, Chukotka, and as far north as the Chukchi Sea (Leatherwood and Dahlheim 1978; Braham and Dahlheim 1982; Burdin et al. 2006). Both transient (mammal-eating) and resident (fish-eating) killer whales occur in the Alaska waters of the eastern Bering Sea as well as around the Commander Islands and Russian Far East in the western Bering Sea (Braham and Dahlheim 1982; Burdin et al. 2007). Based on photo-identification catalogs of individual whales, minimum population estimates are 1,123, for the Alaska Resident stock and 314 for the Gulf of Alaska, Aleutian Islands, and Bering Sea Transient stock, resulting in a minimum total estimate of 1,437 whales in the eastern Bering Sea (Angliss and Allen 2009).

The eastern Kamchatka killer whale catalog consists of 434 individuals from the Avacha Gulf, Kamchatka Peninsula, with 264 resident killer whales and 158 resident-type (fish-eating) whales that may have a broader range than the Avacha Gulf (Burdin et al. 2006, 2007; Ivkovich et al. 2010). Since the late 1990s, transient-type killer whales have been observed regularly feeding on northern fur seal off the Commander Islands (Mamaev and Burkanov 2006). A total of 45-50 killer whales have been sighted off the Chukotka coast from 1983-2001, primarily from July to September, then migrating south in November (Grachev et al. 2002). Melnikov and Zagrebin (2005) reported seeing 788 killer whales over a 10 year period (1990-2000) from the shores of the Chukotka peninsula, 11.6% of which were involved in marine mammal attacks, including gray whales and pinnipeds. Population trends for killer whale throughout the entire Bering Sea are currently unknown (Angliss and Allen 2009; Burdin et al. 2007).

10.1.5 Gray whale

Two populations of gray whale (*Eschrichtius robustus*) exist in the North Pacific: the eastern Pacific stock, and a very small western North Pacific stock. The western stock is found primarily in the Sea of Okhotsk, although numerous sightings have been made off southeast Kamchatka. Gray whales have historically been reported to occur off the Commander Islands (Barabash-Nikiforov 1938), but sightings are relatively rare in this area over recent years (Weller et al. 2003; Tyurneva et al. 2009; Savenko et al. 2009). Annual shore-based counts of eastern Pacific gray whales migrating south have been conducted along the central California coast since 1967. Analyses of these data resulted in an estimate of the annual rate of increase from 1967-1968 through 2001-2002 at 1.9% (SE = 0.32%; Rugh et al. 2005). Abundance estimates in the late 1990s-early 2000s have been around 20,000 animals. It is expected that a population close to or at the carrying capacity of the environment, such as the eastern Pacific gray whales, will be more susceptible to fluctuations in the environment, which may explain the recent correlation between gray whale calf production and environmental conditions, as well as the 1999-2000 mortality event (Moore et al. 2001; Perryman et al. 2002; Gulland et al. 2005).

10.1.6 North Pacific right whale

The North Pacific right whale (*Eubalaena japonica*) may be the most endangered large whale in the world. Historical whaling records suggest that the North Pacific right whale ranged across the entire North Pacific north of 35°N (Scarff 1986, 2001) but recent data show a pronounced longitudinally bimodal distribution (Josephson et al. 2008). Two stocks of North Pacific right whale are currently recognized: a Western North Pacific and an Eastern North Pacific stock, although the former is believed to feed primarily in the Okhotsk Sea (Rosenbaum et al. 2000; Brownell et al. 2001). During 1965-1999, there were only 82 sightings of right whale in the entire eastern North Pacific with the majority of these occurring in the Bering Sea and adjacent areas of the Aleutian Islands (Brownell et al. 2001). A minimum of 17 individual whales was seen in 2004, including 2 probable calves (Angliss and Allen 2009). In 2008, 9-12 individual right whales were identified during NMFS vessel and aerial surveys (Kennedy, unpublished). Reliable estimates of abundance and population trends for the North Pacific right whale stock are currently not available.

10.1.7 Other marine mammals

Limited information on population levels of other marine mammals in the Bering Sea, including Beluga whale, harbour porpoise, Dall's porpoise, Pacific white-sided dolphin, sperm whale, Baird's beaked whale, humpback whale, fin whale, minke whale and bowhead whales, is available (Angliss and Allen 2009; Burdin et al. 2007;

Moore et al. 2002; Savenko et al. 2009; Calambokidis et al. 2008; Zerbini et al. 2006), providing approximate estimates of current or recent population levels (Table BS-13), but no information is available on population trends during the focus period.

11.0 Ecosystem Considerations

(Hunt, Mueter)

The period 2002 to 2009 was unusual in that the Bering Sea experienced four years with low sea ice cover and extraordinarily warm summers (2002-2005), followed by a series of four years with some of the heaviest sea ice cover since the early 1970s and cold summers (2006-2009). During this time frame (2002-2009), there have been several comprehensive research programs in the eastern Bering Sea including BASIS (2002-present), which also covered parts of the western Bering Sea, the Pribilof Domain Project (2004), BEST (Bering Sea Ecosystem Study) (2007-2010), BSIERP (Bering Sea Integrated Ecosystem Research Program) (2008-2012), and NPCREP (North Pacific Climate Regimes and Ecosystems Productivity) (2004-present). Conducted in the context of striking environmental variability, these programs in sum have provided and continue to provide an unprecedented opportunity to assess how the Bering Sea ecosystem responds to periods of cold and warm conditions. This summary section, examines the impacts of the recent warm and cold periods, newly available contrasts between the northern and southern portions of the eastern Bering Sea shelf, the state of knowledge of controls of year-class strength in walleye pollock and new evidence for density-dependence in fish stocks and determinants of carrying capacity.

11.1 Comparison of a warm period (2002-2005) with a cold period (2006-2009)

The occurrence of four unusually warm years (2002-2005) followed by four unusually cold years (2006-2009) provided the opportunity to learn how a warm southeastern Bering Sea might differ from a cold one. Many aspects of the ecology of the southeastern shelf were affected by differences in water temperature, cold pool extent, and stratification. Given that there is evidence for greater weight-at-age in groundfish during the warmer years, it might be concluded that the Bering Sea should be particularly productive in future periods of warmer climate and that post-recruitment fish will enjoy higher growth rates when temperatures are warmer. However, the recruitment of some species of commercially valuable groundfish appeared adversely affected by unusually warm conditions. Although the Oscillating Control Hypothesis predicts that production of strong cohorts of age-0 pollock should occur in warm years (Hunt et al. 2002), strong year-classes failed to emerge in the warm years of 2002-2005 despite a declining biomass, and there were possibly strong year-classes in the cold years of 2006 and 2008. The Oscillating Control Hypothesis also predicts that in years when water temperatures are low, zooplankton prey is expected to be limiting and therefore strong year-classes would be unlikely to result.

The reasons for these results became clear upon examination of data on crustacean zooplankton, the condition indices of age-0 in summer and fall, and diets of age-0 and older pollock (Coyle et al. 2008; Hunt et al. 2008; Moss et al. 2009). In the warm years of 2001-2005, the small neritic species of crustacean zooplankton thrived, whereas the medium-large copepod *Calanus marshallae* and the shelf euphausiid, *Thysanoessa raschii*, were scarce (Coyle et al. 2008; Hunt et al. 2008; this chapter). In these warm years, age-0 pollock were abundant in the BASIS surveys, but they were in very poor body condition with an energy content that was unlikely to be sufficient for overwinter survival (Moss et al. 2009). In contrast, in the cold years of 1999 and 2006-2008, both *C. marshallae* and *T. raschii* were abundant (Coyle et al. 2008; Hunt et al. 2008). In the cold years of 2006-2008, age-0 pollock were in good condition and energy rich, though apparently not as abundant as they were in the warmer years.

The diets of age-0 pollock differed between the warm and cold years. In the warm years, they consumed mostly small crustacean zooplankton and also smaller age-0 pollock, and neither *C. marshallae* nor *T. raschii* were important components of their diets (Moss et al. 2009). In contrast, in the cold years, age-0 pollock diets were dominated by *C. marshallae* and euphausiids; cannibalism was reduced. In the warm years, age-0 pollock were also an important component of the diets of juvenile salmon, whereas in cold years, euphausiids and large copepods were the dominant salmon prey (Moss et al. 2009). These results suggest that the availability of plentiful supplies of large copepods and euphausiids in summer and fall are essential not only to reducing consumption of age-0 pollock, but also to ensure that the age-0 pollock surviving to the fall have sufficient energy reserves to survive their first winter.

The finding that numbers of age-0 pollock are greater in the summers of warm years fits the prediction of the Oscillating Control Hypothesis (Hunt et al. 2002) but the failure of these fish to recruit, particularly in a period of declining adult biomass, does not (Hunt et al. 2008). There is still the possibility of alternating top-down and bottom-up control of pollock populations, but the added factor of starvation over the first winter and the switching of predators from large crustacean zooplankton to age-0 pollock in warm years when the zooplankton are scarce must be taken into account.

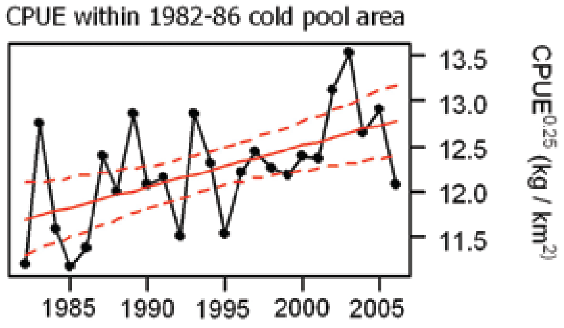
Two non-exclusive hypotheses have been put forward to explain the scarcity of *C. marshallae* and *T. raschii* in warm years. One, based on the work of Baier and Napp (2003) suggests that at least *C. marshallae* requires an early bloom, normally associated with the melting of the sea ice, to provide food essential for the recruitment of copepodites from the nauplii. At present, there are no hypotheses available about the role of sea ice in the recruitment of *T. raschii*, although in the Barents Sea, this species has been found to increase in cold periods and decrease in warm periods (Drobysheva 1967, 1994). The other hypothesis is that strong stratification in summer depresses post-bloom new production and therefore the large crustacean zooplankton, lacking appropriate food resources, leave the water column when the surface layer warms (Coyle et al. 2008). These hypotheses are discussed in some detail in Hunt et al. (2008).

11.2 Contrasts between the northern and southern portions of the eastern Bering Sea shelf

The physics of the northern portion of the eastern Bering Sea shelf are dominated by advective processes whereas in the southern portion of the shelf, physical processes are dominated by tidal forcing (Stabeno et al. 2001, 2010). Recently, Stabeno et al. (2010) have shown that the northern and southern portions of the shelf are separated in summer by a strong, cross-shelf front that occurs just south of St. Matthew Island. North of the frontal area, stratification is dominated by salinity whereas south of the front, temperature is the dominant determinant of stratification. End-of-winter nitrate concentrations over the northern shelf were more variable than those over the southern shelf. In both cold and warm years, the seasonal draw-down of nitrate and phosphate was greater and less variable over the southern Middle Domain than it was over the north. These differences may result from the greater on- and off-shelf advection in the north.

Because there is strong pelagic-benthic coupling in the northern shelf region (Grebmeier et al. 1988, 2006; Grebmeier and McRoy 1989; Highsmith and Coyle 1992; Lovvorn et al. 2005), it is perhaps not surprising that there is strong denitrification and (or) anammox removal of nitrogen from the system, thereby creating anomalously low nitrate-phosphate ratios when compared to the global mean or to the southern shelf. Unexpectedly, everywhere on the eastern shelf, nitrate-phosphate ratios were lowest in spring, rather than in fall after summer denitrification. However, summer/fall surface chlorophyll$_a$ biomass was higher in the south than in the north. Subsurface chlorophyll$_a$ concentrations mirrored the pycnocline depth, with deeper blooms observed over the northern shelf.

Less attention has been paid to the species composition and biomass of zooplankton (and fish) in the northern Bering Sea, though useful results should be forthcoming from the BEST / BSIERP programs and from the northward extension of the U.S. NMFS groundfish trawl surveys. However, older work suggests that mesozooplankton species composition in the north is similar to that in the south, with oceanic species that have been advected onto the shelf dominating to the west, and species typical of the Middle Domain in the south dominating in the eastern portions of the northern shelf (Springer and Roseneau 1985; Springer et al. 1989; Hunt and Harrison 1990). Likewise, our knowledge of fish distribution and abundance in the northern Bering Sea is less advanced than in the southeastern Bering Sea where most of the commercially important stocks are found. Species common to the southeastern Bering Sea shelf penetrate north to the Chukchi Sea and beyond (e.g., Wyllie-Echeverria 1995; Barber et al. 1997; NPFMC 2009; Norcross et al. 2010), and recently Mueter and Litzow (2008) have shown that a number of Bering Sea fish species that are typical of temperate waters moved north into the region of the southern cold pool during the warm years of 2002-2005 when there was little sea ice and the cold pool was small and not as cold as usual (Fig. BS-66). However, in the recent stanza of cold years (2006-2008), there is little evidence that these fish shifted back southward to warmer waters (Mueter unpublished). As conditions change, it will be of interest to see if the distributions of these fish populations track climate variability or if there is an environmental ratchet northward (*sensu* Orensanz et al. 2004). A long-term northward shift could have major impacts on the fishing industry and shore-based communities that serve this industry, and it also could have significant impacts on the structure of an ecosystem presently relatively free of groundfish predators.



[Figure BS-66] Change in CPUE for temperate groundfish species in the area occupied by the cold pool in 1982 to 1986 (adapted from Mueter and Litzow; 2008).

11.3 Comparison of climate and fisheries patterns in the eastern and western Bering Sea

Between 2000 and 2008 there has been only a very weak correspondence in air temperatures on the two sides of the Bering Sea. Although temperatures appeared out of phase early in this period, they were largely in phase for the years 2002 to 2005, after which they were again briefly out of phase. Although we were unable to obtain data on zooplankton populations in the western Bering Sea to compare with those available from the eastern shelf, comparison of fisheries statistics between the eastern and western areas showed that over the periods 1954 to 2004 and 1964 to 2004, the aggregated catches of all major fisheries tended to be positively correlated (r= 0.64 and r= 0.36, respectively), suggesting that the two sides of the Bering Sea were responding similarly to shared climate forcing.

11.4 Issues of carrying capacity and density-dependent control

Weight-at-age and weight-at-length were used as indicators of fish condition and then examined to determine the relationships of these indices to both the biomass of a particular species and to temperature. Although most species had anomalously high weight-at-age and weight-at-length in periods of warm water and bottom temperatures, there was no evidence in the short time series available that density-dependent constraints on growth were significant.

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