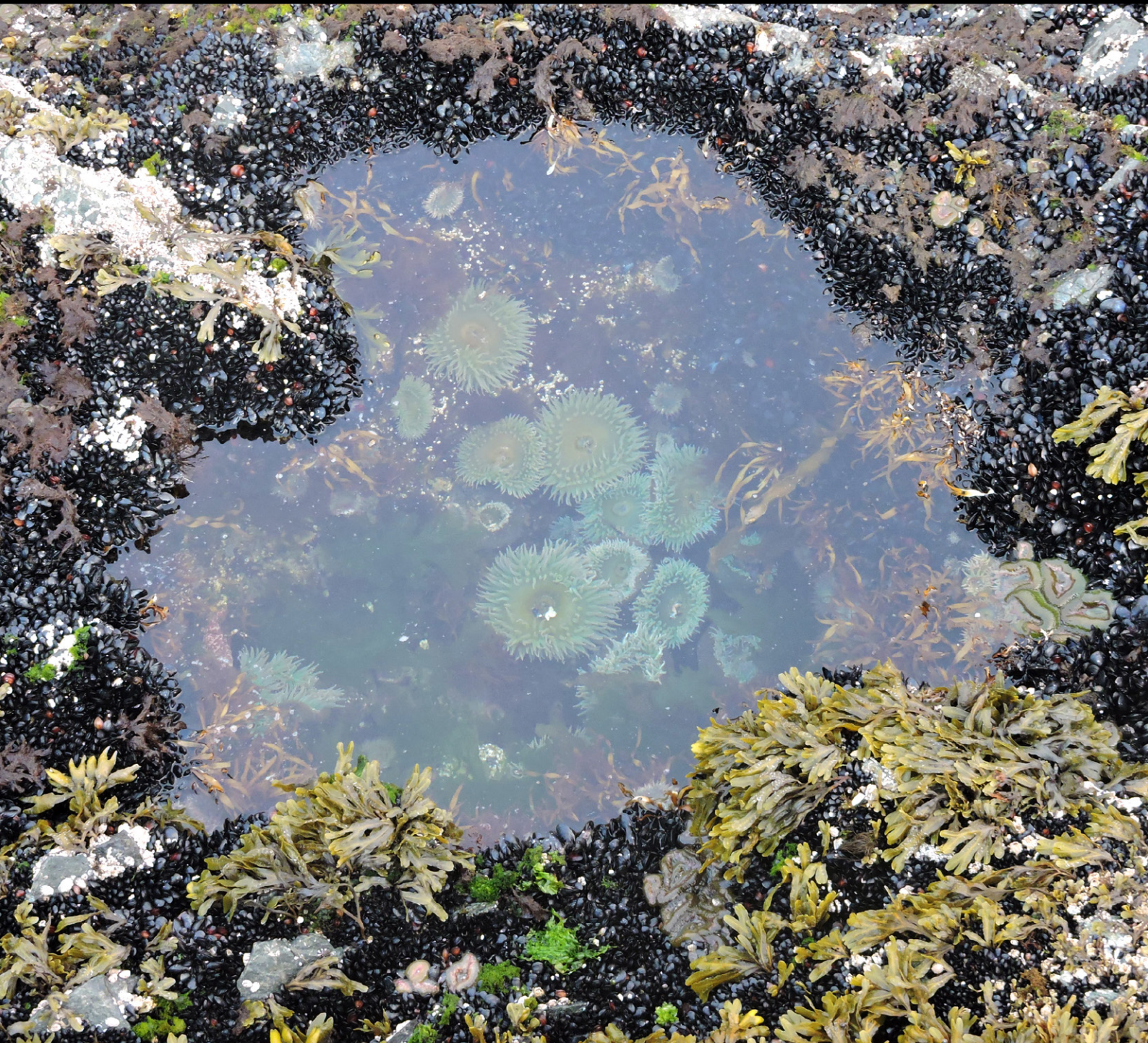


Regional Report  
for PICES Region:

**14**

PICES SPECIAL PUBLICATION 7

# Marine Ecosystems of the North Pacific Ocean 2009–2016



# PICES North Pacific Ecosystem Status Report, Region 14 (Northern Bering Sea)

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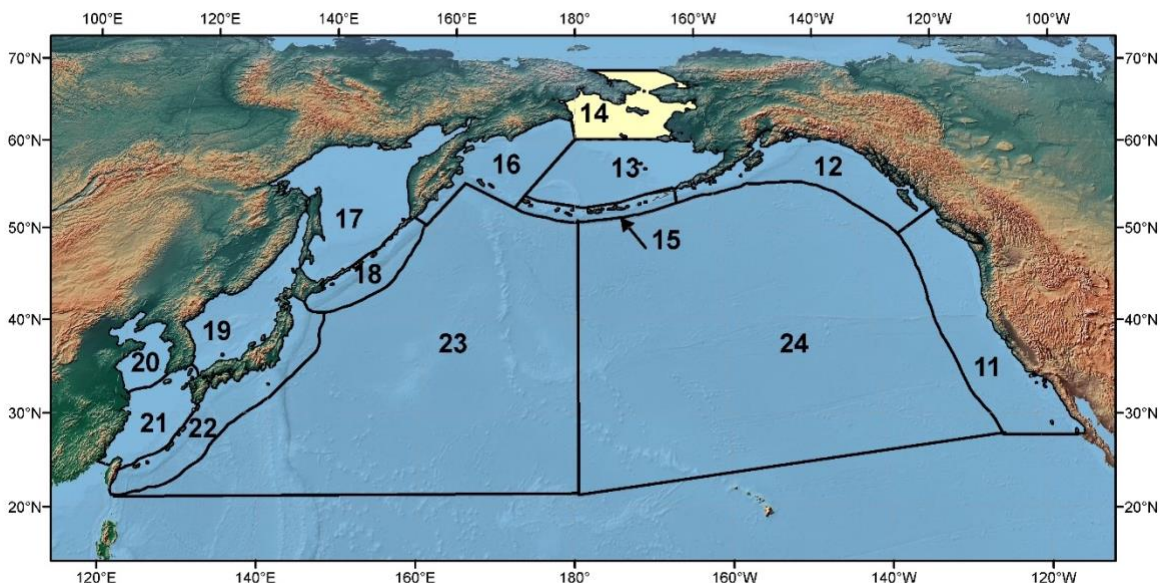


Figure R14-1. The PICES biogeographical regions and naming convention for the North Pacific Ocean with the area discussed in this report highlighted.

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## 1. Highlights

The northern Bering Sea (NBS) encompasses one of the largest continental shelves in the world. Pacific water with high nutrient levels is channeled northward to the northern Bering Sea Shelf (NBSS) and drives planktonic and benthic production as well community dynamics in the greater Pacific Arctic (Panteleev et al. 2012). Mean current flow is northward into the Arctic Ocean over most of the year (Woodgate et al. 2005) and dynamics in this region have important influences on sea ice in the Arctic (Woodgate et al. 2010) and global patterns in hydrography (Aagaard and Carmack 1989) and thermal-haline circulation (Hu et al. 2010). Important ecosystem features include seasonal sea-ice coverage (Baker et al. 2020a), highly seasonal production (Carmack and Wassmann 2006), and benthic-dominated food webs (Grebmeier et al. 2006; Whitehouse et al. 2014). The NBS supports an Arctic-associated biological community, including a benthic invertebrates, pelagic fishes, Arctic marine birds and mammals, and Indigenous communities with distinct regional cultures and extensive knowledge of and reliance on these marine resources.

Sea ice extent and duration influence annual primary production of ice-associated algae and open-water phytoplankton (Arrigo and van Dijken 2015; Moore et al. 2018). Winter sea ice also impacts water mass characteristics and the persistence of cold waters at depth that often persist through the summer (Wyllie-Echeverria and Wooster 1998; Baker et al. 2020b). In many respects, the NBS is more closely connected in hydrographic and biological characteristics to the Chukchi Sea to the north than to the southern Bering Sea (Walsh et al. 1997; Sigler et al. 2017). Historically, an important Arctic-subArctic temperature front has formed at approximately 60° N (Fig. R14-2), separating the northern and southern sectors of the contiguous eastern Bering Sea shelf (Stabeno et al. 2012a; Kivva 2016). Recent indications suggest that this front is moving northward, with potential for a restructuring of the ecosystem (Grebmeier et al. 2006; Huntington et al. 2020; Polyakov et al. 2020). This chapter provides a summary of this system in the 2009-2015 timeframe relevant to this report, and also provides insight on important shifts in this system in more recent years 2016-2020.

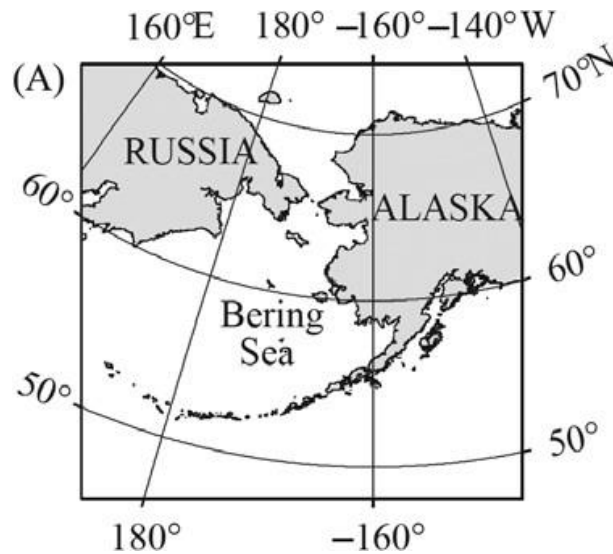


Figure R14-2. Bering Sea and delineation of the NBS at 60°N

## 2. Introduction

### 2.1. System description - the Northern Bering Sea

The northern Bering Sea (NBS) serves as an important pathway and connection between the Pacific and Arctic Oceans (Baker et al. 2020b). The physical environment is structured by regional circulation and wind stress (Danielson et al. 2014; Woodgate et al. 2012, 2005b), air-sea-ice heat flux (Drucker et al. 2003), ice cover (Paquette and Bourke, 1981), water mass mixing (Woodgate and Aagaard 2005), coastal discharge (Aagaard et al. 2006), and topographic controls (Kinder et al. 1986; Weingartner et al. 2005; Woodgate and Aagaard 2005; Spall 2007). Biochemical and geochemical environmental conditions and production are influenced by these physical factors and in turn influence phytoplankton production dynamics, nutrient cycling, and benthic-pelagic coupling (Walsh et al. 1989). Transport of waters in this area has an important role in exchange and advection of production from the Pacific to Arctic (Panteleev et al. 2012).

Historically, this region has been relatively data poor, though this is rapidly changing. This region has been the focus of several large research programs in recent years, including the Distributed Biological Observatory (DBO; <https://www.pmel.noaa.gov/dbo/>), Study of Environmental Arctic Change (SEARCH; <https://www.search.arcticscience.org/>), Arctic Observing Network (AON; <https://www.nsf.gov/div/index.jsp?org=OPP>), Arctic Ecosystem Integrated Survey (IES; <http://web.cfos.uaf.edu/wordpress/arcticeis/>), Sustaining Arctic Observing Networks (SAON; <https://iasc.info/data-observations/saon>), Synthesis of Arctic Research (SOAR; <https://www.pmel.noaa.gov/soar/>), the Russian-US Long-term Census of the Arctic (RUSALCA, <https://www.pmel.noaa.gov/rusalca>), NOAA Ecosystem Monitoring Assessment (EMA; <https://www.fisheries.noaa.gov/alaska/ecosystems/alaska-ecosystem-monitoring-and-assessment>), and fisheries-oceanographic surveys through the Bering-Aleutian Salmon International Survey (BASIS; <https://www.fisheries.noaa.gov/alaska/population-assessments/bering-arctic-and-subarctic-integrated-survey>), the Marine Arctic Ecosystem Study (MARES; <https://www.nopp.org/projects/mares/>), and the North Pacific Research Board (NPRB) Pacific Marine Arctic Regional Synthesis (PacMARS; <http://pacmars.eol.ucar.edu/>) and Arctic Integrated Ecosystem Research Program (IERP; <https://www.nprb.org/arctic->

[program/about-the-program/](#); Baker et al. 2020b, 2022).

At the same time, this region is experiencing rapid transformation (Huntington et al. 2020) and there is relatively limited historical data to serve as comparison. As a result, baseline understanding of the region is being developed in the context of a system in transition. The directive for this publication is to summarize the 2009-2015 period. However, since the system is in rapid transition, the report also incorporates some relevant data through 2020.

This region has not been defined nor described in previous versions of the PICES North Pacific Ecosystem Status Report (Perry and McKinnell 2004; McKinnell and Dagg 2010). We therefore clearly define this region in the introductory section to follow.

## 2.2. Definition of the Northern Bering Sea and regional delineation

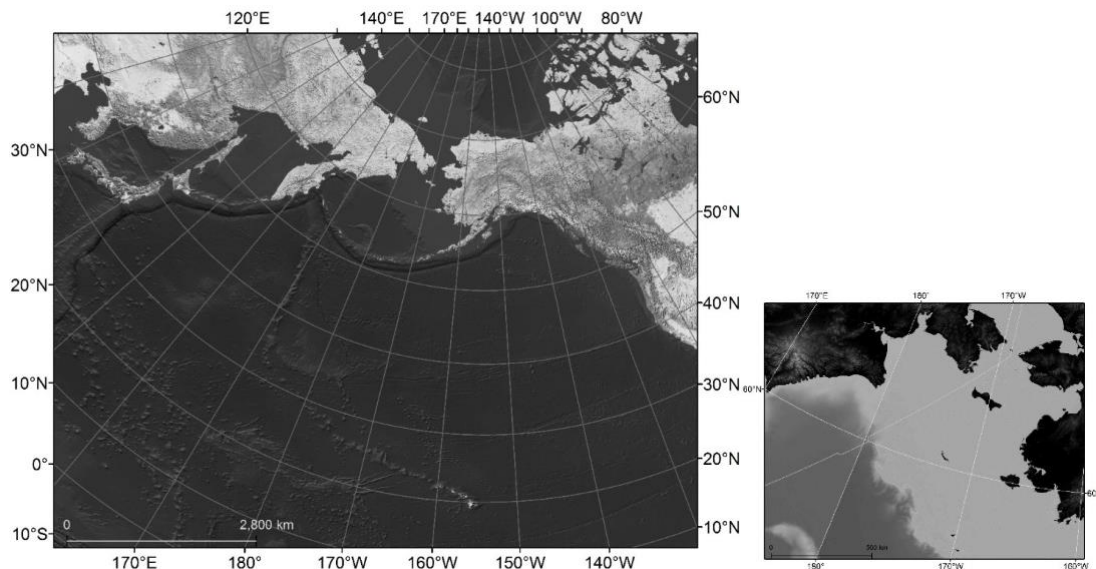
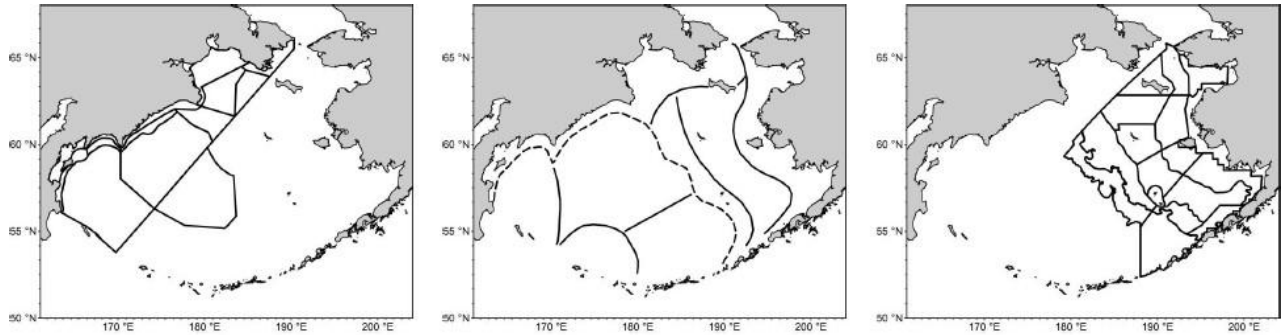


Figure R14-3. Map of the North Pacific and NBS (inset).

The NBS is here defined as all areas of the Bering Sea north of 60°N (Stabeno et al. 2012a; Sigler et al. 2017) (Figure R14-3). This delineation includes the northern part of the eastern Bering Sea Shelf from Nunavut Island in the east (60°N, 164°W) to Cape Navarin (62°N, 179°E) in the west. Several different regional delineations have been applied to the Bering Sea as a whole, including approximate boundaries of 8 distinct ecosystems (Coachman 1993) and standard biostatistical regional in the Russian EEZ (Shuntov 1988; Volvenko 2003) and in the US EEZ (Ortiz et al. 2012) (Figure R14-4). Other regional delineations have been developed using oceanographic boundaries (Allen and Smith 1988; Piatt and Springer 2007), and integrated analyses of physical attributes and biological distributions (Baker and Hollowed 2014; Baker et al. 2020a; Kivva 2016).

Several different delineations have also been developed to mark the boundaries within the Bering Sea and to note differences between the between North Pacific and Arctic biogeographic regions. In defining boundaries for the northern Bering Sea, others have defined the southern boundary using the 60°N demarcation (Briggs 1995), the Anadyr River and Yukon River drainages (Andiashev 1939), and Cape Navarin. The northern boundary is defined at the Bering Strait and confluence of the Chukchi Peninsula and Seward Peninsula (Kussakin 1975, Golikov 1990).



Standard bio-statistical regions (*Shuntov, 1988; Volvenko, 2003*)

Approximate boundaries of 8 ecosystems of the BS (*Coachman, 1990*)

Marine regions for the Bering Sea shelf and slope (*Ortiz et al., 2012*)

Figure R14-4. Various schematics used to delineate the Bering Sea (50-70°N, 160°E-210°W) [source: Petryashov et al. 2013] (Figure R14-5).

### 2.3. Justification of delineation at 60°N

The authors of the Bering Sea ecoregions in the PICES North Pacific Ecosystem Status Report use 60°N latitude to delineate the boundary between the northern (PICES Region 14) and eastern (PICES Region 13) Bering Sea on the basis of available data and survey designs, existing research and analyses in these areas, and physical and biological distinctions between these ecological systems. This delineation is also supported by broadscale analyses of the physical oceanography and hydrography (Stabeno et al. 2012a; Baker et al. 2020a) and zoogeography of the region (Sigler et al. 2017).

#### *Physical and biological criteria and past analyses of biogeography*

More details on the rationale for delineation of the northern Bering Sea at 60°N are provided here, including benthic topography, regional oceanography and circulation, ice coverage, and species distribution and biogeography. Summer circulation patterns appear to separate at 60°N and this transition is marked by shifts in geostrophic velocities and temperature (Cokelet 2016; Hollowed 2012); the southern extent of minimum sea ice in the Bering Sea is also noted at 60°N. Historically, areas north of this latitude are covered with sea ice every year whereas south of 60°N is characterized by variable annual sea ice extent, with implications for atmospheric-oceanic interactions, wind mixing, wave activity, salinity, heat content, stratification, and phenology and pathway of primary productivity (e.g., open water planktonic versus ice algae; Overland and Pease 1982; Sigler et al. 2014). Eisner et al. (2015) and Siddon et al. (2020) show spatial variation in zooplankton and fish assemblages differ over the southern shelf compared to the northern shelf with the transition occurring near 60°N (Nunivak Island). Past analyses of biogeographic structure also note important shifts in species composition at approximately 60°N (Mueter and Litzow 2008; Baker and Hollowed 2014).

Several past analyses of these systems have used 60°N as the breakpoint between large marine ecosystems. Specifically, the northern domain of the Bering Sea is defined at 60°N in analyses that include physical oceanography (NCAR/CESM simulations, Cheng et al. 2014) carbonate chemistry (Cross et al. 2014; Mathis et al. 2014), sediment analysis (Horak et al. 2013), primary production (Mordy et al. 2012), microzooplankton (Stoecker et al. 2014), zooplankton (Eisner et al. 2014), and larval fish (Smart et al. 2012). Other studies

specifying a distinct NBS also use this delineation (Cooper et al. 2012). Several meta-analyses have been conducted that indicate 60°N as a breakpoint. These include marine regions delineated in The Bering Ecosystem Study (BEST)/The Bering Sea Integrated Ecosystem Research Program (BSIERP) research community on basis of consultation with experts in oceanography, bathymetry, benthic fauna, fish, seabird and marine mammal distribution (Ortiz et al. 2012). Previous reviews have reached similar conclusions (Sigler et al. 2011; Stabeno et al. 2012b). Statistical analysis of community composition, physical parameters shifts, and environmental gradients also identify 60°N as a significant breakpoint (Mueter and Litzow 2008; Baker and Hollowed 2014). Further rationale for this breakpoint is provided below:

#### *Physical Oceanography*

- Evident breaks in vertical profiles of the water column were noted at 60°N in hydrographic temperature and salinity profiles in summer cruises (Goes et al. 2014).
- Analyses in the western Bering Sea identify 60°N as a significant breakpoint (Kinder et al. 1986) as flow intensifies along the east coast of Siberia forming the Anadyr current.
- Bottom and surface velocity vectors (Zhang et al. 2012).
- Distinct patterns in stratification at 60°N (Ladd and Stabeno 2012)
- Geostrophic velocity vectors and circulation patterns diverge at 60°N (Cokelet et al. 2016; Hollowed et al. 2012).
- Bering Slope current turns west at 61°N (Ladd et al. 2014)
- Intensified flow in the approach to Bering Strait at 60°N (Woodgate and Aagaard 2005).
- Influx of freshwater inputs through the Yukon River and Kuskokwim River
- ROMS model results suggest significant divergence in patterns at 60°N for sea surface temperature, ice cover, and wind stress (Hermann et al. 2016).
- 60°N marks the southern extent of minimum sea ice extent in the Bering Sea. Areas north of this latitude are covered with sea ice every year. The area south of 60°N is characterized by variable annual sea ice extent, with implications for atmospheric-oceanic interactions, wind mixing, wave activity, salinity, heat content, stratification, and phenology and pathway of primary productivity (planktonic production and ice algal pathways). These observations are supported from historical analyses 1958-1980 (Overland and Pease 1982) as well as more recent analyses (Sigler et al. 2014).

#### *Chemical Oceanography*

- Significant differences in trends are noted at 60°N for ammonium and Chl fluorescence (spring and summer surveys 2007-2008; Mordy et al. 2012).
- A breakpoint was identified at 60°N for nutrients including phosphate, silicate and nitrate and Chl-a production and diatom concentration (Goes et al. 2014).

#### *Biological Oceanography*

- Phytoplankton display distinct trends north and south of 58-62° N for diatoms, cryptophytes, dinoflagellates, haptophytes, and chlorophytes (Mordy et al. 2012).
- Phytoplankton community production is distinct north and south of 60°N (Mordy et al. 2012)
- Notable differences of north and south of 60°N were observed in large crustacean zooplankton abundance and species composition (Hermann et al. 2016)

#### *Juvenile Fish Distributions*

- Data on juvenile fish distributions are available from the NOAA BASIS (Bering Arctic-Subarctic Integrated Surveys) surveys. These surveys are conducted over both the southern and northern Bering Sea shelves with a split at 60°N. It is worth noting that the southern Bering Sea survey covers the inner, middle, and outer domains while the

- northern survey predominantly samples the inner domain.
- Eisner et al. (2015) shows the spatial variation of large zooplankton assemblages; assemblage structure differs over the southern shelf compared to the northern shelf with the transition occurring near 60°N
- Eisner et al. (2015) also shows the spatial variation of fish clusters; assemblage structure differs over the southern and northern shelves with the transition occurring just south of 60°N, depending on year.
- Eisner et al. (2018) examines zooplankton assemblages seasonally (spring, summer, fall) over the Bering Sea shelf in three cold years (2008-2010). In spring and summer, assemblage structure is delineated more so by domain with distinct clusters in the inner, middle, and outer domains. By fall, assemblage structure has a stronger latitudinal gradient with transition occurring just south of 60°N.
- Siddon et al. (2020) south of 60°N. In summer and fall, fish assemblages differed over the southern and northern shelves with the transition occurring at or just south of 60°N (Nunivak Island).

#### *Adult Fish Distributions*

- The relative proportion of fishes and invertebrate change with latitude in the Bering Sea, such that flatfishes (*Pleuronectidae*) and cods (*Gadidae*) dominate (90%) overall fish catch, but decline in northern Bering Sea, while other fishes such as sculpins (*Cottidae*) and eelpouts (*Zoarcidae*) increase (Stevenson and Lauth 2012).
- In the EBS, fishes make up approximately 70% of the total catch weight and 30% in the NBS (Stevenson and Lauth 2012).
- 60°N marks a shift in distribution for forage fish (Andrews et al. 2016)
- 60°N marks a shift in distribution of groundfish (Parker-Stetter et al. 2016; Baker 2021)

#### *Survey data*

While many sampling frameworks have been applied to the Bering Sea, 60°N marks a convenient breakpoint for distinguishing data collected in existing surveys, transects, and mooring. The North Pacific Anadromous Fish Commission NBS surveyed from 60°N via pelagic trawl in 2014 and 2017 (<https://www.npafc.org>). The Bering-Aleutian Salmon International Survey (<https://apps-afsc.fisheries.noaa.gov/Quarterly/jfm2007/jfmfeaturelead.htm>) also is initiated at 60°N

#### *Biogeography and Community Dynamics*

- Species composition and species dynamics are distinct at 60°N (Mueter and Litzow 2008)
- Community shifts for fish and invertebrates are evident at 60°N (Baker and Hollowed 2014)

#### *Social Dynamics and Human Dimensions*

- Subsistence harvest and community dynamics are also distinct north and south of 60N (Renner and Huntington 2014)



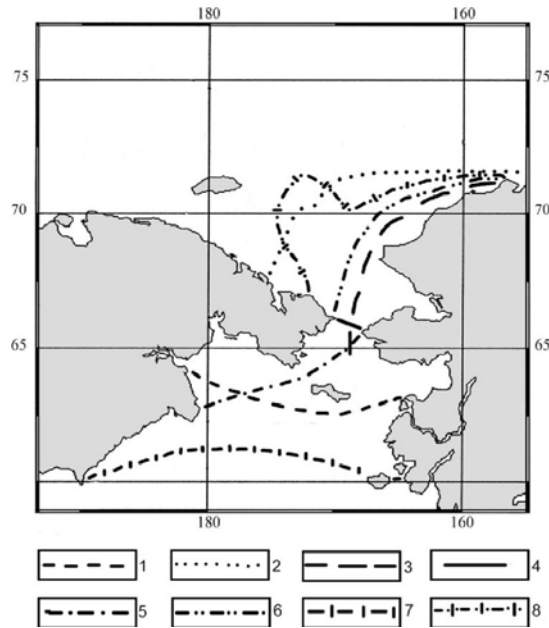


Figure R14-5. Various schematics to determine important physical and biogeographic breakpoints between the subarctic and Arctic systems in the Pacific, including 1 – Andiashev 1939; 4 – Kussakin 1975; 5 – Golikov 1980; 7 – Briggs 1995 [source: Petryashov et al. 2013].

#### 2.4. Unique characteristics of the northern Bering Sea

The NBS is distinguished from the EBS and western Bering Sea (WBS) on the southern extent the dynamics of the Bering Sea Basin. The mean cyclonic gyre in the basin (Ladd 2014) is defined by the southward Kamchatka Current (Panteleev et al. 2006), eastward Aleutian North Slope Current (Reed and Stabeno 1999; Stabeno et al. 2009) and northwestward Bering Slope Current (BSC, Johnson et al. 2004). Analysis of satellite altimetry and in situ data (Pantaleev et al. 2012) noted significant lagged correlations between transport in the Alaskan Stream, Bering Sea Current and Kamchatka Current, suggesting continuity of flow throughout the Bering Sea Basin (Ladd 2014). Velocities in the BSC are only significant south of 59°N (Ladd 2014), at which point it turns off shelf to flow westward across the Bering Sea at that latitude (Stabeno and Reed 1994) and turning to the Kamchatka Current at 62°N (Ladd 2014).

#### 2.5. Regional delineation within the NBS

Within the NBS, there are several distinct regions, each with distinctive traits and processes. These constituent regions include (clockwise from the north): the Bering Strait, the Chirikov Basin and St Lawrence Island, the Seward Peninsula and Norton Sound, the inner northern Bering Sea shelf and Nunavut Island, the middle northern Bering Sea shelf and St Matthews Island, the outer northern Bering Sea shelf, the northern Bering sea slope, the northern Bering Sea basin (100-3500m), Cape Olyutorskiy and the Koryak Coast (0-1000m), Cape Navarin, the Gulf of Anadyr (0-100m), and the Chukchi Peninsula and Provideniya Bay. Petryashov et al. (2013) define 5 distinct subregions in the northern Bering Sea on the basis of the distributions and communities of benthic macrofauna (Figure R14-6). These include (1) the Koryak region between Cape Olyutorsky and Cape Navarin, (2) Nunivak island to the Yukon River Delta, (3) the Gulf of Anadyr, (4) Norton Sound and St Lawrence Island, and (5) the Chirikov Basin from St Lawrence Island to Bering Strait (Regions 1-5 in Figure R14-6). A regional synthesis developed as part of the North Pacific

Research Board (NPRB) Bering Sea Integrated Ecosystem Research Program (BSIERP) identified 14 discrete regional in the eastern Bering Sea shelf (Fig. R14-7).

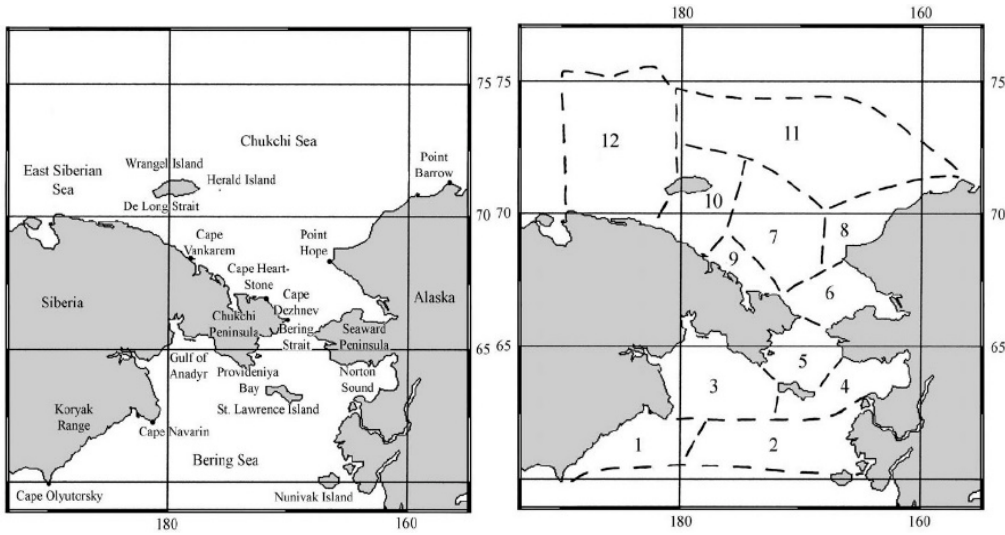


Figure R14-6. Regional portioning within the Pacific Arctic interface [source: Petryashov et al. 2013].

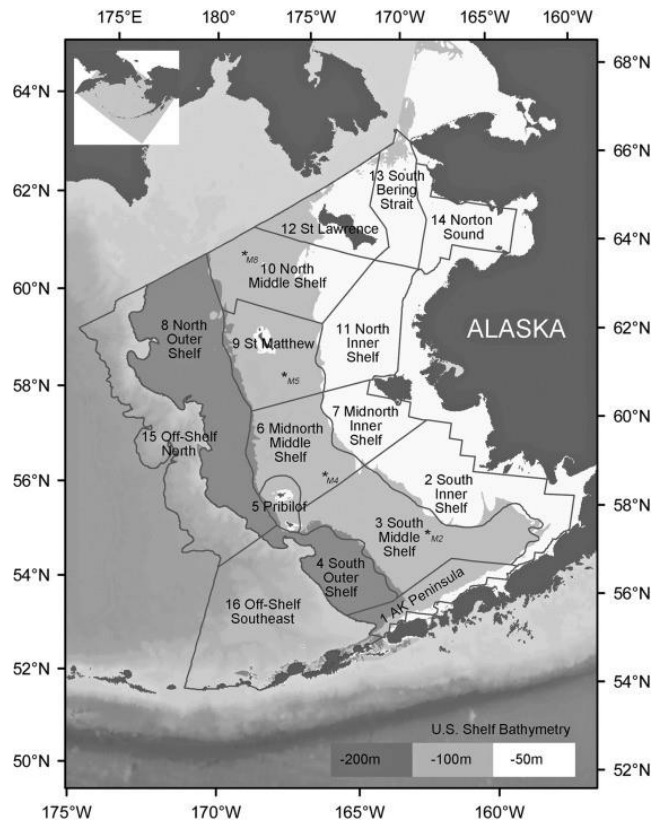


Figure R14-7. Various schematics used to delineate the eastern Bering Sea [source: Ortiz et al. 2016]

## 2.4 Available data

This PICES region has fewer long-term time series than most other North Pacific systems in this volume. Until recently it has received less attention (Wassmann et al. 2011). That situation is changing. Since 2000, several multi-year research programs have focused on this area, including North Pacific Climate Regimes and Productivity (2004-2011), Russian-American Long-term Census of the Arctic (2004- present), Bering Ecosystem Study (2007-2012), NPRB Bering Sea Integrated Ecosystem Research Program (2008-2012), NOAA Bering-Aleutian Salmon International Survey (2002-present). Recent integrated surveys of oceanographic and pelagic and benthic communities include Arctic EIS surveys (2012-2013, August-September), Arctic IERP (2017-2018, May), NOAA-RACE surveys (2017-2019, May-August).

Most research in the region has been conducted within the US and Russian EEZ via federal research (e.g., NOAA, TINRO/VNIRO). The Russian TINRO-Center conducted 4 field campaigns aimed at multidisciplinary physical-biological research of the north-western Bering and south-western Chukchi Seas (2003, 2007, 2008, and 2010). Oceanographic observation and pelagic trawling were conducted in all years and bottom trawling in 2008 and 2010. Several US NOAA research programs have surveyed this area including Bering-Aleutian Salmon International Survey (BASIS), eastern Bering Sea Trawl Survey (1982-2018), and the NBS bottom trawl survey (2010,2017,2018) (Figure R14-8; Fig. R14-9). Previous bottom trawl surveys of the US portion of the NBS were conducted in 1976, 1979, 1982, 1988, 1991 (Hamazaki et al. 2005; Stevenson and Lauth 2012); NOAA plans to conduct biennial surveys in the future (Hollowed et al. 2017; R. Lauth, personal communication). Other dedicated programs have focused special projects or research and analysis on this data, including the Loss of Sea Ice (LOSI, 2015-2019). Significant data are also available by other national efforts conducted by European, Asian, and North American nations (e.g., KOPRI, JAMSTEC) or through academic research. Several large-scale regional and collaborative studies have been implemented in recent years. These studies include: Russian-American Long-term Census of the Arctic (RUSALCA, 2004-2015), Arctic Long-term Monitoring Array (ALTIMA 2016-2018), Pacific Marine Arctic Regional Synthesis (PacMARS 2012-2014), Arctic Ecosystem Integrated Survey (Arctic EIS, 2012-2016), Synthesis of Arctic Research (SOAR 2015-2019), NPRB Arctic Integrated Ecosystem Research Program (AIERP, 2016-2019).

The NPRB BSIERP (2007-2010) cruise lines were implemented such that two were north and two were south of 60°N. Several sampling efforts collect data specifically at the 60°N breakpoint; these include the east-west MN transect implemented through the BEST/BSIERP project at 60°N across the shelf and the M5 BASIS mooring maintained by NOAA at 60°N (Figure R14-10 right). A NOAA NBS cruise was implemented from 60-65°N (Bering Strait) in 1982, 1985, 1988, 1991, 2010, 2017, and 2018. Midwater and surface trawls have been implemented via Arctic EIS surveys from 60-65°N in 2012 and 2013 [[https://web.sfos.uaf.edu/wordpress/arcticeis/?page\\_id=50](https://web.sfos.uaf.edu/wordpress/arcticeis/?page_id=50)].

Mooring data is available through an increasing number of sources. Mooring A3 in Bering Strait has been occupied continuously since 1997 (Woodgate et al. 2012). NOAA moorings have also been maintained on the eastern Bering Sea shelf at four sites: M2 (56.9 N, 164.1 W) since 1995, M4 (57.9 N, 168.9 W) since 1996, M5 (59.9 N, 171.7 W) and M8 (62.2 N 174.7 W) since 2004 (Fig. R14-10 right). All four moorings are deployed on the 70 m isobath. Data are available on temperature, salinity, fluorescence, currents, zooplankton abundance, nitrate, and oxygen as well as air temperature, humidity, barometric pressure, wind velocity and solar radiation (PAR). As part of the ongoing Arctic IERP, moorings were also deployed in 2017 and 2018 in the Chirikov Basin (Fig. R14-10 left)

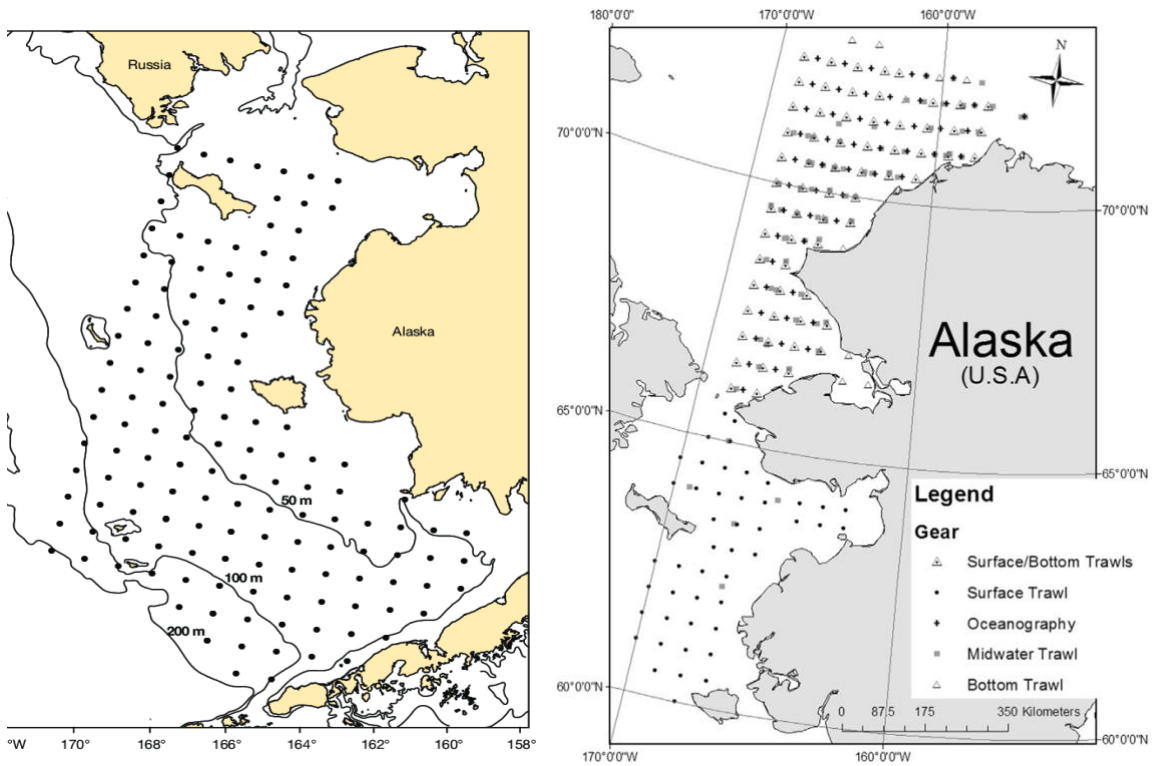


Figure R14-8. Survey stations in the NBS for the Bering Aleutian Salmon International Survey (BASIS) and Arctic IES surveys (Mueter et al. 2017; <https://dx.doi.org/10.1016/j.dsr2.2016.11.005>).

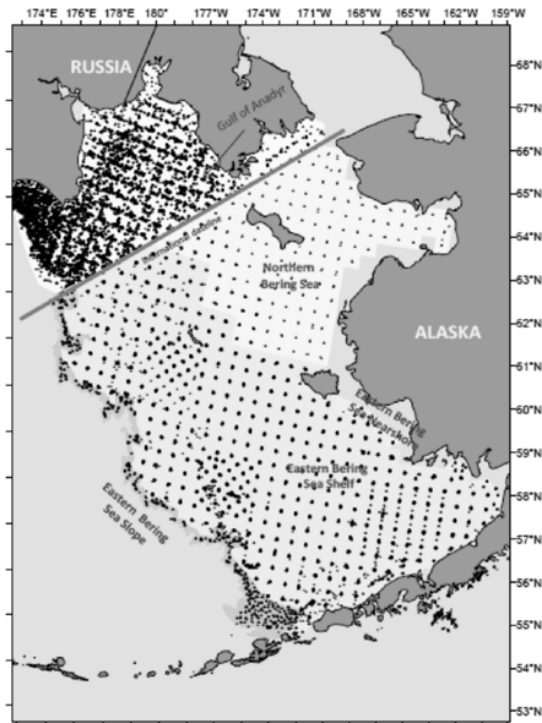


Figure R14-9. Map of bottom trawl survey coverage of the Bering Sea shelf, black points indicate bottom trawl locations [source: Vladimir Kulik (VNIRO) and Stanislav Kotwicki (NOAA)]

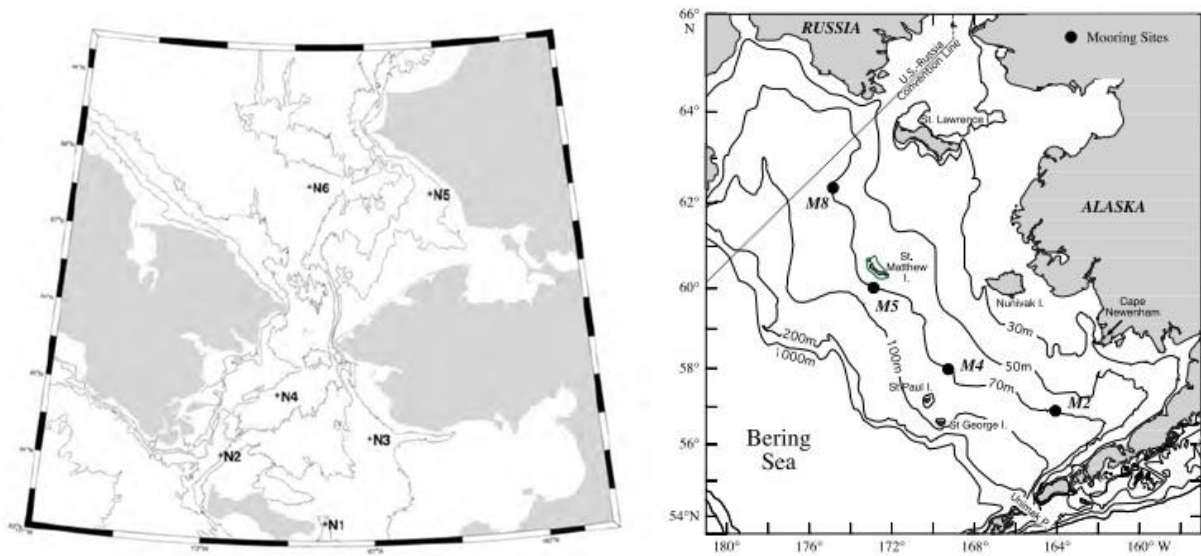


Figure R14-10. Mooring locations deployed in the NBS and Chukchi Sea in the North Pacific Research Board Arctic Integrated Ecosystem Research Program (AIERP), 2017-2019 (left) and moorings deployed along the SEBSS and NBSS in the NOAA Pacific Marine Environmental Laboratory array, 2010-2019 (right). Mooring M5 marks the southern extent of the NBS. Mooring M8 is in the center of the NBS. AIERP Moorings are at the following locations in the Chirikov Basin: N1 (63°17.80'N, 168°25.68'W); N2 (64°09'N, 171°31.56'W); N3 (64°23.37'N, 167°05'W); N4 (64°55.70'N, 169°55.09'W).

## 2.5 Synthesis and System Update

While hard physical boundaries are difficult to define in the ocean, trends in seasonal ice and water temperature divide the eastern Bering Sea shelf, with a rough transition between the northern and southern Bering Sea between 59° and 61°N. In the NBSS, there is less obvious stratification than the more sharply stratified southern shelf. While many studies have noted the distinction between the northern and southern Bering Sea, in recent years, these divisions seem to be eroded. This raises important questions as to whether these distinctions will persist in the context of climate change.

Until recently, northern Bering Sea ecosystems were characterized by extensive seasonal sea ice cover, high water column and sediment carbon production, and tight pelagic-benthic coupling of organic production. Here, we show that these ecosystems are shifting away from these characteristics. Changes in biological communities are contemporaneous with shifts in regional atmospheric and hydrographic forcing. In the past decade, geographic displacement of marine mammal population distributions has coincided with a reduction of benthic prey populations, an increase in pelagic fish, a reduction in sea ice, and an increase in air and ocean temperatures. These changes now observed on the shallow shelf of the northern Bering Sea should be expected to affect a much broader portion of the Pacific-influenced sector of the Arctic Ocean.

### 3. Atmosphere

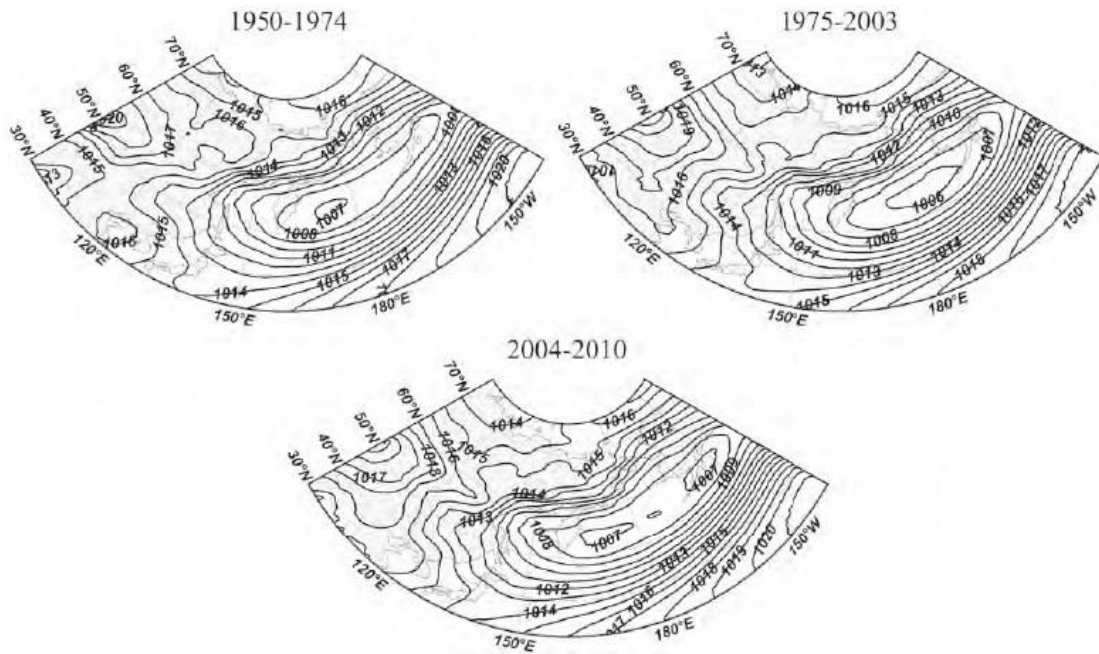


Figure R14-11 Mean annual sea level pressure in the North Pacific for 1950-74, 1975-2003 and 2004-10 with the western, eastern and western shift of the Aleutian Low [Source: Khen et al.2013].

Atmospheric forcing has implications for air temperatures, water temperatures, and slow regimes. Significant negative correlations have been identified between sea ice concentrations in the southeastern Bering Sea shelf and the Pacific Decadal Oscillation (PDO) in winter and significant positive correlations between Arctic Oscillation (AO) and sea-ice cover in the northern Bering Sea (Frey et al. 2015). From 2006-2011, the mean position of the Aleutian Low shifted east into the Gulf of Alaska (Danielson et al. 2011; Overland et al. 2012) from a westward position over the Bering Sea (2000-2005) (Figure R14-11). Model results (Danielson et al. 2014) suggest that Bering Strait transport anomalies are primarily set by location of the Aleutian Low. Storms centered over the Bering Sea propagate continental shelf waves on and transfer northward velocity anomalies through the Bering Strait.

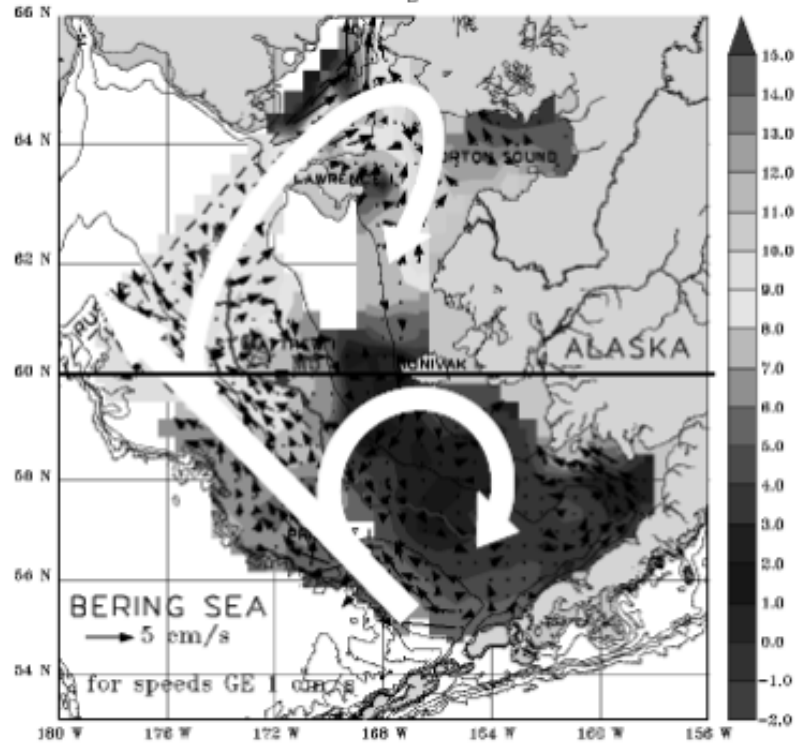


Figure R14-12 Temperature and geostrophic velocities distinguishing the southeastern Bering Sea and northern Bering Sea [Source: NOAA/PMEL, E.D. Cokelet]

Winds over the Bering shelf can also redistribute on-shelf flow via Ekman transport (Danielson 2012). Southerly and southeasterly winds drive coastal convergence along the Alaska coast while northerly and northwesterly winds over the central Bering shelf result in coastal divergence with currents forced south (Danielson et al. 2014). If sufficiently strong, this may reverse flow in Bering Strait (Danielson et al. 2012). Summer circulation patterns also separate north and south of 60°N (Figure R14-12).

## 4. Physical Oceanography

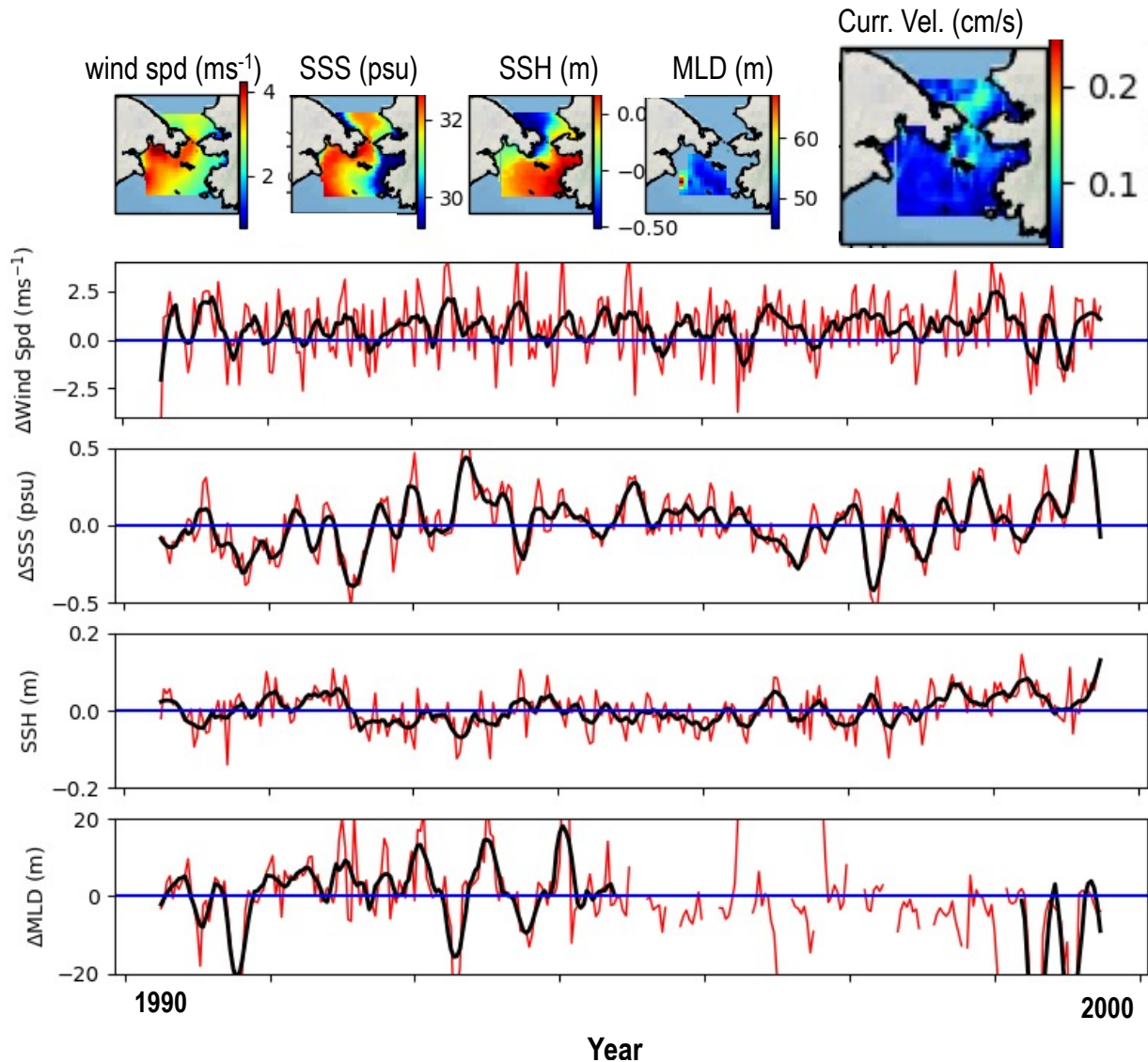


Figure R14-13. Time series anomaly and spatial variation of physical data in NBS, 1990-2020. Model datasets are compiled from NASA satellite data and include: no ice CCMP wind speed (PODAAC), Sea Surface Height and Salinity from Copernicus Marine Environment Monitoring Service Global Ocean Physical Reanalysis, Current Velocity from OSCAR satellite data (PODAAC; no time series is shown), Mixed Layer Depth from NOAA GODAS model. Credit: Chelle L. Gentemann, Senior Scientist, Earth & Space Research.

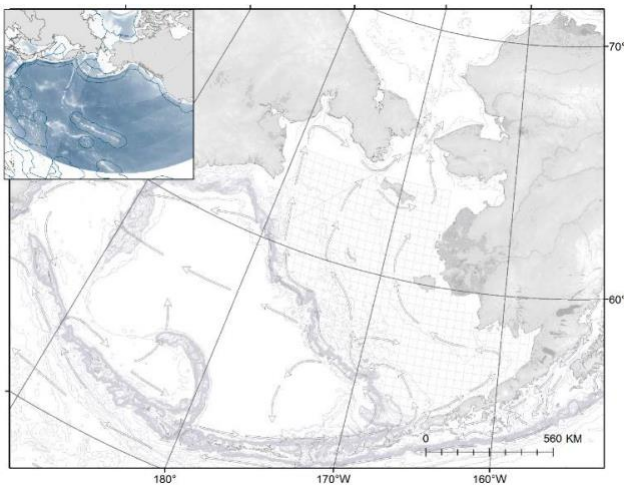
### 4.1. Physical Flow and Currents (Figure R14-14)

The NBS is a transit point for Pacific waters flowing northward through Bering Strait into the Arctic. The primary currents include nutrient-rich Anadyr Water near the Siberian coast, Bering Shelf Water along the shelf and shelf break, and nutrient-poor Alaska Coastal Water along the Alaskan coast (Coachman et al. 1975; Woodgate et al. 2005). The northward flow is driven by differing sea-level heights between the North Pacific and Arctic oceans (Stigebrandt 1984; Aagaard et al. 2006). This flow advects nutrients, organic carbon, plankton, and the hydrographic properties of the waters along the Bering slope and the



central Bering shelf (Walsh et al. 1989; Grebmeier et al. 2015). Water mass boundaries are typically indistinct (e.g., Bering Shelf Waters and Anadyr Waters mix within and downstream of Bering and Anadyr straits; Pisareva et al. 2015). However, a strong density front separates the Alaska Coastal Water from the offshore waters (Hunt and Harrison 1990; Gawarkiewicz et al. 1994; Weingartner et al. 2005). Modeling (Clement et al. 2005; Maslowski et al. 2001; Kinney et al. 2014; Hu and Wang 2010) and observational (Mizobata et al. 2002, 2006) studies indicate that mesoscale eddies play a decisive role in the exchange of properties between the northern BS shelf and the southern BS basin, controlling transport of the Pacific waters into the Arctic Ocean. Process studies also confirm the importance of mesoscale instabilities along the slope and topographic interactions on local largescale circulation along the BS shelf break (Panteleev et al. 2012).

Figure R14-14. Physical flow and currents of Northern Bering Sea [Source: Baker MR]



Several distinct oceanographic regions and features are defined below.

*Bering Strait* – The Bering Strait Alaska Coastal Current, the Bering Slope Current, and the Anadyr Current flow north from the Bering Sea through the Bering Strait, carrying heat and nutrients north from the Pacific Ocean into the Arctic.

*Alaska Coastal Current (ACC)* - The ACC flows northward along the inner shelf. It forms a nearly continuous corridor of low salinity water along the Alaska coastline (Sverdrup 1929; Royer 1982; Weingartner et al. 2005) and transports Alaska Coastal Water northward through the eastern Bering Strait (Coachman 1975; Woodgate and Aagaard 2005). It is characterized by fresh, buoyant, low-nutrient water discharged from large rivers—including the Nushagak, Kvichak, Kuskokwim, Yukon, Kobuk, and Noatak—that drain central Alaska (Arctic Monitoring and Assessment Program, 1998).

*Anadyr Current (AC)* – The AC flows along the Siberian coast. It originates at the northern end of the Bering shelf break, flows northward through Bering Strait (Stabeno et al. 1999), and circumscribes the Gulf of Anadyr, transporting Anadyr Water to Anadyr Strait, the Chirikov Basin and Bering Strait. This surface current is characterized by warm, salty, nutrient-rich water from the central Bering shelf.

*Bering Shelf Water (Central Channel, BSW)* – North of St. Lawrence Island, BSW flow north through the central channel, transporting Bering Shelf water (low salinity, nutrient-rich) Pacific water into the Chukchi Sea. Reversals of the northward flow occur in fall and

winter, driven by strong southward winds (Stabeno et al. 1999).

*Bering Slope Current* – The BSC transports water northwest along the Bering shelf break (Stabeno et al. 1999). At the northern end of the shelf break at Cape Navarin, the Bering Slope Current divides into the westward-flowing Kamchatka Current and the eastward-flowing Anadyr Current (Stabeno et al. 1999, Grebmeier et al. 2015). The AC current is the main pathway for transportation of relatively warm and salty BSW into the Arctic. Seasonality in the BSC is pronounced with stronger flow close to the shelf-break in winter and weaker flow off-shelf the rest of the year (Ladd, 2014). This current forms the eastern boundary of the Bering Gyre.

*Kamchatka Current* – The Kamchatka Current flows southward along the Siberian coastline from Cape Navarin, where the Bering Slope Current terminates (Stabeno et al. 1999). This current forms the western boundary of the Bering Gyre.

Thermohaline attributes in the NBS include persistent northward flow, seasonality and processes related to ice formation (Gladyshev and Khen 1995). Northward flow of water from the Pacific to the Arctic is driven by a sea surface height difference of approximately 0.5 m between the North Pacific Ocean and the Arctic Ocean (Shtokman 1957; Coachman and Aagaard 1966; Stigebrandt 1984). This gradient drives the northward flow. Water flows north through Bering Strait at approximately 0.8 Sv (Woodgate and Aagaard 2005; Panteleev et al. 2010; Luchin and Panteleev 2014). The flow is steered by the constricting coastline and seafloor bathymetry. Synoptic and seasonal variability are regulated by local wind stress (Aagaard et al. 1985) and sea ice conditions (Luchin and Panteleev 2014). Local wind conditions significantly modify northward flow at Bering Strait and may at times reverse it (Woodgate and Aagaard 2005; Panteleev et al. 2010). Other influences fresh coastal water (Weingartner et al. 1999), polynya waters (Danielson et al. 2006) and fronts associated with marginal ice zone meltwater (Lu et al. 2017).

An increase in flux through the Bering Strait was documented 2001-2014 from ~0.7 Sv to ~1.2 Sv (quantified for the mooring A3, Diomed Islands, Woodgate et al. 2012, 2015; Figure R14-15). This shift in volume also affects heat and freshwater exchange. The 2007 heat flux was, at the time, the highest recorded (Figure R14-15). Estimates suggest also significant increase in Bering Strait freshwater flux to 3000-3500 km<sup>3</sup> in 2014, compared to 2000-2500 km<sup>3</sup> in 1990s climatology (Woodgate et al. 2015; Figure R14-15).

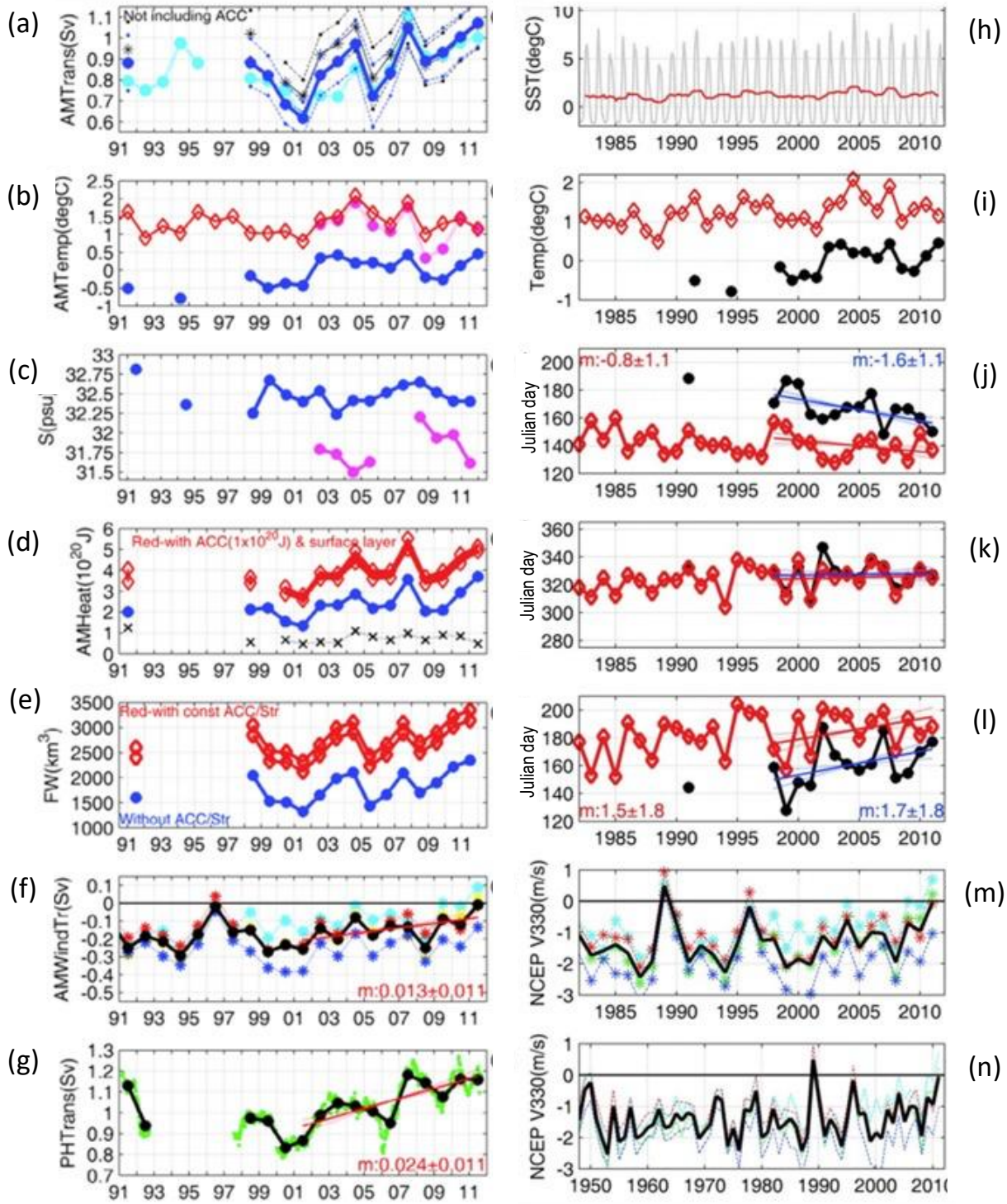


Figure R14-15. Annual means (x-axis, time in years) of Bering Strait mooring data from 1991 to 2011, adopted from (Woodgate et al. 2012, 2015). Right column of plots: Bering Strait summer satellite (MODIS) Sea Surface Temperature (SST) image marking moorings (black dots) and NCEP wind points (X). Bering Strait annual mean (AM) time-series from 1991–2011 of: (a) transport calculated from A3 (blue) or A2 (cyan), with error bars (dashed) calculated from variability; including adjustments estimated from 2007–2009 Acoustic Doppler Current Profiler data (black); (b) near-bottom temperatures from A3 (blue) and A4 (magenta-dashed), and the NOAA SST product (red diamonds); (c) salinities from A3 (blue)

and A4 (magenta); (d) heat fluxes: blue - from A3 only; red – including ACC correction (1 1020 J) and contributions from surface layer of 10 m (lower bound) or 20 m (upper bound) at SST, with black x indicating heat added from 20 m surface layer; (e) freshwater fluxes: blue – from A3 only; red – including 800–1000 km<sup>3</sup> (lower and upper bounds) correction for stratification and ACC; (f) transport attributable to NCEP wind at each of 4 points and the average thereof (black); and (g) transport attributable to the pressure-head term from the annual (black) or weekly (green) fits. Uncertainties are order 10–20%. Red lines in Figures (e) and (f) indicate best fit for 2001–2011. Left column of plots: Time-series of: (h) 30-day (grey) and 365-day (red) smoothed SST data for the Bering Strait region; (i) annual mean SST (red diamonds) and A3 lower layer (LL) temperature (blue dots); (j) first day in year when 30-day smoothed SST (red diamonds) or A3 LL temperature is above 0C; (k) as per (j) but for last day in year when temperatures are above 0C; (l) as per (j) but for number of days above 0C; annual mean NCEP winds (i.e., northwestward) at each of 4 points (coloured X in Figure 1a) and the average thereof (black) for (m) 1982–2011 and (n) 1948–2011.

Bering Strait is typically covered with ice from late December to May. While the rapid loss of sea ice has been observed since 2004, this trend did not hold for the Bering Strait region and southern Chukchi shelf in the time period of this report (2009-2015). Although sea ice retreat has exposed new ocean areas to increased solar heating, it also allowed exposure to atmospheric forcing, increasing environmental variability. The amount of sea-ice persisting on the Chukchi Shelf largely depends on the regional wind field (Wood et al. 2015ab). Calm conditions in 2012 resulted in a high densities of summer sea ice at Wrangel Island and Long Strait (Pisareva et al. 2015; Wood et al. 2015ab), despite low sea ice extent elsewhere in the Arctic.

#### 4.2. Water Masses [Hydrography/Stratification]

There are three primary distinct water masses in the region. Each are described below:

*Alaskan Coastal Water* (ACW) on the northeastern shelf is a low-salinity (<31.8 psu), seasonally warm water mass composed of coastal water from the SE Bering Sea. It is influenced by the Yukon River, the Kuskokwim River and other drainages. Primary production is low during summer following a spring bloom (Walsh et al. 1989); the zooplankton community is typical of the coastal zone farther south.

*Anadyr Water* (AW) is relatively saline (>32.5 psu), rich in nutrients and highly productive (Weingartner et al. 2005). It carries a considerable biomass of zooplankton to the northern shelf, including large oceanic copepods (Walsh et al. 1989; Springer et al. 1996), species otherwise restricted to the outer shelf and oceanic domains of the BS.

*Bering Sea Water* (BSW) is a mixture of slope and coastal waters with an intermediate density (31.8 - 32.5 psu) and longer shelf residency. North of St Lawrence Island, dense AW intrudes below BSW resulting in a highly productive and stable water column (Springer et al. 1996). This results in high pelagic primary production, much of which descend to the benthos (Coyle et al.2007). A strong frontal system develops in the open water system between the offshore nutrient rich BSW and the coastal nutrient depleted ACW (Coachman et al. 1975; Grebmeier et al. 1988). As these water masses flow north towards the Bering Strait, the AW and BSW masses mix to form the Bering Shelf-Anadyr Water (BSAW) (Feder et al. 2005).

### Bering Sea Cold Pool (Figure R14-16)

There is a notable thermal discontinuity between the near bottom waters of the SEBS and NBSS (Stabeno et al. 2012a). This mass of bottom water with temperatures less than 2°C is referred to as the cold pool (Takenouti and Ohtani 1974; Stabeno et al. 2002). This cold pool is a legacy of sea ice extent. This feature forms as a result of ice formation in the winter and subsequent trapping of this cold water in place as sea ice melts and surface water warms in spring and summer. It persists from winter until the water column is homogenized in the fall through wind mixing and low surface temperatures. This cold pool varies in annual extent and volume (Figure R-14-17). Recently higher air temperatures and lower winter ice cover have resulted in a substantial contraction of the summertime extent of the cold pool and an associated increase in mean seawater temperature (Baker et al. 2020b). In the northern Bering Sea, measurements of temperatures within the cold pool obtained over 12 years (1988 to 2005) suggest bottom water temperatures are increasing, particularly in recent years (2015-2019).

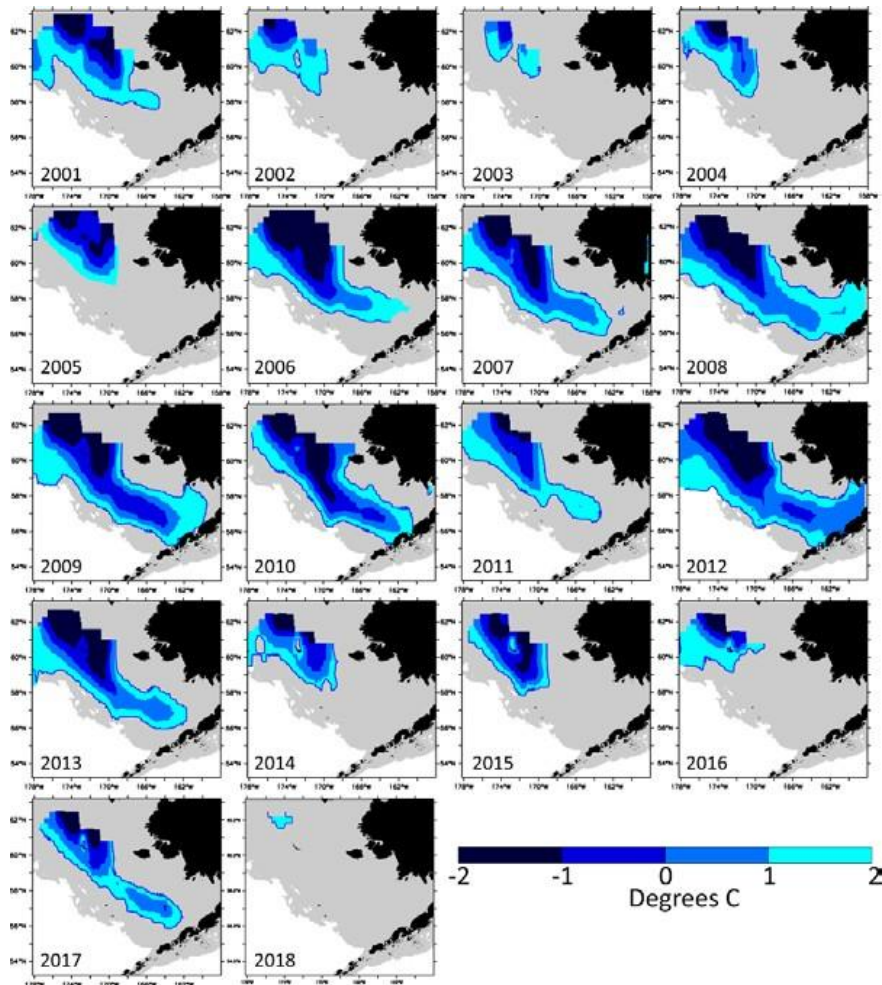


Figure R14-16. Interannual variation in Cold Pool extent in Bering Sea (Stabeno, Ecosystem Consideration Report, 2019)

### 4.3. Sea Surface and Bottom temperature

Overall sea surface and bottom temperatures have risen in this area in recent years. This is evident in satellite data on SST on a monthly level (Figure R14-17) as well as in overall anomalies from the mean (Figure R14-18). This is in contrast to relatively stable temperatures 2004-2016 (Figure R14-19). In 2017 and 2018 those trends of elevated temperature in the NBS were significantly higher than further south in EBS (Figure R14-18).

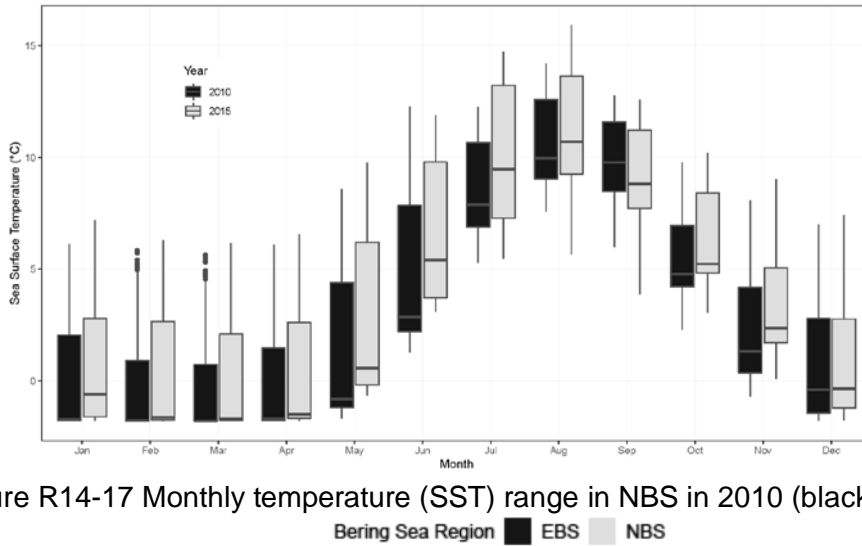


Figure R14-17 Monthly temperature (SST) range in NBS in 2010 (black) and 2015 (gray).  
Bering Sea Region ■ EBS ■ NBS

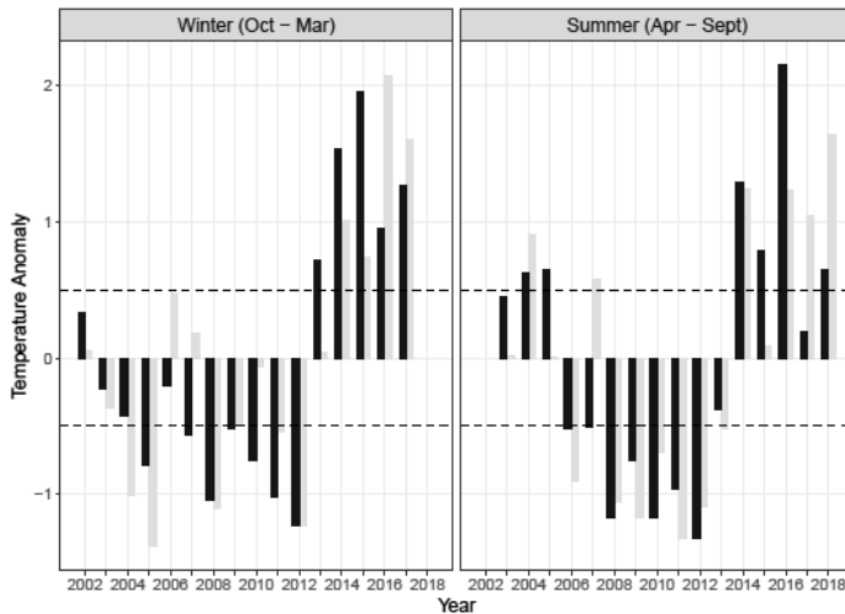


Figure R14-18. Annual temperature (SST) anomalies 2002-2018 in the NBS (gray) and the EBS (black)

**Sea surface temperature monthly 4 km [MODIS-Aqua MODISA L3m SSTv2014]**

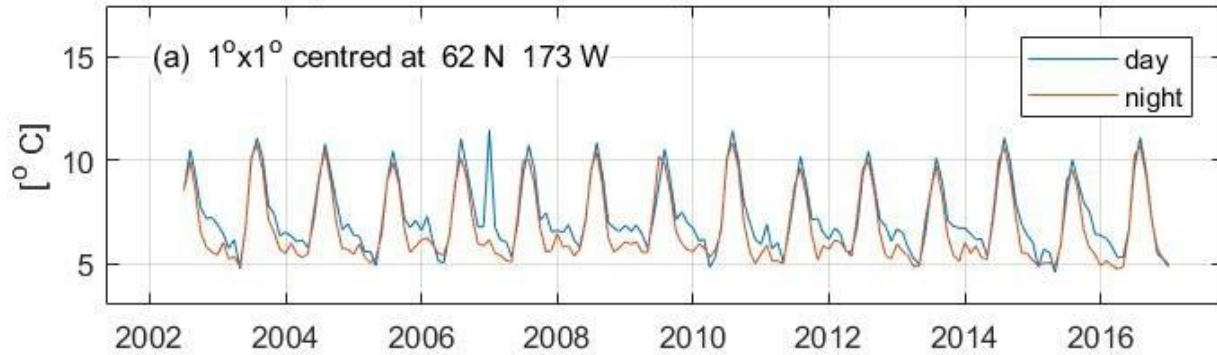


Figure R14-19. Submitted ETSO, Time series of MODIS SST data observed in the NBS. The panel represents the SST data sensed at 11 microns (day and night) averaged over an area 1×1° longitude centered at the location given in the panel.

There are important observable shifts in standard oceanographic measures (e.g., temperature, salinity) on latitudinal (north-south) and longitudinal (east-west) gradients (Figure R14-20, R14-21). There are also important regional dynamics relevant to areas such as Norton Sound (Sigler et al. 2017) and the Gulf of Anadyr (Figure R14-22; Zuenko and Basyuk 2017).

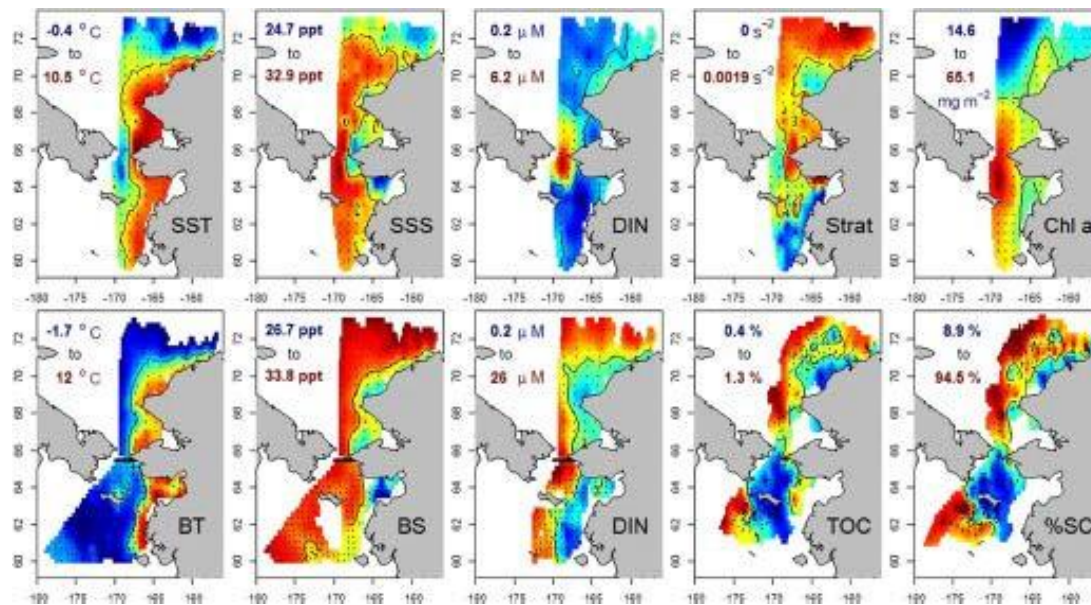


Figure R14-20. Environmental conditions in surface (2012) (upper) and bottom waters (2010) (lower), including temperature (SST, BT), salinity (SSS, BS), dissolved inorganic nitrogen (DIN), mean stratification (Strat), integrated chlorophyll (Chl a), total organic carbon in sediments (TOC), and percent of silt and clay (%SC). Values for TOC and %SC are based on samples obtained between 1970 and 2012. Color scale ranges from minimum (dark blue) to maximum (dark red) of predicted values from geospatial models [source: Sigler et al. 2017].

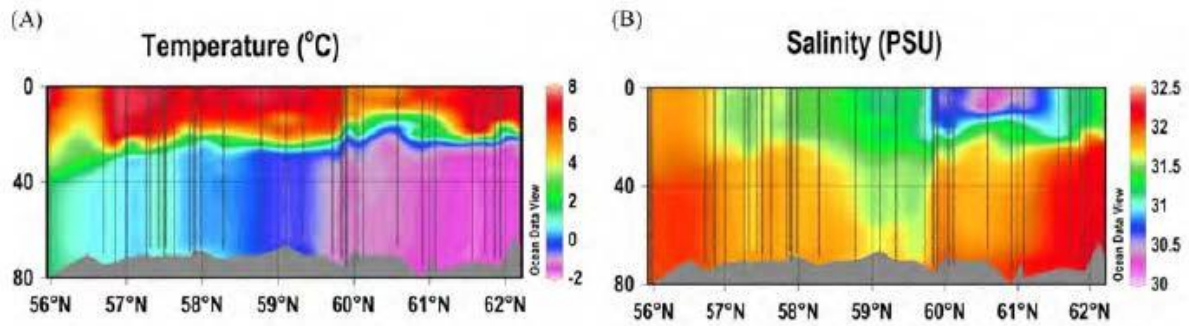


Figure R14-21. Vertical sections of temperature and salinity along the MN line (BSIERP, 60N) [source: Goes et al.2014].

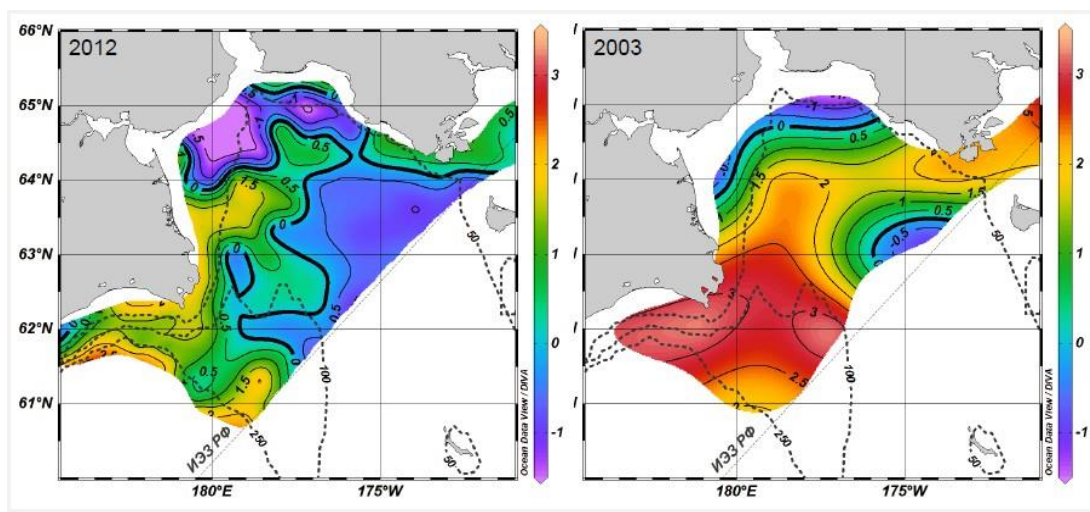


Figure R14-22. Annual mean temperature in the Gulf of Anadyr in 2003 and 2012 [source: Zuenko and Basyuk 2017]



#### 4.4. Sea Ice

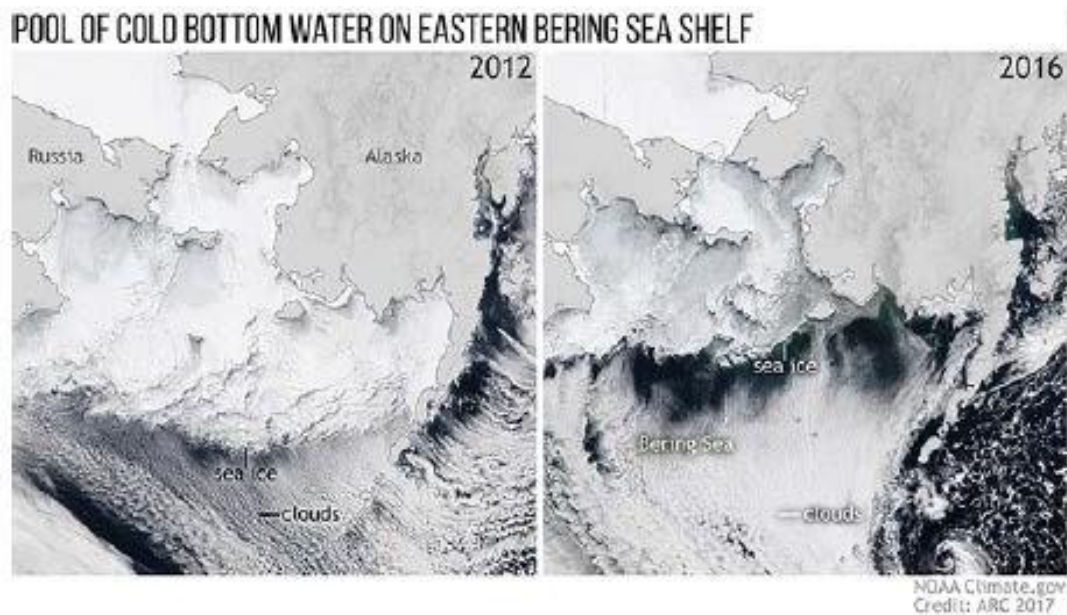


Figure R14-23 Sea ice maximum in March 2012 and March 2016

Sea ice covers this region for 5-7 months of the year with maximal and minimal areal extent in March and September, though maximum sea ice extent varies considerably between years (Figure R14-23). Ice forms in the Arctic and proceeds south through the Bering Strait. The southern extent of this sea ice is governed by a combination of processes, including southward advection, air-sea heat flux, and melting at the leading edge of the ice (Sigler 2011)

Ice cover changes seasonally in different locations due to different processes (Cheng et al. 2014). At mooring M8 (Figure R14-10), ice cover increases rapidly in the first half of winter due to advection and local freezing. Ice cover at M8 decreases in spring due to a combination of advection and thermodynamic melting. At M5 (Figure R14-10), winter ice growth is a result of advection offset by local melting (Cheng et al. 2014). South of the Siberian coast and along the northern Bering Sea inner shelf, local freezing is offset by outward advection. The balance is reversed in the offshore locations along the ice edge, where inward advection is canceled by local ice melt.

Winter 2018 had the lowest ice year on record in the Bering Sea. These conditions were not predicted to occur until mid-century (Stabeno et al. 2019). Models predict reduced winds out of the north, setting the stage for similar years with low-ice years and a small or nonexistent cold pool. Figure R14-24, 25, 26 and 27 show interannual variation of sea-ice condition and relevant environmental variables and shifts over time relative to baseline data. The lack of sea ice in this region has important implications for new dynamics in the region (Huntington et al. 2020).

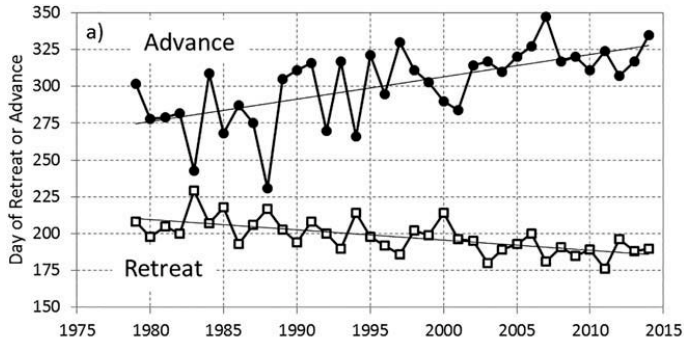


Figure R14-24. Time series and linear trends for a) the Julian Day of sea ice retreat and advance and b) the open water period in days. Adopted from [Serreze et al. 2016]

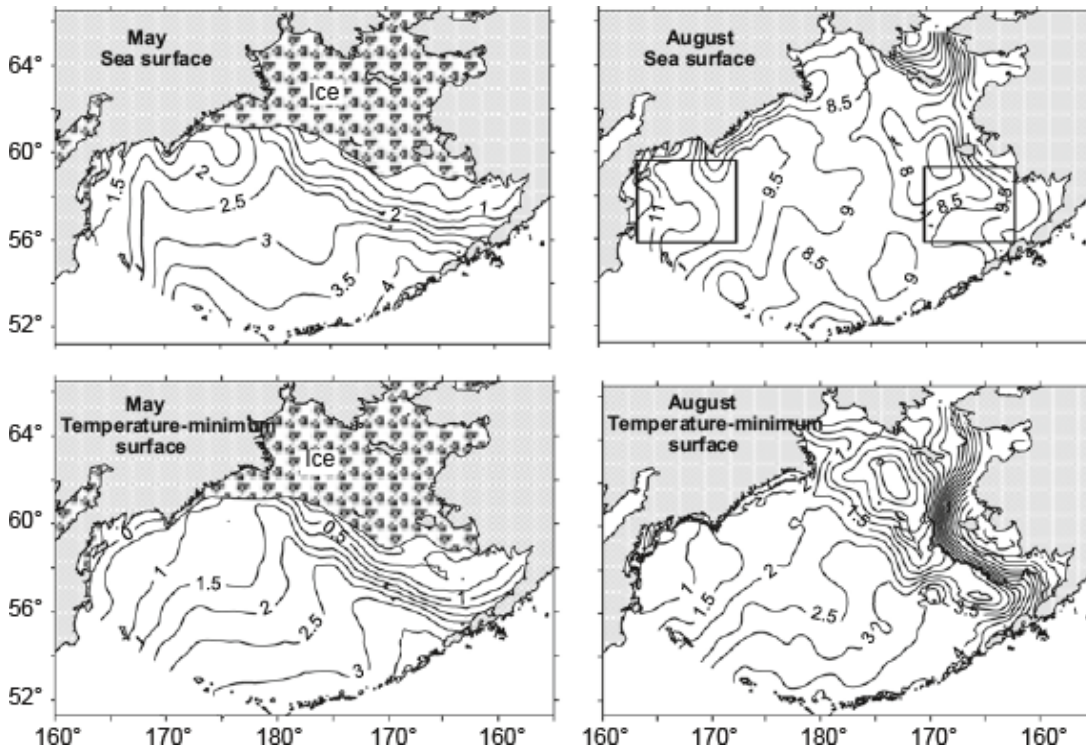
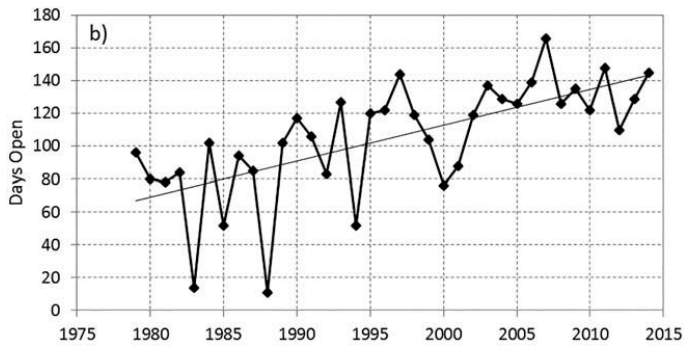


Figure R14-25. Sea surface minimum temperature and ice extent in May and August 1950-2007 [Source: Khen et al. 2013]

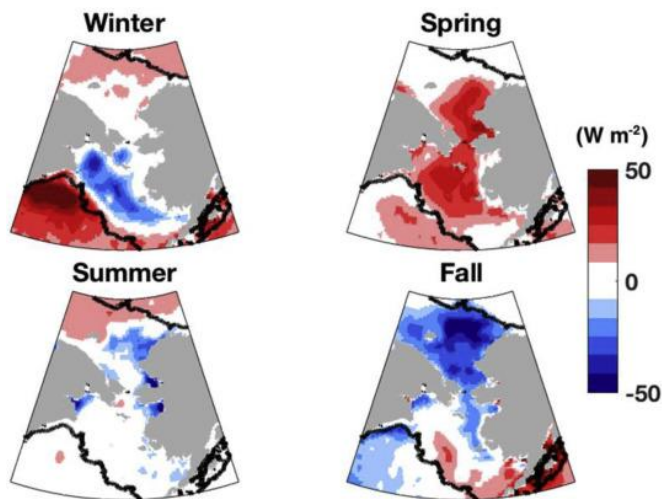


Figure R14-26 Seasonal surface heat flux anomalies ( $\text{W m}^{-2}$ ) for 2014–2018 relative to 1979–2013; 200 m depth marked in black contour [Source: Danielson: et al. 2020)].

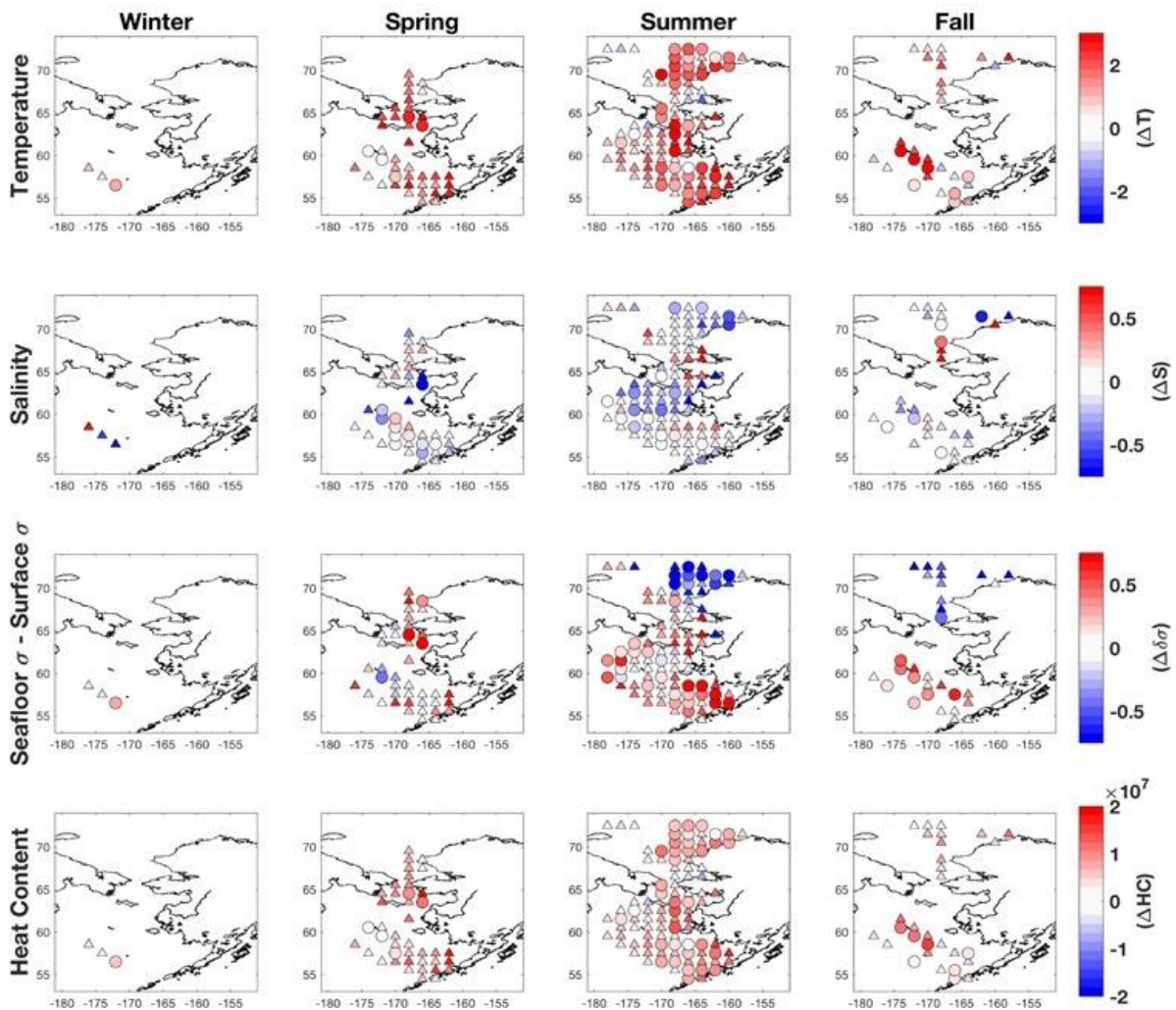


Figure R14-27. Difference between 2014–2018 and the mean of 1950–2018 for sea surface temperature, sea surface salinity, sea floor and surface density gradient, and heat content in the Bering Sea; the Bering Sea has lost 40% of its contribution to regional cooling 2014–2018 in contrast to a 1950–2018 baseline [Source: Danielson et al. 2020)].

## 5. Phytoplankton

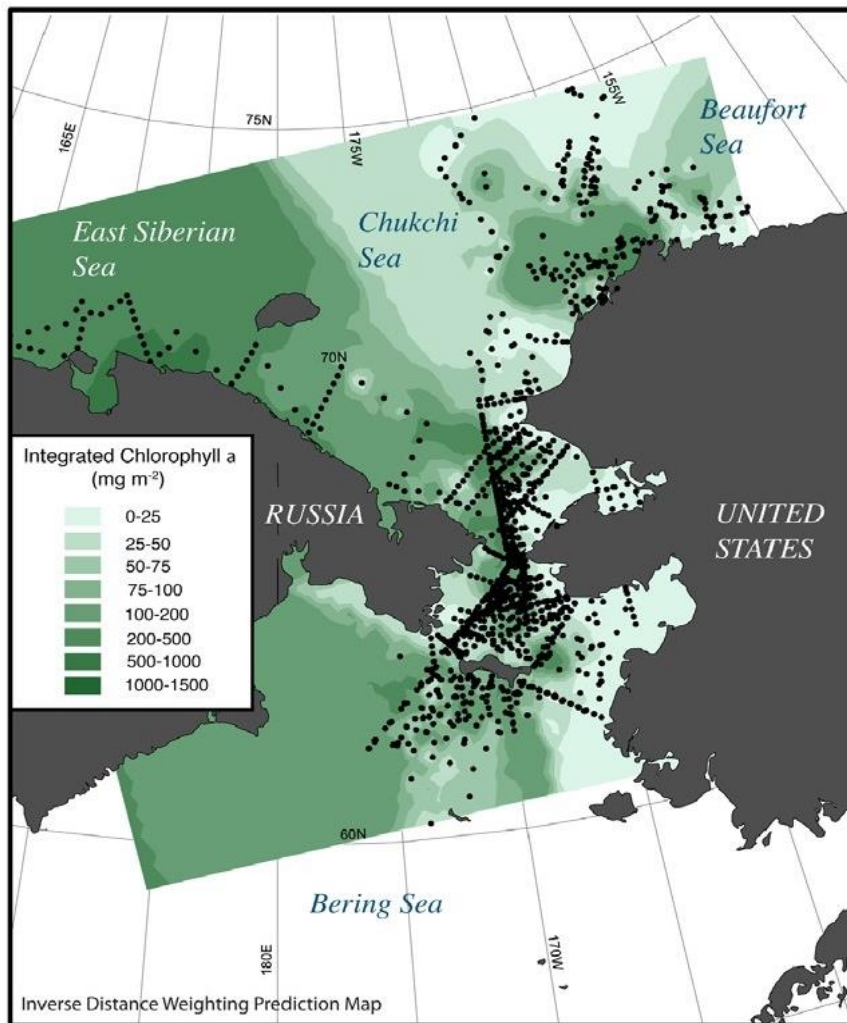


Figure R14-28. Integrated chlorophyll-a (mg m<sup>-2</sup>) April-September 1976-2004 [source Grebmeier et al. 2006]

The NBS is highly productive with productivity occurring both at the sea ice edge and in open water. Annual primary production estimates for the region range 50-800g C m<sup>-2</sup> y<sup>-1</sup> (mean 470; Springer and McRoy 1993; Springer et al. 1996; Hill and Cota 2005). Much of the spring primary production is associated with ice algae and the ice-edge bloom (Figure R14-29).

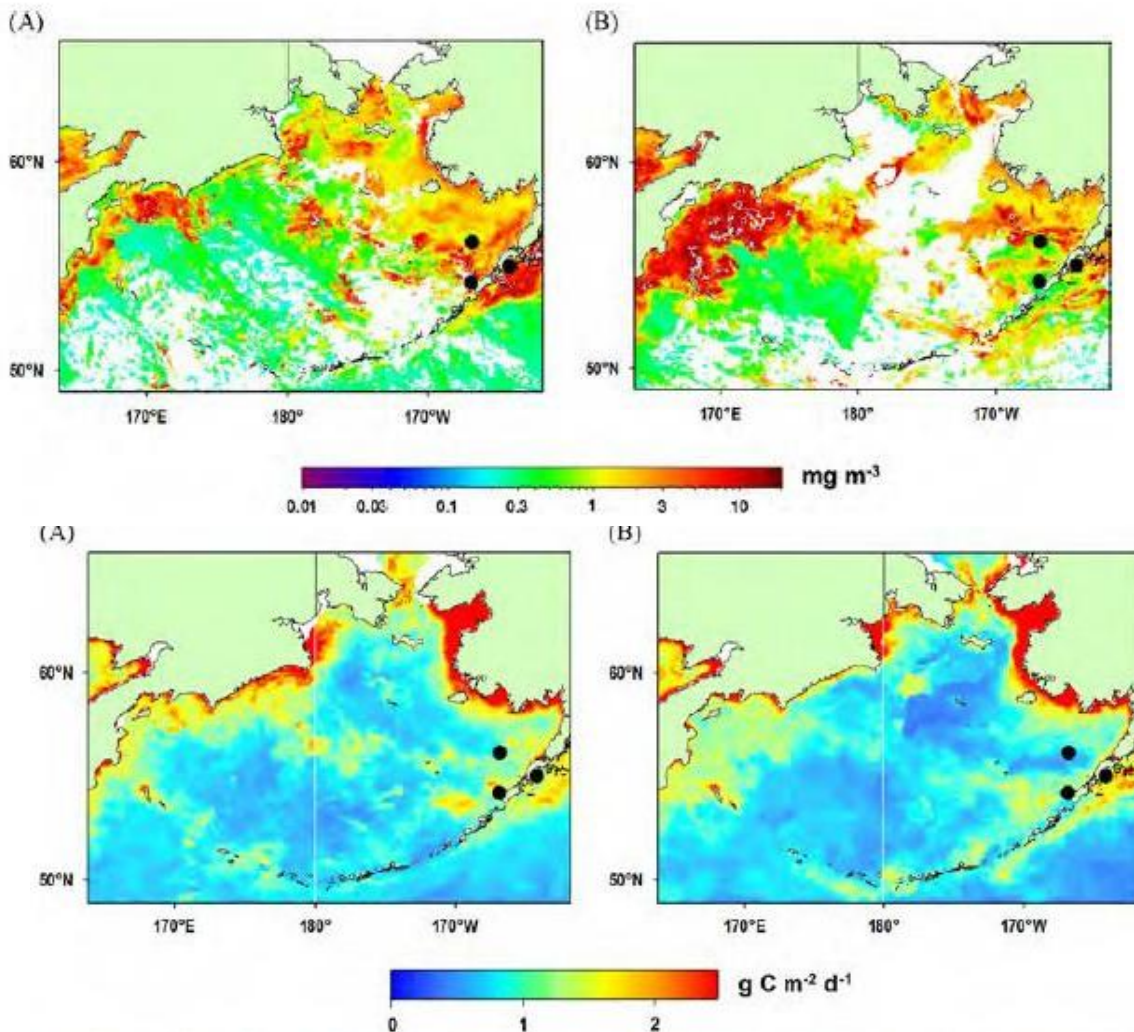


Figure R14-29. Surface Chl a in May 2011 (top left) and 2012 (top right) and mean rates ( $\text{g C m}^{-3} \text{d}^{-1}$ ) of primary productivity May-August 2011 (bottom left) and 2012 (bottom right). Reference stations in black [source: Stauffer et al. 2014]

Critical controls on water column production include the duration and extent of seasonal sea ice, water temperature and water mass structure (Grebmeier et al. 2006)(Figure R14-30). Overall there is higher primary productivity in the spring than summer and the proportion of primary production generally aligns with the proportion of carbon. Production in AW water produces is maintained by nutrient replenishing from waters to the south. In contrast, the spring bloom in the ACW is not maintained due to nutrient depletion (Grebmeier et al. 2006).

Seasonal ice retreat and its subsequent effects on stratification and mixing promote early blooms. Zooplankton populations are unable to metabolize most production and have a relatively smaller overall role in organic carbon cycling relative to other regions of the Arctic (Walsh et al. 1989, 2005). With relatively little pelagic grazing, a large amount of in situ and advected pelagic production mostly sinks and supports a rich benthic community dominated by invertebrates and small epibenthic fishes (Norcross et al. 2013). Strong benthic-pelagic coupling is a dominant characteristic of this shallow ice-dominated system and high benthic

biomass results (Grebmeier et al. 2006, 2015).

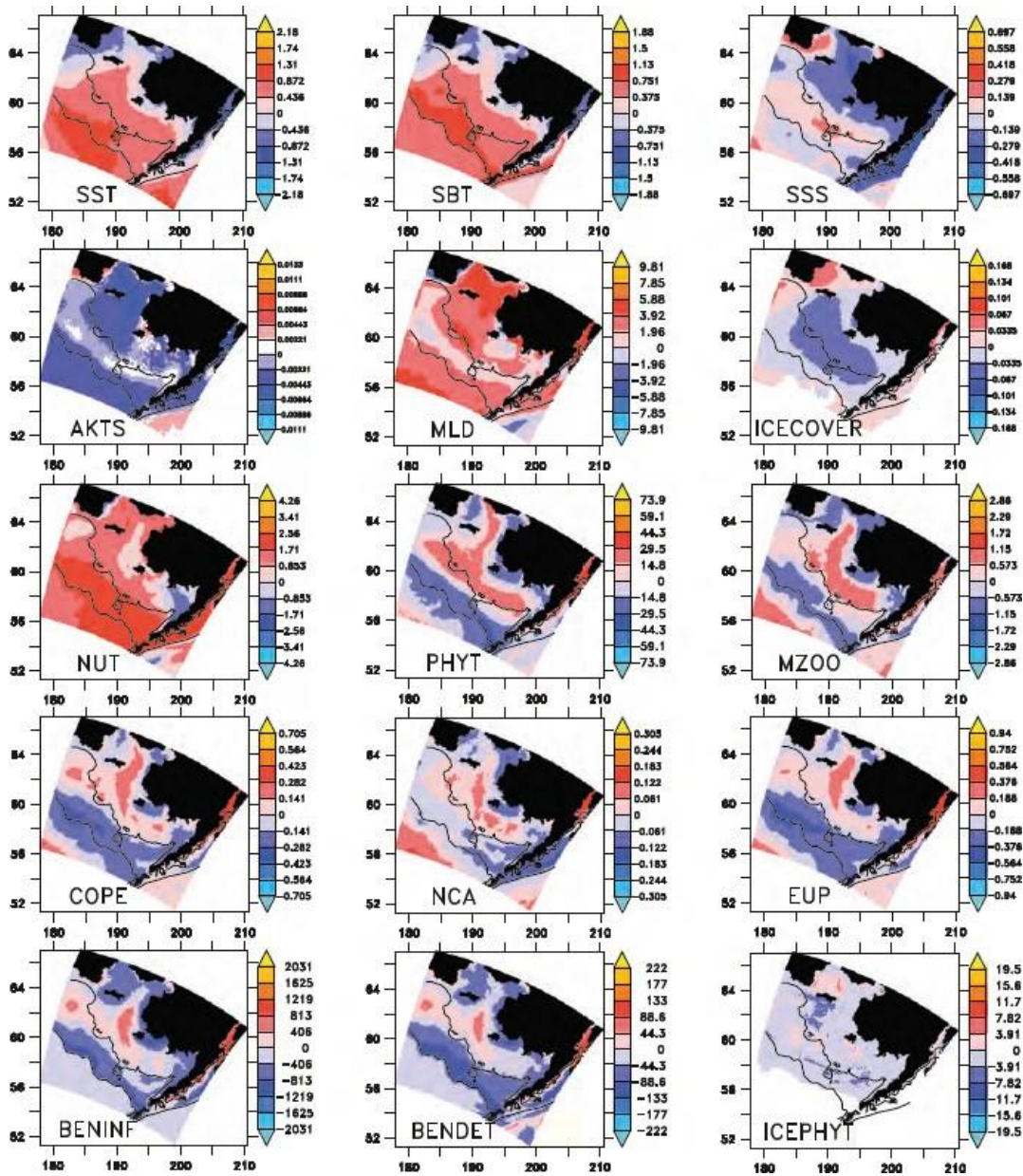


Figure R14-30. Spatial loadings of an Empirical Orthogonal Function analysis, using a continuous series constructed from hindcasts (1970–2009). Dissolved inorganic nitrogen (NUT), phytoplankton (PHYT, ICEPHYT) are shown here in relation to temperature (SST, SBT), salinity (SSS), mixed layer depth (MLD), vertical mixing (AKTS) and microzooplankton (MZOO), copepods (COPE, NCA), euphausiids (EUP), and benthic detritus (BEDDET) and infauna (BENINF) (source: Hermann et al. 2013).

## 6. Zooplankton

The NBS has higher abundance of small zooplankton (43,000-45,000 individuals  $m^{-3}$ ) than the southeastern Bering Sea (10,000-20,000 individuals  $m^{-3}$ ; Sigler et al. 2011). Predominant species include *Pseudocalanus* spp., *Oithona* Sp. It also has higher relative abundance of meroplankton (bivalve and barnacle larvae). Large zooplankton include

*Calanus marshallae*, *C. glacialis*, *Eucalanus* Sp., euphausiids, amphipods, chaetognaths and cnidarians). Euphausiids are common and crustacean zooplankton comprise 90% of the total abundance with NBS higher densities (1,400-2,300 individuals m<sup>-3</sup>) compared to the southeastern Bering Sea (100-300 m<sup>-3</sup>, 55-60% of total biomass). Springer et al. (1989) note correspondence in the zooplankton community to water mass type. In the AW, oceanic species, including the large Pacific copepods *Neocalanus cristatus* and *Neocalanus plumchrus* and smaller *Eucalanus bungii* and *Metridia pacifica* comprise the main herbivorous zooplankton, with larvaceans (*Oikopleura* sp.). In the BSW located between AW and the nearshore ACW the predominant species is the subarctic herbivorous copepod *Calanus marshallae*, with the low salinity nearshore waters dominated by the smaller *Pseudocalanus* spp. and *Acartia longiremis*. Cluster analyses suggest that the northern Bering Sea is more similar to the Chukchi Sea to the north than the contiguous southeastern Bering Sea shelf for both small and large zooplankton species (Sigler et al. 2011).

Several studies have noted distinct zooplankton assemblages in the Chukchi Sea and northern Bering Sea correlated to the various water masses in the region (Stepanova, 1937; Wirketis, 1952; Pavshikov, 1984; Hopcroft et al. 2010; Eisner et al. 2013; Questel et al. 2013; Ershova et al. 2012). Bering Sea Shelf and Anadyr waters are populated with widespread shelf species (*C. marshallae*) but also support large oceanic copepods (*Neocalanus* spp. *E. bungii*). These copepods originate from the Bering Sea outer shelf. In Bering Strait, upwelling at Anadyr and Bering straits enhances primary production and sustains these more oceanic species (Eisner et al. 2013). Integrated studies also note that zooplankton communities appear to form distinct assemblages, including: (1) a nearshore assemblage affiliated with the Alaska Coastal Water; (2) A southern Chukchi assemblage corresponding to Bering Sea Shelf and Anadyr waters; and (3) a northern Chukchi shelf assemblage associated with the near-bottom Winter Water and surface ice melt water separated by a pycnocline (Figure R14-31; Sigler et al. 2017). Southern Chukchi assemblages are largely comprised of Bering Sea origin species advected into the Chukchi Sea, while northern Chukchi assemblages are more reflective of Arctic assemblages (Figure R14-31; Figure R14-32; Sigler et al. 2017).

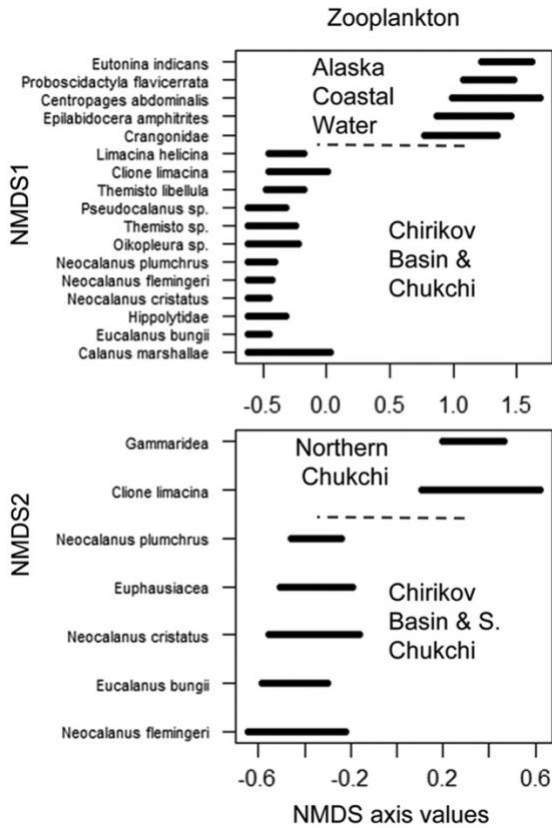


Figure R14-31. Zooplankton taxa. Bar graphs of core use area in northern Bering Sea and Chukchi Sea relative to water mass and geographic region. Dashed lines group species with similar NMDS values. Based on 2010 and 2012 samples for all taxa and areas [source: Sigler et al. 2017]

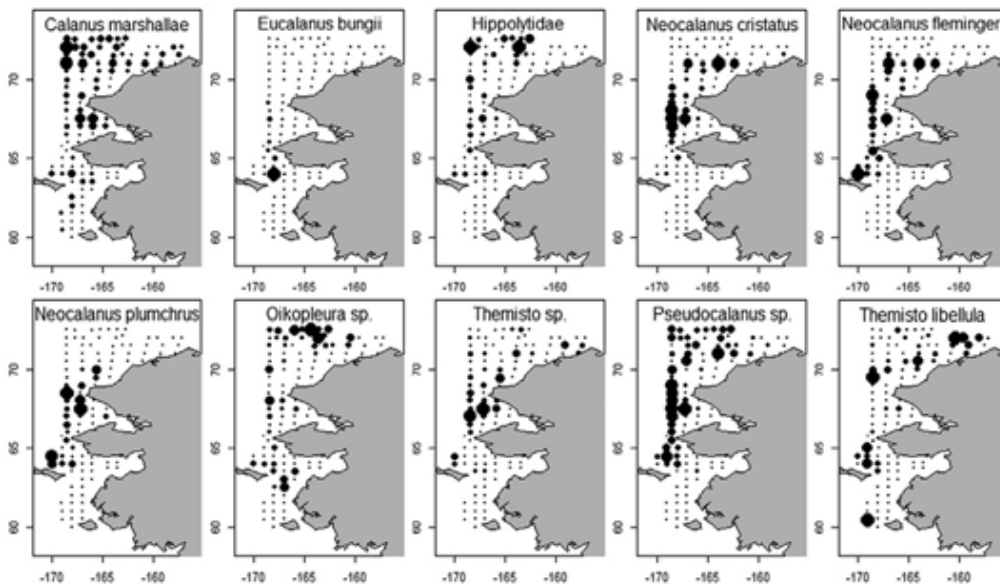


Figure R14-32 Zooplankton species distributions in the northern Bering Sea and Chukchi Sea [2010, 2012; source: Sigler et al. 2017]



Mean species composition in the western Bering Sea were provided by Zuenko and Basyuk (2017; Figure R14-33).

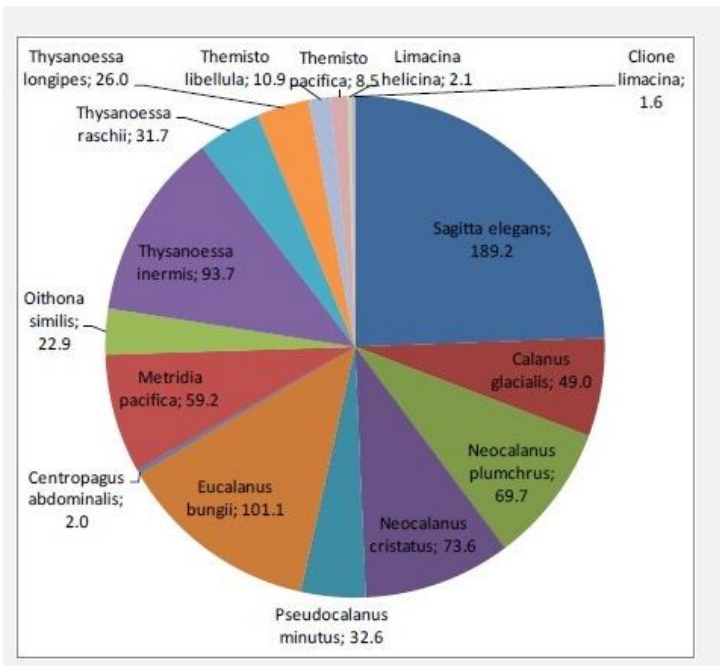


Figure R14-33 Mean species composition of zooplankton in western Bering Sea [source: Zuenko and Basyuk 2017]

High abundances of small (low-lipid) and low abundances of large (high-lipid) copepods were observed on the southeastern Bering Sea shelf during warm years (Figure R14-34; Eisner et al. 2014; Kimmel et al. 2018). Copepod abundances in the northern Bering Sea followed a similar trend. Reduced ice cover, elevated temperatures, and delayed spring bloom depress large copepod production but permitted rapid proliferation of small copepods (Figure R14-35); numbers of small euphausiids were low in the southern Bering Sea but higher in the northern Bering Sea. Elevated numbers of small copepods suggest that warm conditions led to enhanced growth rates and egg production, resulting in population increases (Kimmel et al. 2018; Duffy Anderson et al. 2019).

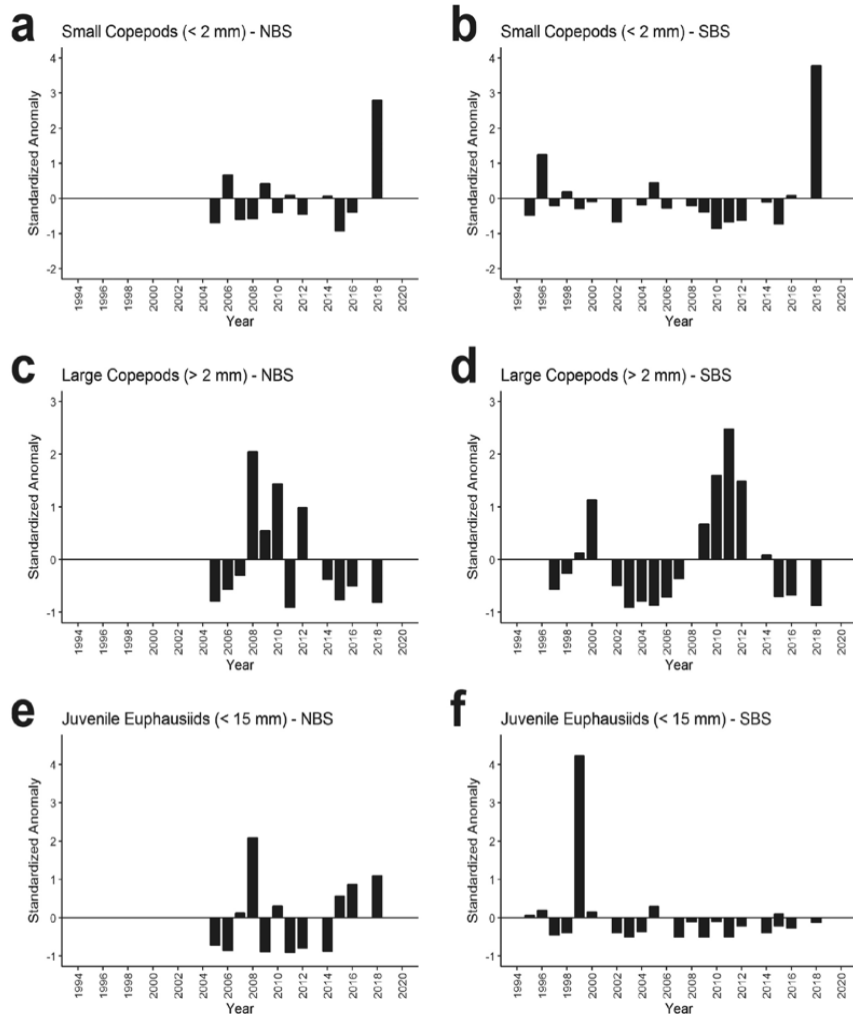


Figure R14-34. Standardized annual anomaly in zooplankton abundance (large copepods > 2 mm) in the northern Bering Sea and southern Bering Sea [source: Duffy Anderson et al. 2019]

## 7. Benthos and Benthic Habitat

### 7.1. Bathymetry

Bathymetry and current flow of NBS is shown in Figure R14-35 and R14-36. The NBS shelf is shallow (30-80m) and this area was exposed (i.e., above sea level) during the last glaciation period. Most of the sediment contributed to the NBS since then is associated with the Yukon River and high speed near bottom currents in ACW. Most of this has high silt content, but also includes fine grain sand and clay. Where the coastal current is strongest, sediment is relict deposits of sand and gravel from the glacial or metamorphic bedrock. Tidal currents and wind drift are more significant than wave drift of estuarine density circulation (McManus et al. 1984). Approximately 1,600-line km of high-resolution seismic reflection data in the Navarin Basin were collected in August 1982 from the U.S. Geological Survey (USGS) Research Vessel S.P. LEE and deals with seafloor hazards pertinent to Outer Continental Shelf oil and gas lease sale activity. Microfile copies of the seismic records are available for purchase from the National Geophysical Data Center (NGDC; now the National Centers for Environmental Information, NCEI). A detailed analysis of bathymetry in Chirikov Basin is also available (McManus et al. 1984).

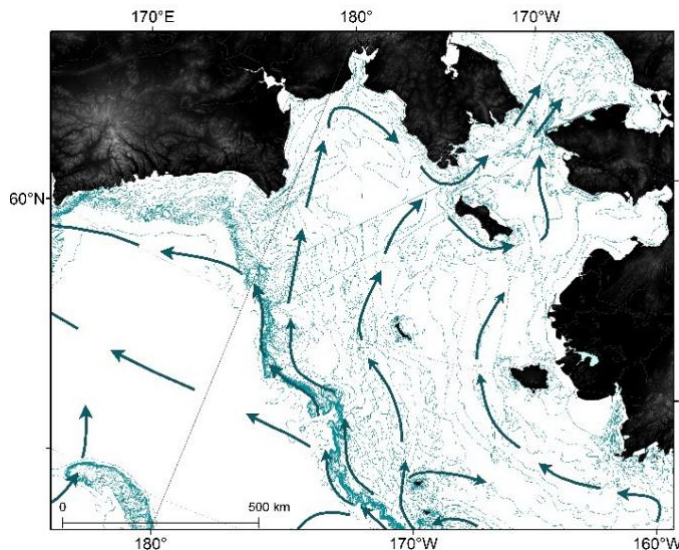


Figure R14-35 (up). Bathymetry and current flow Northern Bering Sea (NBS) shelf [source: Baker 2021]

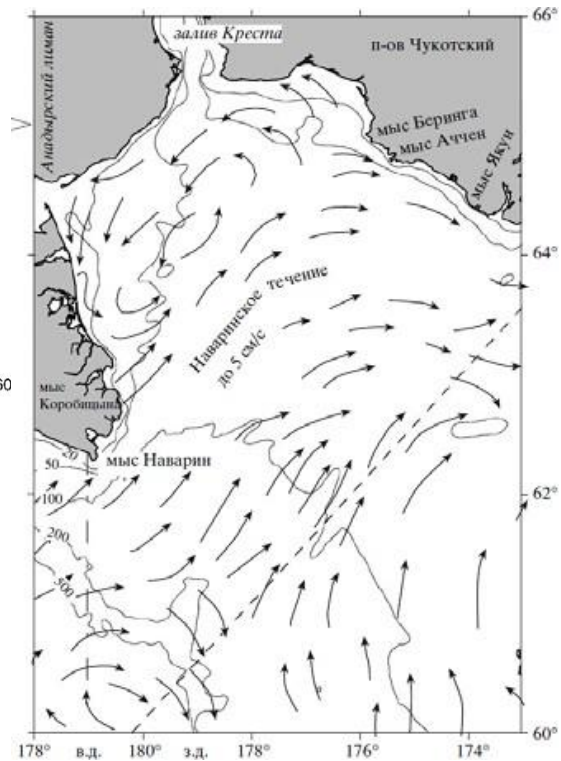


Figure R14-36 (right). Bathymetry and currents in NWBS [Source: Savin 2008]

Several bathymetric analyses have been completed including a digital elevation model with nominal 1-km grid spacing over the domain 45°N- 80°N and 130°E-120°W, based on ship sounding datapoints, including Electronic Navigation Chart point soundings, research vessel soundings, multibeam swath mapping datasets and digitized point soundings from paper nautical charts (Danielson et al. 2014). More proximate and detailed information is available in regional extents, including more than 230,000 National Ocean Service bathymetric soundings from 39 smooth sheet surveys in Norton Sound that were integrated with multibeam data from NOAA/NOS surveys (Prescott and Zimmermann 2015) (Figure R14-37). Analyses of benthic sediments have also integrated sediment datasets to map surface substrates throughout the region (Baker et al. 2022).

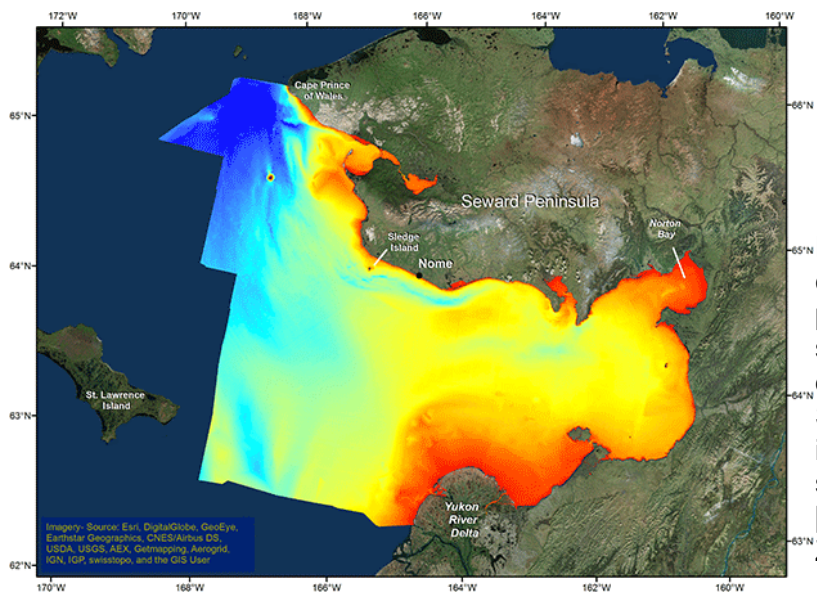


Figure R14-37. Bathymetry compilation from the eastern point of St. Lawrence Island, southeast to the Yukon River delta and north along the Seward Peninsula; shading indicates depth profile from shallow (red) to deep (blue) [source: Prescott and Zimmermann 2015]

## 7.2. Benthic Habitat

The majority of production in the NBS descends to the benthos. Zooplankton grazing and the microbial loop in this area has low impact on overall carbon cycling (Walsh et al. 1989) and the combination of high production and low grazing pressure on a shallow shelf, results in a high amount of organic carbon settlement on the benthos (Chl-a 10-1500 mg m<sup>-2</sup>). This supports a benthic community macroinfaunal biomass (40-760 g wet wt m<sup>-2</sup>; Grebmeier et al. 2006). Most sediment respiration is related to benthic macrofauna (Grebmeier and Barry 2007). SCOC values range 10-40 mmol O<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup> (84-335 mg C m<sup>-2</sup> d<sup>-1</sup>; Grebmeier et al. 2006). Particularly high benthic biomass occurs in the regions southwest of St Lawrence Island and in the Chirikov Basin (Figure R14-38, R14-39).

The broad shallow (30-80 m) shelf of the NBS supports some of the highest benthic faunal biomass (Grebmeier and Cooper 1995; Highsmith and Coyle 1992). Meso- and macro-zooplankton populations have a relatively minor role in organic carbon cycling relative to other regions of the Arctic (Walsh et al. 1989, 2004, 2005). The Chirikov Basin supports ice-associated plankton blooms, is fueled with nutrients and zooplankton in AW that converges in the Bering Strait region and exhibits strong benthic- pelagic coupling. This high nutrient content and mixing generated at waters converge towards Bering Strait results in hotspots of production (Grebmeier and Dunton 1989; Feder et al. 1994). Longterm sampling of these benthic macrofaunal communities suggests these hotspots are consistently productive across several decades (Moore and Stabeno 2015)

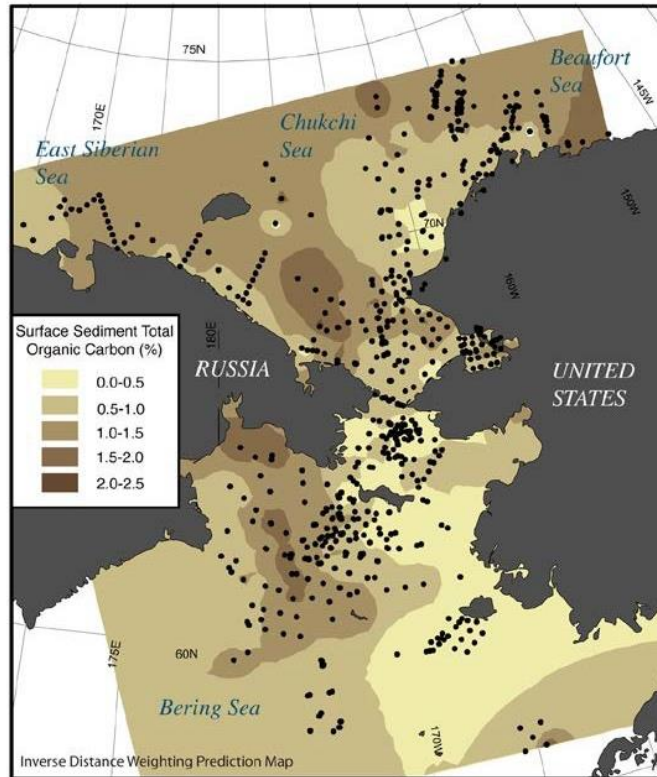


Figure R14-38. Surface sediment total organic content in the northern Bering Sea and Chukchi Sea region [source: Grebmeier et al. 2006]

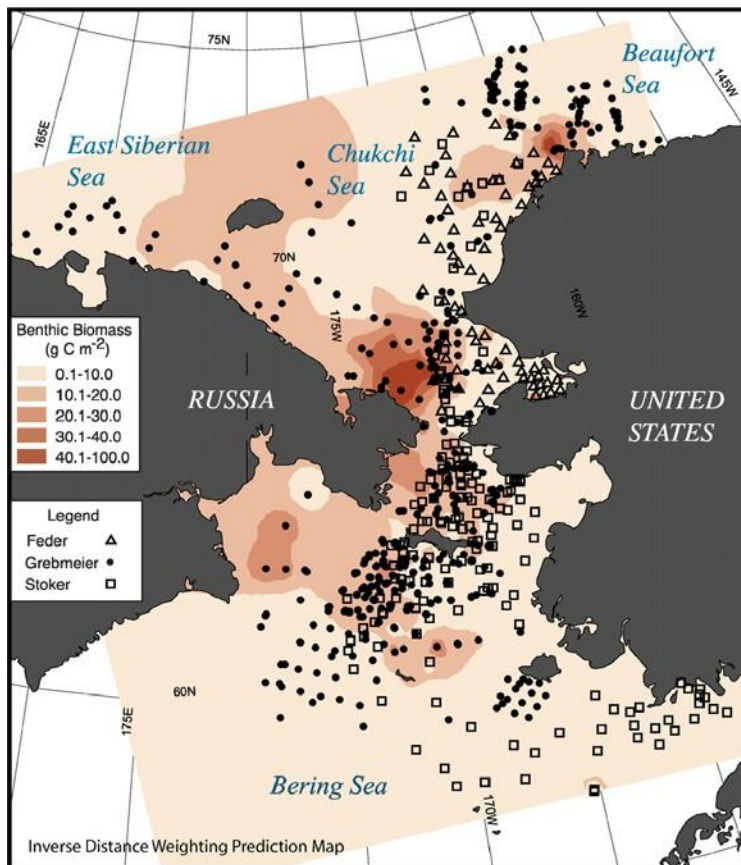


Figure R14-39 Benthic biomass throughout the northern Bering Sea and Chukchi Sea [source: Grebmeier et al. 2006]

### 7.3. Benthic Infauna

Most offshore sediments in the NBS are soft substrate, including mud and sand. This supports large populations of infauna, predominantly bivalves, amphipods and polychaetes (Grebmeier et al. 1995). Prevalent species also include *Nuculana radiata*, *Nucula belloti*, and *Malcoma calcarea*. Benthic infaunal biomass ranges 10-20 g C m<sup>-2</sup>; (Grebmeier et al. 2006). Sediment type influences community diversity and composition while carbon inputs determine biomass (Grebmeier and McRoy 1989, Grebmeier and Dunton 2000). In the north, sediments coarsen. Sediments in the Chirikov basin north of St Lawrence Island are more sandy and the region north of St Lawrence to Bering Strait is dominated by amphipods and bivalves in sandy mud. At St Lawrence Island sand, gravel and rock predominate as a function of Anadyr Current scour. High currents in this region and Bering Strait maintain gravel and rock with a predominance of epifauna.

### 7.4. Benthic Epifauna

As defined in this volume, the NBS supports 261 macrobenthic species (Petryashov et al. 2013). Throughout the Russian areas (Koryak, Gulf of Anadyr), abundance is largely uniform (Petryashov et al. 2013). This may reflect continuous conditions in AW, winnowed substrates associated with fast currents and related oceanographic processes in the Bering Slope Current and Chirikov Basin. Epifaunal abundance is lower in the areas encompassed

by ACW and BSW. Throughout the NBS echinoderms, mainly sea stars and basket stars dominate the invertebrate epifaunal biomass (Feder et al. 2005). This is in contrast to the southeastern Bering Sea, where the benthic system is dominated by crustaceans, large crabs and demersal fishes. Prevalent epifauna include sponges (*Halichondria*), corals (*Gersemia*), barnacles (*Balanus*), amphipods (*Ampelisca*, *Anonyx*), gastropods (*Nuptunea*), mussels (*Mytilus*), urchins (*Strongylocentrotus*), sand dollars (*Echinarachnius*) sea stars (*Ctenodiscus*, *Crossaster*, *Asterias*, *Leptasterias*) brittle stars (*Ophiopholis*, *Ophiura*), basket stars (*Gongonocephalus*), tunicates (*Boltenia*), and crabs (*Chinocete opilio*, *Hyas*, *Temessus*, *Pagurus*). In the Gulf of Anadyr, sand dollars and brittle stars are abundant as well as crabs and predatory gastropods (Sirenko and Koltun 1992). The benthic environment in the Gulf of Anadyr supports snow crab, hermit crab, gastropods, basket stars and brittle stars. The Anadyr Strait supports communities of sponges, barnacles, and ascidians. In coastal waters epifauna include sea anemones, worms, gastropods, bivalves, and sand dollars, with sand dollars particularly prevalent at the frontal interface between coastal and offshore waters in the Gulf of Anadyr (Sirenko and Koltun 1992; Feder et al. 2005). Epifauna in Norton Sound include red king crab (*Paralithodes camtschatica*) and predatory sea stars (*Asterias amurensis*). Elsewhere in areas of ACW, there are reduced benthic populations. As current increase to the north, epifauna consists largely of sponges, soft corals, barnacles, urchins, basket stars, and ascidians (Feder et al. 2005).

Important biogeographical shifts have been noted associated with a transformation from arctic to subarctic conditions (Grebmeier et al. 2006). A northward shift of the pelagic-dominated marine ecosystem in the southeastern Bering Sea has been occurring (Grebmeier et al. 2006). Benthic communities and bottom-feeding predators, including sea ducks, such as spectacled eiders (*Somateria fuscgeri*), and marine mammals, including walrus (*Odobenus rosmarus*), gray whales (*Eschrichtius robustus*), and bearded seals (*Erignathus barbatus*) (Sheffield et al. 2001; Moore et al. 2003; Feder et al. 2005) are being replaced by one dominated more by pelagic fish. Additionally demersal fish and epifaunal invertebrates, whose northern distribution is limited by the presence of near-freezing bottom temperatures, appear to be increasingly occupying this region (Grebmeier and Dunton 2000; Wyllie-Echeverria and Wooster 1998;). As demersal fish and predatory invertebrates gain access to this area, it is anticipated that they may replace benthic-feeding sea-birds and marine mammals, who are currently the primary consumers in the northern (Arctic) region of the Bering Sea (Lovvorn et al. 2003; Moore et al. 2003).

## 8. Fishes and Invertebrates

Important fish and invertebrate species in the northern Bering Sea and southern Chukchi Sea include multiple foraging guilds, including (1) planktivores - Arctic cod (*boreogadus saida*), saffron cod (*Eleginus gracilis*), Pacific herring (*Clupea pallasii*), capelin (*Mallotus villosus*), and Arctic sand lance (*Ammodytes hexapterus*); (2) benthivores - yellowfin sole (*Limnada aspera*), Alaska plaice (*Pleuronectes qudrutuberculatus*), Bering flounder (*Hippoglossoides robustus*); pelagic piscivores - walleye pollock (*Gadus chalcogrammus*); demersal piscivores - Pacific cod (*Gadus morhua*), Alaska skate (*Bathyraja parmifera*), Pacific halibut (*Hippoglossoides stenolepis*), Greenland halibut (*Reinhardtius hippoglossoides*); and many benthic invertebrate epifauna and infauna, worms, echinoderms, molluscs, and crustaceans, including the commercially-important snow crab (*Chionectes opilio*) (Lauth, 2011, Lauth et al. 2019; Hollowed et al. 2017). Both fish abundance and individual fish body size in the northern Bering and Chukchi Seas are small compared to the southeastern Bering and Barents seas, which support huge commercial fisheries (Stevenson and Lauth, 2012; Hunt et al. 2013; Norcross et al. 2013).

The eastern Bering Shelf is subarctic and includes both the southern and central Bering

regions. Bottom fish like walleye pollock, Pacific cod, and yellowfin sole are abundant here and at densities orders of magnitude greater than in the Chirikov-Chukchi region. Several studies have revealed a gradient of diminishing commercial fish density with latitude and a significant breakpoint between community of demersal groundfish at 60°N (Mueter and Litzow 2008; Stevenson and Lauth 2012; Hollowed et al. 2017). The boundary is determined in part by the cold pool. South of 60°N, the cold pool varies annually in extent and intensity. Other studies note significant differences in distribution in the NBS and EBS for Arctic versus sub-Arctic gadids (Stevenson and Lauth 2019; Baker 2021) Until recently, subarctic species, including walleye pollock, Pacific Cod, northern rock sole and yellowfin sole were not common in the northern Bering Sea. Instead, this region has been historically characterized by Alaska plaice, Bering flounder, Arctic cod, and saffron cod and Pacific herring. Planktivorous fishes are common while piscivorous species have, until recently been comparatively less common.

While the densities of bottom fish in the northern Bering Sea (36-115 kg ha<sup>-1</sup>) are much lower compared to the southeastern Bering Sea (261 kg ha<sup>-1</sup>; Sigler et al. 2011), pelagic fishes, which reside in the upper mixed layers are not restricted by the cold pool and low temperatures at depth and are able to use the comparatively warmer surface waters. This has allowed for the expansion of these stocks into the NBS and into the Chukchi Sea to the north. Increased numbers of salmonids have been recorded for several years in the NBS (2012-2021). In 2017-2021, large numbers of groundfish (walleye pollock and Pacific cod) have also been recorded, altering previous assumptions about the stability of the conditions and fauna of the NBS ecosystem. The vulnerability of this ecosystem to environmental change is thought to be high, particularly in the context of sea ice decline and warming water temperatures. Recent reductions in sea ice have the potential to fundamentally alter the organization of this ecosystem.

Important work on pelagic fishes (Eisner et al. 2013, De Robertis et al. 2017, Levine et al. 2022, Baker et al. 2023; Gunther et al. 2023), epibenthic fishes and invertebrates (Norcross et al. 2013; Logerwell et al. 2015), demersal fishes (Stevenson and Lauth 2019; Baker 2021), and macrofaunal benthos (Feder et al. 2007; Petryashov et al. 2013; Grebmeier et al. 2015) has been done in this region. Important breakpoints in community composition have been associated with attributes of the physical system (Baker and Hollowed 2014) and distinct water masses (Sigler et al. 2017). These analyses provide insight into potential shifts in species distribution in association with anticipated shifts in ocean conditions (Hollowed et al. 2017).

### **8.1 Eastern NBS (US waters) – Bottom Trawl Surveys**

Until recently, regular groundfish surveys were uncommon. The NOAA Alaska Fisheries Science Center conducted groundfish surveys in the northern Bering Sea in 2010 and 2017 and implemented annual surveys since 2019 (Figure R14-40).

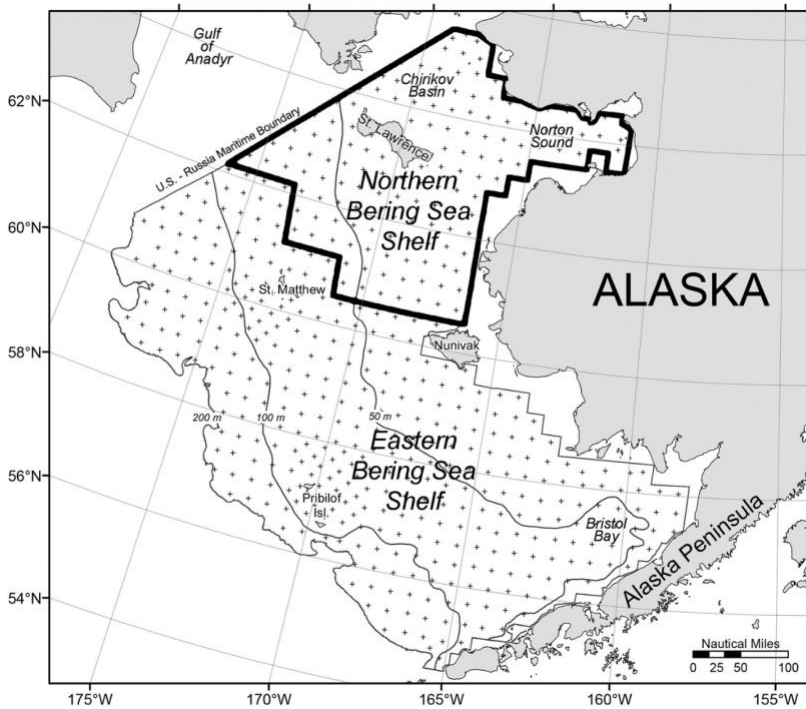


Figure R14-40 NOAA groundfish travel surveys in the eastern and northern Bering Sea [Source: Robert Lauth]

Several comprehensive ecosystem-wide surveys have been conducted in recent years, including the Bering Sea Integrated Ecosystem Research Program (BSIERP) (2005-2010), RUSALCA, Arctic IES (2012-2013), and Arctic IERP (2017-2019) surveys (Baker et al. 2020b).

Partial surveys of the NBS were conducted triennially from 1976 through 1991 (Wolotira et al. 1977; Bakkala and Wakabayashi 1985; Bakkala et al. 1985, 1992; Sample and Wolotira 1985; Walters et al. 1988), and a US-Russian cooperative survey sampled the NBS, including the Gulf of Anadyr in 1990 (Sample and Nichol 1994; Zimmermann et al. 1994). Those surveys reported pollock and Pacific cod south of St. Lawrence Island, but the only in trace amounts (Wolotira et al. 1977; Sample and Wolotira 1985) and relatively small size ranges (< 20 cm) further north in the Chirikov Basin. The US-Russian cooperative survey also found low concentrations of both species through-out the NBS and in the Gulf of Anadyr (Sample and Nichol 1994).

Bottom trawl surveys in US waters in 2010 were conducted during a cold year when most of the continental shelf was covered by the cold pool (< 2 °C) water including all areas from the coastline to U.S.-Russia Maritime Boundary in the northern survey area. Surveys in 2017 were conducted in a year with water temperatures above the long-term mean and the cold pool was completely absent in the inner domain (depths < 50 m) of the northern survey area. These two surveys recorded significantly different spatial distributions for populations of fish species, including walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), flatfish, and jellyfish (Figure R14-41). The fish community in the NBS is increasingly dominated by gadids (Stevenson and Lauth 2012, 2019). Recent shifts in the distribution of walleye pollock and Pacific cod north suggests that significant portions of commercially important groundfish species may be in areas outside the EBS shelf survey area during the summer sampling period (Figure R14-42). This has necessitated more



directed sampling in the NBS to account for these distributional population shifts, improve abundance indices, account for interannual variance in distribution, and inform stock assessment models.

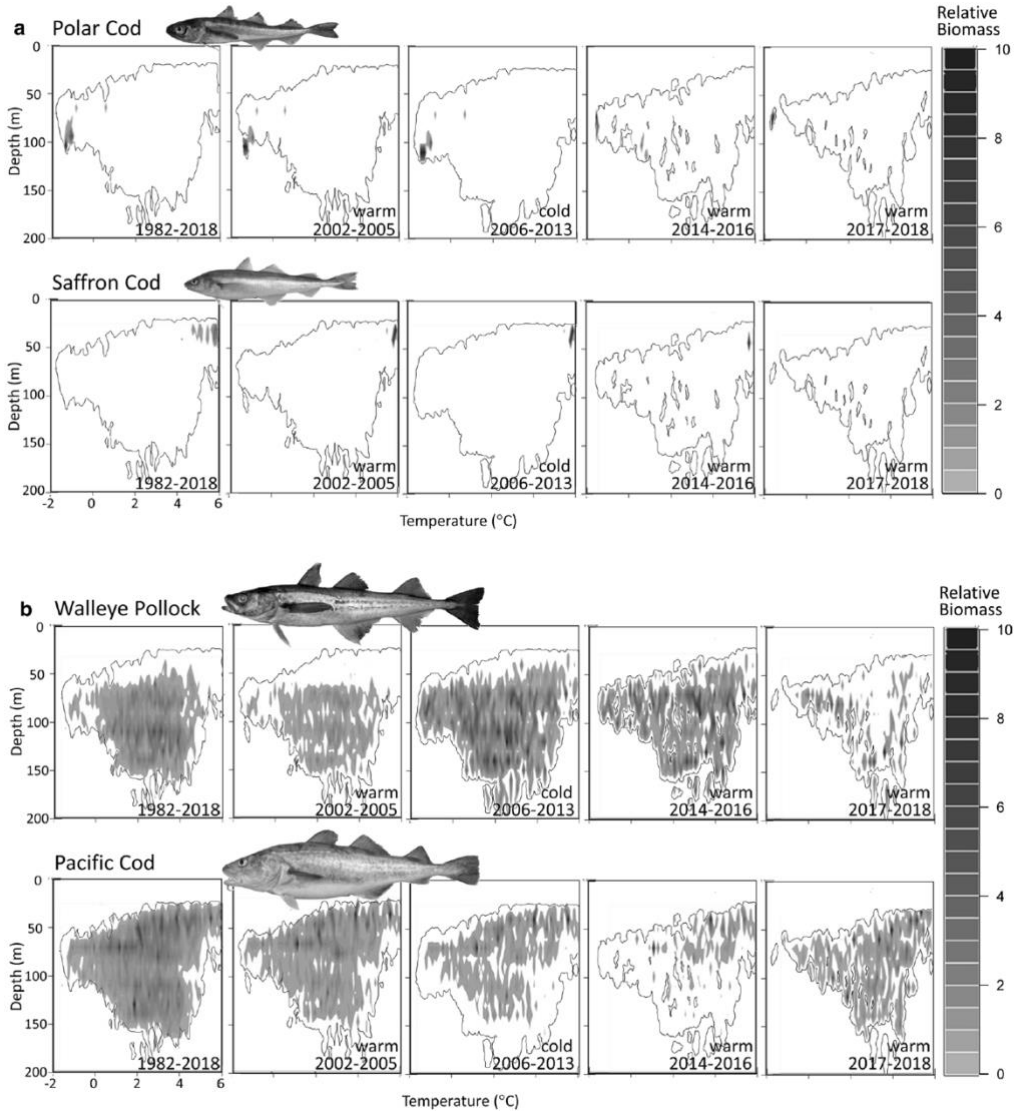


Figure R14-41. Contour plots of relative biomass for polar cod, saffron cod, walleye pollock and Pacific cod for the full time series (1982–2018), warm (2002–2005, 2014–2016, 2017–2018) and cold (2006–2013) periods in the EBSS. Species distributions are shown according to a biplot of temperature and depth. Inset photo credit: polar cod, James Orr NOAA/AFSC; saffron cod, walleye pollock, Pacific cod, Gerald Hoff, NOAA/AFSC [Source: Baker 2021]

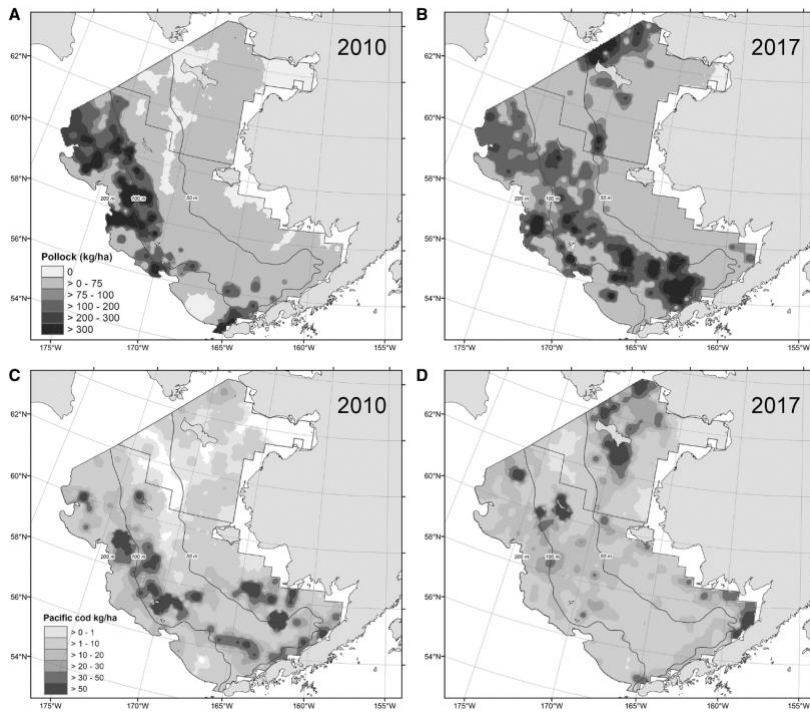


Figure R14-42. Spatial distribution of large gadids in the 2010 and 2017 NOAA bottom trawl surveys of the eastern and northern Bering Sea: for walleye pollock (A, B) and Pacific cod (C, D) [source: Stevenson and Lauth 2019]

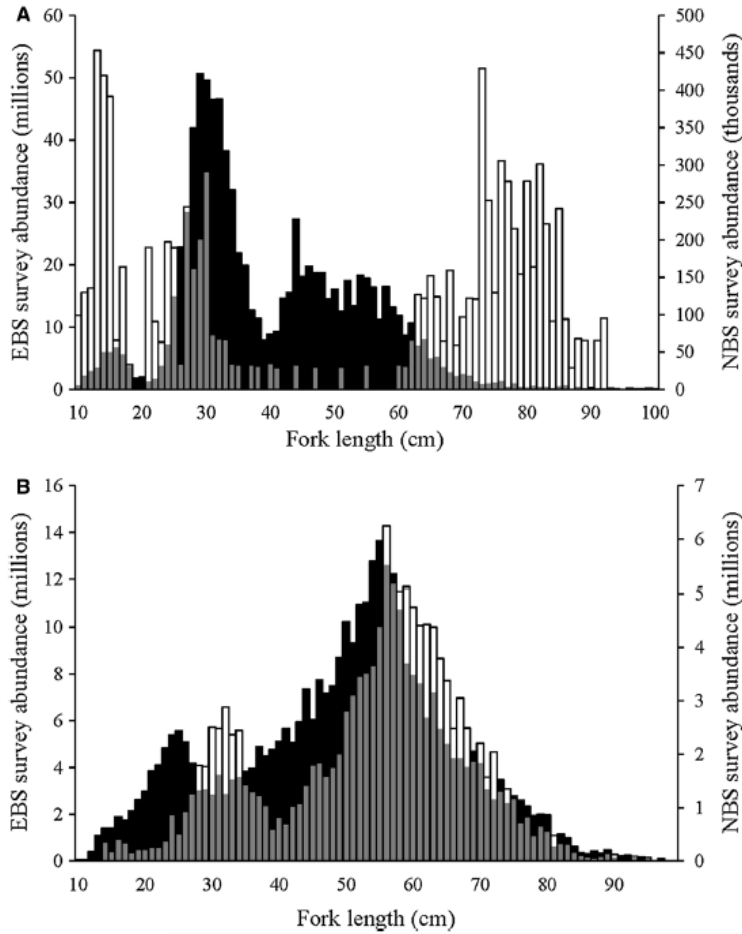


Figure R14-43. Size composition of Pacific cod in the southeastern Bering Sea (black bars) and NBS (clear bars) in 2010 (top) and 2017 (bottom) [source: Stevenson and Lauth 2019]

At higher latitudes in the Bering Sea, the benthic community shifts from a high-biomass assemblage dominated by large gadids and flatfishes to a low-biomass assemblage of smaller gadids (Figure R14-43), predominated by invertebrates such as sea stars, crabs, snails, and tunicates (Figure R14-44) (Grebmeier et al. 2006; Stevenson and Lauth 2012).

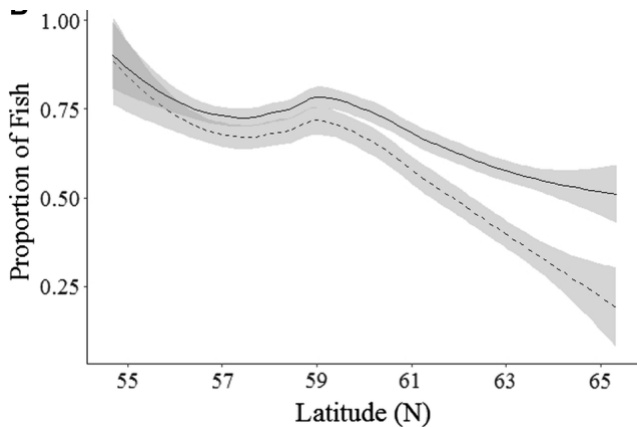


Figure R14-44. Proportion of total catch weight represented by fishes according to latitude for bottom trawl surveys of the eastern and northern Bering Sea in 2010 (dashed line) and 2017 (solid line) [source: Stevenson and Lauth 2019]

A total of 120 fish species were identified in the survey catches from both the EBS and NBS. The EBS had a total of 101 fish species, 49 of which did not occur in the NBS (Table 1). In comparison, the NBS had 71 total fish species 19 of which did not occur in the EBS (Table 1). Walleye pollock and Pacific cod together comprised 40% of the total fish biomass in the EBS compared to only 5% in the NBS. In the NBS, Arctic cod (*Boreogadus saida*) and saffron cod (*Eleginus gracilis*), were among the 12 most abundant fish species.

Present in EBS but absent in NBS		Present in NBS but absent in EBS	
Common name	Scientific name	Common name	Scientific name
Pacific lamprey	<i>Lampetra tridentata</i>	Arctic flounder	<i>Liopsetta glacialis</i>
spiny dogfish	<i>Squalus acanthias</i>	<b>veteran poacher</b>	<b><i>Podothecus veterinus</i></b>
Pacific sleeper shark	<i>Somniosus pacificus</i>	<b>Arctic staghorn sculpin</b>	<b><i>Gymnocanthus tricuspidus</i></b>
big skate	<i>Raja binoculata</i>	<b>hamecon</b>	<b><i>Arctediellus scaber</i></b>
Bering skate	<i>Bathyraja interrupta</i>	brightbelly sculpin	<i>Microcottus sellaris</i>
Aleutian skate	<i>Bathyraja aleutica</i>	belligerent sculpin	<i>Megalocottus platycephalus</i>
whiteblotched skate	<i>Bathyraja maculata</i>	<b>fourhorn sculpin</b>	<b><i>Myoxocephalus quadricornis</i></b>
arrowtooth flounder	<i>Atheresthes stomias</i>	<b>Arctic sculpin</b>	<b><i>Myoxocephalus scorpioides</i></b>
Kamchatka flounder	<i>Atheresthes evermanni</i>	<b>hairhead sculpin</b>	<b><i>Trichocottus brashnikovi</i></b>
flathead sole	<i>Hippoglossoides elassodon</i>	antlered sculpin	<i>Enophrys diceraus</i>
Dover sole	<i>Microstomus pacificus</i>	smoothcheek sculpin	<i>Eurymen gyrinus</i>
rex sole	<i>Glyptocephalus zachirus</i>	coho salmon	<i>Oncorhynchus kisutch</i>
southern rock sole	<i>Lepidopsetta bilineata</i>	Arctic shanny	<i>Stichaeus punctatus</i>
butter sole	<i>Isopsetta isolepis</i>	snake prickleback	<i>Lumpenus sagitta</i>
sawback poacher	<i>Leptagonus frenatus</i>	pighead prickleback	<i>Acantholumpenus mackayi</i>
northern spearnose poacher	<i>Agonopsis vulsa</i>	bearded warbonnet	<i>Chirolophis snyderi</i>
pygmy poacher	<i>Odontopyxis trispinosa</i>	saddled eelpout	<i>Lycodes mucosus</i>
gray starsnout	<i>Bathyagonus alascanus</i>	<b>Canadian eelpout</b>	<b><i>Lycodes polaris</i></b>
smooth alligatorfish	<i>Anoplagonus inermis</i>	fish doctor	<i>Gymnelus viridis</i>
fourhorn poacher	<i>Hypsagonus quadricornis</i>		
searcher	<i>Bathymaster signatus</i>		
northern sculpin	<i>Icelinus borealis</i>		
purplegray sculpin	<i>Gymnocanthus detrisus</i>		
hookhorn sculpin	<i>Arctediellus pacificus</i>		
darkfin sculpin	<i>Malacocottus zonurus</i>		
longfin Irish lord	<i>Hemilepidotus zapus</i>		
yellow Irish lord	<i>Hemilepidotus jordani</i>		
scissortail sculpin	<i>Triglops forficata</i>		
spectacled sculpin	<i>Triglops scepticus</i>		
roughspine sculpin	<i>Triglops macellus</i>		
spinyhead sculpin	<i>Dasycottus setiger</i>		
sailfin sculpin	<i>Nautichthys oculoasciatus</i>		
bigmouth sculpin	<i>Hemitripterus bolini</i>		
Atka mackerel	<i>Pleurogrammus monopterygius</i>		
toad lumpsucker	<i>Eumicrotremus phrynooides</i>		
blotched snailfish	<i>Crystallichthys cyclospilus</i>		
Okhotsk snailfish	<i>Liparis ochotensis</i>		
salmon snailfish	<i>Careproctus rastrinus</i>		
eulachon	<i>Thaleichthys pacificus</i>		
chinook salmon	<i>Oncorhynchus tshawytscha</i>		
pink salmon	<i>Oncorhynchus gorbuscha</i>		
whitebarred prickleback	<i>Poroclinus rothrocki</i>		
prowfish	<i>Zaprora silenus</i>		
roughey rockfish	<i>Sebastes aleutianus</i>		
blackspotted rockfish	<i>Sebastes melanostictus</i>		
Pacific ocean perch	<i>Sebastes alutus</i>		
dusky rockfish	<i>Sebastes variabilis</i>		
northern rockfish	<i>Sebastes polyspinis</i>		
harlequin rockfish	<i>Sebastes variegatus</i>		

Table 1. List of fish taxa from The NOAA Alaska Fisheries Science Center conducted groundfish surveys in 2010 and 2017 exclusive to the EBS and NBS. Taxa in bold were only documented north of 60° N latitude [Lauth et al. 2019]

Previous studies of latitudinal gradients in the fish and invertebrate community composition of the Bering Sea (Mueter and Litzow 2008; Stevenson and Lauth 2012, 2019) have shown that groundfish biomass declines with increasing latitude, and that fish populations move north in warm periods. An influx of pelagic species such as pollock and jellyfish into the NBS may reconstitute this benthic-dominated ecosystem.

### 8.2 Eastern NBS (US waters) – Surface and Pelagic Surveys

Standardized mid-water and surface surveys in the northern Bering Sea such as the Bering Arctic Subarctic Integrated Surveys (BASIS, Gann and Farley 2019) (Figure R14-45) provide indices of pelagic fish and environmental variables at the surface.

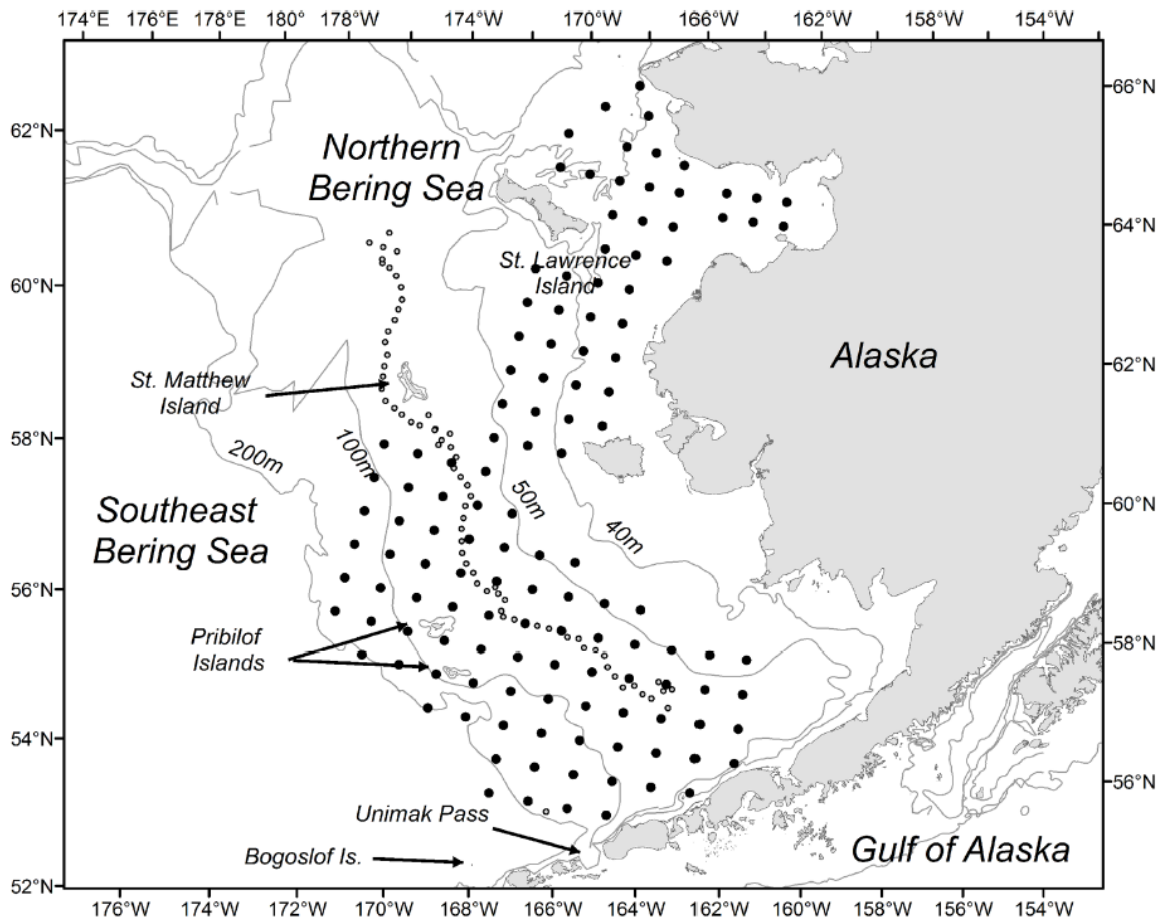


Fig 1. Survey area and geographic extent. Schematic diagram of the southeast Bering Sea and Northern Bering Sea with seasonal sampling in 2015 and 2016 overlaid. Dark circles indicate gridded survey areas; light, small circles indicate latitudinal sampling along the 70 m isobath.

Figure R14-45. Sampling locations of the Bering Arctic Subarctic Integrated Surveys (BASIS) of pelagic fish in 2015 and 2016 [source Duffy-Anderson et al. 2017]

Pelagic fish, larval fish, and jellies were sampled in BASIS midwater and surface trawl surveys late summer, 2002-2016. Four forage fish commonly captured in the trawl included capelin (*Mallotus villosus*), herring (*Clupea pallasii*), sand lance (*Ammodytes hexapterus*). Herring were the most abundant species and were distributed in the northeastern Bering Sea middle and inner domains (0-100 m bottom depth). Capelin were distributed in the central and northern Bering Sea shelf. Sand lance were captured primarily in the inner domain of the eastern Bering Sea shelf. Trends in abundance for forage fishes did not track the recent warm (2002-2005, 2014-2016) and cold years (2007-2013). In contrast to bottom

fish assemblages, these forage fish species did not appear to expand or contract their ranges during warm years relative to cold years (Figure R14-46).

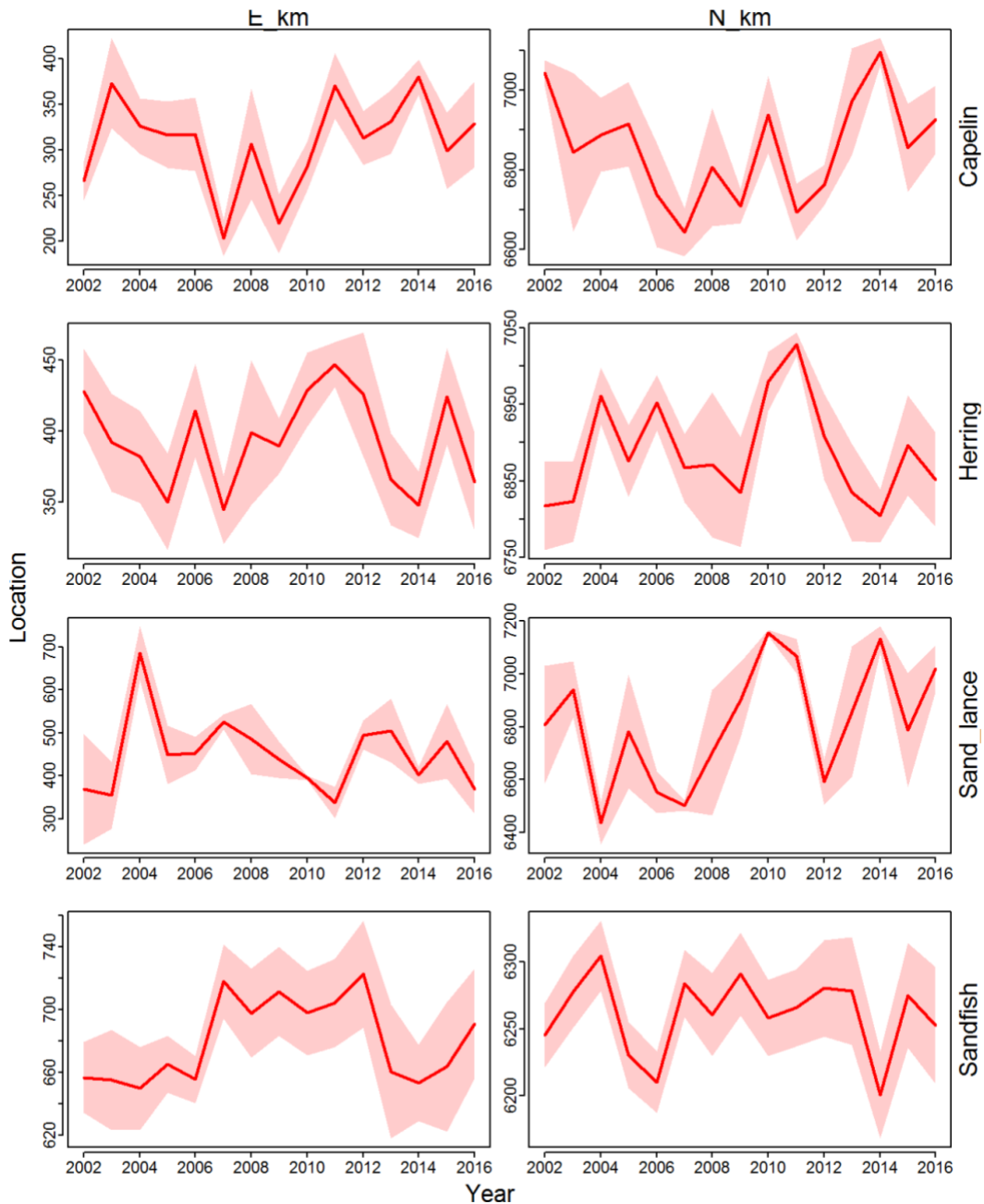


Figure R14-46. Spatial distribution (mean east-west and north-south distributions in UTM (km) for forage fish species 2002-2016 [source Ellen Yasumiishi, unpublished data]

BASIS surveys also provide indices of larval and juvenile stages of groundfish. Diet analyses of age-0 pollock revealed spatial differences in feeding in the NBS relative to other areas of the Bering Sea. Walleye pollock appear to feed primarily on euphausiids on the SEBS shelf and on large copepods in the NBS (Duffy-Anderson et al. 2017). Age-0 pollock CPUE shifted in relation to bottom water conditions (Figure R14-47, Figure R14-48). In 2015, the southeastern Bering Sea had few age-0 pollock relative to the NBS. Abundances

of age-0 pollock from NBS in 2015 were well above average. In 2016, age-0 pollock were abundant in the southeastern Bering Sea and lower in the NBS. Juvenile pollock are not constrained to the same extent as adult pollock by water temperatures and normally use the cold pool as a refugia from predation and cannibalism in the summer.

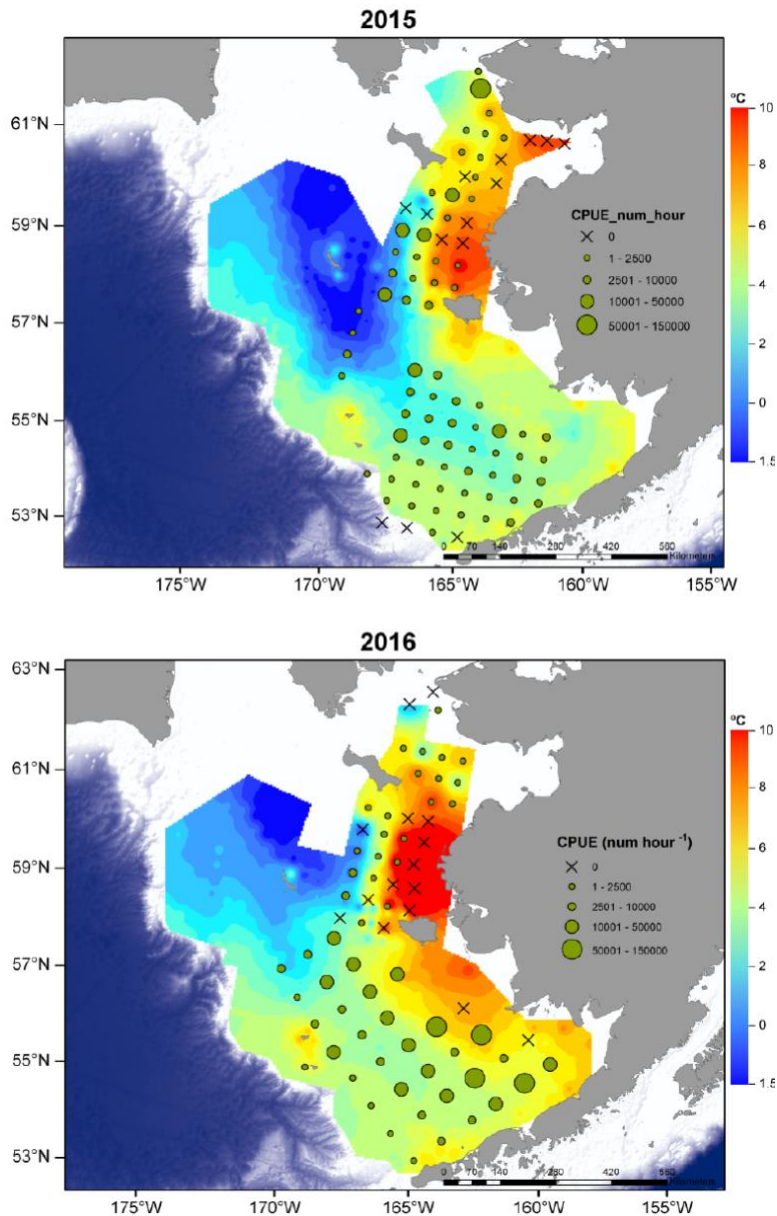


Figure R-14-47. Survey estimates (CPUE) of age-0 pollock in oblique and surface trawling in 2015 (top) and 2016 (bottom). X indicates a trawl conducted but no catch. Heat map presents bottom temperatures (°C) over the southeast and Northern Bering Sea shelves. Cold Pool denoted where bottom temperatures <2 °C (blue color ramp). Catches of age-0 pollock were low over the southern shelf in 2015, with higher catches that year in the vicinity of the Cold Pool (<2 °C). In 2016 trawl catches of age-0 pollock over the southern shelf were higher than in 2015 and reduced in the north relative to the southern shelf. [source Duffy-Anderson et al. 2017]

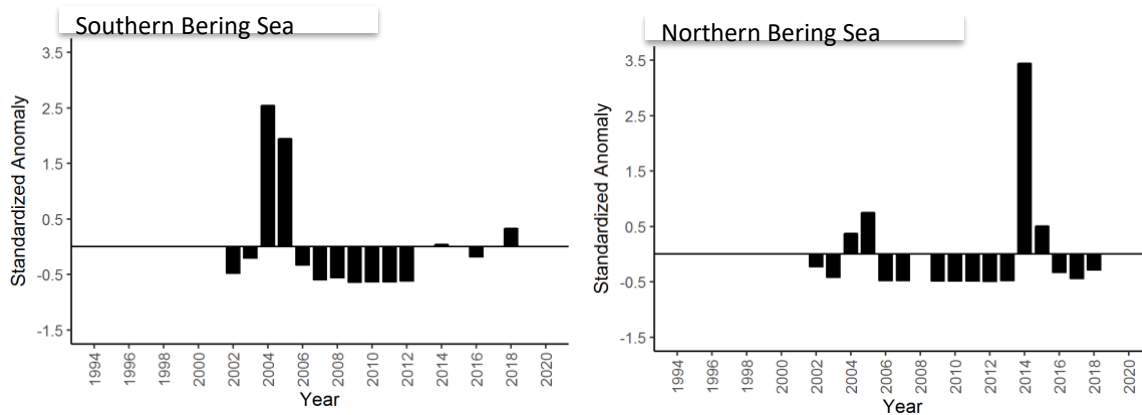


Figure R14-48. Annual standardized anomaly of juvenile pollock abundance in Southern Bering Sea (left) and Northern Bering Sea (right) 2002-2018 [Source: Duffy-Anderson et al. 2019].

Acoustic trawl surveys also provide estimates for groundfish and pelagic fishes in the region. In acoustic surveys conducted 2006-2010, forage fishes such as capelin were distributed throughout the southeaster and northeast Bering Sea shelf, particularly in the inner domain (<50m) whereas larval gadids (age-0 walleye pollock and Pacific cod) were found only in the southern Bering Sea shelf, particularly in the southern nearshore and mid-shelf habitats and areas along the Alaska Peninsula (Figure R14-49).

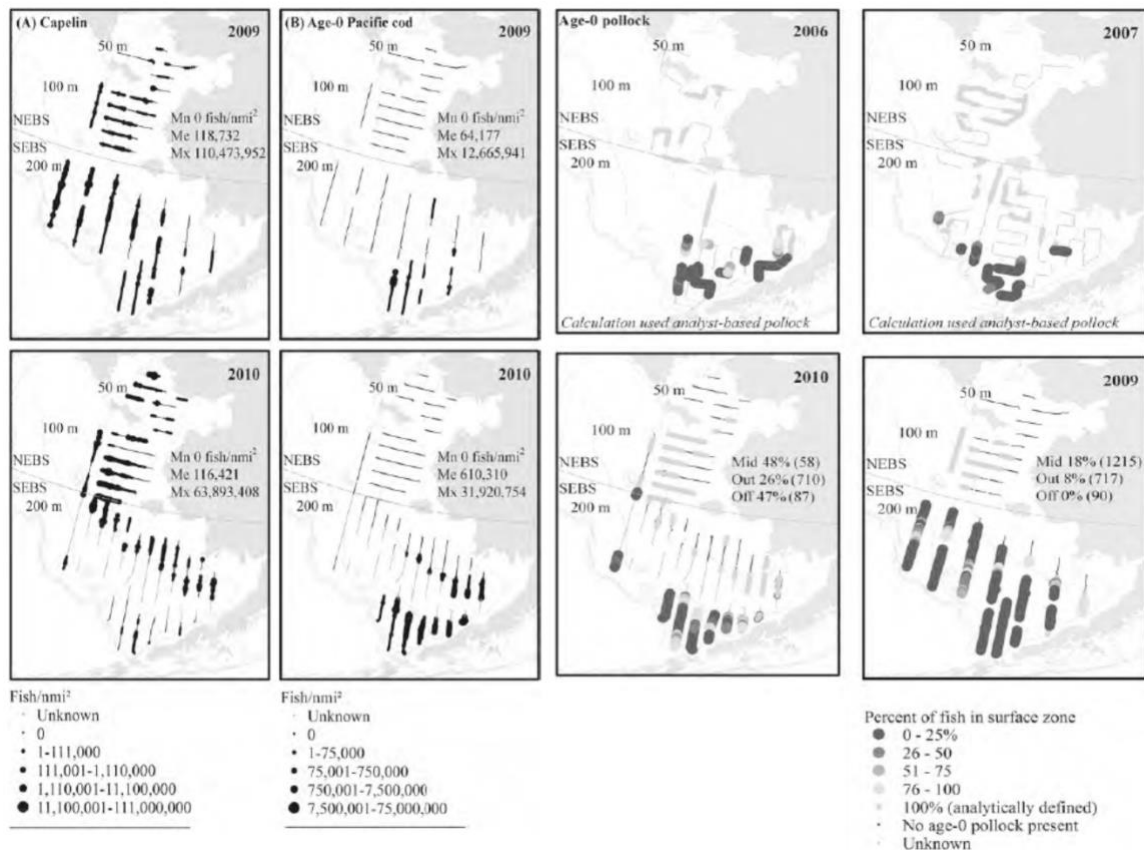


Figure R14-49. Acoustic surveys and distribution of forage fish: Capelin (2009 and 2010), and juvenile gadids: Age-0 Pacific cod (2009 and 2010); Age-0 pollock (2006, 2007, 2009, 2010) [source: Parker-Stetter et al. 2013]



### 8.3 Eastern NBS (US waters) – Integrated Surveys

Several integrated surveys and research efforts have been implemented in this region, including the Distributed Biological Observatory (<https://www.pmel.noaa.gov/dbo/>), the Chukchi Sea Ecosystem mooring (<https://aocs.org/project-page/ecosystems/chukchi-ecosystem-observatory/>), the Russian-American Long-term Census of the Arctic (RUSALCA; <https://www.pmel.noaa.gov/rusalca/>), the Arctic EIS (<https://www.uaf.edu/cfos/research/projects/arctic-ecosystem-integrat/>), the North Pacific Research Board Bering Sea Integrated Ecosystem Research Program (IERP; <https://www.nprb.org/bering-sea-project>) and the Arctic IERP (Figure R14-50) (<https://www.nprb.org/arctic-program/>; Baker et al. 2020b).

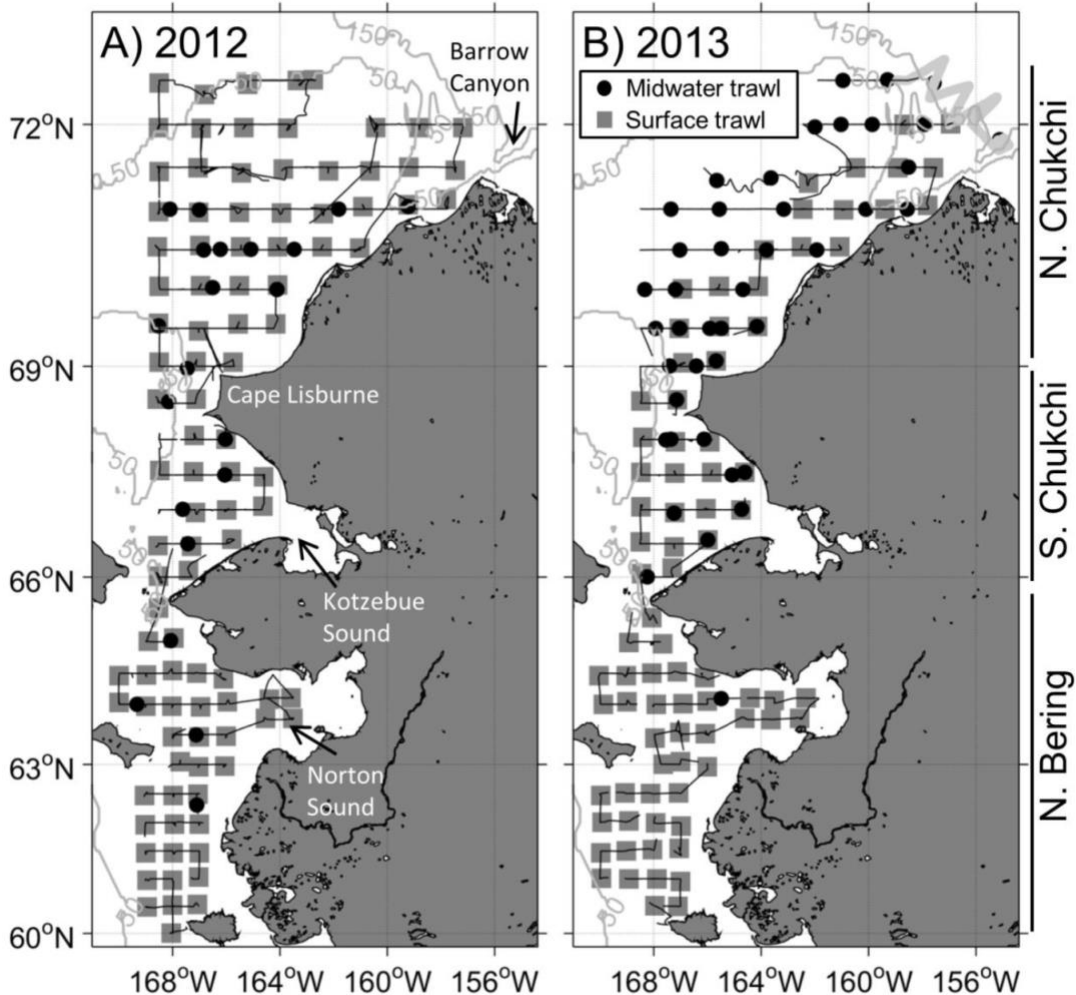


Figure R14-50. Arctic EIS survey stations (2012-2013). The survey track lines are depicted as a black line, surface trawl stations as grey squares, and midwater trawl sites as black dots [Source: Arctic EIS; Mueter et al. 2017]

The primary species observed in acoustic-trawl surveys of the U.S. northern Bering and Chukchi Seas were Arctic cod, saffron cod, Pacific herring, and capelin (De Robertis et al. 2017). These species are abundant in the Pacific Arctic (Eisner et al. 2013; Logerwell et al. 2015). Distributions of Arctic cod, saffron cod and herring were separated along a latitudinal gradient. Strong interannual variance is evident even on short timescales (between 2012 and 2013; De Robertis et al. 2017) (Figure R14-51, Figure R14-52). Pacific herring were most abundant in the northern Bering Sea.

In terms of water properties, planktonic communities and pelagic fish abundance (De Robertis et al. 2017), trends that have been documented in other studies (e.g. Logerwell et al. 2015). Trends suggest that lower temperatures favor Arctic cod and higher temperatures favor saffron cod and Pacific herring (Nikolaev and Stepanenko 2008; Logerwell et al. 2015). Arctic cod, saffron cod, and herring were consistently associated with a specific subset of environmental condition. Age-0 Arctic cod were abundant at high latitudes, intermediate temperatures and high salinities. In contrast, saffron cod and herring were in the warmest and fresh (coastal) waters. Capelin were broadly distributed throughout the survey area. Observations suggest that population dynamics and dispersal mechanisms of pelagic fishes in the Pacific Arctic are strongly influenced by environmental conditions. Improved mechanistic understanding of these associations would improve predictions of how pelagic fishes will respond to increased warming and environmental variability in the Pacific Arctic.

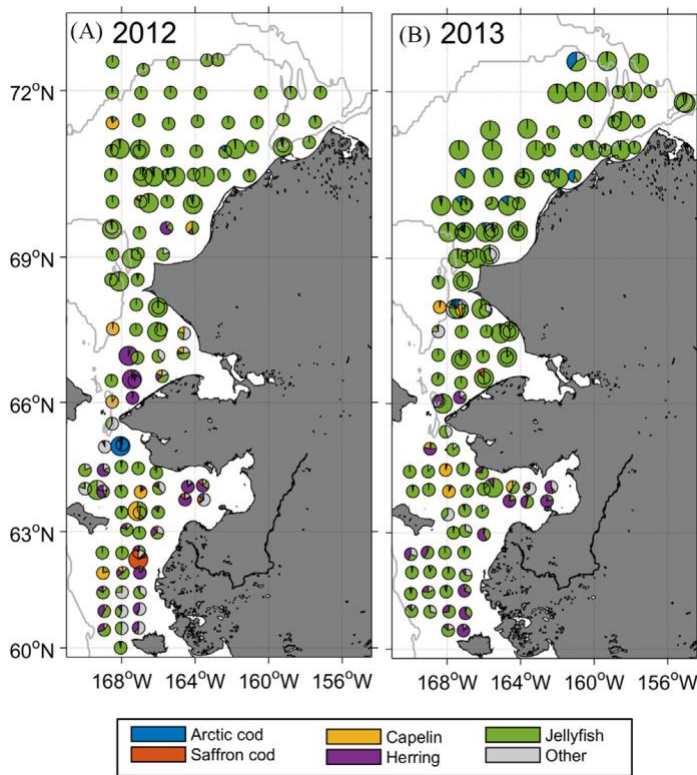


Figure R14-51. Catch composition of key species in the NBS and Chukchi Sea expressed as proportions of trawl catch by weight in 2012 and 2013 for midwater and surface trawl hauls [source: De Robertis et al. 2017]

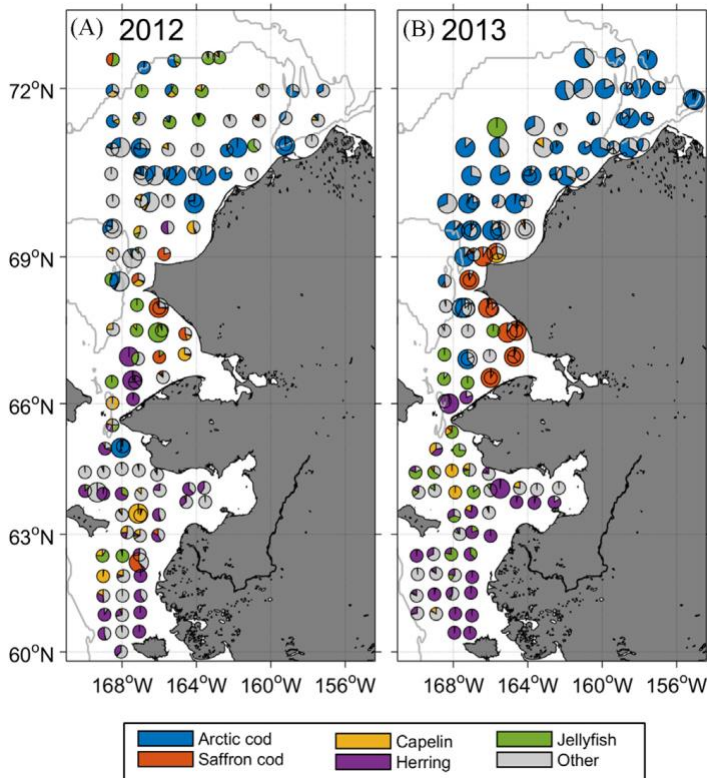


Figure R14-52. Estimated proportion of backscatter attributable to key species derived by combining estimates of species composition from trawl catches and estimates of target strength [source: De Robertis et al. 2017]

Several important physical mechanisms on the dynamic Bering–Chukchi shelf influence the distribution of water masses, bottom sediments, and organic carbon content in the region, influencing habitat, productivity patterns, and prey availability. Water masses transport nutrients, particulate organic matter, and organisms from the Bering Sea northward (transport of Bering Slope-Anadyr Water into Chirikov Basin) and ensure a tight coupling of ecosystem connectivity between the northern Bering and southern Chukchi seas (Sigler et al. 2017). Alaska Coastal Water, which is warmer, fresher, and nutrient-poor (Springer and McRoy, 1993), is typically located in shallower depths, though wind can move these waters offshore to deeper regions (e.g., Danielson et al. 2017). Stratification influences the spring bloom, vertical nutrient flux, and food availability for planktivorous fishes.

Arctic cod were an abundant epibenthic fish in northern Bering Sea and Chukchi Sea surveys. Arctic cod use multiple habitats (Logerwell et al. 2015), and the strongest gradient in Arctic cod distribution was north-south. Analyses of integrated survey data (Sigler et al. 2017) identify main cross-assemblage geographical groupings, including one associated with the Alaska Coastal Water, one associated with the Chirikov Basin and southern Chukchi Sea, and one associated with the northern Chukchi shelf (Figure R14-53). The first two communities connect the northern Bering and southern Chukchi seas. The Alaska Coastal Water community is characterized by a mixture of zooplankton, fish, invertebrate, and seabird taxa; the Chirikov Basin/southern Chukchi community is characterized by large crustacean zooplankton and seabird taxa. Contrast to the Alaska Coastal Water, the Chirikov Basin and southern Chukchi Sea are colder, saltier, and nutrient rich. Assemblages of epibenthic, planktonic and pelagic communities were structured nearshore to offshore and south to north. The nearshore to offshore contrast was greatest in the

Yukon River drainage (Danielson et al. 2017).

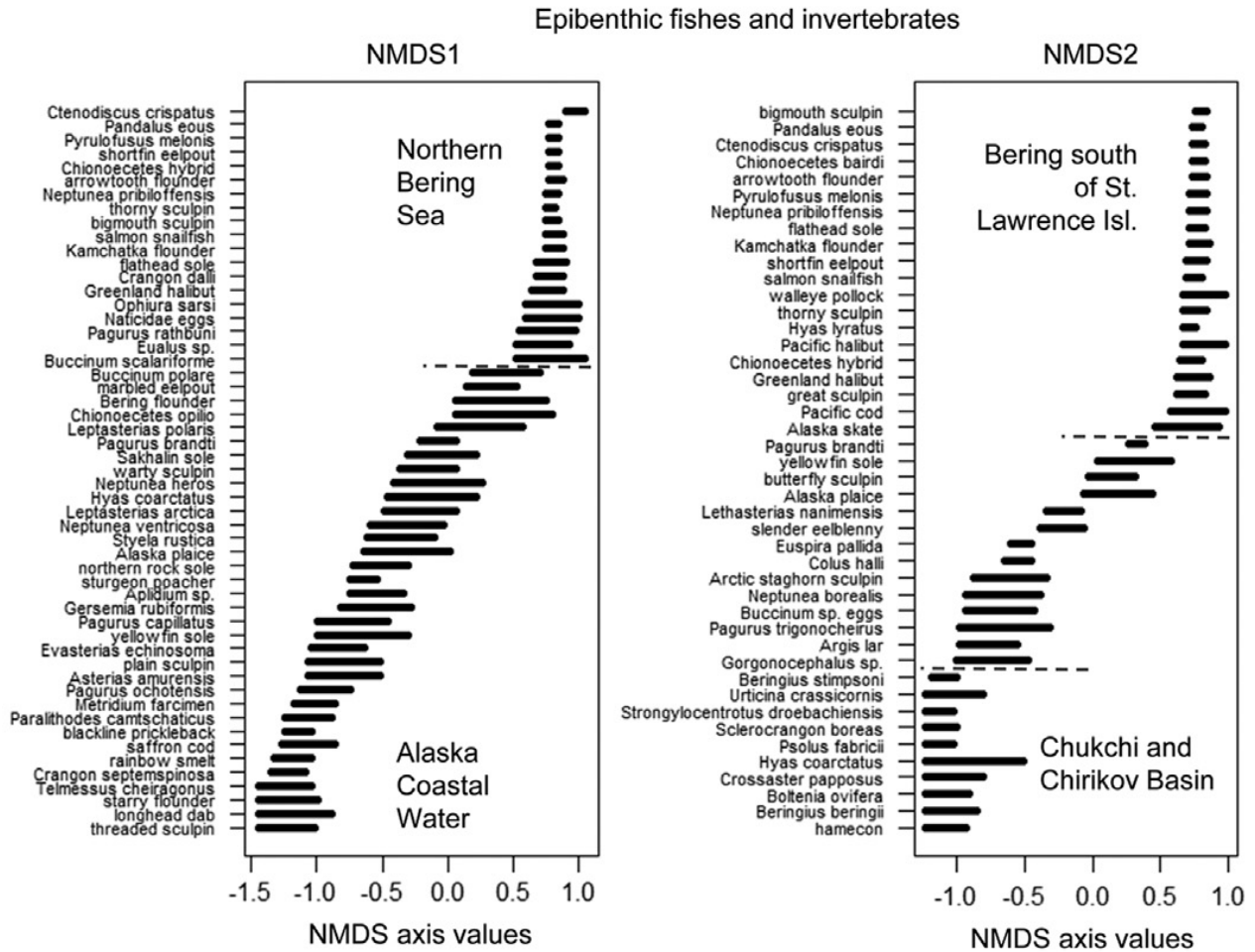


Figure R14-53. Benthic (left) and pelagic (right) taxa sampled in 2010-2013 and incorporated in a Nonlinear Multi-Dimensional Scaling (NMDS) analysis. Dashed lines indicate groups of similar NMDS values, reflecting distinct community assemblages within the northern Bering Sea and southern Chukchi Sea [source: Sigler et al. 2017]

Since 2022, NOAA surveys are conducted regularly in the northern Bering Sea and will provide a better index for shifts in marine taxa over time (Figure R14-54).

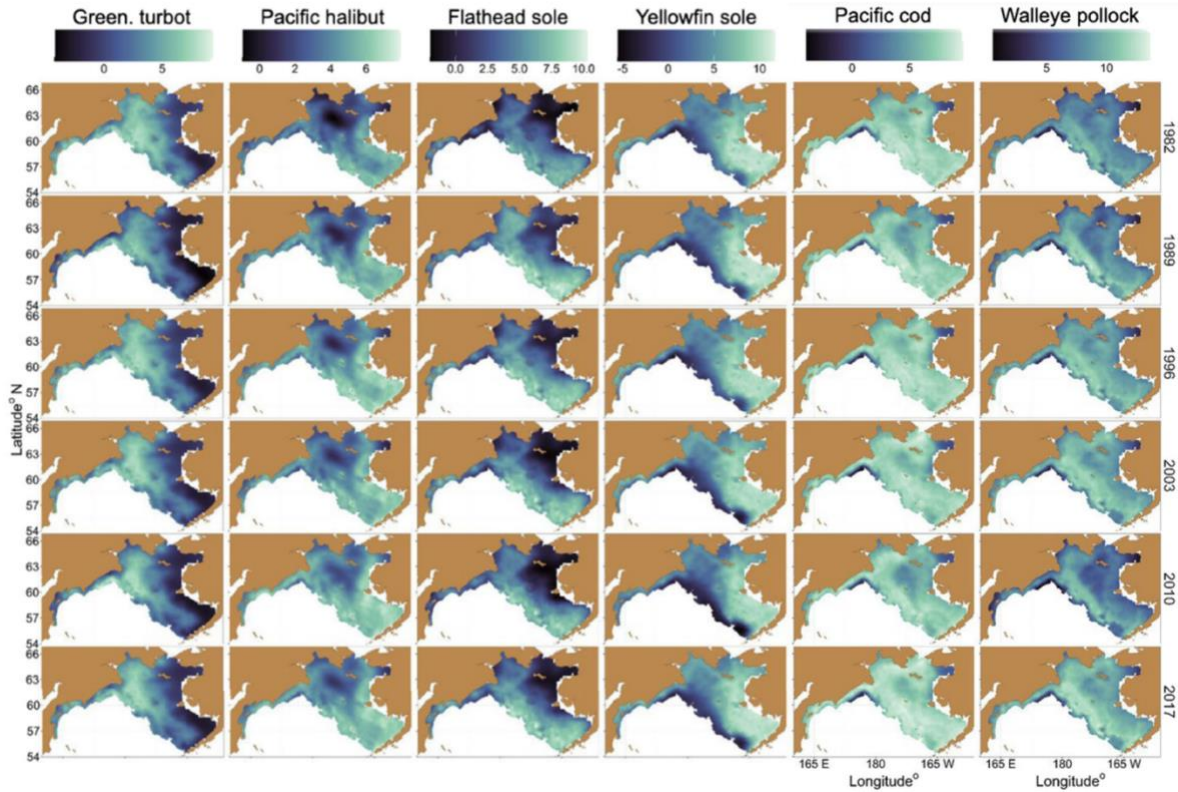
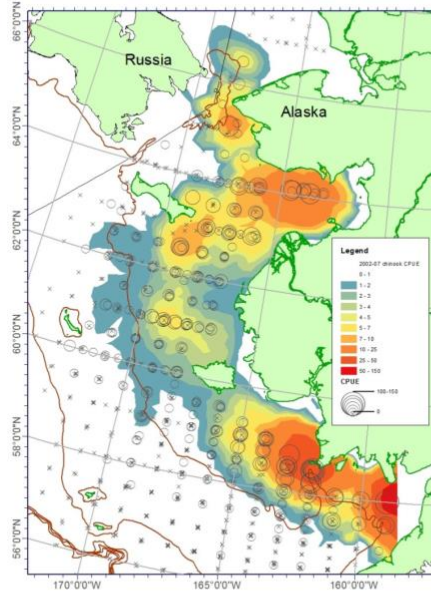


Figure R14-54. Spatial distribution of biomass (log kg/km<sup>2</sup>) by species for years 1982, 1989, 1996, 2003, 2010, and 2017 [source: DeFilippo et al. 2023]

#### 8.4 Eastern NBS (US waters) – Pacific salmon

a) 2002-2007



b) 2009-2011

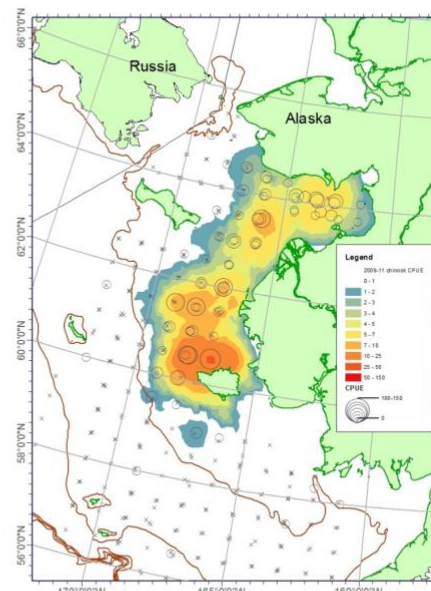


Figure R14-55. Distribution of juvenile Chinook salmon from surface trawl surveys 2002-2011. Circles display CPUE data, shaded low to high (blue to red) [source: Murphy et al. 2013]

Sea ice and its impact on ecosystem level processes on the shelf is an important feature in the marine ecology of western Alaska salmon populations (Murphy et al. 2013). Temperature in the NBS is an important constraint on juvenile migration. Mean latitude position of juveniles was negatively correlated with survival.

Warming temperatures in the marine environment may be advantageous to salmon stocks in the NBS and allow range expansion to the north. Improved early life-history survival (freshwater and early marine) has contributed to an increase in juvenile (freshwater and early marine) abundance since 2013 (Figure R14-55; Figure R14-56) with the warming trend. However, while warming temperatures in the freshwater environments may improve juvenile growth, it may negatively impact survival and productivity in adult spawners.

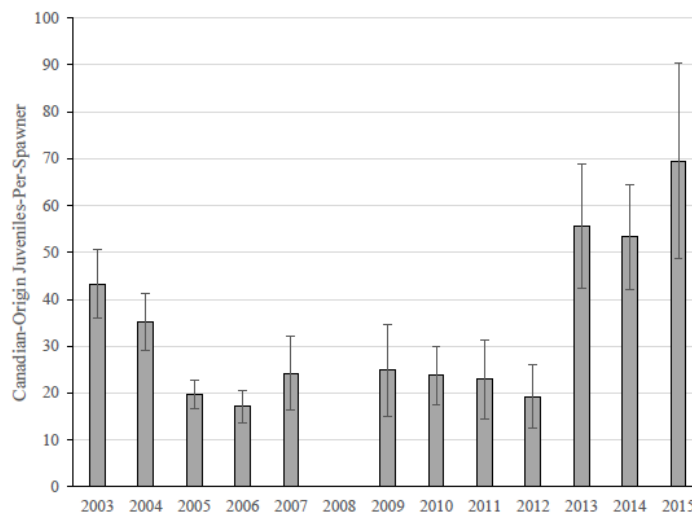


Figure R14-56. Juvenile Chinook salmon abundance and life history survival (juvenile per spawner) for freshwater and early marine stages in the northern Bering Sea [source: Murphy et al. 2013]

Yukon River Chinook salmon have had declining production levels for several years, resulting in reduced harvests since 2000 (Figure R14-57). It has remained low throughout the past two decades, raising concerns for conservation of the stock, local access to the resource, and food security for Indigenous communities. The cause of their production decline remains unclear. Yukon River Chinook salmon stocks utilize marine habitats adjacent to or on the eastern Bering Sea shelf throughout most of their marine life history stage (Myers et al. 2009). Increased in-river temperatures may increase pre-spawning mortality.

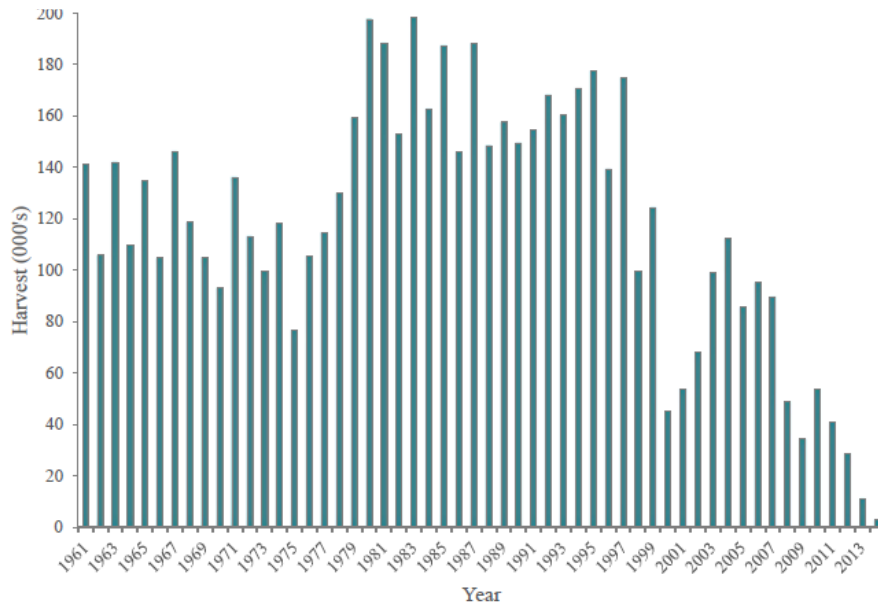


Figure R14-57. Long-term change in Yukon River Chinook salmon harvest (thousands) 1961-2014 [source: Murphy et al. 2013].

### 8.5 Western Regions (Russian waters)

In Russian waters, parts of the northern Bering Sea reflect a more pelagic community (Figure R14-58). This is a consequence of advective and production patterns in the Gulf of Anadyr, circulation patterns, and the deeper waters and pelagic ecosystem of the Bering Sea Basin.

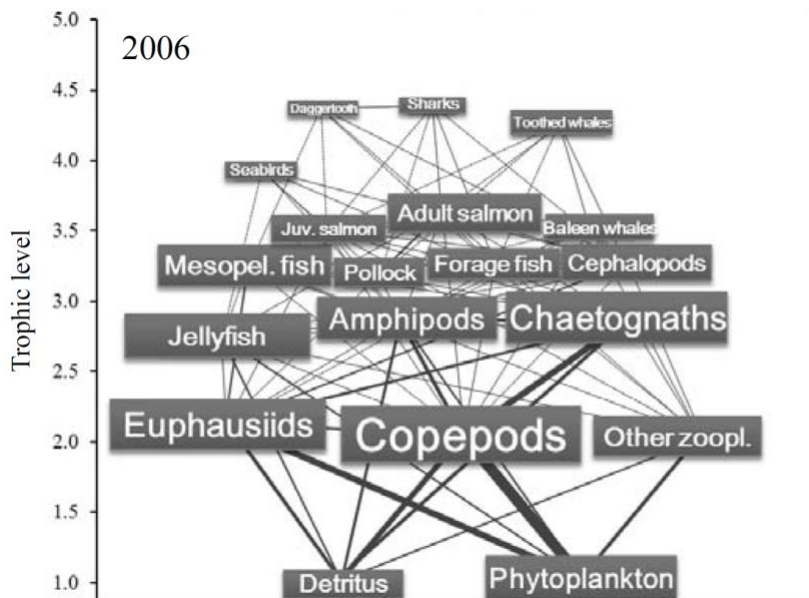


Figure R14-58. Models of the trophic webs of the upper epipelagic layer in the western northern Bering Sea and the Navarin region in 2006; box heights are proportional to the eighth root of the biomass ( $t/km^2$ ); the width of each predator/prey flow is proportional to the eighth root of the volume of the flow ( $t/km^2/year^2$ ) [source Zavolokin et al. 2016]

Bottom trawl surveys, midwater and surface trawl surveys and oceanographic surveys are conducted by the Pacific branch of the Russian Federal Research Institute of Fisheries and oceanography (VNIRO) (Figure R14-59). The area of survey includes the narrow continental shelf of the western Bering Sea in Commander Basin, Aleutian Basin and Koryak coast. Russian surveys also extend north into the Gulf of Anadyr, Anadyr Strait and Bering Strait (Datsky and Andronov 2014).

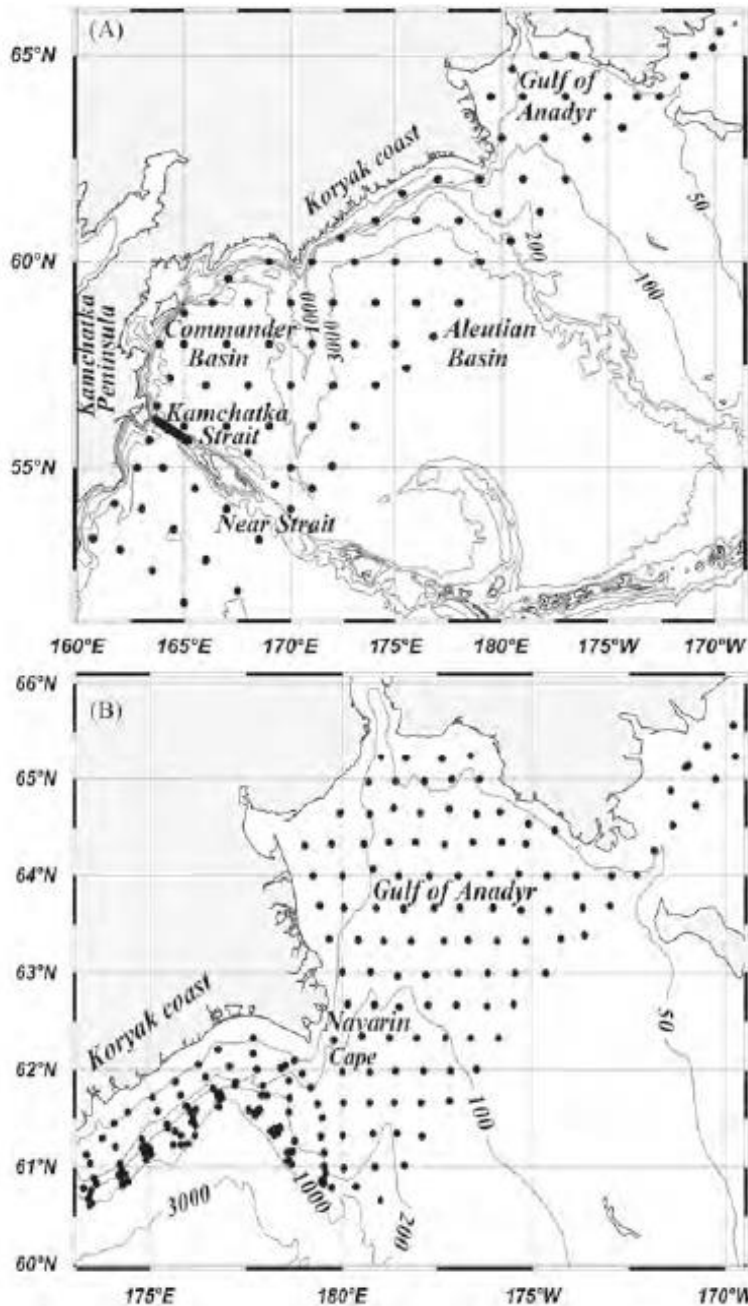


Figure R14-59. Oceanographic stations (black dots) in the Russian (VNIRO) survey area for epipelagic fishes [source: Khen et al. 2013]

Walleye pollock and Pacific cod distributions are well mapped in Russian waters (Figure R14-60, Figure R14-61). Research has been conducted to develop abundance indices,



map distribution according to life stage and seasonal trends and identify critical habitat for juveniles, foraging, and overwintering.

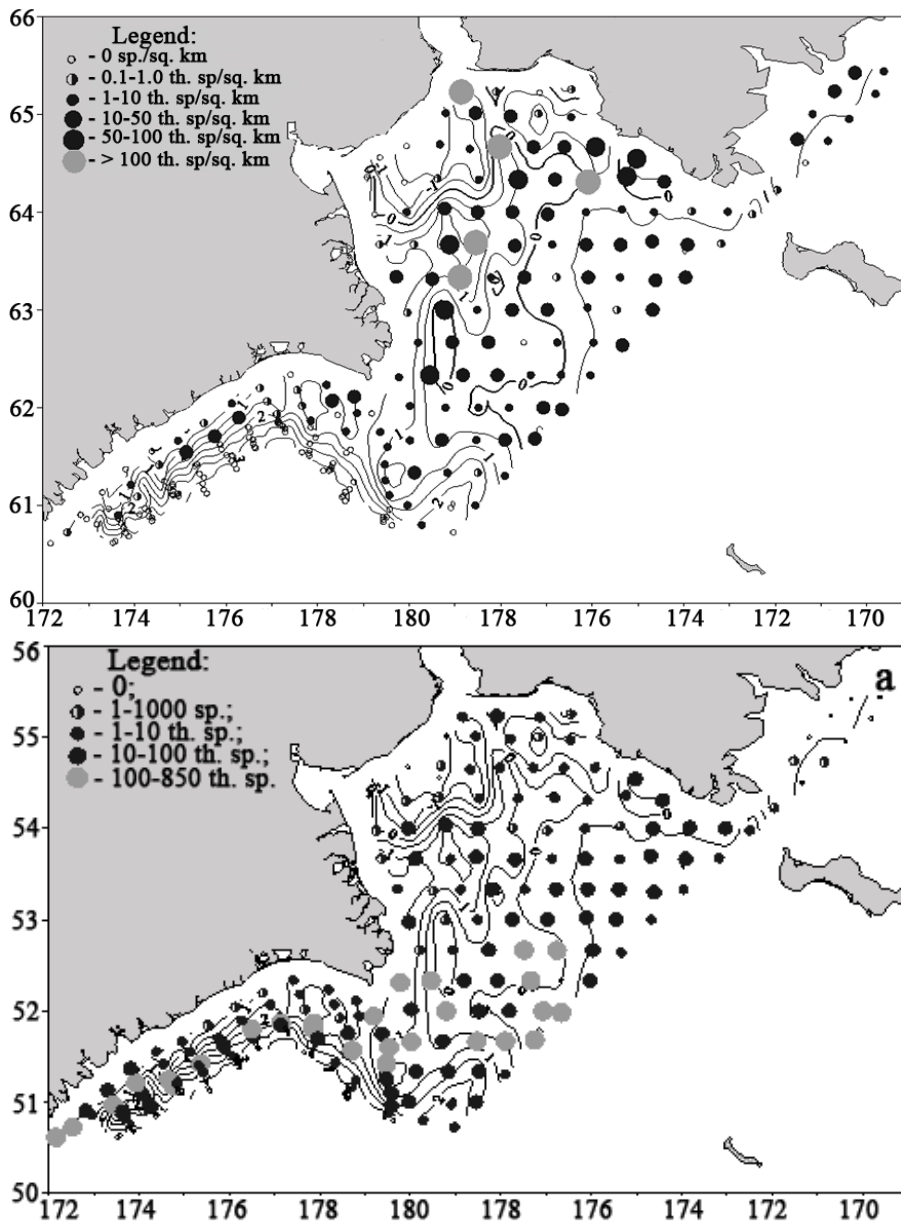


Figure R14-60. Areas surveyed in 2012-2013 for walleye pollock(> 17 cm) density distribution in the Northwestern Bering Sea, July - August 2012

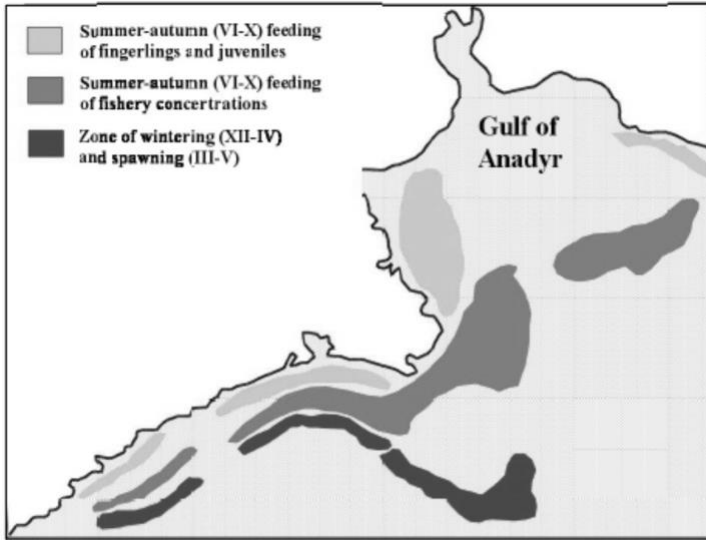


Figure R14-61. Northern Bering Sea Pacific Cod important habitat areas identified related to life stage, season, foraging and fishing [source: Antonov, unpublished data]

Trends in abundance and recruitment over time for many important species in Russian waters in the NBS appear variable. Pelagic fish community composition in the western Bering Sea correlates highly with latitude suggesting that the distributional ranges of fish taxa are primarily the result of geographic location and only secondarily due to water masses and associated habitat preferences (Sigler et al. 2017). This suggests the potential for widespread movement of these stocks across space if environmental conditions (e.g., temperature) allow it. Significant increases are noted in Pacific cod since 2011 (Figure R14-62), the trends in pollock stocks are more complicated (Figure R14-63) though both species have seen increases in the western Bering Sea in the years 2017-2021. Shifts in recruitment may reflect environmental patterns influencing survival and growth conditions. Shifts in abundance may also reflect environmental conditions and movement from US waters to the west, as thermal limitations to movement in the northern Bering Sea erode, allowing movement and distribution for these stocks along the continental shelf.

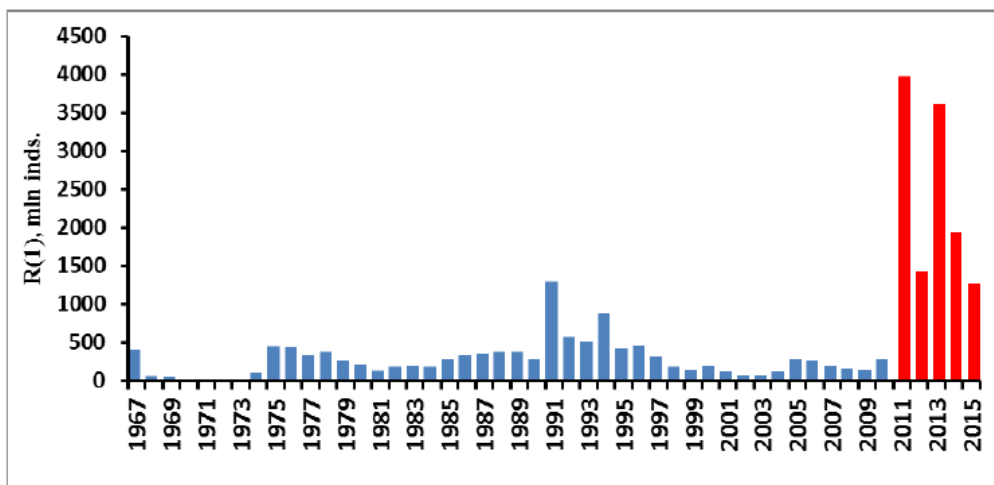


Figure R14-62. Recruitment of northwest Bering Sea age-1 cod; years of spawning [source: Krovin et al. 2017]

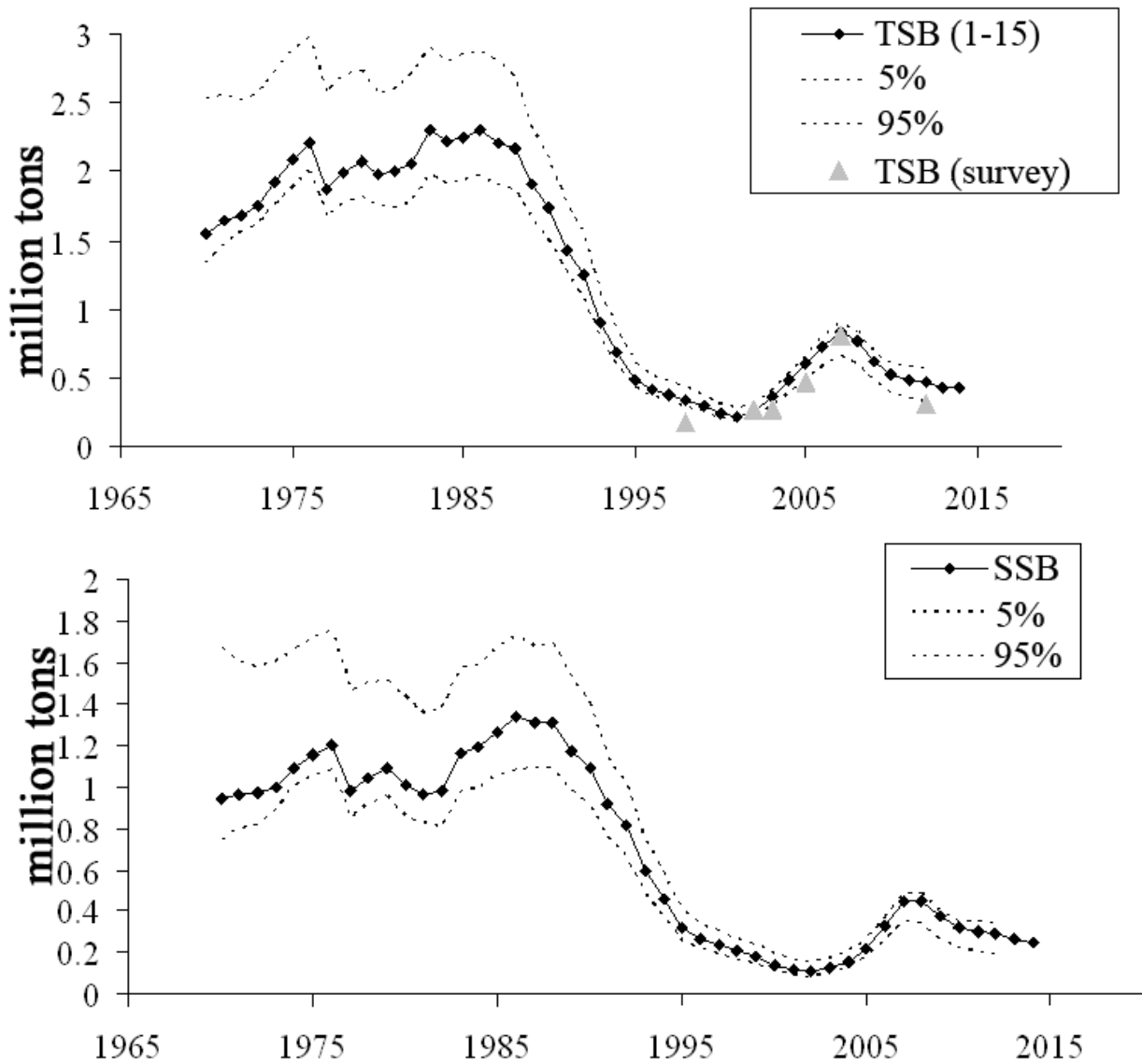


Figure R14-63. Total stock biomass (TSB) of western Bering Sea pollock and bootstrap estimated percentiles from trawl surveys for total stock biomass (TSB) (top) and spawning stock biomass (SSB) (bottom) [source: 24<sup>th</sup> Session of the US-Russia Intergovernmental Consultative Committee (ICC) on Fisheries Paper submitted by Russian Federation, TINRO/VNIRO]

Similar to the eastern regions of the northern Bering Sea, oceanographic regime and conditions have a significant impact on fish distribution and recruitment dynamics. The main oceanographic feature in the area of Cape Navarin is the “Lawrence Cold Pool”, which forms at depth in winter at the bottom of the eastern shelf and persists through summer. Similar to the eastern Bering Sea cold pool, the area of this cold water and its temperature have prominent year-to-year variations in dependence on winter severity (Figure R14-64) The Lawrence Cold Pool becomes wider and thicker after severe winters with the vast ice cover, and vice versa.

Also similar to the eastern Bering Sea (Baker et al. 2020ab; Baker 2021), the western Bering Sea appears to have experienced several warm and cold stanzas since the late 1990s, where multiple consecutive years were characterized by anomalously warm (2001 to

2007 and 2014 to 2015) or cold conditions (2008 to 2013). [Source: Yury Zuenko; Zuenko and Basyuk 2017: Year-to-year changes of water temperature anomaly at the sea surface and at 50 m depth averaged within the biostatistical area № 5 and the Bering Sea ice cover in January-April 1998 – 2015]. These trends provide contrast that contribute insight into how this system might respond to climate change and/or persistent warming.

These shifts in environmental conditions also influence fisheries exploitation. The Russian pollock fishery in the Bering Sea is centered primarily on the feeding grounds at Cape Navarin in the summer-fall season. Seasonal variation of mean CPUE for the pollock fishery in the Navarin area showed its earlier peak (May-July) in 2014 (warm year) and late peak (July-September) in 2013 (cold year) [source: Zuenko and Basyuk 2017]. Long-term dynamics of catch have considerable year-to-year variations with high level in the 1980s, and the late 1990s to early 2000s; low level in the early to mid 1990s and the 2010s). [source: Dynamics of the Russian pollock fishery effort ( $10^3$  days-vessel) and annual catch ( $10^3$  t) in the western Bering Sea, Navarin, Zuenko and Basyuk 2017].

Understanding trends in recruitment, abundance, distribution, movement, life history, and stock structure require further research and benefit from US-Russian collaboration, particularly in the context of environmental change and species response, stock distribution and integrity and important dynamics related to the complex life history of important groundfish species in this region (Figure R14-64).

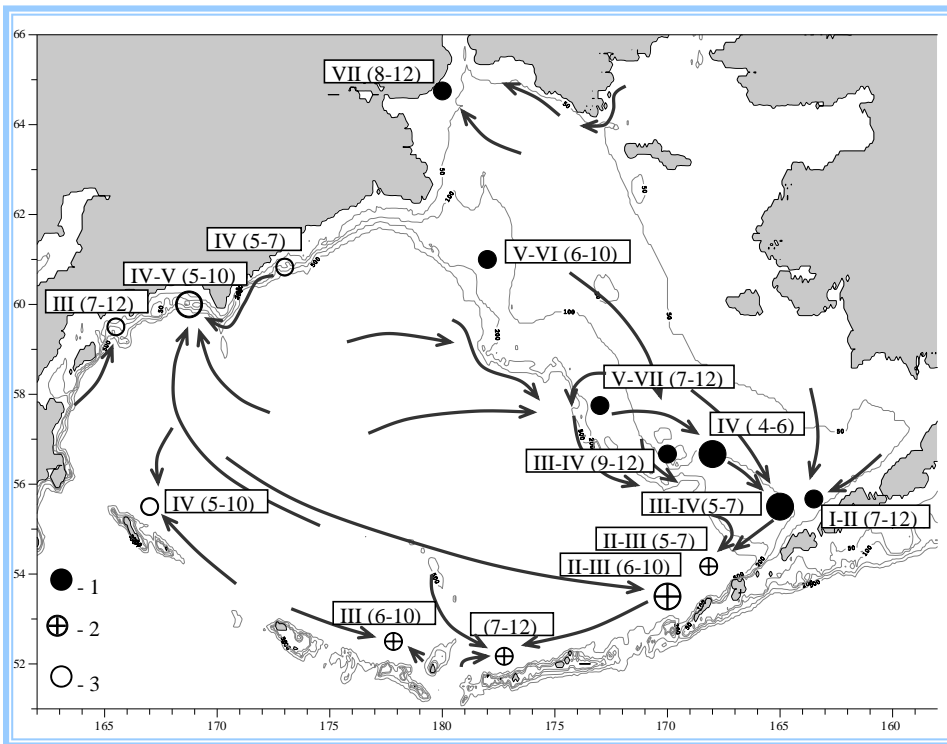


Figure R14-64. Distribution of spawning concentrations and general direction of pre-spawning migrations of the Bering Sea pollock (1 - eastern and northwestern Bering Sea, 2 - area off Aleutian Islands, 3 - western Bering Sea). Months of most intensive spawning indicated by Roman numerals and range of predominant ages of spawning pollock by Arabic numerals. Diameter of the circles reflects relative density of spawning concentrations [source: M. Stepanenko, PICES Annual Science Meeting]

US-Russian collaboration in the area of salmon research and management has also provided important advances. The figures below (Figure R14-65, Figure R14-66) represent salmonid catches in the western Bering Sea and Chukchi Sea. The overall annual catch from the Chukchi Sea fluctuates between 36,000 t and 500,000 t and consist predominantly of salmonids.

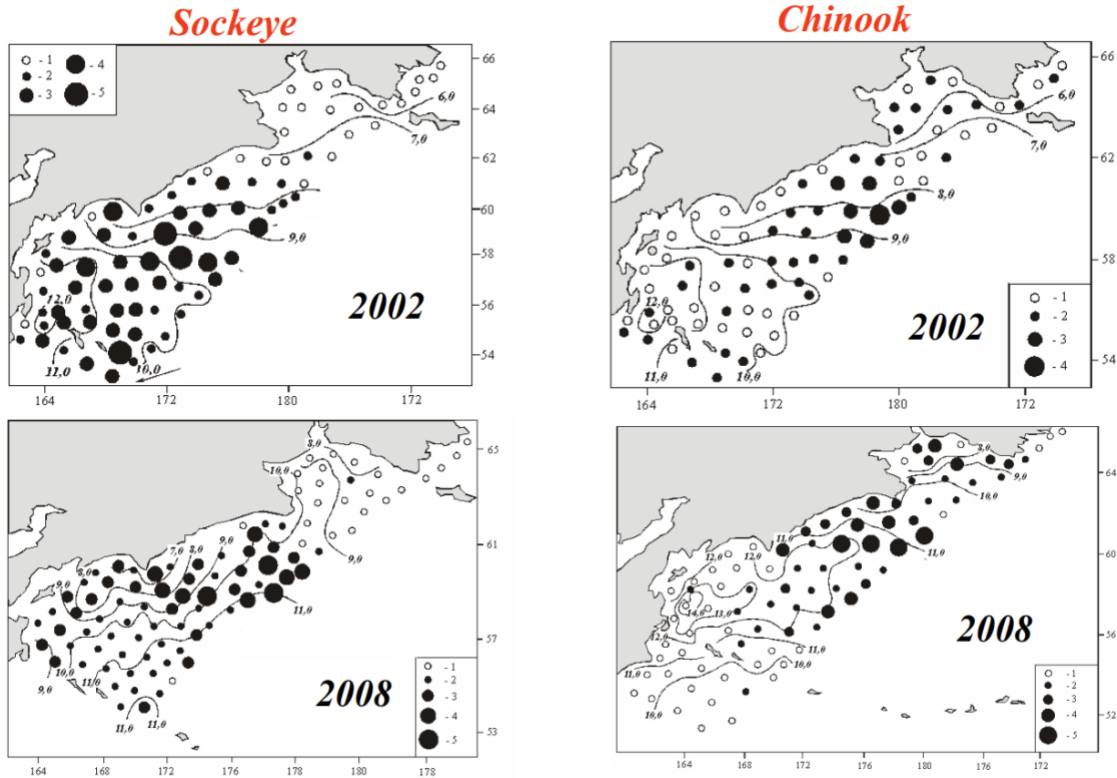


Figure R14-65. Catches of Pacific salmon in the western Bering Sea in 2002 [source Khen et al. 2013]

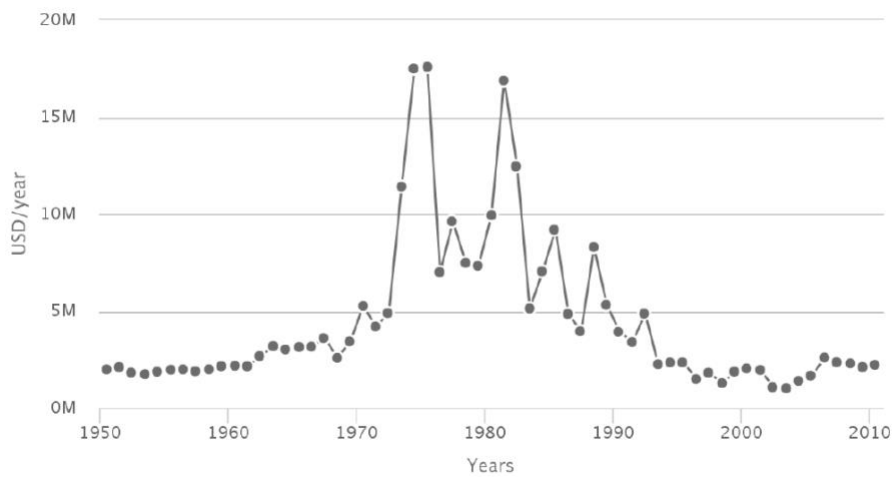


Figure R14-66. Long-term change in annual fisheries catch (by USD) in the Chukchi Sea 1950-2011 [Source: United Nations Transboundary Water Assessment Program 2015; 24<sup>th</sup> Session of the US-Russia Intergovernmental Consultative Committee (ICC) on Fisheries]

## 9. Marine birds

The Pacific Arctic is an important area for marine birds. Both planktivorous and piscivorous birds nest in the NBS and Chukchi Sea with planktivorous auklets the most numerous. Examining distributions within US waters, northern fulmars are predominant in the central offshore area, murres and puffins and auklets dominant in the central area between Seward Peninsula and St Lawrence Island and kittiwakes distributed throughout the region (Figure R14-67). Densities fluctuate dramatically throughout the year, with extremely high densities in the open water season in summer and fall (Figure R14-68).

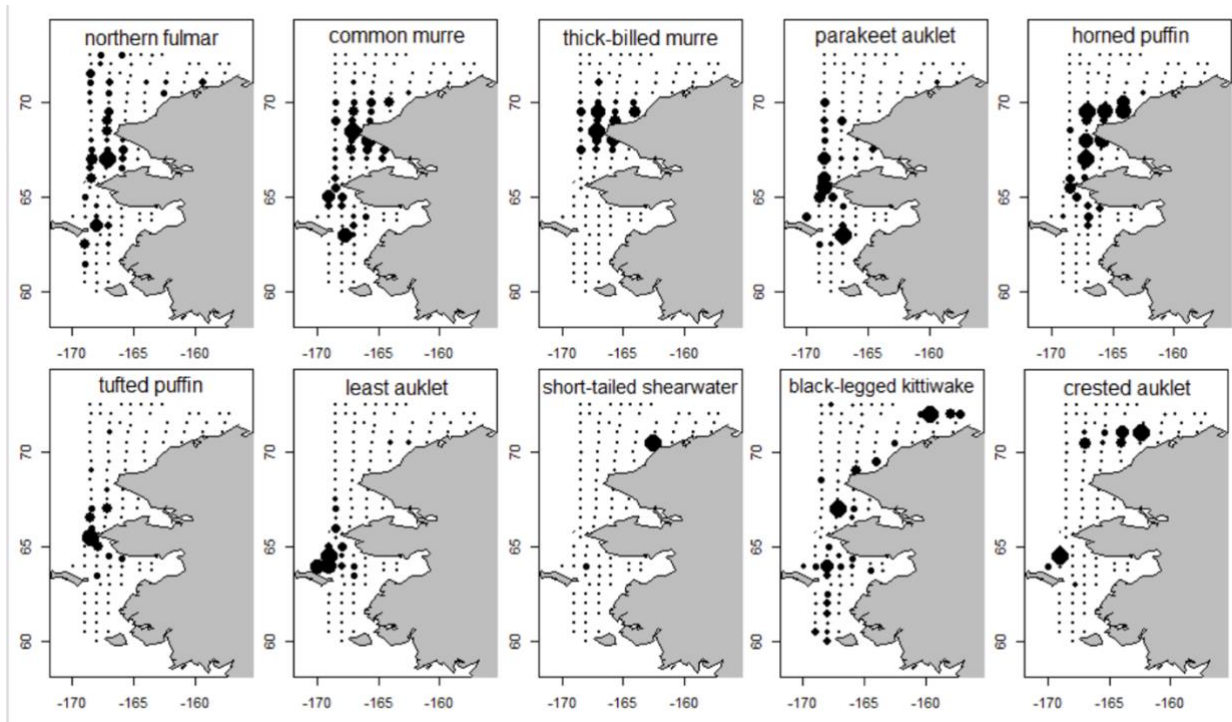


Figure R14-67. Distribution and relative abundance for major pelagic seabird species in the eastern northern Bering Sea and eastern southern Chukchi Sea sampled in 2010 and 2012 [source Sigler et al. 2017].

Highest total densities for seabirds throughout the Bering Sea are in the Chirikov Basin (38 individuals km<sup>-2</sup>, Sigler et al. 2011). Here auklets from King Island, St Lawrence Island and the Russian coast forage at oceanographic fronts and at the pycnocline where copepods are concentrated (Hunt et al. 1990) and access plankton rich AW (Piatt 2003).

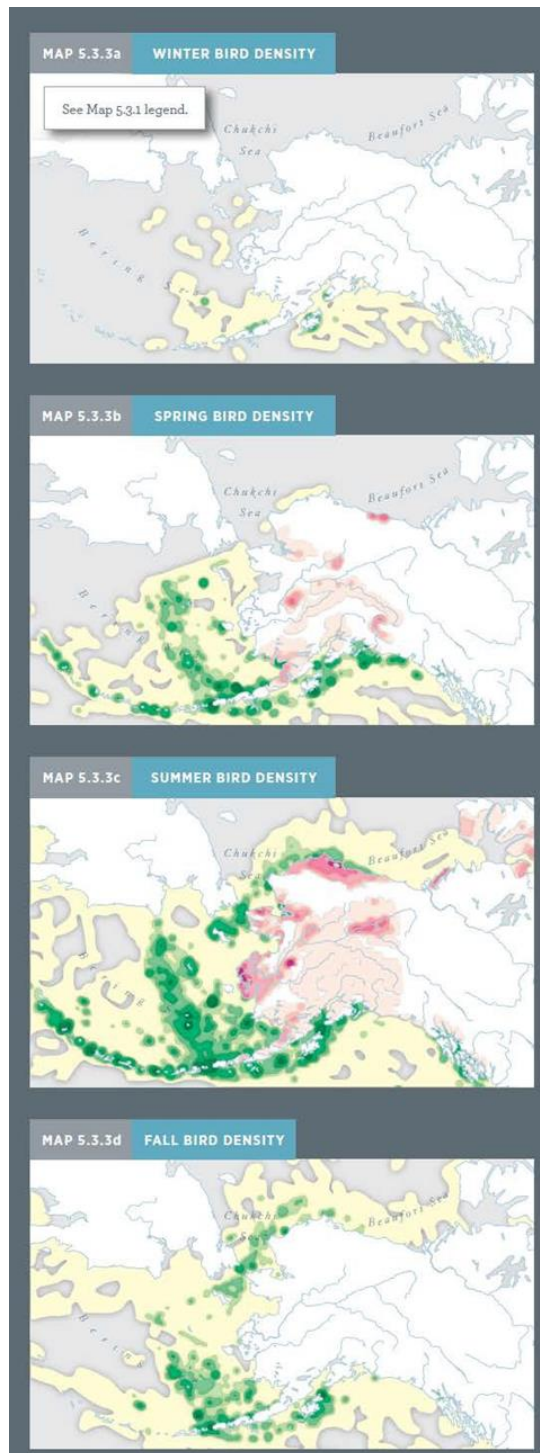


Figure R14-68. Marine bird concentration by season (three-month mean density). Marine birds are relatively rare during the winter period of ice cover (December-February) but return to the region in spring (March-May) with high concentrations in summer and fall, particularly in the areas of intense oceanographic mixing in Chirikov Basin and Bering Strait. Source: Audubon Alaska Atlas

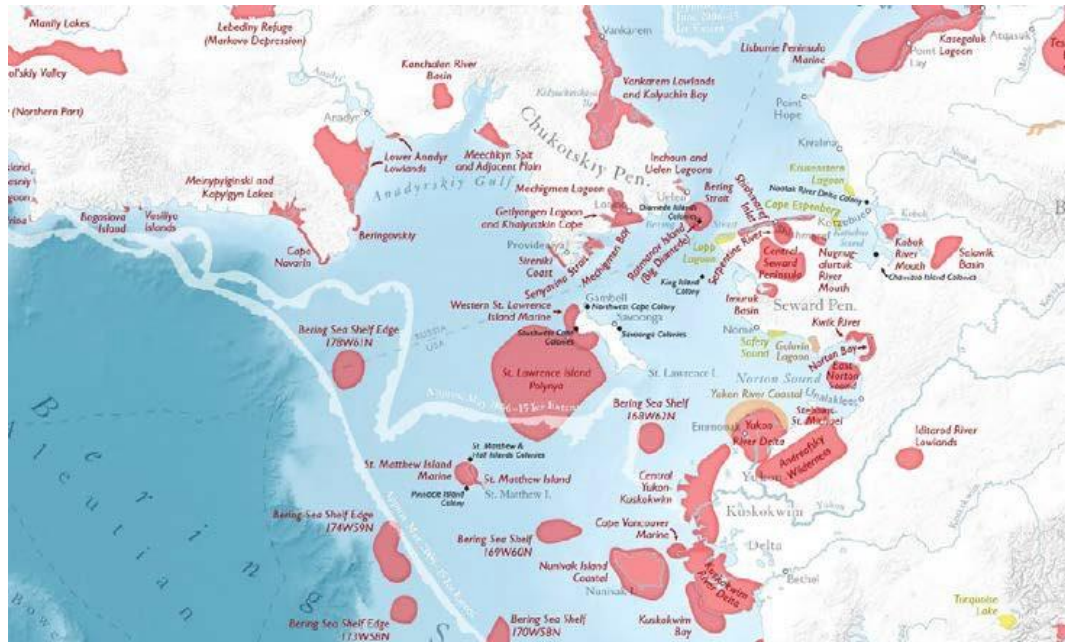


Figure R14-69. Important bird areas in NBS; Source: Audubon Alaska Atlas

The major species of marine birds in the northern Bering Sea include, eiders, loons, phalaropes, kittiwakes, murres, auklets and gulls, petrels, shearwaters and fulmars. The important areas of sea birds in NBS are shown in R14-69 and R14-70. Shearwaters are one of the most abundant pelagic birds in the North Pacific (Shuntov 2009) and migrate to the northern Bering Sea in late April and early May, spending winter in the southern hemisphere. The black-legged Kittiwake (*Rissa tridactyla*), small, pelagic gulls are also in this region, ranging throughout the far northern latitudes of the Arctic and subarctic with a circumpolar distribution (Hatch et al. 2009). The Common Murre (*Uria aalge*) and Thick-billed Murre (*U. lomvia*) are among the most abundant seabirds in the Northern Hemisphere (Gaston and Hipfner 2000), including the NBS. Several species of auklet Parakeet Auklet (*Aethia psittacula*), Crested Auklet (*A. cristatella*), and Least Auklet (*A. pusilla*) also inhabit this region. Red-necked and Red Phalaropes (*Phalaropus lobatus* and *P. fulicarius*) are planktivorous feeders, often targeting upwelling areas, thermal gradients and the ice edges (Warnock et al. 2001). Eiders, the most northern nesting marine birds in the world are also in this region, usually distributed within a few hundred miles of the sea-ice edge and within close range (15 km) of shore (Oppel et al. 2009; Oppel et al. 2011). Eiders are among the deepest diving (30 m) of the sea ducks, foraging for mollusks and crustaceans from the ocean floor. In winter, the global population of 350,000 Spectacled Eiders resides in the polynya south of St. Lawrence Island in the northern Bering Sea.



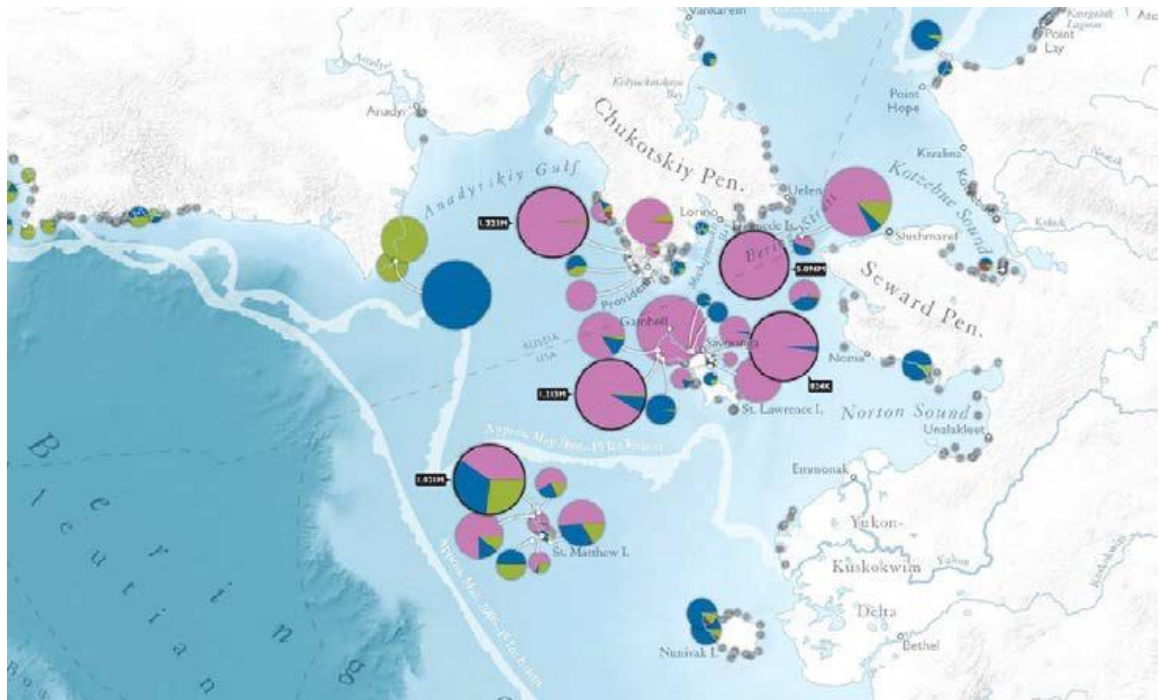


Figure R14-70. Seabirds breeding colonies in NBS; Source: Audubon Alaska Atlas

In 2017, 23 seabird species were observed on cruises on the T/S Oshoro-maru; 98% of the birds were short-tailed shearwater, common and thick billed murres, least and crested and parakeet auklets, and fork tailed storm petrel. The most abundant was the Northern Fulmar. Analyses of distribution patterns suggest that species composition is associated with water mass and prey density (Figure R14-71). Piscivorous divers were widely distributed, while planktivorous divers were associated with AW and high concentrations of large oceanic copepods (Nishizawa et al. 2020).

Since 2016, several mass mortality events have been documented in the Bering and Chukchi Seas. These events have been associated with warm water anomalies and lack of winter sea ice and are notable in their broad geographic area and extended duration. In the NBS, carcass reports have been collected by observers on ship-based surveys, coastal community members (e.g., Kawerak, LEO network), citizen science surveys (COASST) and agency (USGS, USFWS, USNPS) surveys. All data have been collected by the USFWS and archived through the COASST program (Figure R14-72). In 2017, approximately 1,600 marine bird carcasses were reported in the NBS between June and September, predominantly Northern Fulmars (NOFU) and shearwaters (). Mortality was recorded on St Matthews Island, St Lawrence Island, Norton Sound, the Seward Peninsula, Chukotka Peninsula, and Bering Strait. In 2018, mass mortality events were recorded (approximately 1,000 marine birds) in the NBS between May and August, predominantly alcids (95%) including Common (COMU) and Thick-billed Murres (TBMU), and auklets. Mortality was recorded in Norton Sound, St Lawrence Island, Chirikov Basin, Seward Peninsula and Bering Strait.

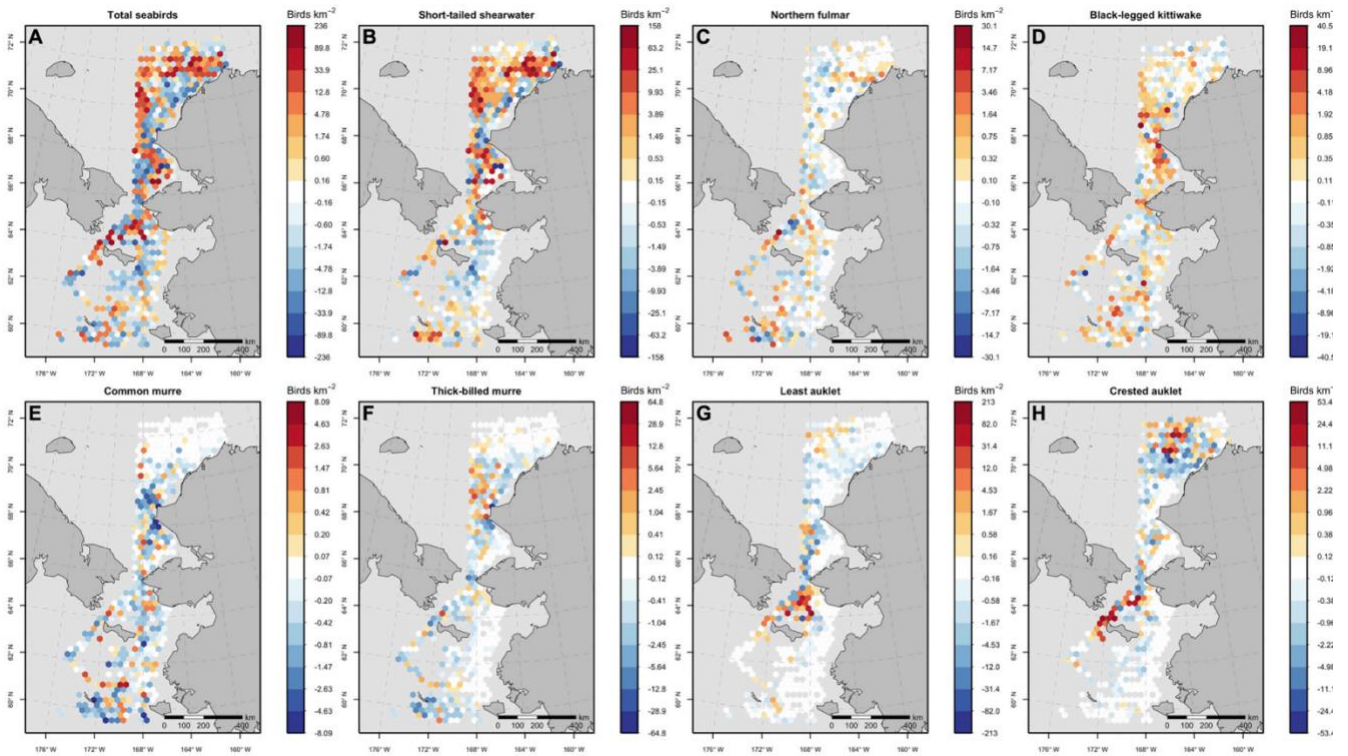


Figure R14-71. Increases (red) and decreases (blue) in densities of total seabirds and seven focal species in 2017–2019, compared to 2007–2016. Mean densities calculated per 30-km grid cell for cells surveyed in both time periods [Source: Kuletz et al. 2020]

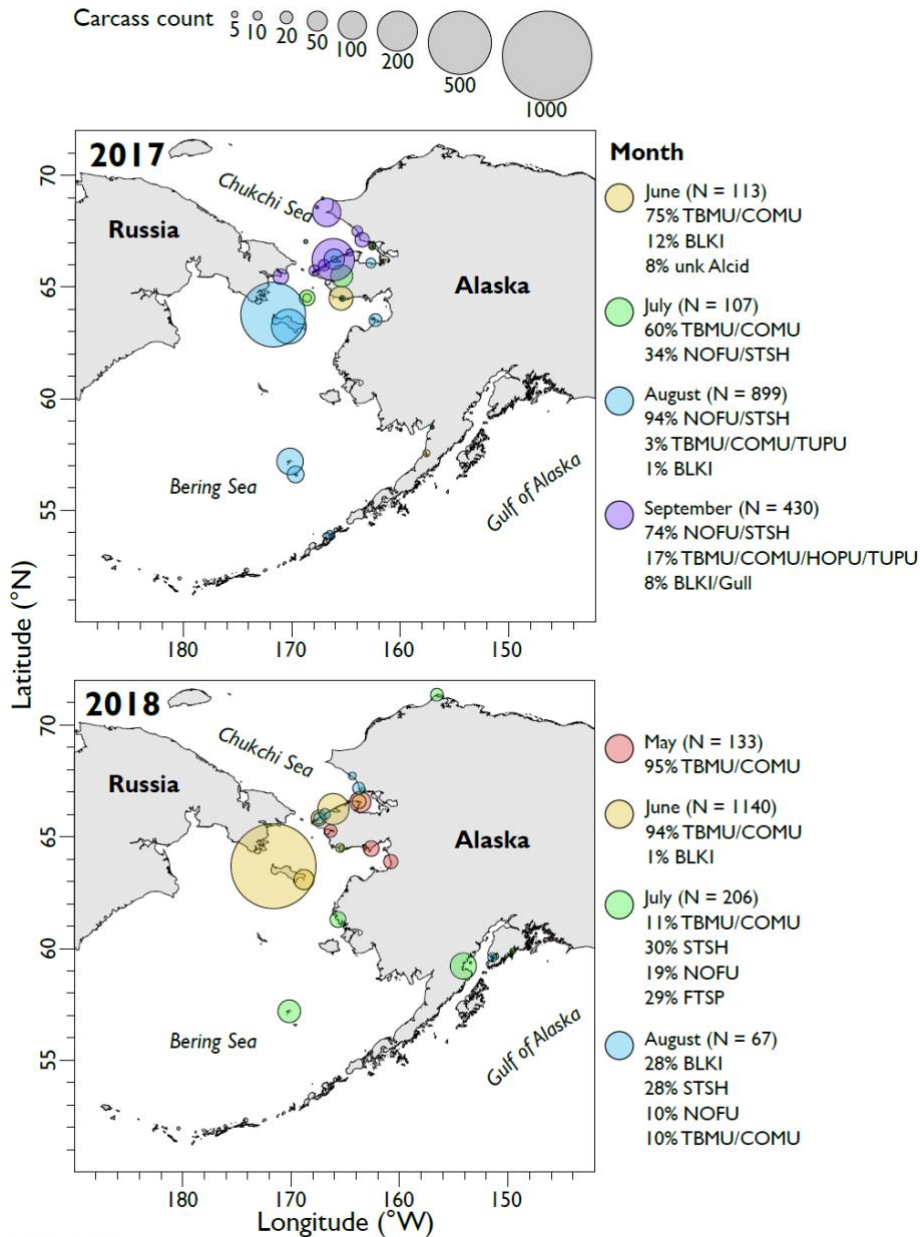


Figure R14-72 Seabird carcass reports by month (colors) and location, with circle size corresponding to scaled carcass count. Species listed include black-legged kittiwakes (BLKI), short-tailed shearwaters (STSH), tufted puffins (TUPU), and horned puffins (HOPU); for other species abbreviations see preceding text. Data sources as described in text. Maps produced by COASST.

## 10. Marine mammals

The high levels of standing stocks of benthic biomass in the NBS (Grebmeier et al. 2006, 2015) support high abundance of Arctic marine mammals, particularly feeding aggregations of benthivores, including Pacific walrus (*Odobenus rosmarus divergens*; Figure R14-73), gray whales (*Eschrichtius robustus*), and bearded seals (Figure R14-74) (*Erignathus barbatus*; Jay et al. 2012 Sheffield et al. 2001; Moore et al. 2003; Feder et al. 2005). Ice-associated seals, including ribbon, ringed, and spotted (Figure R14-74), as well as beluga,

and bowhead whales exploit pelagic resources and migrate seasonally with the sea ice (Simpkins et al. 2003). These species collectively provide higher regional predation pressure than fishes (Feder and Jewett 1978; Grebmeier et al. 1995; Lovvorn et al. 2003; Moore et al. 2003; Simpkins et al. 2003).

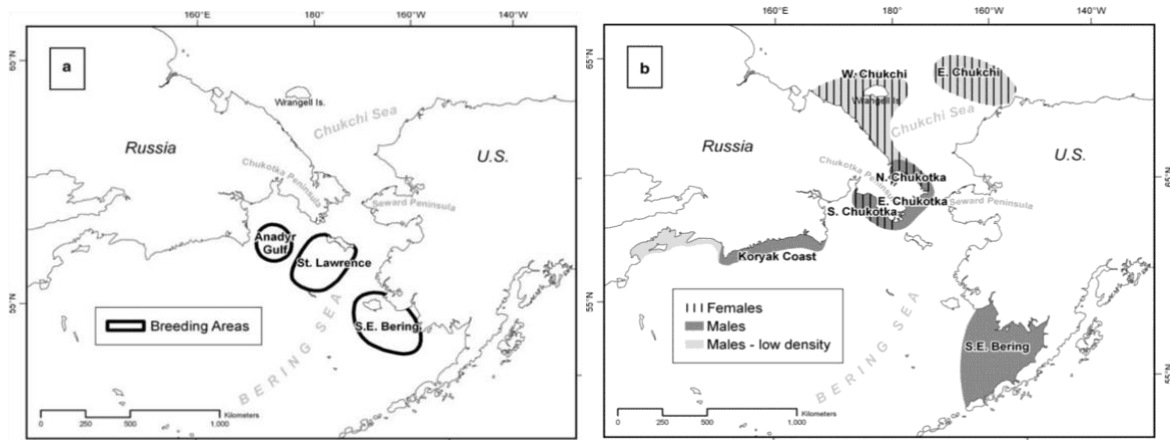


Figure R14-73. Important areas for walrus breeding (left) and foraging (right) in Bering Sea and Chukchi Sea, November-April [Source Jay et al. 2008]

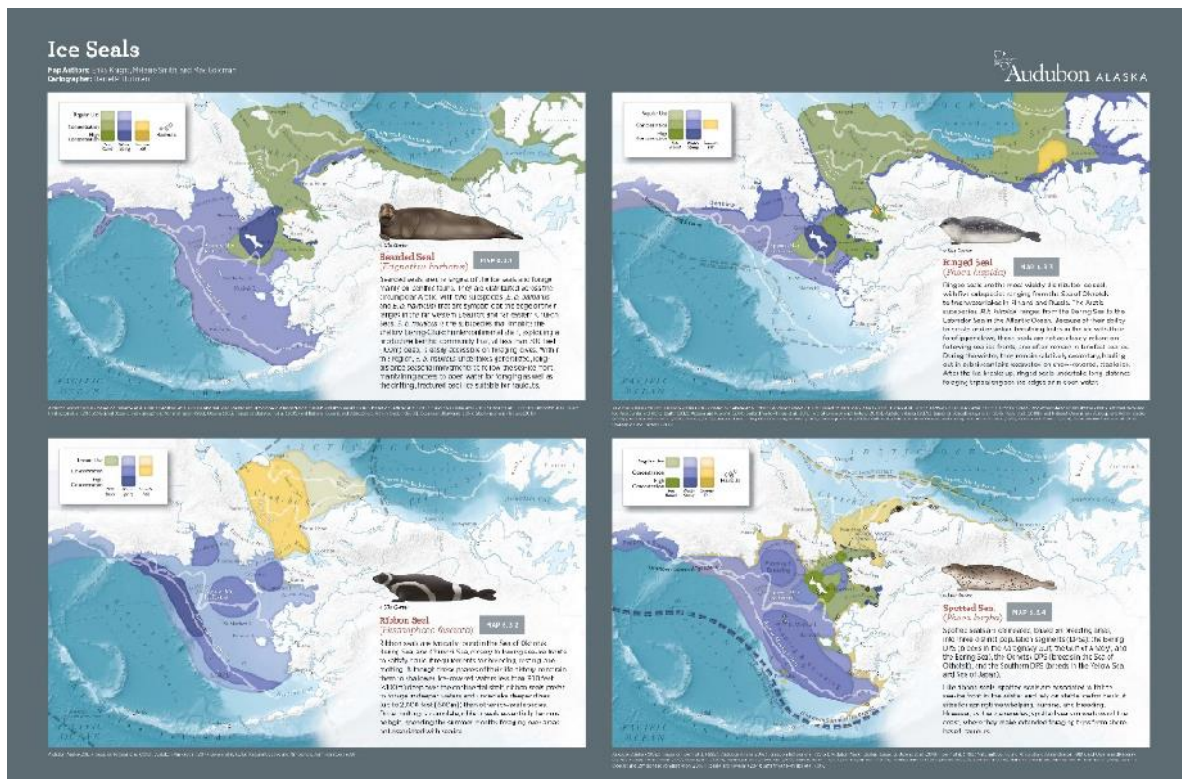


Figure R14-74. Distribution of ice seals in the NBS [Source Audubon Alaska Atlas]

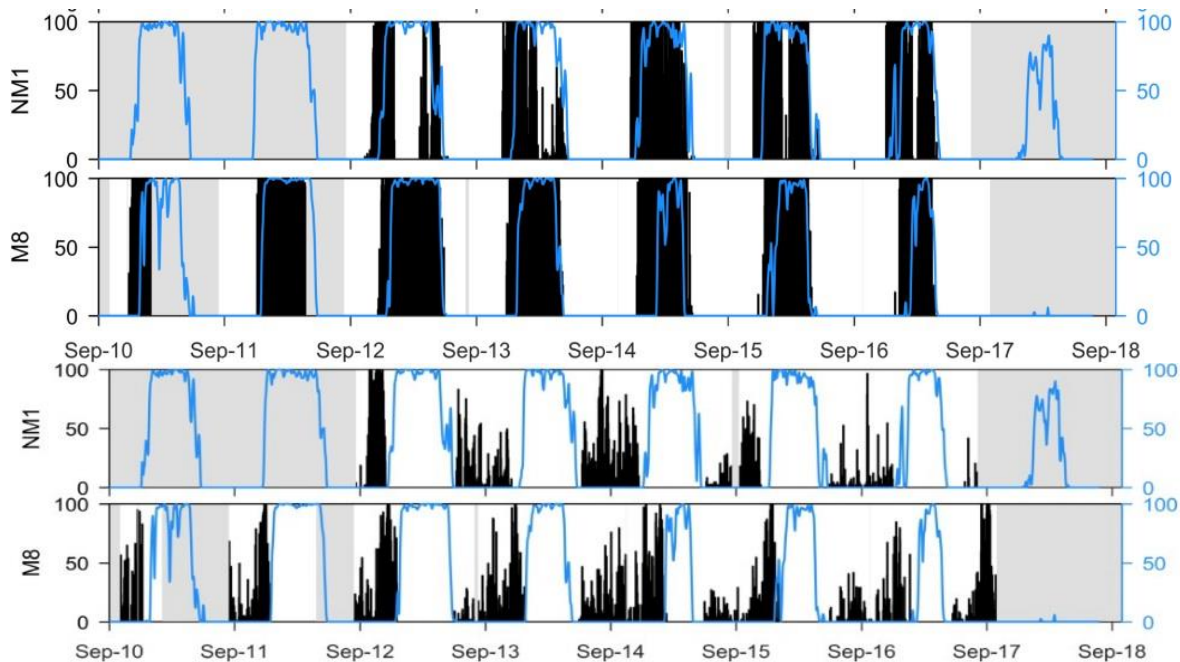


Figure R14-75. Passive acoustic mooring soundings at two moorings – M8 (central NBS) and NM1 (Bering Strait) for an Arctic (bowhead whale, top plots) and subarctic (humpback whale, bottom plots) species in September. Blue density plots indicate ice cover and black lines indicate number of soundings per species [source: K. Stafford].

More recently subarctic mammals seem to be expanding into this region more frequently and remaining for longer periods of time. Hydrophones are available on several moorings in the region. Passive acoustics moorings stationed in the middle of the NBS shelf (M8) and immediately south of Bering Strait (NM1), compare annual trends in sea ice (blue) and recorded whale soundings for Bowhead whales (Fig. R14-75), an Arctic species that summer in the Beaufort Sea and winters in the Bering Sea and Humpback whales, a subarctic species that summers in the Bering Sea and winters in the tropics.

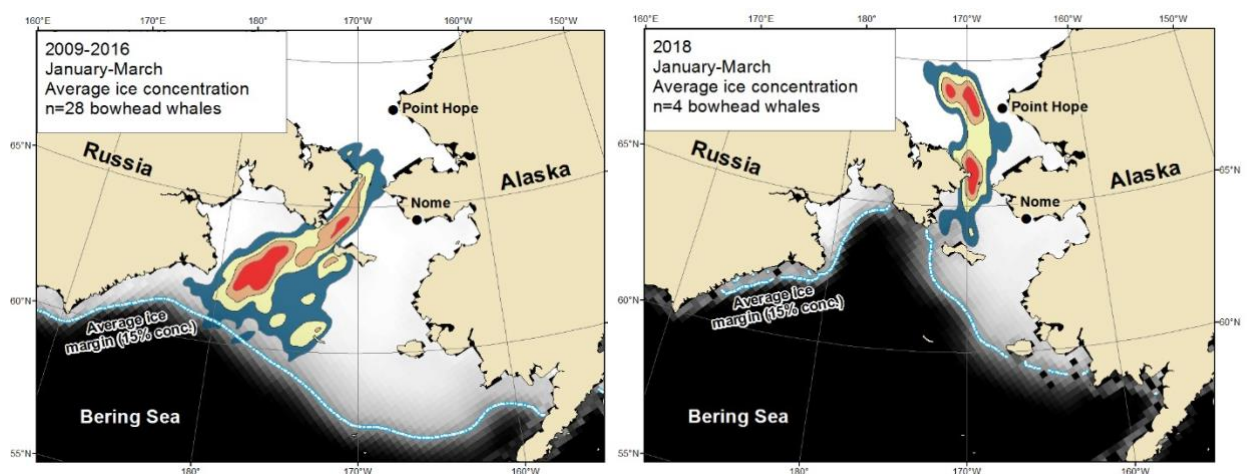


Figure R14-76. Northward shifts in bowhead whale distributions, 2009-2016 compared to 2018 [Source: Citta et al. 2019]

The time series (2009-2018) suggest increased presence of subarctic species and decreased presence (or earlier northern migration) of Arctic species, e.g. Bowhead whale (Citta et al. 2019) (Figure R14-76). Other recordings suggest presence of beluga and bowhead whales in the winter and increasing numbers of humpback, fin and killer whales (Moore et al. 2022; Stafford et al. 2022).

## Acronyms

AW	Anadyr Water
ACW	Alaska Coastal Water
BSW	Bering Shelf Water
ACC	Alaska Coastal Current
NBS	Northern Bering Sea
NBSS	North Bering Sea Shelf
SEBS	Southeastern Bering Sea
WBS	Western Bering Sea
BSB	Bering Sea Basin
NPRB	North Pacific Research Board
PICES	North Pacific Marine Science Organization
NPS	National Park Service,
NPPSD	North Pacific Pelagic Seabird Database
PRISM	Program for Regional and International Shorebird Monitoring
USGS	US Geological Survey

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