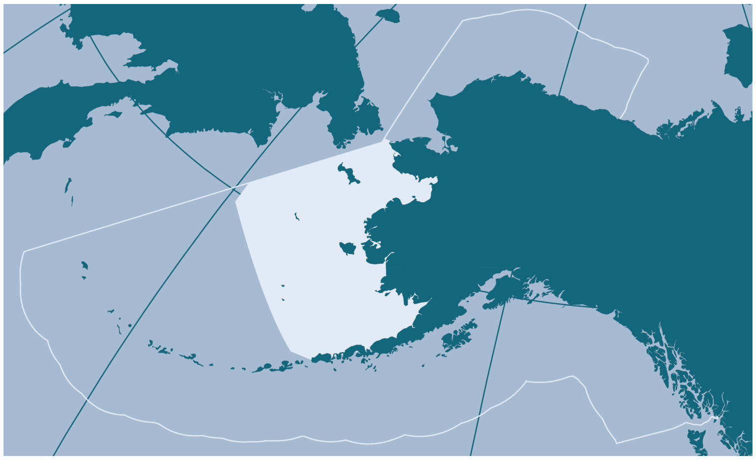
Ecosystem Status Report 2021
Eastern Bering Sea



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2021 Contributing Partners

Purpose of the Ecosystem Status Reports

This document is intended to provide the North Pacific Fishery Management Council, including its Scientific and Statistical Committee (SSC) and Advisory Panel (AP), with information on ecosystem status and trends. This information provides context for the SSC's acceptable biological catch (ABC) and overfishing limit (OFL) recommendations, as well as the Council's final total allowable catch (TAC) determination for groundfish and crab. It follows the same annual schedule and review process as groundfish stock assessments, and is made available to the Council at the annual December meeting when Alaska's federal groundfish harvest recommendations are finalized.

Ecosystem Status Reports (ESRs) include assessments based on ecosystem indicators that reflect the current status and trends of ecosystem components, which range from physical oceanography to biology and human dimensions. Many indicators are based on data collected from NOAA's Alaska Fishery Science Center surveys. All are developed by, and include contributions from, scientists and fishery managers at NOAA, other U.S. federal and state agencies, academic institutions, tribes, nonprofits, and other sources. The ecosystem information in this report will be integrated into the annual harvest recommendations through inclusion in stock assessment-specific risk tables (Dorn and Zador, 2020), presentations to the Groundfish and Crab plan teams in annual September and November meetings, presentations to the Council in their annual October and December meetings, and submission of the final report to the Council in December.

The SSC is the primary audience for this report, as the final ABCs are determined by the SSC, based on biological and environmental scientific information through the stock assessment and Tier process[1],[2]. TACs may be set lower than the ABCs due to biological and socioeconomic information. Thus, the ESRs are also presented to the AP and Council to provide ecosystem context to inform TAC and as well as other Council decisions. Additional background can be found in the Appendix (p. 231).

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[1] `https://www.npfmc.org/wp-content/PDFdocuments/fmp/GOA/GOAfmp.pdf`

[2] `https://www.npfmc.org/wp-content/PDFdocuments/fmp/BSAI/BSAIfmp.pdf`

Eastern Bering Sea 2021 Report Card

For more information on individual Report Card indicators, please see 'Description of the Report Card indicators' (p. 246). For more information on the methods for plotting the Report Card indicators, please see 'Methods Description for the Report Card Indicators' (p. 249).
* indicates Report Card information updated with 2021 data.

- * The **North Pacific Index (NPI)** effectively represents the state of the Aleutian Low. Above (below) average winter (November–March) NPI values imply a weak (strong) Aleutian Low and generally calmer (stormier) conditions. The NPI was above average during the winter of 2020–2021 before returning to near average again in summer 2021.
- * The mean **sea ice extent** across the Bering Sea (ice year is defined as 1 August to 31 July; western and eastern) exhibited no long term trend, although a **steep decline in ice extent** was observed from 2012 (highest extent on record) to 2018 (lowest extent on record). Sea ice extent increased from 2018 to present, with the 2020–2021 daily mean extent of 268,748 km^2 being **near the long-term mean**. Seasonal sea ice extent has implications, for example, to the cold pool, spring bloom strength and timing, and bottom-up productivity.
- * The areal **extent of the cold pool** in the eastern Bering Sea (EBS), as measured during the bottom trawl survey (June–Aug; including strata 82 and 90), has increased since 2018, yet the 2021 extent (58,975 km^2) was **the 4th lowest on record** and remained more than one standard deviation below the grand mean of the time series.
- * The biomass of **aggregate forage fish** (i.e., eulachon, Pacific capelin, sand lance species, rainbow smelt, Pacific sandfish, and a group of minor smelt species) declined steeply between 2015 and 2017, and remained **below their long term mean in 2021**.
- * The biomass of **motile epifauna** measured during the bottom trawl survey (June–Aug) peaked in 2017 and remained **above their long term mean in 2021**. Trends in motile epifauna biomass **indicate benthic productivity**, although individual species and/or taxa may reflect varying time scales of productivity. Collectively, brittle stars, sea stars, and other echinoderms account for more than 50% of the biomass in this guild. The recent (2016–2021) mean biomasses for all three of these functional groups are well above their long term means. The current mean biomasses for all crab functional groups, including hermit crab, king crab, tanner crab, and snow crab are all below their long term means.

- * The biomass of **benthic foragers** measured during the bottom trawl survey (June–Aug) is at the **lowest level over the times series**, more than one and a half standard deviations below 1982–2021 levels. Trends in benthic forager biomass are variable over the time series and **indirectly indicate availability of infauna** (i.e., prey of these species). Dominant species in the benthic foragers guild include Yellowfin sole and Northern rock sole, both of which are below their long-term means in 2021.

- * The biomass of **pelagic foragers** measured during the bottom trawl survey (June–Aug) was generally stable from 2016 to 2019, but dropped in 2021 to their **second lowest value over the time series** (1982–2021). The trend in the pelagic forager guild is largely driven by Walleye pollock which, on average, account for more than 66% of the biomass in this guild. Trends in pelagic forager biomass indicate availability of forage fish (i.e., prey to upper trophic levels) as well as **predator abundance** within the ecosystem. In 2021, the survey index for pollock was the third lowest over the time series. With the exception of Pacific herring, the 2021 index for all other species and functional groups in the pelagic forager guild were below their long term means.

- * The biomass of **apex predators** measured during the bottom trawl survey (June–Aug) was **within normal limits** in 2021. Trends in apex predator biomass reflect relative **predation pressure on zooplankton and juvenile fishes**. The trend in the apex predator guild is largely driven by Pacific cod, whose recent (2016–2021) mean biomass is below their long term mean (1982–2021). In contrast, the current mean biomass of Arrowtooth flounder, Sablefish, and Alaska skate are all above their long-term means.

- * Seafloor **habitat impacted by trawls** (pelagic and non-pelagic trawl, longline, and pot) as of December 2020 showed interactions have remained below the disturbance levels previous to the implementation of sweep modifications on non-pelagic trawl gear in 2009. However, both pelagic and non-pelagic trawling effort has been at or above average since 2013. This increase, as well as the inclusion of 2003–2014 unobserved fishing events (see p. 202), has resulted in an **increase to habitat disturbance**. Fishing gear can affect habitat used by a fish species for the processes of spawning, breeding, feeding, or growth to maturity.

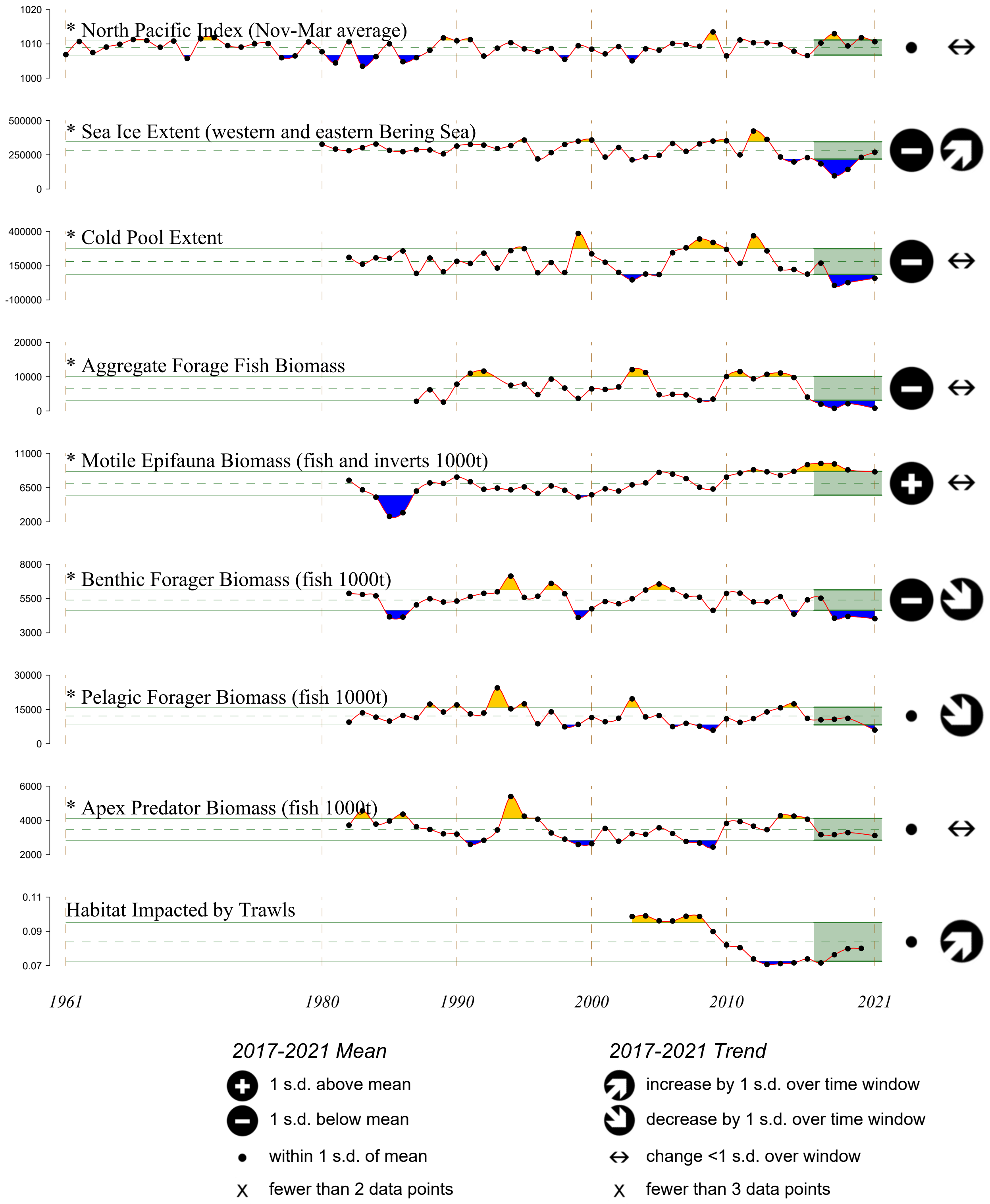

Figure 1: 2021 Eastern Bering Sea report card; see text for indicator descriptions.
* indicates time series updated with 2021 data.

Ecosystem Assessment

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Last updated: November 2021

Current Conditions: 2021

During 2021, continued COVID-related data loss impacted research efforts and had a moderate impact on information used in this report. Examples of data loss include survey cancellations, lab processing delays due to limited building access over the past year, and data processing delays due to survey logistics. Similar to 2020, NOAA scientists, state/university partners, tribal governments, and coastal community members provided contributions to mitigate these losses. Nevertheless, these interruptions to data acquisition in 2020 and 2021 provide evidence of the increase in uncertainty when data streams are interrupted and of the importance of a robust, uninterrupted data acquisition program.

It takes Two to Tango: Sea-ice dynamics are driven by both temperature and winds.
Protracted Warmth
Beginning in approximately 2014, the eastern Bering Sea (EBS) entered a warm phase of unprecedented duration (Figures 25 and 30). The EBS remains in this warm phase, though to a lesser degree compared to the extreme years of 2018 and 2019. Sea-ice formation in fall of 2020 was delayed due to residual warmth in the system, which has become the 'new normal' during this protracted warm phase. Delayed freeze-up leads to shortened ice seasons that has impacts on ice thickness, ice algae, and thermal modulation as well as impacts to transportation and subsistence activities. While the areal extent of sea ice over the Bering Sea (western and eastern) in winter 2020-2021 was closer to the pre-2014 levels than at any point in the last 7 years (Report Card, Figure 1), over the eastern shelf the ice thickness differed between the northern (thicker ice) and southern (thinner/no ice) regions due to opposing prevailing winds (Physical Environment Synthesis, p. 37).

Winds
Tracking the seasonal progression and retreat of sea ice over the shelf highlights the interactive roles of water temperature (i.e., residual warmth in the system) and winds. Atmospheric conditions can have a strong influence on sea surface temperature and ice formation. Wind patterns in February 2021 highlight the decoupling of ecosystem dynamics between the northern and southern Bering

Sea. Over the northern shelf, cold northerly winds prevailed and contributed to ice formation and stability/thickness. Over the southern shelf, warm southerly winds prevailed that contributed to reduced sea ice (Figure 20).

Bottom temperatures and Cold Pool
Summer bottom temperatures varied spatially over the shelf. The northern Bering Sea (NBS) shelf bottom waters were very warm in the inner domain with an area of cold bottom waters over the middle domain to the southwest of St. Lawrence Island. The southern shelf had moderately warm bottom water conditions (Figure 35). The summer 2021 cold pool remained significantly reduced in area and its southern boundary was shifted northwestward. The areal extent of the cold pool has increased since 2018, yet the 2021 extent was the 4th lowest on record and remains more than one standard deviation below the mean (Report Card, Figure 1).

Ecosystem Impacts
Northern Bering Sea
Following two winters (2017/2018 and 2018/2019) of little sea ice in the NBS, and two summers (2018 and 2019) of reduced cold pool extent, ecosystem-wide shifts were observed. NOAA bottom trawl surveys indicate northward shifts in the distribution of groundfish species since 2017. Concerns about the food web dynamics and carrying capacity of the NBS have existed since 2018, highlighted by the gray whale Unusual Mortality Event and short-tailed shearwater mass mortality event. Lagged (delayed) impacts of poor feeding conditions experienced during 2018 may partially explain these mortality events. Both species feed in the Bering Sea during summer; gray whales feed in the northern Bering and Chukchi seas and are benthic feeders (e.g., amphipods, crab larvae) while shearwaters are planktivorous (e.g., euphausiids). Both species embark on long migrations south for breeding. The 2019 mortality events may reflect 2018 feeding conditions in the Bering Sea, conditions experienced during the breeding season, or lack of available prey to complete the migration to the Bering Sea in 2019.

In 2021, multiple ecosystem ‘red flags’ occurred in the NBS: (1) crab population declines (p. 145), (2) salmon run failures in the Arctic-Yukon-Kuskokwim region (p. 26), and (3) seabird die-offs combined with low colony attendance and poor reproductive success (p. 147). In addition, (4) results from the 2021 NOAA bottom trawl survey demonstrate a substantial drop in total CPUE in the NBS between 2019 and 2021 that reflected large decreases in all of the dominant species, including pollock (p. 162). Although the collapses are coincident, the underlying mechanisms, or suite of mechanisms, resulting in the collapses reflect cumulative dynamics over the last few years. The mechanisms are not fully understood, but a common thread in these collapses is the marine environment in the NBS, which underwent an abrupt and dramatic change starting in late 2017. A brief discussion of possible mechanisms is provided below under “What Happened in the Northern Bering Sea?”.

In 2018, more than 50% of Pacific cod biomass in the EBS was found over the northern portion of the shelf. The northward movement of Pacific cod, among other stocks, into the NBS altered the food web through predation pressure as well as fishery dynamics. For example, the impact of Pacific cod predation on snow crab is one hypothesis that may partially explain the decline in snow crab observed in 2021 (Szuwalski (2021)). It is worth noting here that, at this time, there is no evidence that ocean acidification can be linked to recent declines in surveyed snow crab and red king crab populations (see p. 179 for more on ocean acidification).

Corresponding northward shifts in fishing vessel activity and an increased harvest of Pacific cod in the northern regulatory areas occurred from 2016 through 2020. As the fishing fleet shifted northward following the fish, patterns in groundfish discards also shifted. Fixed gear discards in the NBS trended upward from 2016–2018 as some vessels targeting Pacific cod moved their fishing activity northward; these increases were offset by declines in discard biomass in the southern portion (p. 190). Notably, the first reported interaction between fishing vessels from the BSAI groundfish fishery with threatened spectacled eider may be a direct result of this abrupt ecological change (p. 196), as fishing vessels increase in areas near spectacled eider designated critical habitat.

Total CPUE of all fish and major invertebrate taxa sampled during the 2021 NOAA bottom trawl survey decreased in both the northern and southern portions of the survey (p. 162). In the NBS, CPUE increased between 2010 and 2019, but decreased substantially between 2019 and 2021 (Figure 95). Total CPUE in the southern portion decreased between 2019 and 2021 to the lowest level since 2009. The center of gravity for the groundfish community (p. 168) shifted to the north and into shallower water between 2014–2019 with a substantial shift to the northwest in 2016. The groundfish community distribution shifted slightly to the south in 2017, but remained near its northern maximum through 2019. Between 2019 and 2021, the mean distribution across species shifted back to the southeast again (Figure 102).

What Happened in the Northern Bering Sea?

The coincident collapses in the NBS reflect conditions experienced in the marine environment over the last few years. Researchers will continue to investigate possible mechanistic explanations, but some linkages across these collapses may help inform the need for near-term precautionary management decisions. The current protracted warm phase has resulted in cumulative impacts of increased thermal exposure and metabolic demands. Such multi-year stress means population declines observed in 2021 may be the result of impacts occurring over previous years. For example, the lack of a cold pool in 2018 and 2019, and subsequent northward shift of Pacific cod into the NBS, have been proposed as explanations for the snow crab decline observed in 2021[3].

Similarly, salmon run failures in the Arctic-Yukon-Kuskokwim Region included Chinook, chum, and coho salmon (p. 26). The 2021 salmon runs were impacted by environmental conditions over multiple years based on life history strategies, including ocean years 2016–2020 for Chinook salmon, 2017–2020 for chum salmon, and 2020 for coho salmon (Figure 5). Several juvenile salmon abundance indices can be used to forecast future run sizes. Juvenile Chinook salmon abundance in the NBS was below average in 2021 and has been below average since 2017 (p. 117). The juvenile pink salmon index, which is generally higher in warmer years, decreased dramatically in 2021 (p. 119). A new indicator based on juvenile chum salmon may be used to forecast adult returns. However, uncertainty in the current juvenile to adult relationship precludes reliable forecasts until additional years of returns are observed (p. 121). In contrast, the 2021 Bristol Bay inshore run of 67.7 million sockeye salmon is the largest on record since 1963 (Figure 64). The large 2021 sockeye salmon run suggests these stocks experienced positive conditions at entry into the EBS in the summers of 2018 and 2019, and winters of 2018–2019 and 2019–2020 (p. 115).

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[3] `https://meetings.npfmc.org/Meeting/Details/2631`

The loss of sea ice during the current protracted warm phase has impacted water column stratification and the vertical distribution of prey (p. 106). Historically, salinity and temperature contribute equally to the vertical stratification of the water column in the NBS. Without increased salinities due to brine rejection as ice forms, the lack of salinity structure results in weaker vertical stratification, permitting greater vertical mixing. If primary and secondary production is mixed deeper in the water column, a vertical mismatch of prey for surface-foraging seabirds or juvenile salmon may limit prey availability, thus exacerbating increased metabolic demands under increased thermal conditions.

The protracted warmth in the NBS, with an increased frequency and duration of marine heatwaves from fall 2017 through winter 2019 (Watson, 2020), and shifts in species distributions (p. 162) has led to concerns about the food web dynamics and carrying capacity of the NBS. Ecosystem response to the 2014–2016 marine heatwave in the Gulf of Alaska resulted in abrupt changes across multiple trophic levels and there were indications the post-marine heatwave system had reduced resiliency (Suryan et al., 2021). Resiliency existed in 'functional redundancy' – an example being the ability to switch prey – and without that buffer, ecosystem components could not recover from the marine heatwave perturbation. Evidence of prey switching has been observed in seabirds (i.e., least and crested auklets, p. 147), age-0 pollock in the southeastern Bering Sea, and in the diet of Pacific cod in the southeastern Bering Sea reflecting changes in prey availability. For example, in the southeast middle domain, pollock were the dominant prey of Pacific cod in most years, but when pollock abundance was low from 2008–2012, pollock were replaced in Pacific cod diets with a mix of *Chionoecetes* spp. and flatfish. Can ecosystem reorganization keep pace with the rate of environmental changes?

Southeastern Bering Sea

Impacts of the loss of sea ice include increases in water temperature (i.e., lack of cold pool), decreases in ice-associated algae, and increases in salinity, and subsequent changes in water density and water column stratification (p. 57). Community-led monitoring of temperature and salinity on St. Paul Island shows an increasing trend in salinity since 2014 (Figure 32). The long-term increase in water density at St. Paul Island is driven primarily by the increase in salinity (Figure 33). Salinity variability on the shelf is driven by ice melt and advection, river discharge, precipitation, evaporation, in flows from the Gulf of Alaska, and cross-slope exchanges with the basin.

Water density and water column stratification can impact the vertical distribution of organisms, including age-0 fish. Age-0 pollock appear to occur deeper in the water column during colder years and closer to the surface during warmer years (p. 106), affecting their availability to predators. In 2021, age-0 pollock may therefore have occurred higher in the water column. Visual predators, such as seabirds, however, may have had reduced foraging success due to a coccolithophore bloom over the southern shelf (Figure 48). The coccolithophore bloom index remained above average in 2021 (p. 87).

Chlorophyll-a biomass, an indicator of primary productivity over the shelf (p. 80), was low along the shelf-break, continuing that trend since 2014 (i.e., start of current protracted warm phase; Figure 44). Along-shelf winds through 2021 were variable and did not consistently demonstrate upwelling or downwelling favorable conditions (Figure 23). Summer 2021 primary production as measured at mooring M2 appeared to be higher than in previous years (2016, 2017, 2019), but lower than in 2018 (p. 85). Secondary production of zooplankton was assessed in spring along the 70-m isobath (p. 94). Small copepod abundance was slightly reduced, although within historical ranges, therefore unlikely to impact food availability for larval fish. Large copepods are less critical in the spring, but very important by fall. Observations of *Calanus* spp. suggest they were developing more slowly due to the relative colder temperatures, which would result in an increased availability later in the year and potentially support increased overwinter success for age-0 pollock (p. 94).

Species guilds are grouped by functional roles within the ecosystem and trends inform dynamics across these roles (i.e., predation pressure, prey availability) (Report Card, Figure 1). Motile epifauna, which indicate benthic productivity, remained above their long term mean in 2021. Above-average biomass of brittle stars, sea stars, and other echinoderms off-set below-average biomass for all crab functional groups. Benthic foragers were at their lowest level over the times series and indirectly indicate availability of infauna (i.e., prey of these species). A new guild comprised of small forage fishes describes available prey for seabirds and larger fish (i.e., adult pollock). This aggregate forage fish guild indicates a decline in the availability of forage species to predators that may have contributed to other substantial ecosystem changes in the southeastern Bering Sea. In 2021, pelagic foragers, largely driven by adult pollock biomass, dropped to their second lowest value over the time series. Trends indicate availability of forage fish as well as predator abundance within the ecosystem. With the exception of Pacific herring, the 2021 index for all other species and functional groups in the pelagic forager guild were below their long-term means. Togiak herring are an important prey species for piscivorous fish, seabirds, and marine mammals. The high Prohibited Species Catch in the pollock fishery in 2020 supports a strong increase in young EBS herring, as does preliminary Togiak herring data from 2021 (p. 108). Apex predators, largely driven by adult Pacific cod, are below their long term mean in 2021.

For groundfish in the southeastern Bering Sea, bioenergetic indices estimated through 2019 point towards continued increases in thermal exposure and a resulting increase in metabolic demands, as well as declines in foraging and growing conditions (p. 131). For juvenile and adult pollock and Pacific cod, metabolic requirements for prey increased between 2015–2019 relative to historical (1982–2010) rates. Meanwhile, the relative foraging rates for juvenile pollock and Pacific cod declined markedly. Of particular note, from 2015–2019 juvenile Pacific cod scope for growth remained well below the long-term average (1982–2010) (Figure 77). Fish condition, as measured by length-weight residuals, trended downward from 2019 to 2021 for multiple groundfish species, including benthic, pelagic, and apex predators (Figure 72), indicating poor feeding conditions across trophic niches. Conversely, juvenile pollock (100–250 mm) condition has trended upward since 2017, indicating positive bottom-up drivers. Additionally, based on results from the multispecies model CEATTLE (p. 136), juvenile pollock experienced improved top-down conditions through predation release (i.e., due to declining biomass of groundfish predators) (Figure 79).

Complete Recap of the 2020 Ecosystem State

Some ecosystem indicators are updated to the current year (2021), while others can only be updated to the previous year (or earlier) due to the nature of the data collected, sample processing, or modeling efforts. Therefore, some of the "new" updates in each Ecosystem Status Report reflect information from the previous year(s). Below is a complete summary of 2020 that includes information from both previous and current indicators.

During 2020, the vast majority of NOAA Fisheries surveys were canceled in the eastern and northern Bering Sea due to COVID-19 travel restrictions. 2020 was an on-year for the biennial NOAA ecosystem and acoustics surveys, in addition to annual trawl surveys. Therefore numerous contributions of ecosystem information for this Report were unable to be updated last year. Due to these survey limitations, the interpretation of the ecosystem state bridged from basin-scale, satellite-derived indicators to local-scale community observations. While gaps existed, NOAA scientists, state/university partners, tribal governments, and coastal community members provided new and innovative contributions to inform our understanding of the ecosystem status. For example, coastal community members, tribal governments, and state/university partners provided all information on seabird dynamics in 2020 and the U.S. Fish and Wildlife Service biologists helped to synthesize the information and provide implications.

Following two years of physical oceanographic perturbations, the EBS experienced a return to near-normal climatic conditions in 2020. The winters of 2017/2018 and 2018/2019 had unprecedentedly low sea ice and reduced spatial extent of the cold pool, removing the thermal barrier between the southern and northern Bering Sea shelves. Distributional shifts in groundfish stocks were observed (e.g., more than 50% of the overall biomass of Pacific cod biomass occurred in the NBS in 2018). Ecosystem impacts in response to these conditions include changes in overall productivity and the potential for new trophic pathways.

Considerable cooling during winter 2019/2020 allowed for rapid build-up of sea ice, exceeding median ice extent in parts of February and March 2020. However, ice thickness was low, and retreated quickly in spring. Based on Bering 10K Regional Ocean Modeling System (ROMS) hindcast simulation, this ephemeral ice was estimated to be sufficient to form a cold pool of average spatial extent. After two years of little to no sea ice over the Bering Sea shelf, the near-normal ice extent observed in 2020 appeared to have only minimal mitigating effects on the warmth in the upper water column (i.e., sea surface temperatures). This vertical stratification of the water column is more typical of shelf conditions and affects predator/prey dynamics.

Above-average sea surface temperatures returned in spring 2020 and remained above average through summer 2020. Satellite-derived indicators of sea surface temperature (SST) facilitated examination of marine heatwave thresholds for the EBS. Heatwaves occurred during early years of the time series that begins in 1985, but the frequency and duration of heatwaves have increased dramatically, especially in the NBS, where residual heat and low sea ice extent has resulted in significantly increased cumulative annual thermal exposure since 2017.

Chlorophyll-a concentrations were lower in 2020 than 2019 in all regions except the southern outer domain. Chl-a concentrations over the southern inner and middle shelves had been below average since 2016. In the NBS, the concentrations over the inner and middle shelves were below average and the outer shelf was low and continued a decreasing trend since 2014. Primary producers provide fundamental energy and nutrients for zooplankton grazers and higher trophic level species; these trends indicate lower energy transfer to support the food web over the southern and northern Bering Sea shelves in 2020. The timing of the peak spring bloom in 2020 was earlier than the long-term average; for the southern inner and middle shelves it occurred about a week earlier. This contrasts with 2018 which was among the latest, while 2017 was among the earliest spring blooms. New information derived from the Continuous Plankton Recorder (p. 91) shows that the copepod community size and mesozooplankton biomass anomalies for 2020 were negative, where they had been positive in 2019. The mean diatom abundance anomaly was also negative in 2020. Such changes in abundance or biomass, together with size of the copepod community, influences the quantity and quality of prey available to predators. The coccolithophore bloom index was below average in 2018 and 2019 but increased, particularly on the middle shelf, in 2020. Coccolithophores may be a less desirable food source for microzooplankton in this region and smaller coccolithophores result in longer trophic chains. The striking milky aquamarine color of the water during a coccolithophore bloom can also reduce foraging success for visual predators. Combined, these indicators of primary production suggest limited and/or poor quality of the prey base to support trophic energy transfer (e.g., juvenile fish, seabirds) in 2020.

The 2020 Togiak herring population was predominantly comprised of age-6 and age-7 fish (the 2013 and 2014 year classes). Oceanographic conditions over the southeastern Bering Sea shelf transitioned from below-average (i.e., cold) in 2013 to above-average (i.e., warm) in 2014. While the recruitment of age-4 fish to the spawning population in 2018 was still the largest estimated recruitment since 1982, the magnitude of that recruit class was estimated in the 2020-forecast model to be lower than was previously estimated. The incidental catch of herring in the 2020 directed pollock fishery was unusual because it occurred during a period of relatively high nominal CPUE values for pollock fishing and also was highest in the winter fishing A season. Several hypotheses were explored in the Noteworthy "Incidental Catch of Herring in Groundfish Fisheries Increased in 2020" in Siddon et al. (2020); the pollock fleet may have encountered high numbers of Togiak age-4 fish that provides partial explanation of the abrupt increase of incidental catch in 2020.

Commercial salmon harvests in 2020, based on preliminary data from ADF&G, indicated that statewide total harvests were below the preseason forecast, but nearing the 2018 total harvest. The 2020 Bristol Bay salmon inshore run was the 5th largest on record and 74.5% higher than the 1963–2019 average. A projected decrease in the number of pink salmon in 2020 may have had a positive impact on fish-eating seabirds (i.e., less competition for prey).

In 2020, at the Pribilof Islands, seabird attendance appeared similar to that in recent years while breeding observations suggested it was an average, to slightly below average, year for most fish-eating species (e.g., kittiwakes, murres). Planktivorous species (i.e., auklets) had been declining and continued to be low in 2020, at least at St. Paul Island. Warmer water temperatures from 2014–2019 seem to have negatively affected least auklets, and likely parakeet auklets. In the NBS, on St. Lawrence Island, reproductive success and colony attendance differed among fish-eating and planktivorous seabirds suggesting foraging impacts differed across trophic levels. In the Bering Strait region, emaciation and starvation were observed in some seabirds throughout the summer and beach-cast carcasses of several species of seabirds were observed on the eastern and western sides of the Bering Strait.

Seabird bycatch estimates from the groundfish fisheries (p. 196) decreased 52% from 2019 to 2020. While a reduction in seabird bycatch in the Federal fisheries off Alaska is positive, several events occurred during the 2020 fishing seasons which may partially explain this reduction: (i) the COVID-19 pandemic disrupted normal fishing operations throughout Federal Fisheries, including lost fishing days; (ii) an expansion of the fleet over space (i.e., into the NBS), and (iii) reductions in catch over time (e.g., from 247,000 t in 2016 to ∼150,000 t in 2020). Additionally, the first reported interaction between a fishing vessel from the BSAI groundfish fishery with threatened spectacled eider may be a direct result of ecological change in the EBS. Recent changes in ocean temperatures and the resulting ecological response of commercially valuable fish species, mainly Pacific cod, has led to an increase in the amount of fishing vessel traffic in areas near spectacled eider designated critical habitat.

Direct and indirect indicators of groundfish recruitment success provided information on the status of 2020 year classes. The 2020 springtime drift pattern was mixed, indicating larvae (e.g., age-0 pollock) may have been retained over the southern middle shelf. However, lower primary production in spring 2020 may have limited the prey base to support trophic energy transfer to large, lipid-rich copepod taxa. The abundance of large copepods is positively correlated with the recruitment success of pollock. Years of low recruitment for pollock portend lower rates of cannibalism as adult pollock biomasses decreases. The climate-enhanced multispecies model (CEATTLE) estimates of age-1 predation mortality for pollock was at the long-term mean in 2020 as declines in total predator biomass are contributing to reduced predation rates and mortality.

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† indicates new Ecosystem Status Indicator contribution
* indicates Ecosystem Status Indicator contribution updated with 2021 data

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Ecosystem Indicators

Noteworthy Topics

Here we present items that are new or noteworthy and of potential interest to fisheries managers.

Adult Salmon Run Failures Throughout the Arctic-Yukon-Kuskokwim Region

The Arctic-Yukon-Kuskokwim (AYK) Region experienced unprecedented salmon run failures during the 2021 season. Chinook, chum, and coho salmon runs were extremely weak throughout the entire region (Figures 2, 3, and 4). The 2021 Yukon River salmon season was particularly dire due to concurrent record low run sizes of Chinook, summer chum, fall chum, and coho salmon. For the first time since statehood, all Yukon River salmon directed gillnet fisheries were closed for the entire season, leading to extreme food security and social, cultural, and economic hardships. Even with fishery closures, it is unlikely that the Yukon River salmon run sizes were adequate to meet minimum spawning escapement goals or U.S./Canada Treaty objectives. Fishery restrictions were also required throughout the Kuskokwim and Norton Sound Management Areas, but the situation was mitigated somewhat by Chinook and coho salmon runs within historical ranges and adequate abundances of other salmon species to allow for limited harvest opportunities.

The record low chum salmon runs are of particular concern because chum salmon are the most abundant salmon species returning to the AYK Region and are a critical subsistence, personal use, and commercial resource. Historically, AYK chum salmon have shown resilience and the ability to bounce back from years of low run abundance. Since the mid-2000's, AYK chum salmon runs have been healthy, characterized by several years of record large run sizes, sustainable fisheries, and consecutive years of meeting or exceeding escapement objectives. Failure of age-4 chum salmon returning to AYK rivers in 2020 forewarned the multiple age-class failure that was observed in 2021. The potential for continued low chum salmon abundance over the coming years should not be overlooked given the changing marine conditions, unprecedented low escapements in 2021, generally low escapements in 2020, and numerous pre-spawn mortality events documented in 2019.

The cause of poor Chinook, chum, and coho salmon runs throughout the AYK Region are not known, but prevailing hypotheses are focused on sub-optimal conditions for growth and survival in the marine environment. AYK salmon species display a wide range of life history strategies and residency times in freshwater and marine environments (Figure 5). The number of spawners

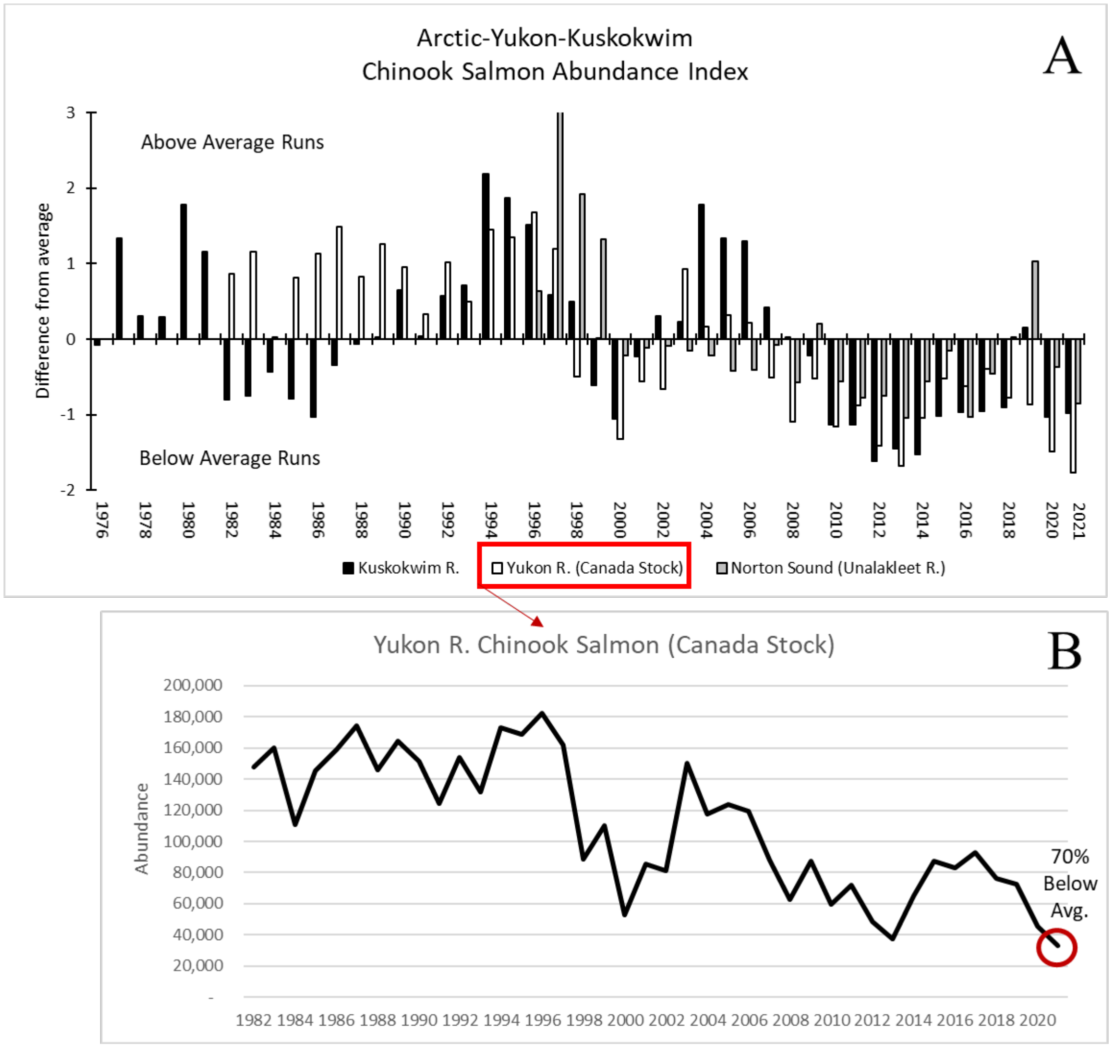

Figure 2: Relative changes in Chinook salmon adult run abundance throughout the Arctic-Yukon-Kuskokwim Region based on three indicator stocks (A), with a focus on the Canadian-origin Yukon River stock (B).

that contributed to the 2021 AYK Chinook, chum, and coho salmon runs were generally within or exceeded escapement goals, and there are no known freshwater environmental factors that easily explain the concurrent poor returns observed in 2021. AYK salmon age and size trends lend some support for marine influences. AYK Chinook salmon have trended towards earlier age-at-maturation and smaller sizes-at-age (e.g., Lewis et al. (2015) and Ohlberger et al. (2018)) and that pattern was again observed in preliminary 2021 data. Yukon River chum salmon and Yukon and Norton Sound coho salmon displayed record low body size, at age, in 2021, suggesting poor growth conditions in the marine environment.

An additional concern for Yukon River Chinook salmon has emerged with the resurgence of ichthyophonus disease after many years of low prevalence. Infection occurs via diet consumed during the marine life stage, and the disease progresses during the adult in-river migration. In 2020

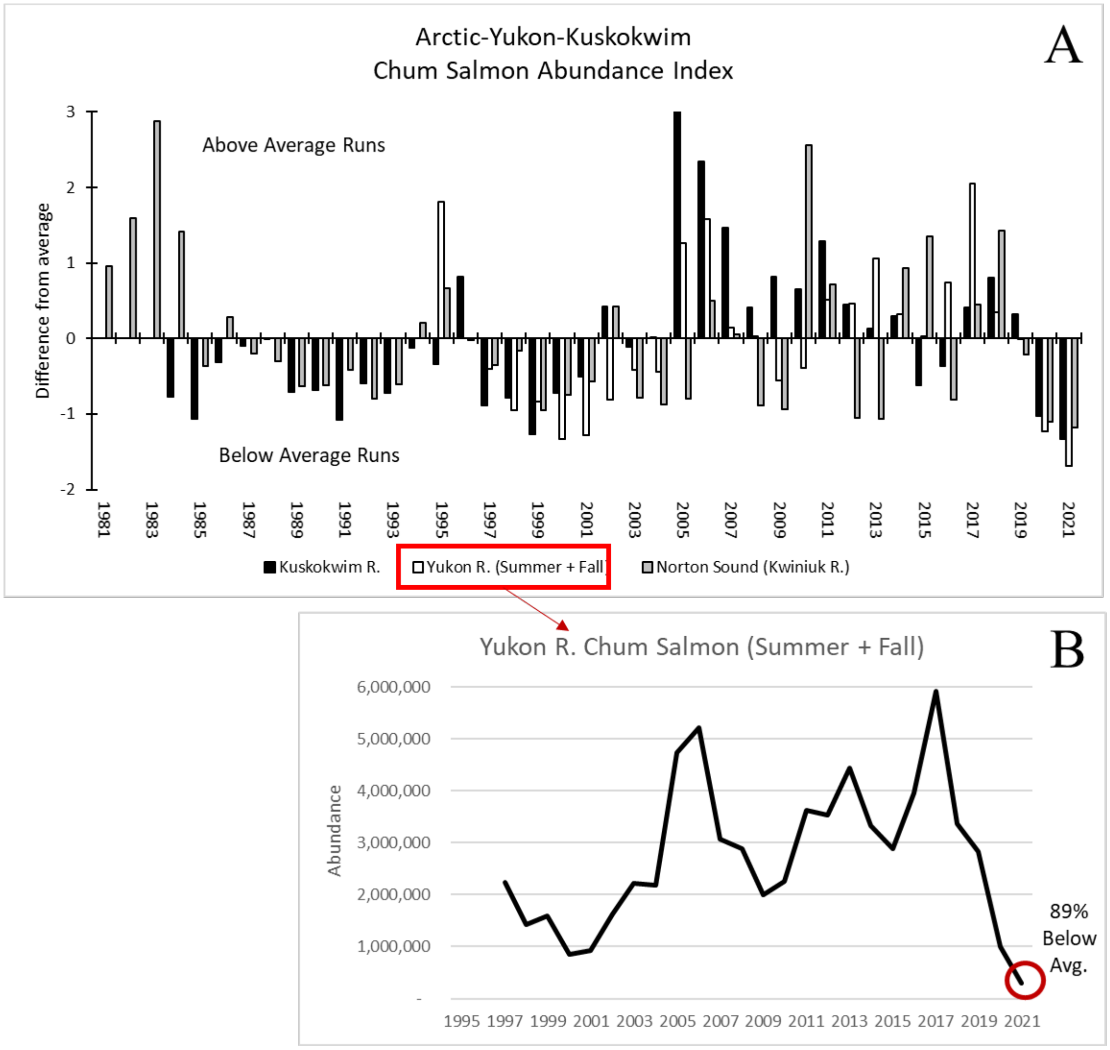

Figure 3: Relative changes in chum salmon adult run abundance throughout the Arctic-Yukon-Kuskokwim Region based on three indicator stocks (A), with a focus on the Yukon River stocks (B).

and 2021, the prevalence of ichthyophonus appears to be near record high levels (based on opportunistic and limited sampling) with currently unknown implications for in-river survival, migration, and spawning success.

The Alaska Department of Fish & Game is addressing the declining salmon runs across the AYK Region through a wide range of applied research initiatives. Efforts include adult salmon tagging programs, increased escapement monitoring, improvements to salmon forecast and total run estimation methods, investigations into the impact of ichthyophonus disease on adult pre-spawn mortality, and expanding the capacity of marine research programs to identify factors that may be affecting the productivity of AYK salmon. Long-term research prioritization and inter-agency collaboration will likely be required to address the needs of salmon fishery management agencies in a changing environment.

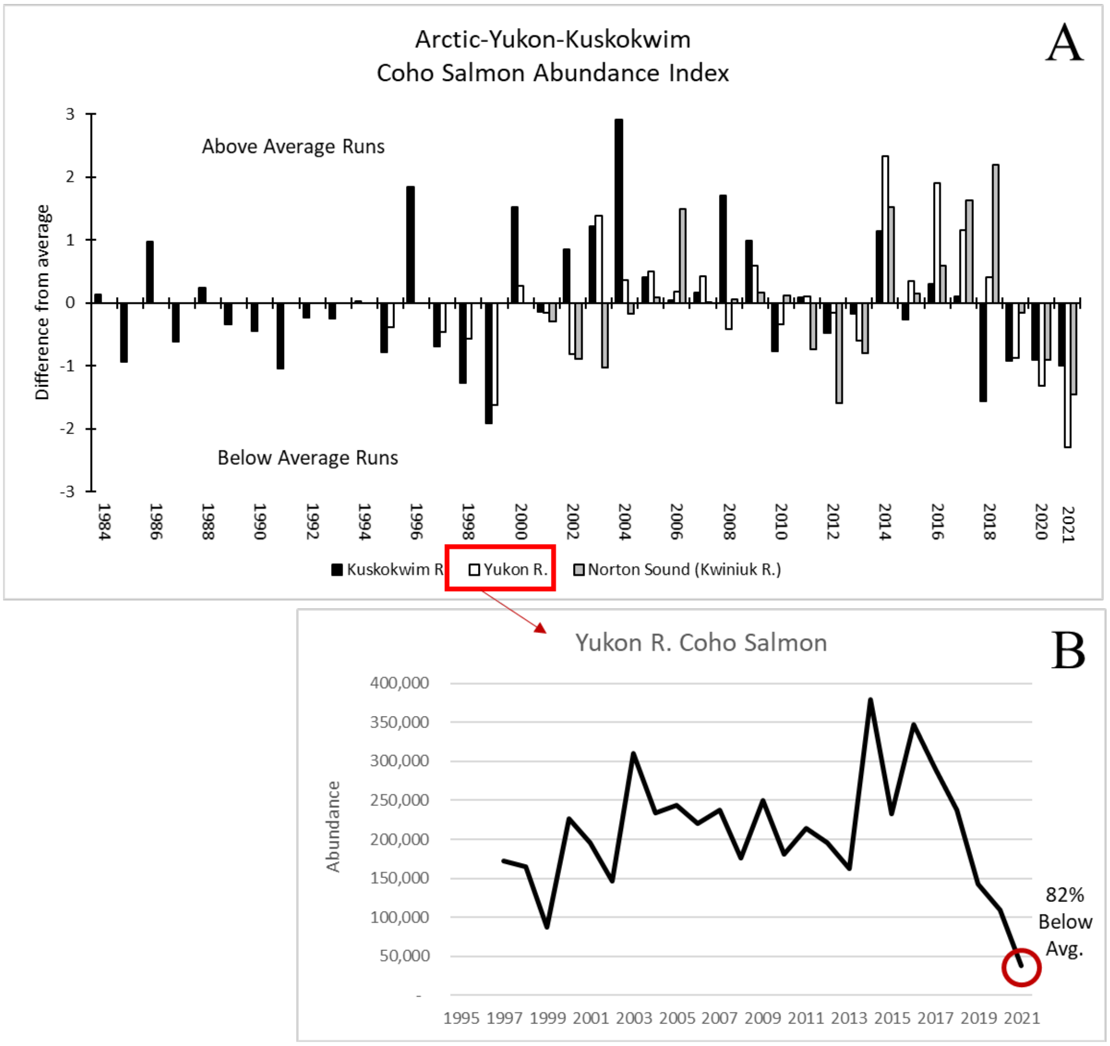

Figure 4: Relative changes in coho salmon adult run abundance throughout the Arctic-Yukon-Kuskokwim Region based on three indicator stocks (A), with a focus on the Yukon River stock (B).

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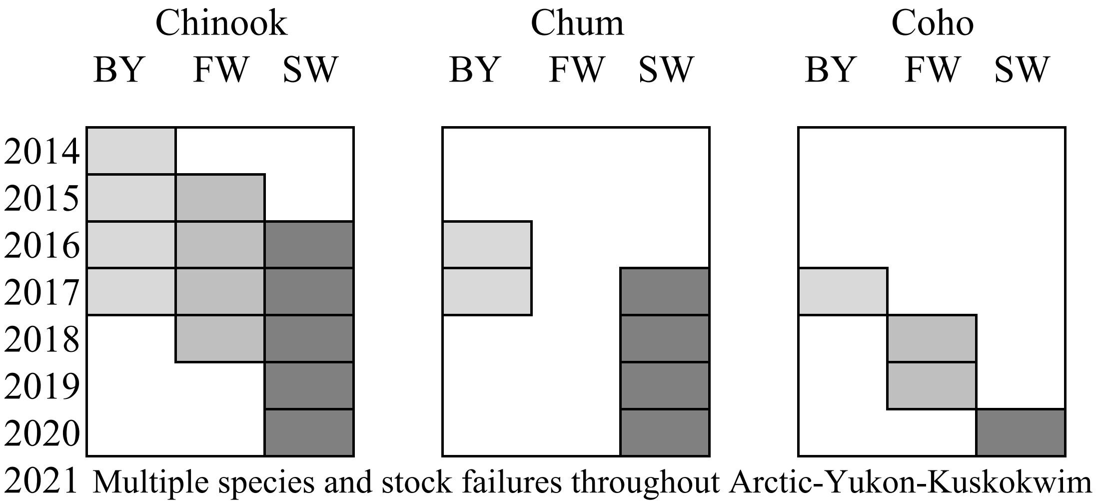

Figure 5: Common life history strategies displayed by Arctic-Yukon-Kuskokwim Region Chinook, chum, and coho salmon. Shaded boxes highlight the years during which salmon returning in 2021 were subject to freshwater and marine environments. **Note:** The 2021 salmon runs to AYK were impacted by environmental conditions experienced during the brood year (BY) spawning, freshwater (FW) rearing, and marine (SW) growth phases. AYK Chinook salmon typically spend 1 year in FW and 2–5 years in SW. Chum salmon out-migrate immediately after emergence and typically spend 3–4 years in the marine environment. Coho salmon typically spend 2 years in FW and 1 in SW.

Getting to the Bottom of it: an Exploration of ROMS Bottom Temperatures

The Bering Sea ROMS model (Bering10K) originated as a subdomain of the larger Northeast Pacific ROMS model (NEP5) approximately a decade ago. Since that time, several peer-reviewed publications have documented its subsequent development along with quantitative and qualitative validation of the model's performance against physical and biogeochemical observations from the region. First, we highlight several of these publications that focus on various aspects of the coupled ocean-ice-biogeochemical model complex.

Because sea ice dynamics play such a key role in biophysical processes in this region, successful simulation of sea ice advance and retreat, and the interannual variations in both timing and magnitude of sea ice processes, were a necessary precursor for a regional model to be useful in the Bering Sea region. Danielson et al. (2011) discusses the performance of a 35-year hindcast simulation of the NEP5 model, focusing on modes of variability within the ocean and sea ice modules. While this paper predates the Bering10K model, many of its skill metrics, especially those demonstrating successful simulation of currents, stratification, tidal harmonics, and sea ice concentration, are applicable to the smaller Bering Sea domain as well.

Hermann et al. (2013) is the first paper to focus specifically on the Bering10K model. Model validation focused on climatological circulation patterns compared to *in situ* drifters, as well as water column hydrography (seasonal and interannual patterns in stratification, mixed layer depth, temperature, etc.) compared to long-term moorings located in the middle shelf region.

Biogeochemistry within the Bering10K model is currently simulated using the custom BESTNPZ model (Gibson and Spitz, 2011). Kearney et al. (2020) provides an in-depth evaluation of biophysical and biological metrics related to the implementation of this model within the three-dimensional Bering10K model. This includes a quantitative comparison of cold pool extent within the model compared to measurements from the annual groundfish survey. We also revisit many of the earlier validation metrics related to sea ice extent, mixed layer depth, stratification, and currents, and compare simulated primary production with both satellite-derived and *in situ* measurements. This paper also includes a history of the updates that were made to the coupled regional model over its 10-year history.

Finally, Kearney (2021) provides a more in-depth look at how the simulated surface and bottom temperatures within the Bering10K model compare to the data collected from the annual continental shelf groundfish survey over its 40-year history. This technical report expands upon the details underlying the cold pool validation metrics presented in Kearney et al. (2020), and presents several maps of skill metrics (such as bias, correlation, RMSE, etc.) for both bottom and surface temperature across the southeastern and northern shelf regions.

Next, we present several comparative examples of satellite-derived sea surface temperature and ROMS bottom temperature data that facilitate examination of spatial (i.e., vertical differences) and temporal (i.e., phenological) impacts of temperature dynamics between surface and bottom waters on organisms in the eastern Bering Sea.

Spatial patterns are evident when looking across depth-defined strata (i.e., inner vs. middle/outer shelf) (Figure 6). The left hand panels show temperature variability in the inner domain (10–50m) while the right hand panels show variability in the middle/outer domain (50–200m). The impact of mixing in the inner domain results in bottom waters having larger swings in temperature, whereas stronger stratification in the middle/outer domain leads to more stable bottom water temperatures.

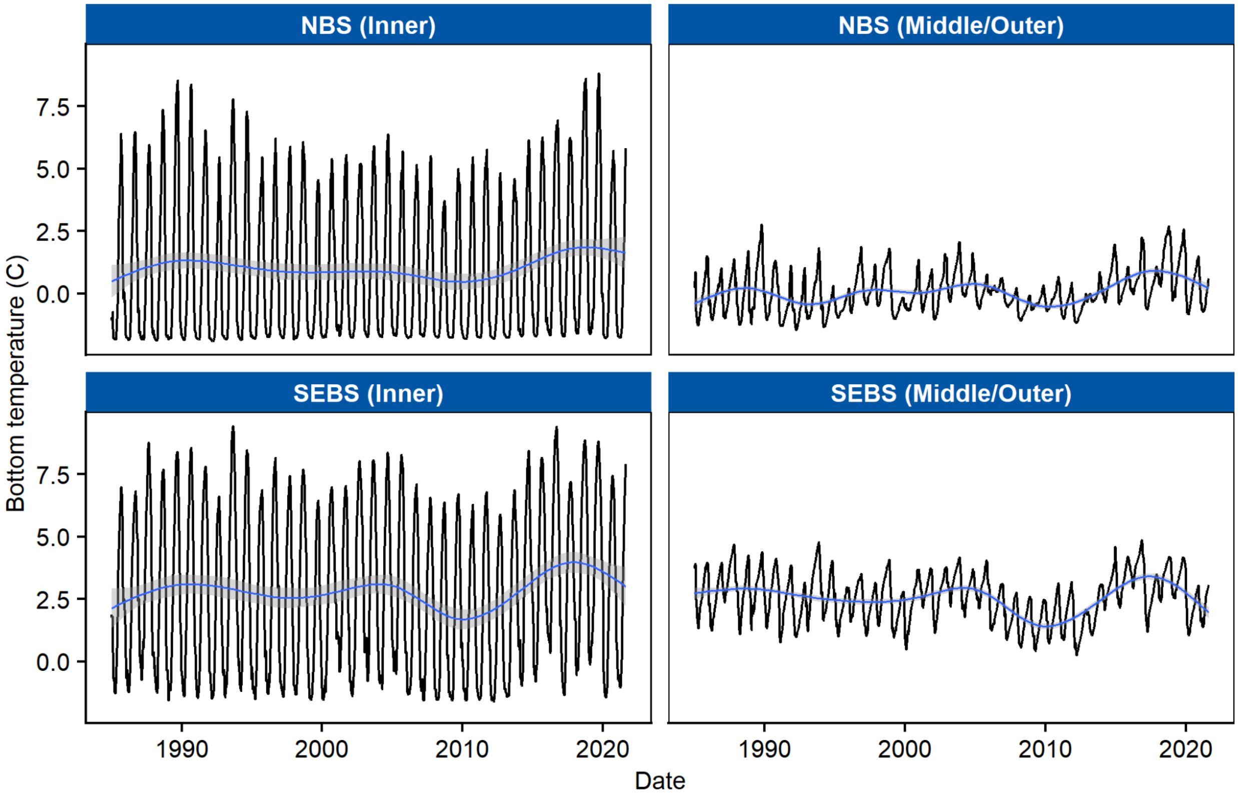

Figure 6: ROMS bottom temperatures averaged within depth-defined strata for the Northern and Southeastern Bering Sea regions.

Temporal patterns (within and across years) of water temperature dynamics have impacts on individual species' phenological responses and subsequent match/mismatch patterns. In Figure 7, the bottom panel shows warm waters persisted at depth through fall 2019 whereas surface waters were relatively cooler. Both surface and bottom temperatures were closer to the long-term mean in 2021.

Figure 8 highlights a potentially phenologically important trigger for organisms' early life history development as well as horizontal and vertical distributions. The relative timing each year when the surface water temperature drops below bottom water temperature has varied over the time series, with greater variability in the inner domain than in the middle/outer domains.

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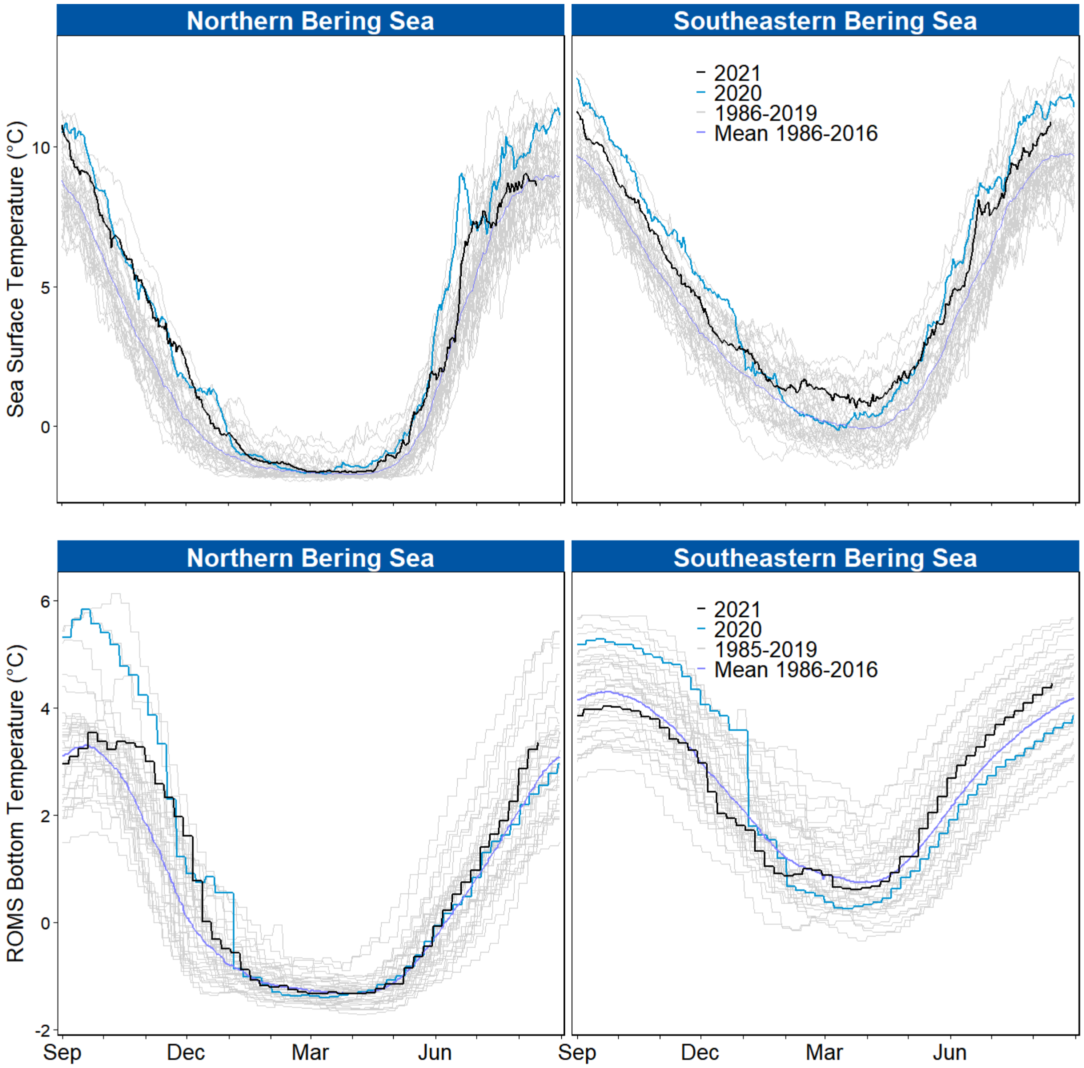

Figure 7: Phenology of SST (satellite-derived, source: Coral Reef Watch) and bottom temperature (derived from ROMS) in the northern and southeastern Bering Sea. Years are plotted Sept–Aug with Sept–Dec appended to the subsequent year. Frequency of data is daily for SST and weekly for ROMS. Depths are filtered to between 10–200m. **Note** different y-axis scales for SST and bottom temperatures.

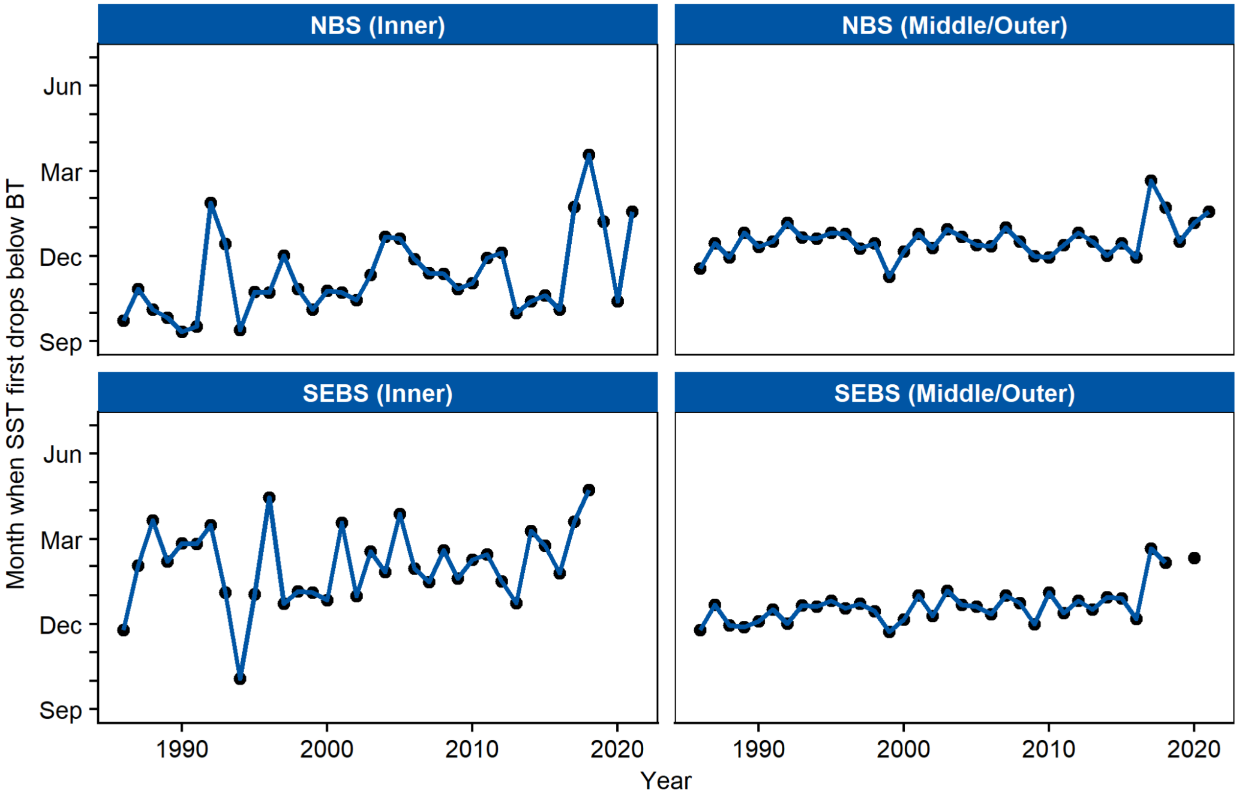

Figure 8: Relative timing within each year during which the average regional surface temperatures dropped below the bottom temperatures. Years are plotted Sept–Aug with Sept–Dec appended to the subsequent year. Missing values in 2019–2021 in SEBS regions demonstrate that the surface temperature never dropped below the bottom temperature in that year.

Ice seal Unusual Mortality Event: an update

On September 12, 2019, NOAA Fisheries declared an Unusual Mortality Event (UME) for three species of ice seals in Arctic waters of Alaska. This declaration resulted from elevated numbers of dead bearded, ringed, and spotted seals on Alaska shores, which were reported, beginning in June 2018, from Kotlik in the northern Bering Sea to Utqiaġvik in the northern Chukchi Sea. The UME investigation continued in 2020 through 2021.

Prior to the 2019 ice seal UME declaration, strandings during 2010–2017 averaged 29 ice seals annually. For the next four years, confirmed strandings included 111 ice seals (June 1–December 31, 2018), 164 seals (2019), 34 seals (2020), and 41 seals (2021) (Table 1, Figure 9). These bearded, ringed, spotted, and unidentified stranded seals were confirmed from dedicated surveys and opportunistic sightings.

Table 1: Confirmed ice seal strandings related to the UME in the Bering and Chukchi seas.

Year	Bearded	Ringed	Spotted	Unidentified	Total
2010–2017 Average					29
2018[a]	35	29	20	27	111
2019	50	35	26	53	164
2020	9	7	7	11	34
2021	10	20	7	4	41
TOTAL[b]	104	91	60	95	350

[a] 1 June–31 December 2018

[b] 1 June 2018–8 October 2021

The reports from 2018–2019 indicated several seals were emaciated at the time of death. Stranding reports for seals from 2020–2021, however, did not identify emaciation as a factor in the seals' condition. Most photographs and reports identified the 2020–2021 stranded seals as healthy and robust.

In 2020, strandings in June (15 seals) were at the same level as in July and August (16 seals). In 2021, there were fewer strandings during June (14 seals), than in July and August (68 seals). Of note, photos and/or skin samples confirmed only 50% of stranding reports in 2020 and 47% of the stranding reports during 2021.

The ongoing COVID-19 pandemic severely limited NOAA's ability to travel to collect tissue samples, morphometric data, and/or conduct surveys during 2020–2021. Coastal residents were essential for the documentation and reporting of strandings while conducting their normal daily activities (ATV, boating, and walking). However, because of the remote locations, decomposition of the stranded seals, and a lack of traveling biologists/veterinarians, sampling and full necropsies of ice seals remained uncommon.

The increased mortality of seals reported during 2018–2019 coincided with the dramatic reduction in the extent, quality, and duration of sea ice habitat for pupping and nursing in the northern Bering Sea during both years (Boveng et al., 2020). The increased mortality of young seals during June 2018–2019 could also indicate impacts from the effects of a transitioning ecosystem, such as competition for prey. In a study by the Alaska Fisheries Science Center, spotted seal pups

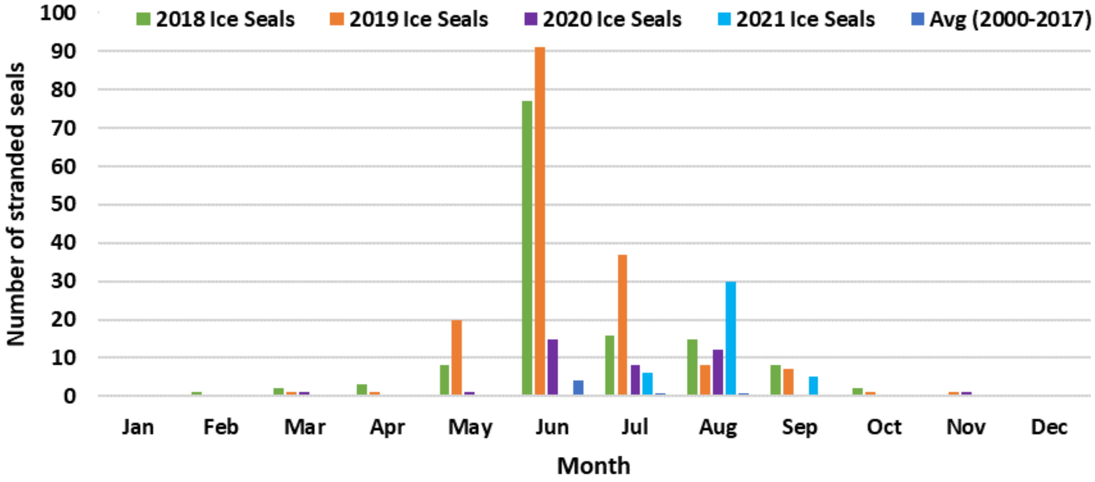

Figure 9: Number of confirmed ice seal strandings in Alaska by month.

and ribbon seals[4] of all age classes declined in body condition over a longer period (2007–2018), coincident with a decline in Bering Sea ice extent, quality, and duration (Boveng et al., 2020). The ice seal UME of 2018–2019 may therefore reflect an ecological shock from those two extreme years superimposed on a longer-term trend.

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[4] Ribbon seals were not among the identified strandings in the UME, but they typically are reported in much lower numbers than bearded, ringed, and spotted seals, likely due to their smaller population and more offshore habits.

Ecosystem Status Indicators

Indicators presented in this section are intended to provide detailed information and updates on the status and trends of ecosystem components. Older contributions that have not been updated are excluded from this edition of the report. Please see archived versions available at: `http://access.afsc.noaa.gov/reem/ecoweb/index.php`

Physical Environment Synthesis

This synthesis section provides an overview of physical oceanographic variables and contains contributions from (in alphabetical order):

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Last updated: October 2021

Executive Statement
Beginning in approximately 2014, the eastern Bering Sea (EBS) entered a warm phase of unprecedented duration. As of August 31st, 2021, the EBS remained in this warm phase, though to a lesser degree compared to the extreme warm years of 2018 and 2019. Satellite observations of sea surface temperature remain in excess of one standard deviation above the long term average for much of the past year. These warm – but not extreme – conditions are mirrored in *in situ* observations of sea level air temperature and bottom temperature. Compared to normal conditions, the cold pool remains significantly reduced in area, and its southern boundary is shifted significantly northwestward. Sea ice formation in fall of 2020 was delayed due to residual warmth in the system, which has become the 'new normal' in this protracted warm phase. While the areal extent was closer to the pre-2014 levels than at any point in the last 7 years, ice thickness differed between the northern (thicker ice) and southern (thinner/no ice) shelves due to opposing prevailing winds.

Synthesis Summary
Along with much of the North Pacific, the EBS entered a continuous warm phase beginning in 2014 that, to present, has not subsided. Saint Paul Island has been the site of continuous air temperature records since 1920, and the intensity (2–6°C above average) and duration of the current warm phase is unmatched over the >100 year record (Figure 25). These trends are reflected in sea surface temperature (SST) observations from the NOAA Coral Reef Watch Program dating back to 1985. From 2014 onward, SSTs in both the northern and southern EBS have remained much higher than the average from 1985–2014 (Figure 28). However, after the extremely warm years of 2018 and 2019 (e.g., SST anomalies in the northern Bering Sea [NBS] of 2°C above average), conditions in 2020 and 2021 subsided to ∼1°C above average (Figure 28). From February–April, 2021, SST was normal in the NBS (<-1°C), but above average (by ∼1°C) outside those months, while in the southeastern Bering Sea, 2021 temperatures were about 1°C warmer than average throughout the entire year (Figure 27).

The current warm phase is also present at depth. Bottom trawl surveys conducted over the Bering Sea shelf show elevated temperature after 2014 (Figure 35). Although no survey data were collected in 2020, the 2021 data show that the bottom temperature anomaly was only ∼0.5°C above normal in 2021, while in 2018 and 2019, these anomalies reached nearly +2°C (Figure 35). Longline surveys conducted every other year since 2009 along the shelf break (250–500m) indicate the temperature anomaly there was 0.10°C above average in 2021, which is lower than the 0.30°C and 0.15°C anomalies reached during the 2017 and 2019 surveys, respectively (Figure 40). These anomaly values may actually be higher, since the record only goes back to 2009 (impacting the short period-of-record average).

The area of the cold pool (bottom water <2°C) estimated from the bottom trawl survey in 2021 was 58,975 km^2, which is well below one standard deviation from average, yet significantly higher than the years of 2018 (∼10,000 km^2) and 2019 (∼35,000 km^2) (See Figure 1). The 2021 cold pool comprised ∼10% of the total survey area, significantly less than the ∼20–70% frequently found prior to 2018 (Figure 36). The southern boundary remains shifted significantly northwestward (59°N) from years prior to 2018. Regional Ocean Modeling System (ROMS) hindcast simulations corroborate the *in situ* trawling data, finding that bottom temperature in 2021 (3.30°C) was about 0.5°C warmer than the average from 1970–2020 (2.79°C) (Figure 38).

The extended warm phase in the EBS has also impacted ice formation and areal extent. Following the pattern of many years after 2014, the sea ice extent in the Bering Sea between October 15–December 15, 2020 was under 6x10^4 km^2, approximately half the long term average (Figure 11).

Daily sea ice extent remained below average throughout virtually the entire sea-ice season, though later in the season extent recovered to a level typical of the "low ice" years of the early 2000s (Figure 13).

Reversing recent trends, the ice thickness in much of the NBS was substantially higher in March, 2021, than in the previous several years (Figure 15, a–d). A driving factor may be the origin of the prevailing wintertime winds. During February 2018 and 2019 there were extremely strong southerly winds over the entire Bering Sea, advecting heat from the south, which likely inhibited ice formation (Figure 19) throughout the region. In February, 2020, moderate northerly winds prevailed (advecting cold polar air from high latitudes). Interestingly, in February 2021, these northerly winds intensified over the northern portion of the shelf and likely contributed to the stability and thickness of sea ice in the north, while southerly winds prevailed over the southern portion of the shelf and likely inhibited ice formation in the south (Figure 20).

Introduction

In this section, we provide an overview of the physical oceanographic conditions impacting the EBS, describe conditions observed during 2021, and place 2021 in context to recent years. The physical environment has implications for ecosystem dynamics and productivity important to fisheries within the system and their management. We merge across information sources, from broad-scale to local-scale, as follows:

Outline

1. Climate Overview
2. Regional Highlights
3. Sea Ice
4. Winds and Ocean Currents
5. Surface and Bottom Temperatures
6. Seasonal Projections of SST from the National Multi-Model Ensemble (NMME)

1. Climate Overview

Contributed by Nick Bond, *nicholas.bond@noaa.gov*
Climate indices provide a means of characterizing the state of the North Pacific atmosphere-ocean system. Five commonly used indices are presented here: the NINO3.4 index for the state of the El Niño/Southern Oscillation (ENSO) phenomenon, PDO index (the leading mode of North Pacific SST variability), North Pacific Index (NPI), North Pacific Gyre Oscillation (NPGO), and Arctic Oscillation (AO). The time series of these indices, with the application of three-month running means, from 2011 into spring/summer 2021 are plotted in Figure 10. Two indices, the NPI and the AO, best represent conditions impacting the EBS shelf and are described in more detail below.

The state of the Aleutian low is often summarized in terms of the NPI, with negative (positive) values signifying relatively low (high) SLP. Following a near-neutral state in fall 2020, the NPI was strongly positive during the winter of 2020–2021 before returning to an average of near-neutral

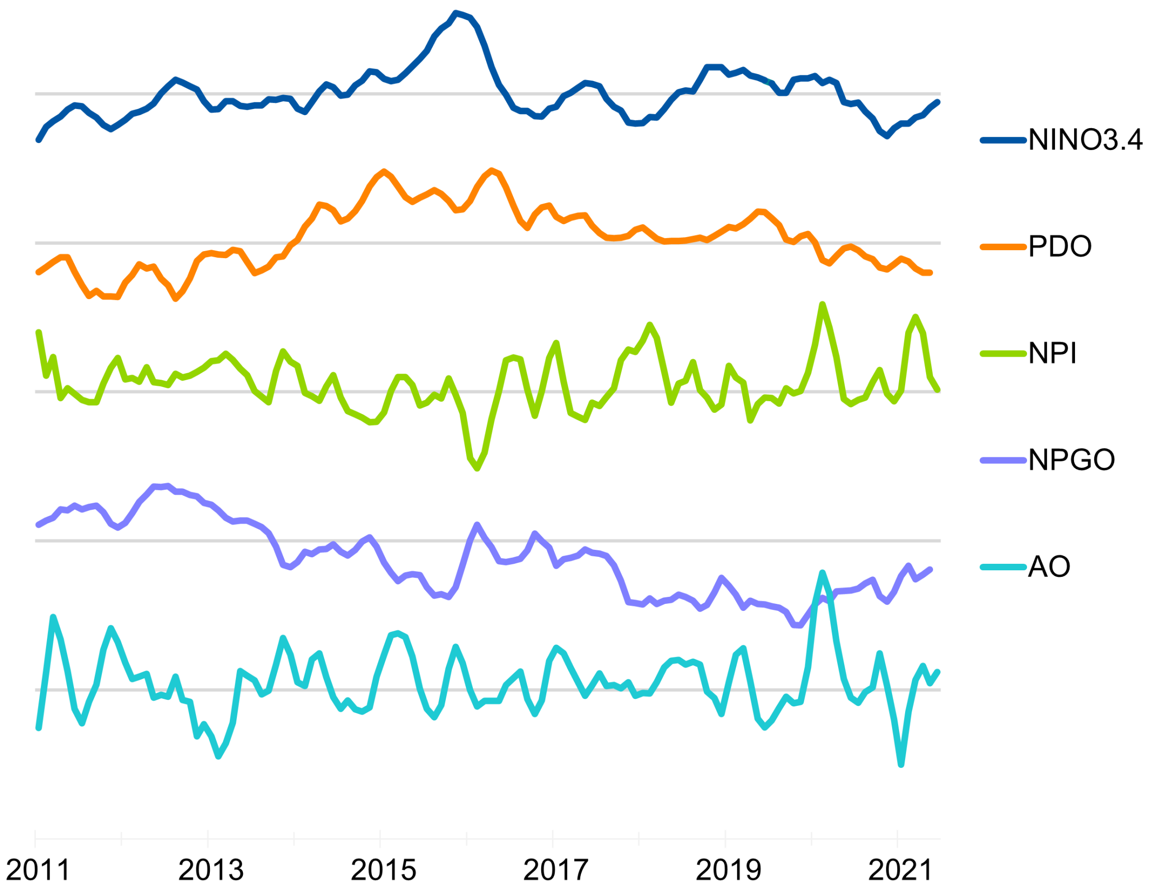

Figure 10: Time series of the NINO3.4, PDO, NPI, NPGO, and AO indices (ordered from top to bottom) for 2011–2021. Each time series represents monthly values that are normalized using a climatology based on the years of 1981–2010, and then smoothed with the application of three-month running means. The distance between the horizontal grid lines represents 2 standard deviations. More information on these indices is available from NOAA's Physical Sciences Laboratory at `https://psl.noaa.gov/data/climateindices/`.

again in summer 2021. The NPI has been positive during 4 out of the last 5 winters; this aspect of the atmospheric forcing of the North Pacific helps account for the overall decline in the PDO over the interval.

The AO represents a measure of the strength of the polar vortex, with positive values signifying anomalously low pressure over the Arctic and high pressure over the North Pacific at a latitude of roughly 45°N. The AO switched from strongly positive early in 2020 to temporarily negative during the winter of 2020–2021, followed by mostly positive values in spring and summer 2021 with considerable month-to-month variability.

2. Regional Highlights

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Summary

The North Pacific atmosphere-ocean climate system during autumn 2020 through summer 2021 featured generally higher than normal sea level pressure (SLP) across a broad band between roughly 25° and 50°N and lower than normal SLP from eastern Siberia into the southern Chukchi Sea. The region of positive SLP anomalies in the middle latitudes of the North Pacific generally corresponded with positive sea surface temperature (SST) anomalies. This high pressure, particularly during the winter of 2020–2021, meant that the Aleutian Low was weaker than normal, which is consistent with the moderate La Niña that was co-occurring in the tropical Pacific. The PDO was negative during the period of interest here, in large part due to the persistent positive SST anomalies in the western and central North Pacific. The climate models used for seasonal weather predictions are indicating elevated odds of La Niña conditions re-developing in the latter part of 2021. These models as a group are indicating SST distributions in early 2022 that include colder than normal temperatures for the Gulf of Alaska and near-normal temperatures for the Aleutian Islands and EBS. For the latter region, sea ice is expected to extend south over the shelf to at least 60°N.

Alaska Peninsula

Positive SST anomalies were present in this region during the latter portion of 2020, especially on the Bering Sea side. The weather early during the winter of 2020–2021 was warmer than normal, followed by cooler air temperatures in late winter and early spring 2021. The late summer of 2021 included some cool and occasionally stormy weather accompanied by upper ocean temperatures that were warm on the north side of the peninsula and near normal on the south side.

Aleutian Islands

The winter of 2020–2021 was stormy for the Aleutian Islands. Anomalous winds from the west were associated with suppressed poleward flow through Unimak Pass. A relatively calm period followed during the spring of 2021. Near normal values of SST prevailed in this region from late 2020 through the spring of 2021, with warming during the following summer.

Eastern Bering Sea

The EBS shelf was quite warm in the autumn 2020, and experienced a late arrival of sea ice. The following winter of 2020–2021 included wind anomalies from the northeast and initially warm air temperatures, with a cooler period in late winter. This winter along with the previous winter of 2019–2020 featured much cooler weather than those of the previous four years. One result was the development of considerable ice north of 60°N; the southern part of the southeast Bering shelf had a light ice year. The summer of 2021 appears to have been somewhat stormy with the wind mixing perhaps resulting in nutrient fluxes and ultimately bursts of primary production after the spring bloom.

Bering Sea Deep Basin

The western, deep portion of the Bering Sea transitioned from warmer than normal (0.5 to 1°C) SSTs in the latter part of 2020 to near normal temperatures during the first half of 2021. Warm anomalies developed in the western portion of this region in summer 2021. Similar to the EBS shelf, its northern portion experienced a relatively stormy summer in 2021.

Arctic
The Arctic region of northern Alaska is undergoing rapid warming in association with global climate change, and the period of fall 2020 through summer 2021 was no exception. The ice cover during the summer of 2021 was low relative to historical norms, but not nearly to the extent of the record-setting year of 2012. The decline in ice extent during August 2021 was less than usual due to persistent low SLP, and cool air temperatures, over the Beaufort Sea. The ice edge in the Chukchi and Beaufort Seas during late summer 2021 was not that far from its median position for the period of 1981–2010, but the pack north of this edge had ice of unusually low concentration and it is possible that the greater proportion of open water will tend to slow the freezing during the fall of 2021.

3. Sea Ice

Contributed by Rick Thoman, *rthoman@alaska.edu*
Early Season Ice Extent
While mean annual ice extent in the Bering Sea (both eastern and western) has shown no significant trend until recently, this is not the case for early season ice. The presence or absence of early sea ice in the Bering Sea is important because, at least during the passive microwave era, nearly all ice in the Bering Sea is first year ice, therefore Bering Sea ice thickness is related to both the air temperature and the age of the ice.

Trends
The mean daily extent for the two months from October 15 through December 15 shows considerable interannual variability, but with a strong negative linear trend during the past 40 years (Figure 11). This trend was robust even prior to the two recent low ice seasons and is a realization of delayed ice formation due to residual warmth in the system. Fall 2020 ice extent continued the post-2012 pattern of very late development of sea ice. Overall, this was the fourth lowest early season ice extent since 1979–1980.

Annual Bering Sea Ice Extent
The Bering Sea has historically been ice-free in the middle and late summer, with ice developing during the second half of October. To account for this seasonal cycle, the Bering Sea ice year is defined as 1 August to 31 July. Bering Sea ice extent data are from the National Snow and Ice Center's Sea Ice Index, version 3 (Fetterer et al., 2017), and use the Sea Ice Index definition of the Bering Sea (effectively south of the line from Cape Prince of Wales to East Cape, Russia).

Trends
The mean sea ice extent exhibited no long term trend, although a steep decline in ice extent was observed from 2012 (highest ice extent on record) to 2018 (lowest ice extent on record) (Figure 12). 2020–2021 seasonal extent recovered to a level typical of the "low ice" years of the early 2000s. This was due to the strength of a slow melt-out in the spring.

Bering Sea Daily Ice Extent
Tracking the seasonal progression and retreat of sea ice highlights the interactive roles of water temperature (i.e., warmth in the system) and winds (Figure 13). After a very slow start, ice extent increased rapidly in January only to stall out by the end of the month, and then was unusually steady from February into early April. After mid-March ice extent was highest since 2017 (March), 2016 (April), and 2013 (May).

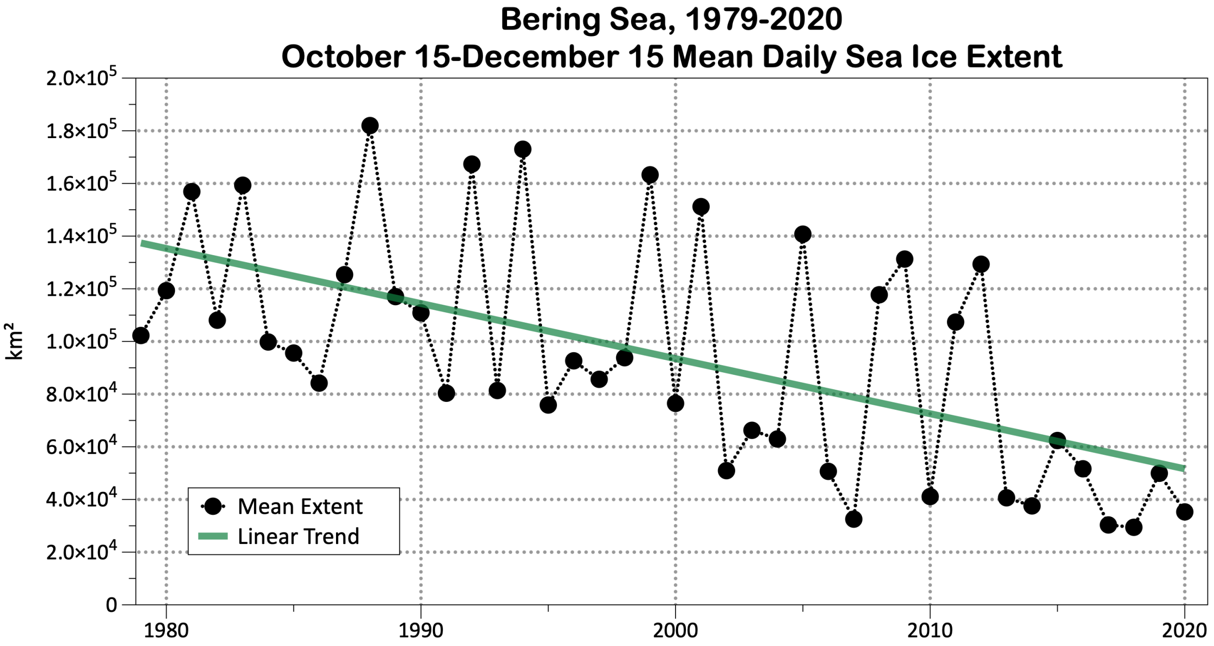


Figure 11: Early (15 Oct–15 Dec) mean sea ice extent in the Bering Sea, 1979–2020. Source: National Snow and Ice Data Center Sea Ice Index version 3.

Sea Ice Thickness

Bering Sea ice thickness was calculated for the 3rd week in March using merged SMOS/CryoSat-2 sea ice thickness estimates. SMOS is the Soil Moisture and Ocean Salinity satellite and CryoSat-2 is the Sea Ice Radar Altimetry from the European Space Agency CryoSat-2 satellite. SMOS estimates are most reliable at ice thickness ≤1m, CryoSat-2 at ice thickness ≥1m. Ice thickness was calculated for five areas over the Bering Sea: Gulf of Anadyr (Bering W), Bering Strait, Norton Sound, St. Lawrence Island to St. Matthew Island (Bering NC), and St. Matthew Island and St. Paul Island (Bering S) (Figure 14).

Trends

Ice thickness was near the higher levels of 2012 and 2013 in the northern and western Bering Sea regions (Figure 15), but very low south of St. Matthew Island (Figure 16). This reflected the unusual weather pattern that prevailed from late January into March, which allowed ice in the north to thicken but prevented ice from moving very far south of St. Matthew Island. While the 11-year period of record is much too short to establish any kind of trend, this period is likely indicative of the modern era range of interannual variability that can be expected at this time of year, as both 2012 (high ice extent year) and 2018 and 2019 (low extent) are represented in the period of record. However, it is important to notice that in some areas, estimated uncertainty of the thickness estimates are a significant fraction of estimated mean thickness, especially pre-2016, suggesting that the estimates should be used with caution.

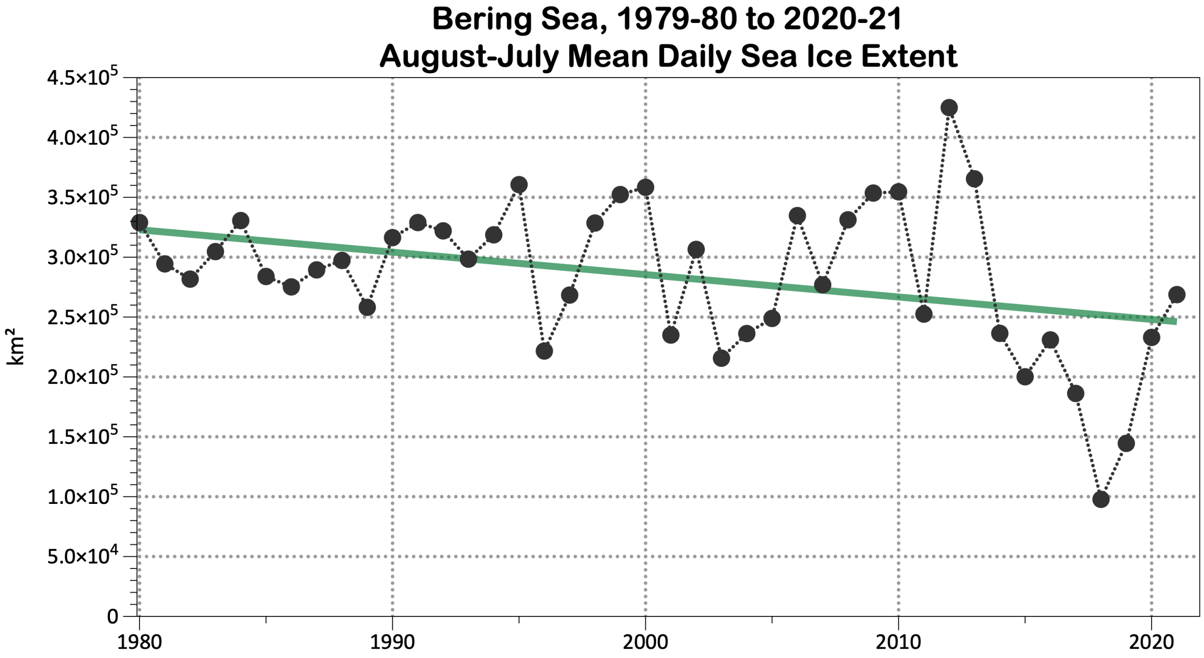


Figure 12: Mean sea ice extent in the Bering Sea from 1 August to 31 July, 1979/1980–2020/2021.

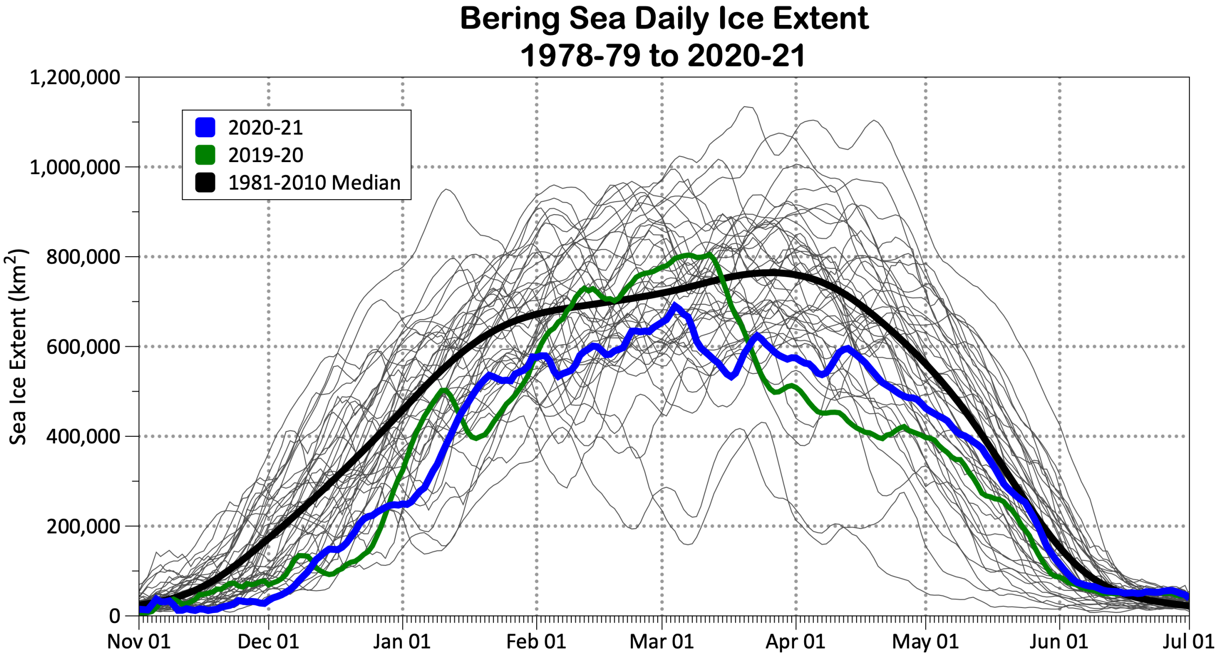


Figure 13: Daily ice extent in the Bering Sea. The most recent year (2020–2021) is shown in blue, 2019–2020 in green, and the historical median in black. Individual years in the time series are shown in gray.

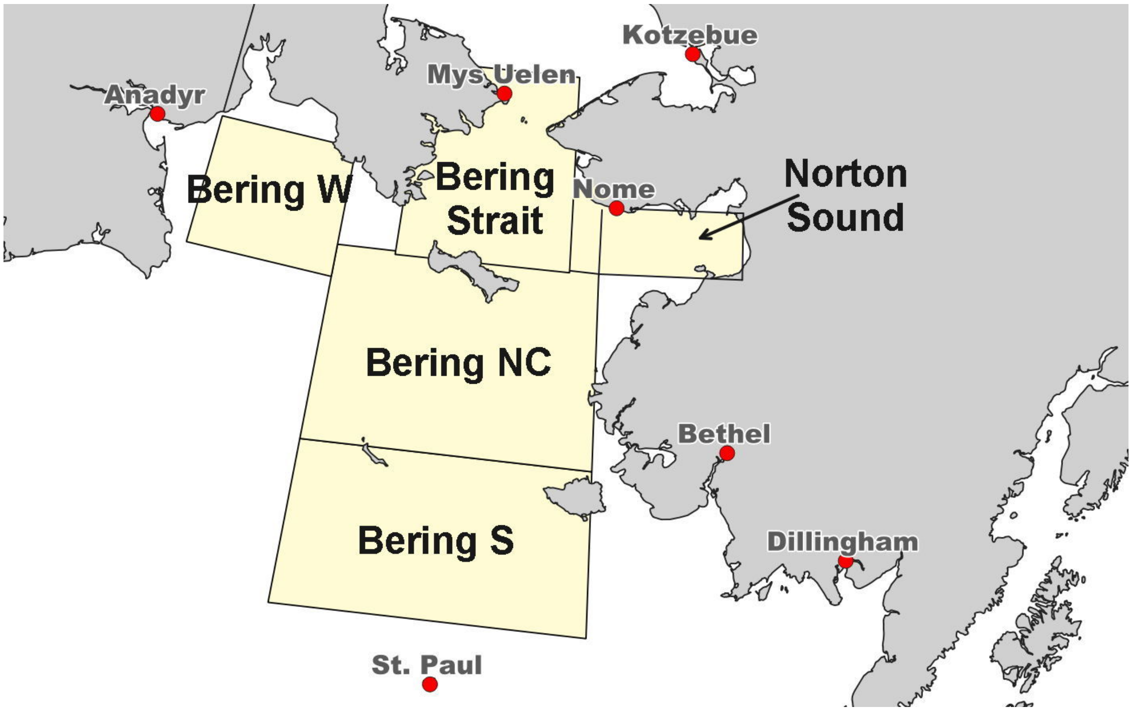
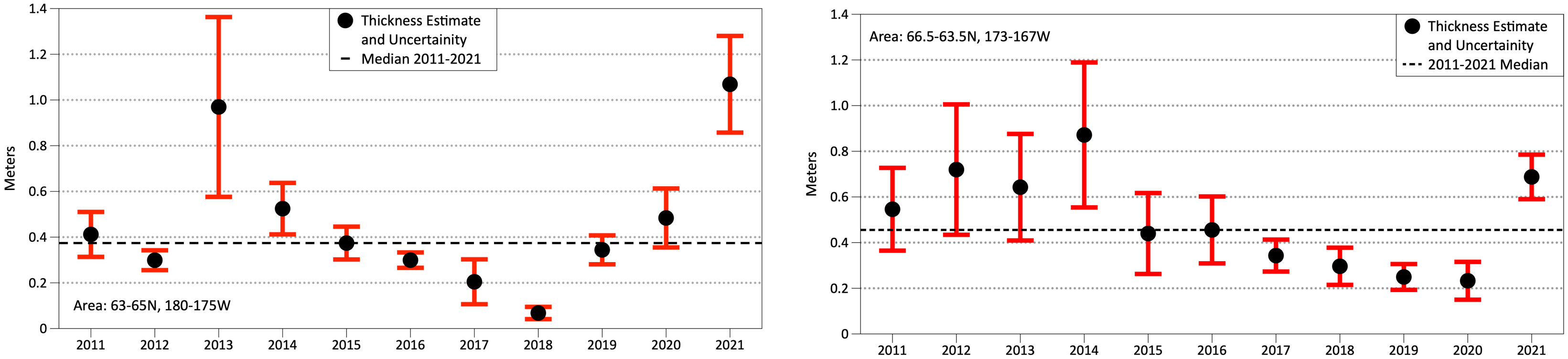
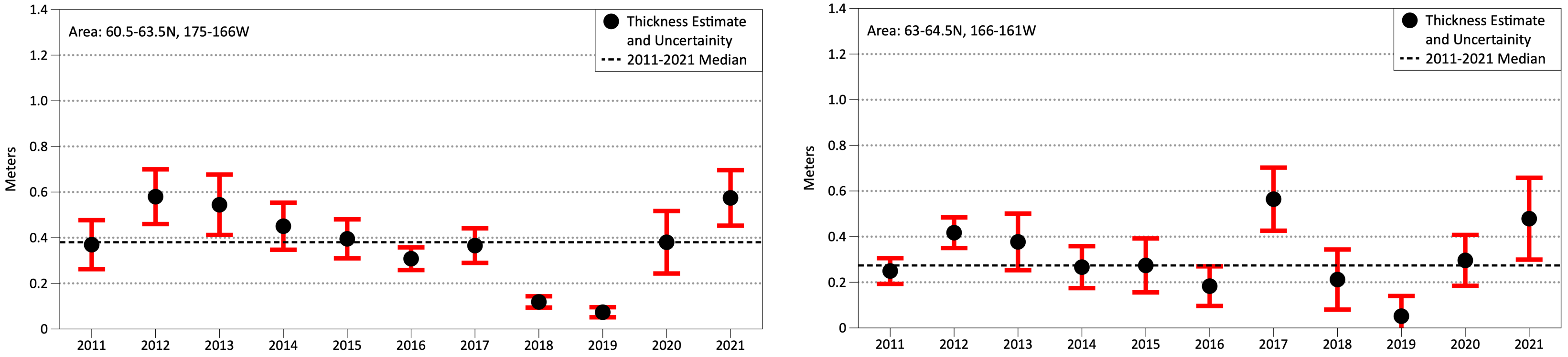


Figure 14: Map showing the five areas over the Bering Sea within which ice thickness indices were calculated: Gulf of Anadyr (Bering W), Bering Strait, Norton Sound, St. Lawrence Island to St. Matthew Island (Bering NC), and St. Matthew Island and St. Paul Island (Bering S)



(a) Gulf of Anadyr (b) Bering Strait



(c) St. Lawrence Island to St. Matthew Island (d) Norton Sound

Figure 15: Sea ice thickness in the Bering Sea for (a) Gulf of Anadyr, (b) Bering Strait, (c) St. Lawrence Island to St. Matthew Island, and (d) Norton Sound. Source: Alfred Wegener Institute, `https://www.meereisportal.de/en/`

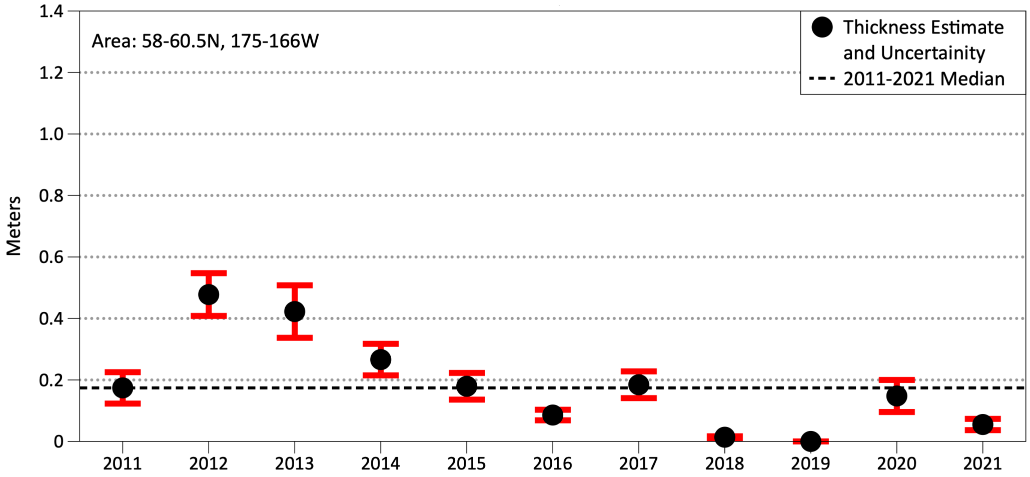


Figure 16: Sea ice thickness between St. Matthew Island and St. Paul Island. Source: Alfred Wegener Institute, `https://www.meereisportal.de/en/`

4. Wind and Ocean Currents

Sea Level Pressure Anomalies

Contributed by Nick Bond, *nicholas.bond@noaa.gov*

The state of the North Pacific climate from autumn 2020 through summer 2021 can in part be summarized in terms of seasonal mean sea level pressure (SLP) anomaly maps. The SLP anomalies are relative to mean conditions over the period of 1981–2010. The SLP data are from the NCEP/NCAR Reanalysis project and are available by NOAA's Physical Sciences Laboratory (PSL)[5].

The SLP pattern during autumn (Sep–Nov) 2020 (Figure 17a) included positive anomalies south of the Aleutians and negative anomalies over northeastern Siberia. This SLP distribution resulted in anomalous winds from the southwest for the Bering Sea and suppressed storminess for the southeast Bering Sea shelf.

The winter (Dec–Feb) of 2020–2021 (Figure 17b) featured strongly negative SLP anomalies in the southwestern Bering Sea and positive SLP anomalies in the eastern part of the mid-latitude North Pacific. The consequence was enhanced westerlies stretching from the Aleutians to the GOA.

The positive SLP anomalies in the NE Pacific persisted through spring (Mar–May) of 2021 (Figure 17c), with their spatial extent expanding west of the dateline and northward into the Bering Sea and GOA. The highest pressures were at roughly a latitude of 45°N, again resulting in westerly wind anomalies for the Bering Sea and GOA.

The distribution of SLP anomalies across the North Pacific during summer (Jun–Aug) of 2021 is shown in Figure 17d. As is often the case during this time of year, the seasonal mean anomalies were generally of moderate amplitude. The negative SLP anomalies over the NBS extending across the Chukchi Sea to north of Alaska implies enhanced storm activity for those regions.

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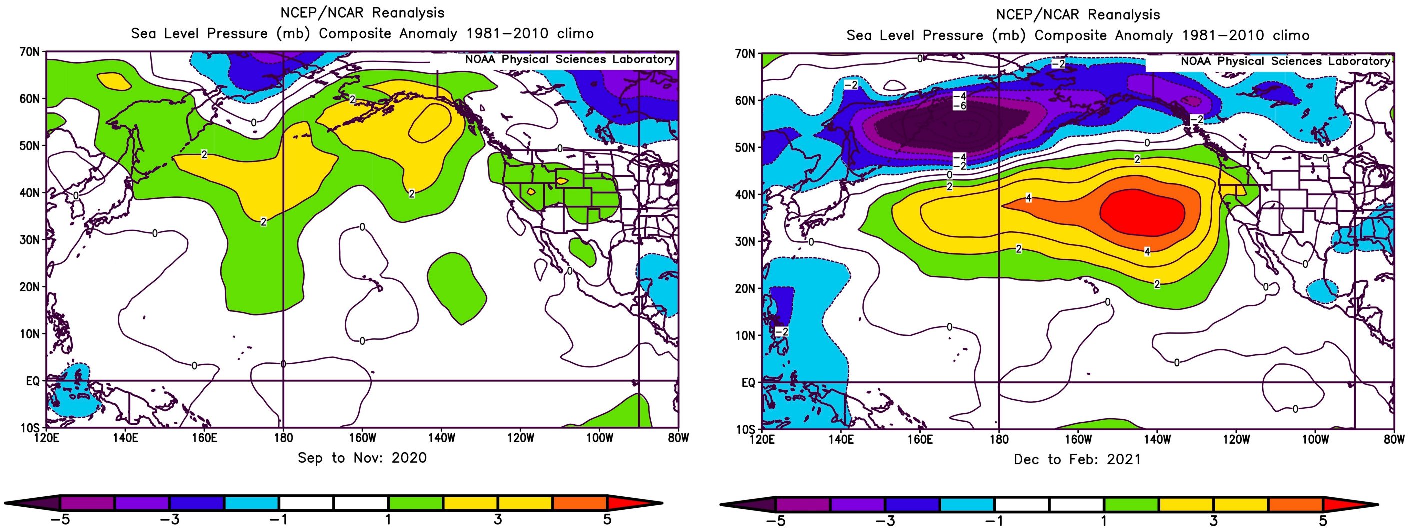
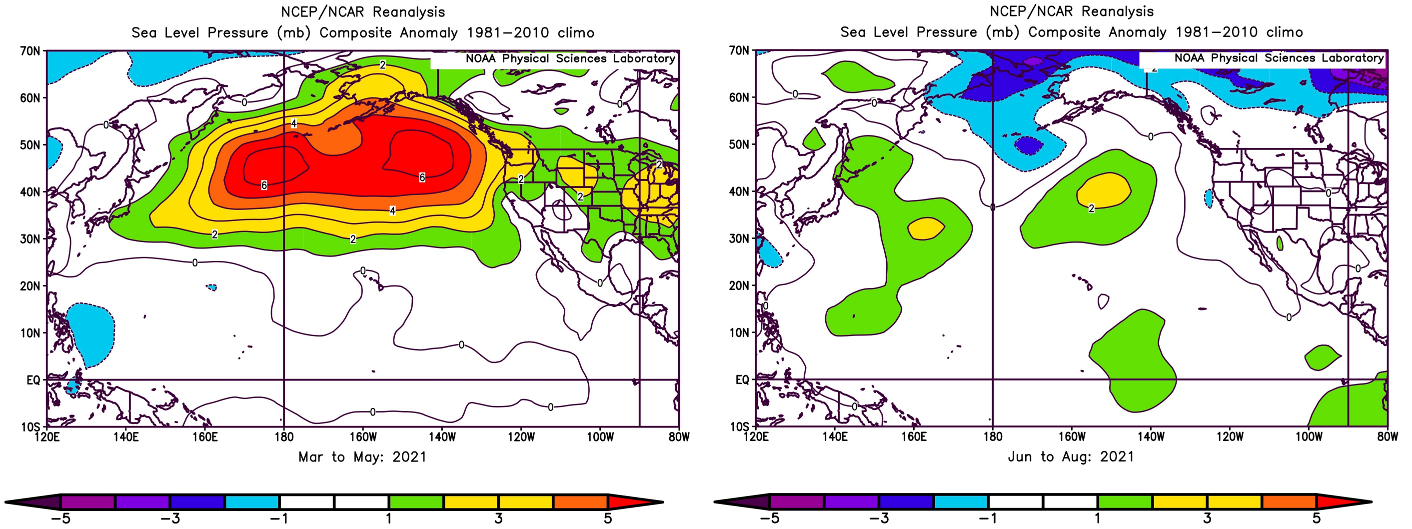
[5] `https://www.psl.noaa.gov/cgi-bin/data/composites/printpage.pl.`



(a) Autumn (b) Winter



(c) Spring (d) Summer

Figure 17: Sea level pressure anomalies for autumn (Sept–Nov 2020), winter (Dec 2020–Feb 2021), spring (Mar–May 2021), and summer (Jun–Aug 2021).

Winter Wind Speed and Direction

Contributed by Rick Thoman, *rthoman@alaska.edu*

The average winter (Nov–Mar) wind speed categorizes years as having prevailing north winds or south winds. No long-term trend is exhibited, although winters ending in 2018 and 2019 were among 5 years with the strongest south winds, which contributed to low sea ice extent in those years. For winter 2020–2021, the south wind component was the 10th strongest in the 73 year record, and this contributed to the low max sea ice extent (Figure 18).

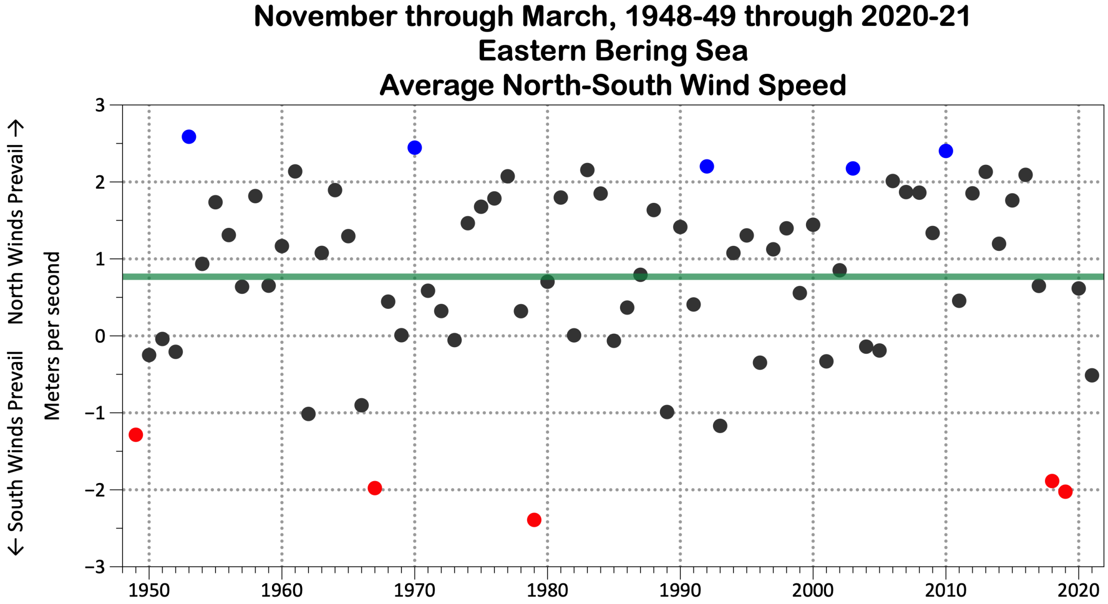


Figure 18: Winter (Nov–Mar) average north-south wind speed in the Bering Sea, 1949–2021. Red dots denote five years with strongest south winds, blue dots the five strongest north winds. **Note:** the north-south (meridional) component of the wind is plotted inverse to meteorological convention with south to north as negative values and north to south as positive values. Source: NCEP/NCAR reanalysis.

Spatial Variability of Prevailing February Winds

Contributed by Tyler Hennon, *tdhennon@alaska.edu*

NCAR/NCEP 10m wind reanalysis was used to examine the spatial variability of the prevailing winds during the month of February. *Nota bena:* wind speed and the length of velocity vectors do not have a 1:1 correlation in Figures 19 and 20. For example, strong winds that oscillate between northerly and southerly will have high speed but a short velocity vector (velocities average near zero), whereas steady strong southerlies will have both a high speed and long velocity vector.

Trends

In 2018, February winds were nearly universally strong and southerly over much of the Bering (Figure 19), which was also the case for 2019 (not shown). These strong southerly winds advected warm air from lower latitudes to the Bering Sea. In February, 2020 (not shown), moderate northerly winds prevailed (advecting cold polar air from high latitudes). Interestingly, in February 2021, these northerly winds intensified (Figure 20) over the northern portion of the shelf while southerly winds prevailed over the southern portion of the shelf. These different atmospheric conditions can have a strong influence on sea surface temperature and ice formation.

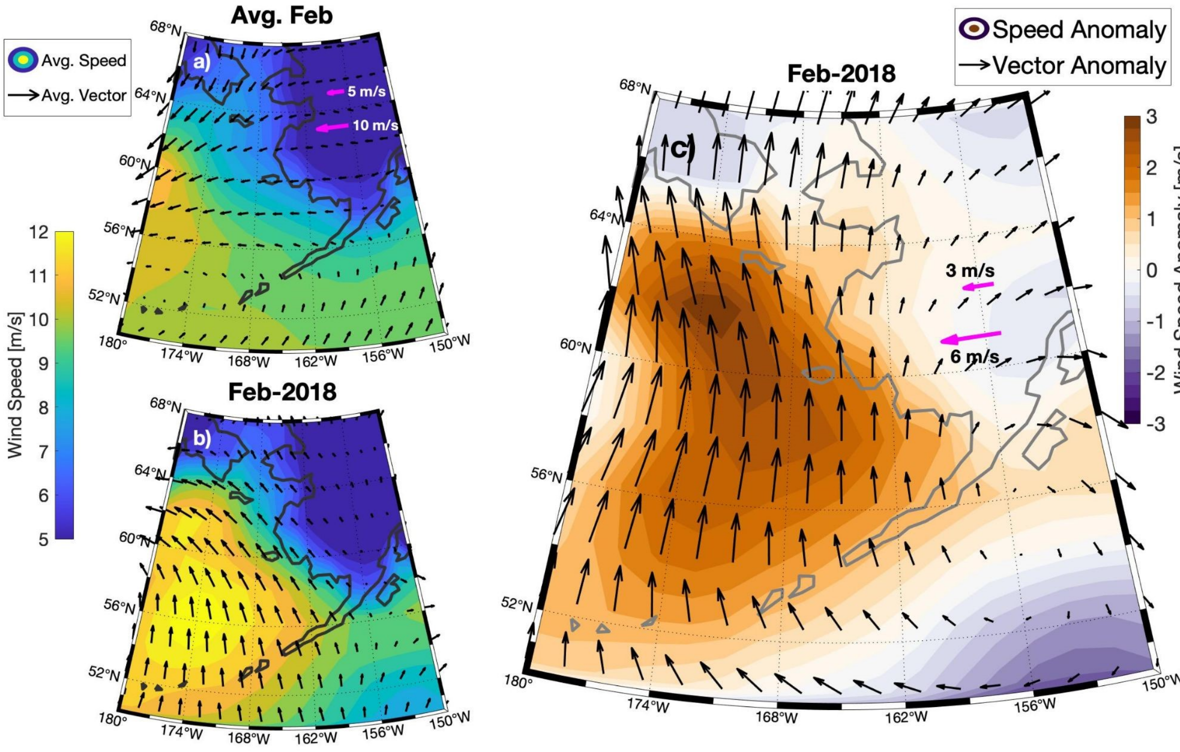


Figure 19: Spatial variability of prevailing winds. a) Average 10m wind vectors (black arrows) and wind speed (color map) during February 2000–2021. Magenta arrows indicate vector scale. b) As in a), but the average for only February 2018. c) The wind vector anomalies (black arrows) and speed anomalies (color map) for February 2018, which is the difference between (b) and (a).

Spring Jet Stream and Sea Level Pressure

Contributed by James Overland, *james.e.overland@noaa.gov*

NCEP/NCAR reanalysis from March to May 2021 shows a weak sea level pressure gradient that is suggestive of a counterclockwise circulation cell over the Bering Sea (Figure 21, top left), which may explain the warmer than average near-surface air over the same time frame (Figure 21, top right). While no obvious circulation cell is present from June to August 2021 (Figure 21, bottom left), again the weak gradients suggest southwesterly air currents transporting heat to the southern Bering Sea, a pattern which is also generally reflected in the sea surface air (Figure 21, bottom right).

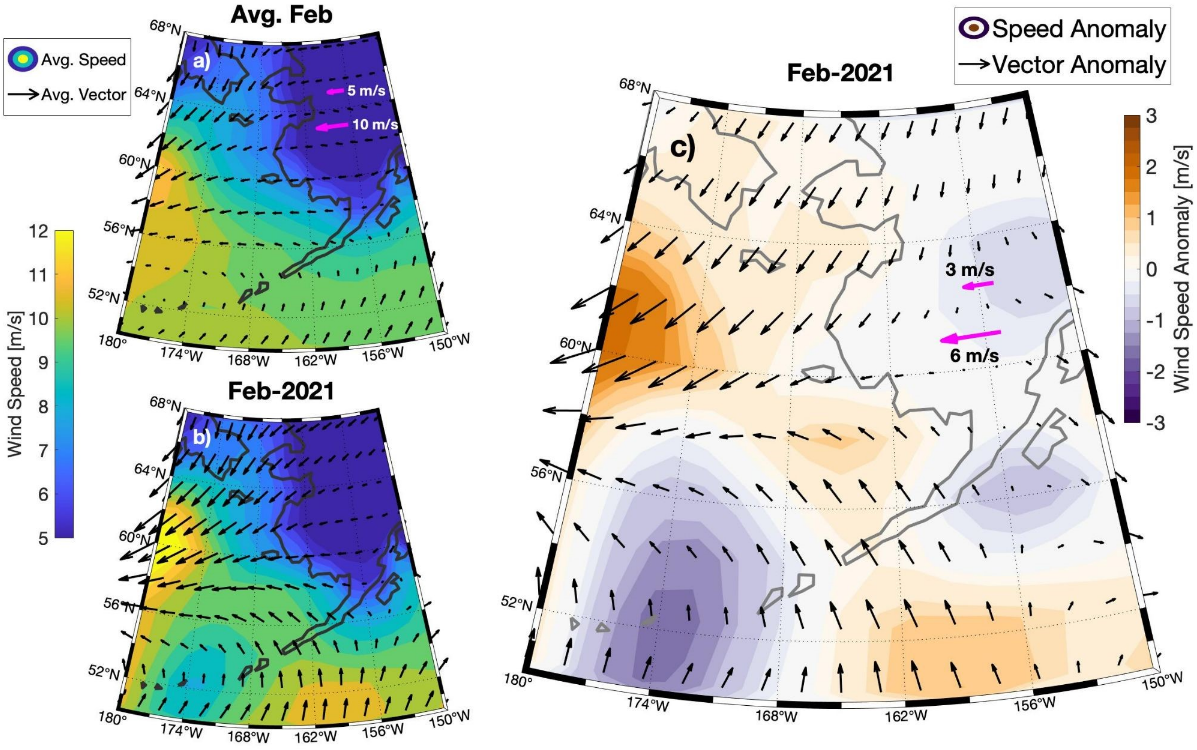


Figure 20: Spatial variability of prevailing winds. a) Average 10m wind vectors (black arrows) and wind speed (color map) during February 2000–2021. Magenta arrows indicate vector scale. b) As in a), but the average for only February 2021. c) The wind vector anomalies (black arrows) and speed anomalies (color map) for February 2021, which is the difference between (b) and (a).

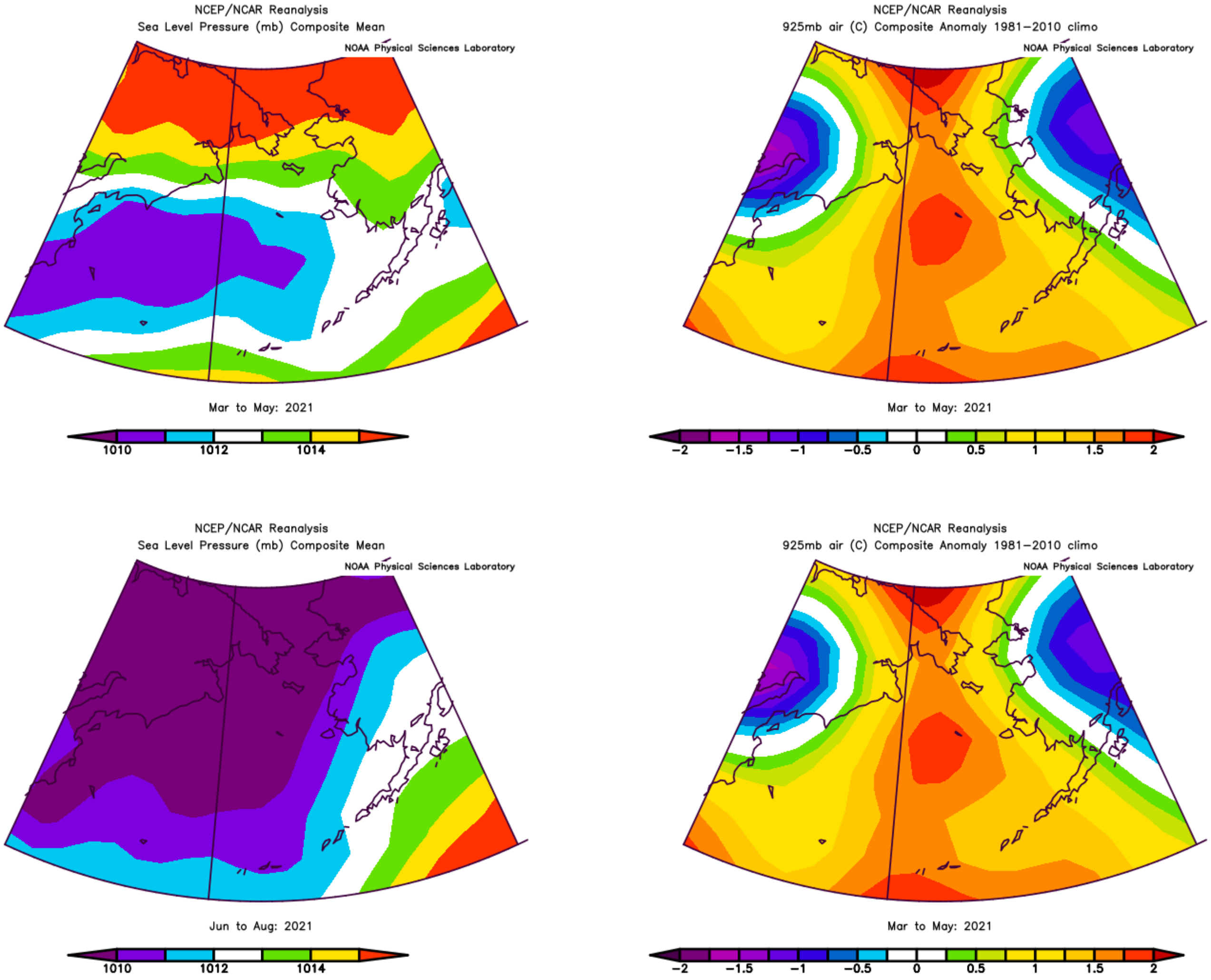


Figure 21: Left panels: Sea level air pressure from March–May 2021 (top) and June–August 2021 (bottom). Right panels: Air temperature at 925 mb from March–May 2021 (top) and June–August 2021 (bottom).

Winds at the Bering Sea Shelf Break

Contributed by Tyler Hennon, *tdhennon@alaska.edu*

NCEP/NCAR wind reanalysis was used to look at the along- and cross-slope wind components at the Bering shelf break. Four-times daily wind data dating back to January 2000 were interpolated to a transect approximating the shelf break (Figure 22), and the zonal and meridional components were rotated into along- and cross-shelf components. These components of wind were then averaged across the whole transect for each month dating back to 2000.

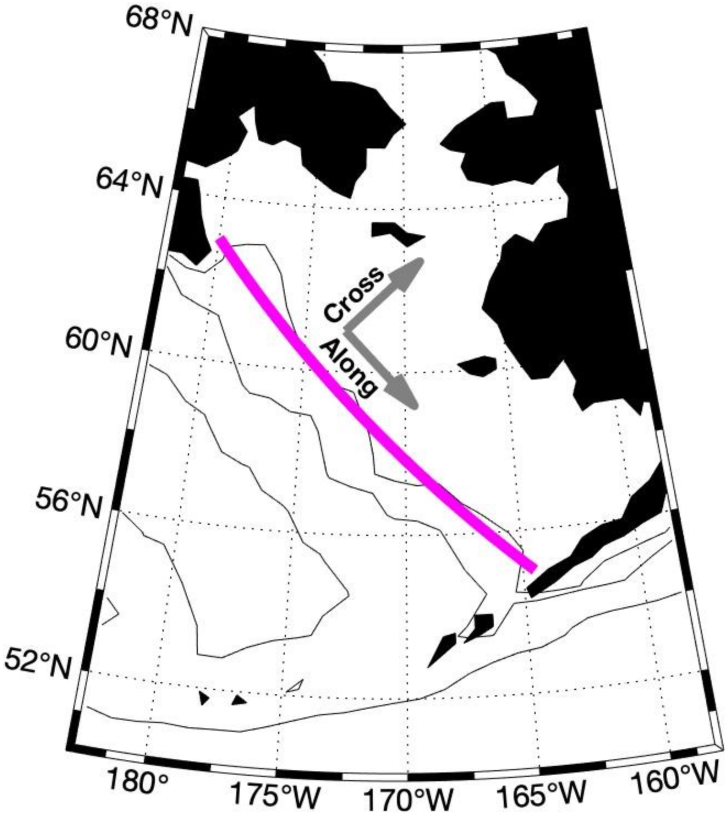


Figure 22: The magenta line shows the line chosen to evaluate along-shelf and cross-shelf wind components in the Bering Sea. Annotation arrows show the direction used to define positive cross and along shelf components of wind. Contours show isobaths at 100m, 500m, and 3500m.

The average annual cycle (2000–2021) is more apparent in the cross-shelf component than the along-shelf, and wind speeds are generally higher for the cross-shelf component as well (Figure 23, top panel). January to May of 2020 was marked by weak, but consistent, along-shelf winds coming from the southeast (negative in Figure 23), which is favorable for upwelling (Ekman transport is 90° to the right of wind direction in the northern hemisphere). Thereafter and through October 2021 along-shelf wind did not consistently demonstrate upwelling or downwelling favorable conditions. The behavior of the cross-shelf winds, which provoke currents that are along-shelf, generally resembled the average annual cycle (the 2000–2021 mean), albeit with considerably more scatter.

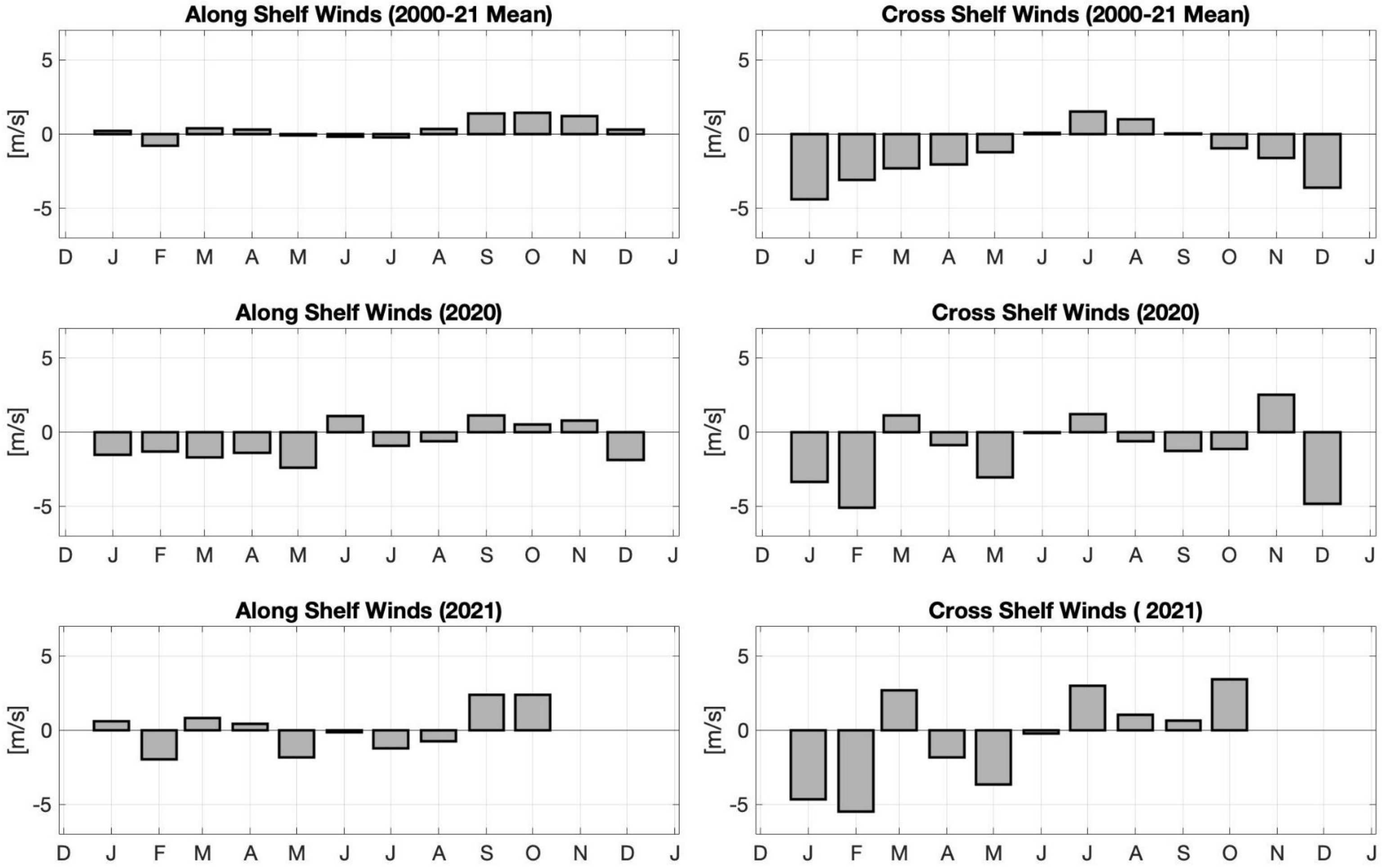


Figure 23: Along-shelf (left set of panels) and cross-shelf (right set of panels) wind components averaged along the magenta line in 22. Top panels show the monthly averages across the period of record. Middle panels show the monthly averages for 2020, and bottom panels show the average monthly average for 2021. Positive along-shelf winds are defined as blowing to the southeast, and positive cross-shelf winds are defined as blowing to the northeast.

Eddy Kinetic Energy

Contributed by Wei Cheng, *wei.cheng@noaa.gov* and Tyler Hennon, *tdhennon@alaska.edu*

Eddy kinetic energy (EKE) measures the variability from mean currents, and is defined as $(u'^2 + v'^2)/2$, where u' and v' are anomalies from the long term averages of zonal and meridional velocities, respectively. There are numerous processes that can elevate EKE, such as meandering currents, a change in current speed, or the occurrence of a classic oceanic eddy. All of these processes can potentially impact the transport of heat, nutrients, as well as planktonic matter.

The source of velocity anomaly estimates is based on altimetric data from the Copernicus programme, which has archived daily observations from 1993 to the present. Average EKE on the Bering Sea shelf is very low, while the average values of EKE associated with the Bering Sea shelf break current are weak compared to regions of the Aleutian Islands or Gulf of Alaska, where the currents are stronger. Figure 24 highlights several regions of the shelf break with moderately strong EKE. In each region, there is significant seasonality, with the highest EKE usually occurring in the spring to early summer.

During 2020, EKE on the shelf break was quite low, particularly from January through April in the northwest regions (Figure 24). Wind conditions were fairly average during this time frame, which may act to suppress EKE (current variability can be induced by anomalous winds). In the first half of 2021, however, winds were slightly stronger than average (Figure 24), which may be a factor in explaining why EKE was generally higher in the first half of 2021 compared to the first half of 2020.

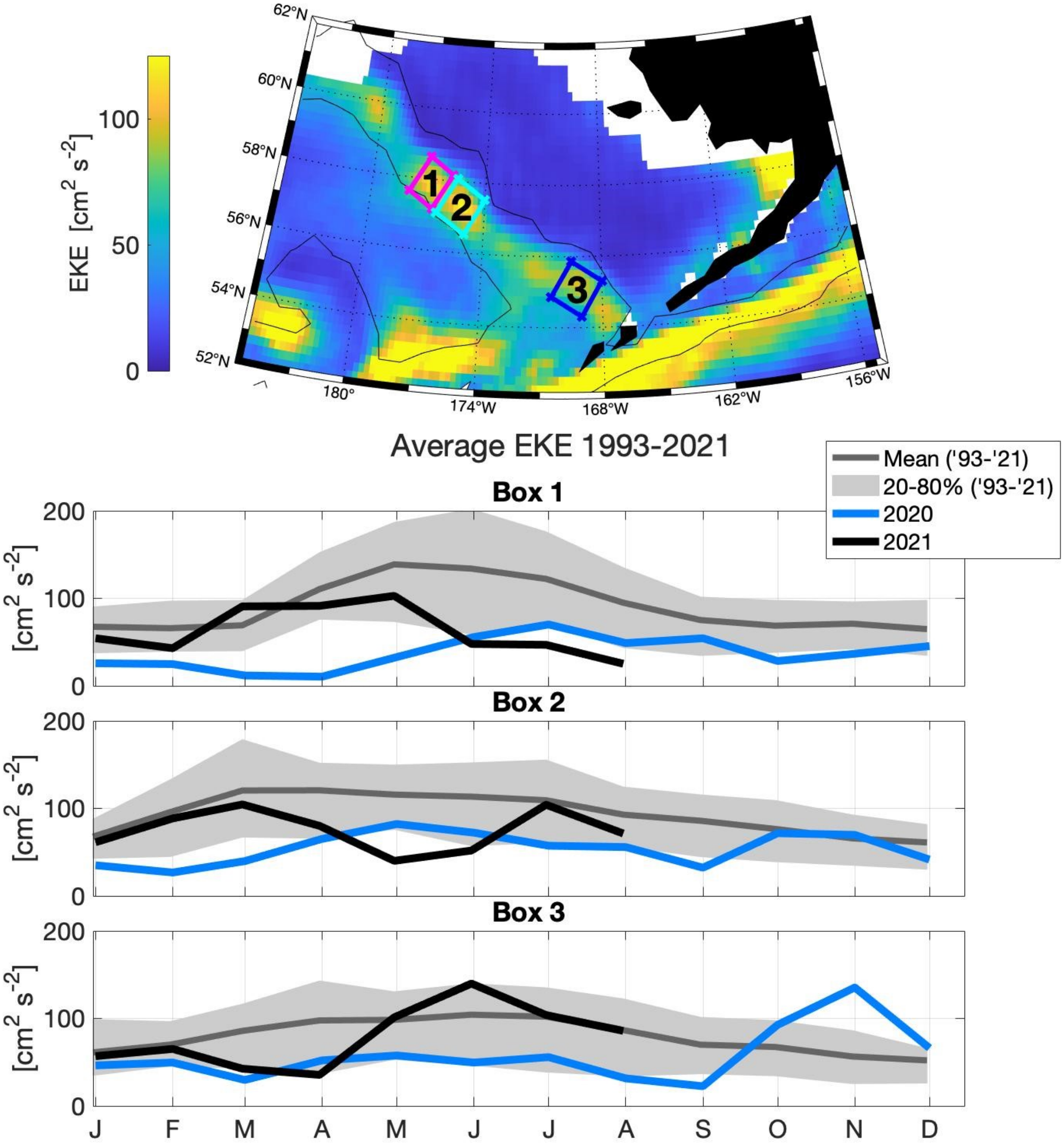


Figure 24: Top: Boxes show the spatial boundaries used for averaging eddy kinetic energy (EKE) for three areas along the Bering Sea shelf break. Lower panels: EKE from 1993–present. The gray line represents the mean for each month from 1993–2021 and the shaded region represents the 20$^{\text{th}}$–80$^{\text{th}}$ percentile for each month for the same time frame. Blue lines show EKE for 2020, and black lines show 2021.

St. Paul Air Temperature Anomalies

Contributed by James Overland, *james.e.overland@noaa.gov* and Muyin Wang, *muyin.wang@noaa.gov*

Monthly surface air temperature anomalies at St. Paul Island (WMO ID 25713) are shown in Figure 25. The anomaly is computed relative to the 1981–2010 period mean. Data are obtained from `https://data.giss.nasa.gov/gistemp/station_data_v4_globe`.

Trends

A linear trend of 0.57°C/decade has been observed since 1980 in addition to continuous positive anomalies that have dominated the region since 2014, with a maximum temperature anomaly of 6.66°C reached in February 2019.

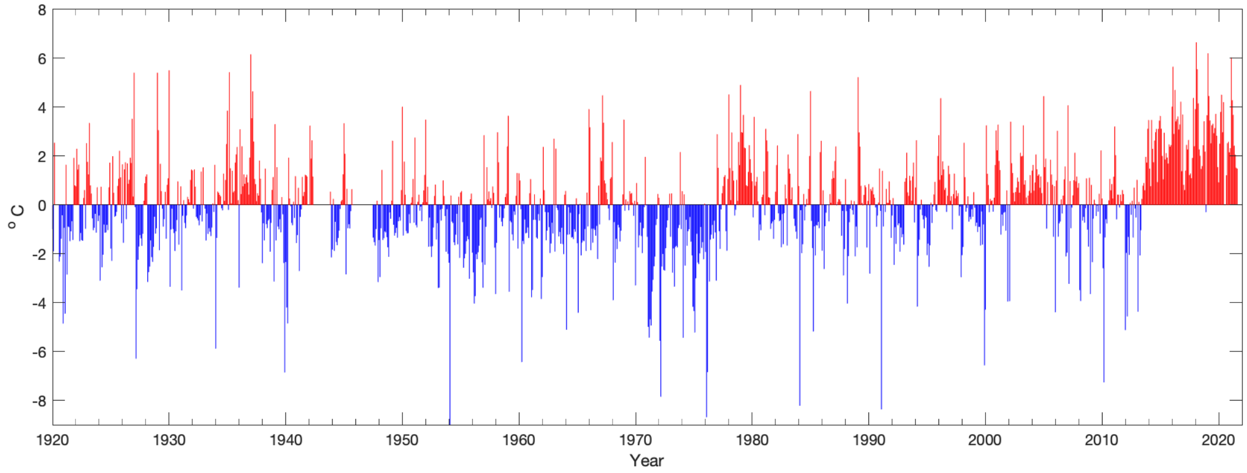


Figure 25: St. Paul Air Temperature Anomalies.

5. Surface and Bottom Temperatures

North Pacific Sea Surface Temperature (SST) Anomalies

Contributed by Nick Bond, *nicholas.bond@noaa.gov*

The state of the North Pacific climate from autumn 2020 through summer 2021 can in part be summarized in terms of seasonal mean sea surface temperature (SST) anomaly maps. The SST anomalies are relative to mean conditions over the period of 1981–2010. The SST data are from NOAA's Optimum Interpolation Sea Surface Temperature (OISST) analysis and are available by NOAA's Physical Sciences Laboratory (PSL)[6].

The autumn of 2020 (Figure 26a) included warmer than normal SSTs across virtually the entire North Pacific Ocean. Particularly warm waters with anomalies exceeding 2°C were present east of Hokkaido, in the northwestern Bering Sea near the Gulf of Anadyr, and in the eastern portion of the basin along 40°N from 160° to 130°W. The equatorial Pacific east of the dateline was cooler than normal in association with the development of moderate La Niña conditions.

The magnitude of the positive SST anomalies in the North Pacific moderated late in 2020. For the winter (Dec–Feb) of 2020–2021 as a whole, Figure 26b shows that the region of relative warmth

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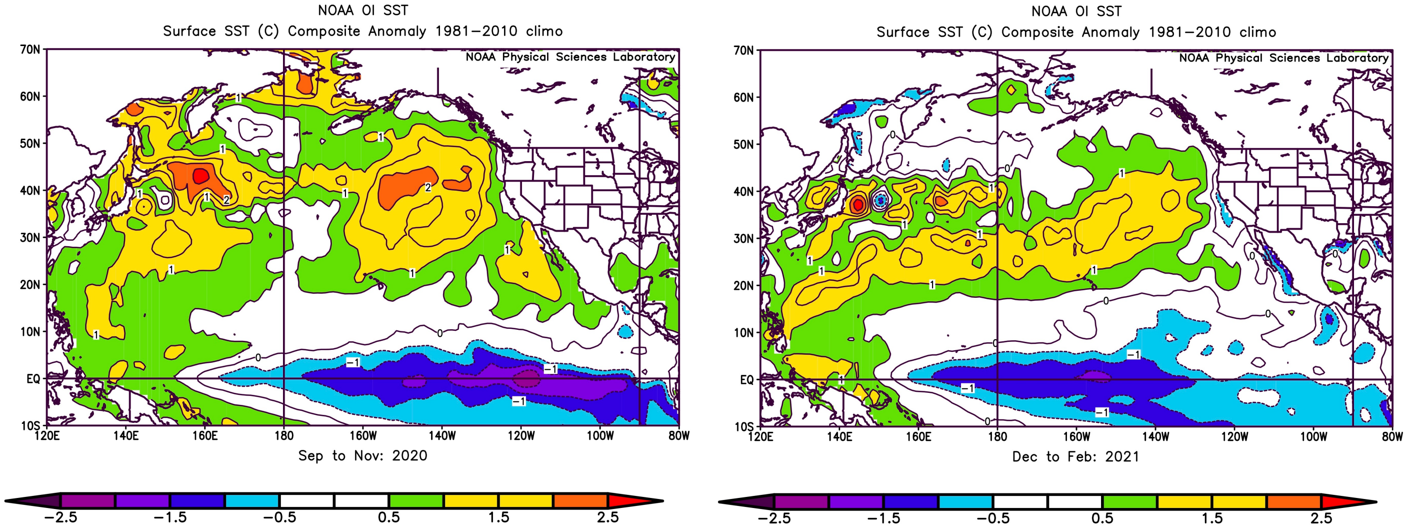
[6] `https://www.psl.noaa.gov/cgi-bin/data/composites/printpage.pl.`

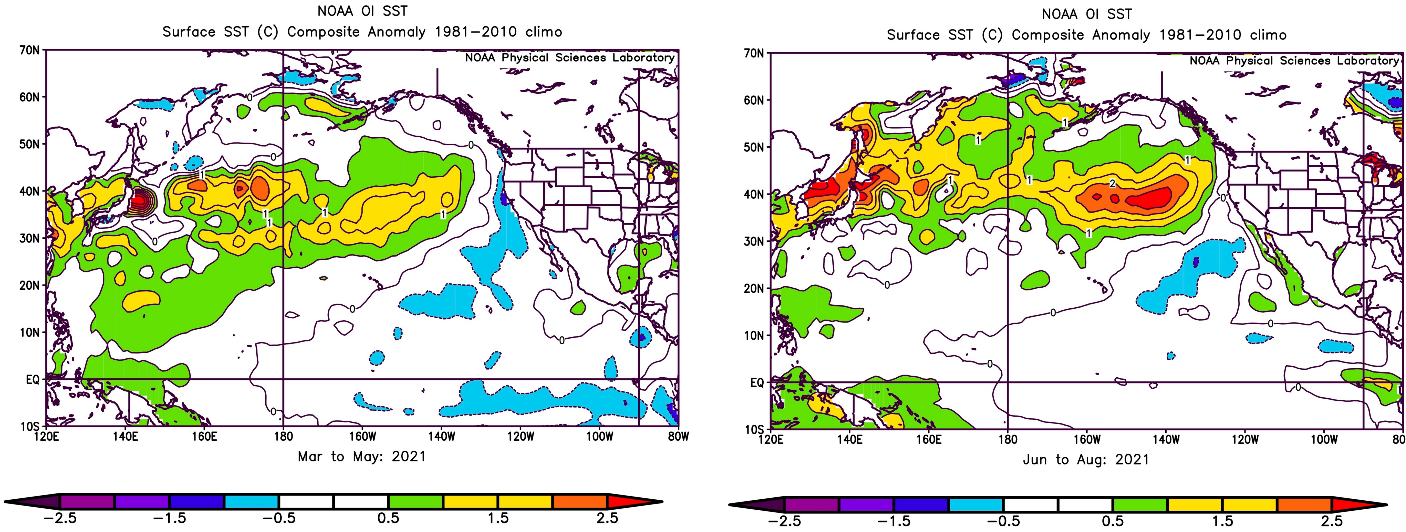
was confined largely to a basin-wide band between 15° and 45°N, with mostly minimal anomalies (< 0.5°C magnitude) on the Bering Sea shelf and in the GOA. La Niña remained present, with the most prominent anomalies occurring in the central tropical Pacific.

The large-scale SST anomaly pattern in the North Pacific during spring (Mar–May) of 2021 (Figure 26c) was similar to that of the previous winter. There were increases in the magnitudes of the warm anomalies in the western North Pacific from Japan to the dateline, and to a lesser extent for the southeastern Bering Sea. The tropical Pacific returned to near-neutral ENSO conditions, with slightly cool SSTs east of the dateline.

During the summer (Jun–Aug) of 2021 (Figure 26d), the positive SST anomalies in the mid-latitudes of the North Pacific increased to the east of the dateline well off the coast of the US lower 48 states. There were minor warm SST anomalies on the southeastern Bering Sea shelf. The tropical Pacific was in a near-neutral state.



(a) Autumn (b) Winter



(c) Spring (d) Summer

Figure 26: Sea surface temperature anomalies for autumn (Sept–Nov 2020), winter (Dec 2020–Feb 2021), spring (Mar–May 2021), and summer (Jun–Aug 2021).

Bering Sea SST Trends and Anomalies

Contributed by Jordan Watson, *jordan.watson@noaa.gov*,
and Matt Callahan, *matt.callahan@noaa.gov*

Satellite SST data (source: NOAA Coral Reef Watch Program) were accessed via the NOAA CoastWatch West Coast Node ERDDAP server[7]. Daily data were averaged within the southeastern (south of 60°N) and northern (60°–65.75°N) Bering Sea shelf (10–200m depth). Detailed methods are available online[8].

SST Trends

The northern and southeastern Bering Sea regions continue to experience SSTs that are warmer than the 30-year baseline (1985–2014) conditions. While the southeastern Bering Sea saw conditions in 2021 that were generally cooler than during the previous year, much of the fall and winter in the NBS were similarly warm as the previous year. The exception to this has been the summer of 2021, which has been cooler than that of the summer 2020 in general (Figure 27).

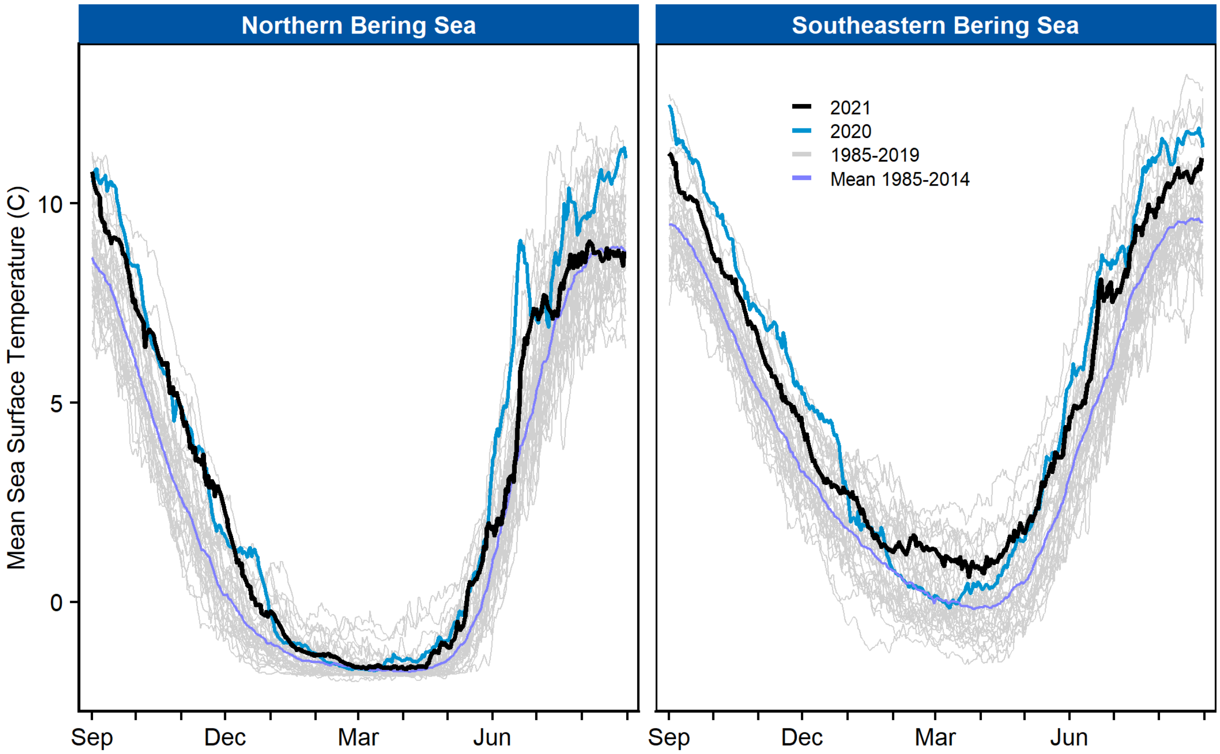


Figure 27: Mean SST for the northern (left) and southeastern (right) Bering Sea shelves. The most recent year (2020–2021; through August 31, 2021) is shown in black, winter 2019/2020 is shown in blue, and the historical mean is shown in purple. Individual years in the time series are shown in light gray.

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[7] `https://coastwatch.pfeg.noaa.gov/erddap/griddap/NOAA_DHW.html`

[8] `github.com/jordanwatson/EcosystemStatusReports/tree/master/SST`

SST Time Series Trends

Trend analysis removed seasonality and noise from the SST time series (Edullantes, 2019) to better illustrate the long term trends in the SST data (Figure 28). Trends are compared to the mean (±1 SD) from a 30-yr baseline (1985–2014) and demonstrate that both the northern and southeastern Bering Sea are experiencing a persistent warm stanza, greater in both magnitude and duration than that of the early 2000s. In the most recent data, the intensity of the warm stanza has softened relative to the previous few years of data. **Note:** The time series trend analysis requires truncation of the ends of the time series (due to differencing) so the trend line extends only into March 2021.

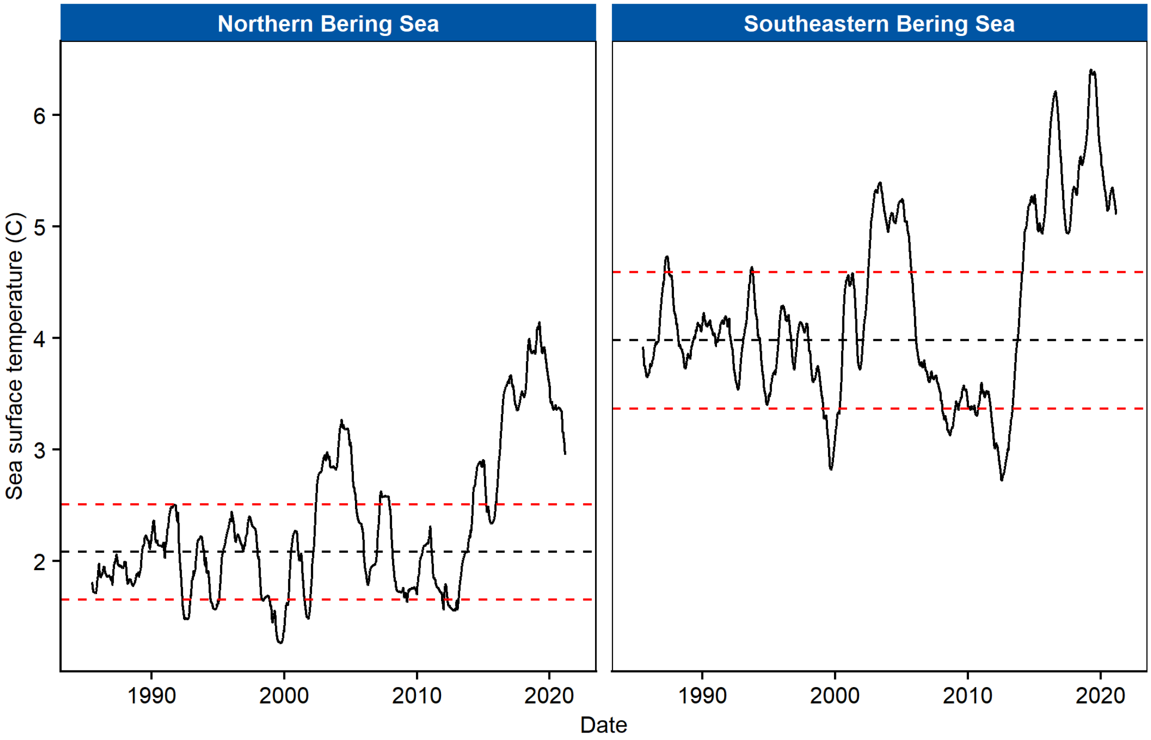


Figure 28: Time series trend of SST (seasonality and noise removed) for the northern (left) and southeastern (right) Bering Sea shelves. The black horizontal dotted line is the 30-year mean (1985–2014) of the trend and the red lines are ±1 SD.

Marine Heatwave Index

Marine heatwaves in 2021 have been relatively minor compared to recent years, with only a few brief and relatively mild events (Figure 29). Notably however, while actual marine heatwaves were not triggered as often or as severely during 2021, temperatures hovered just below the heatwave thresholds for much of the year.

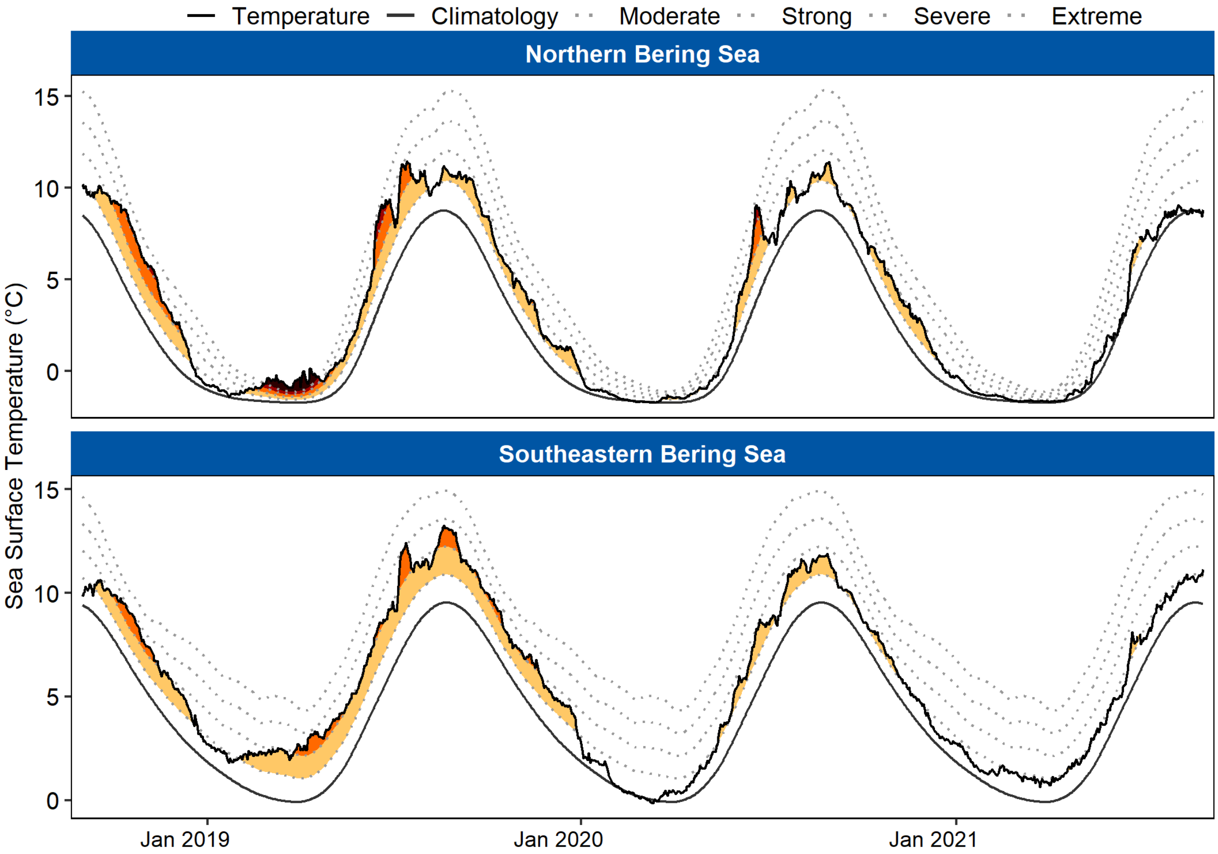


Figure 29: Marine heatwaves in the northern and southeastern Bering Sea since September 2018. The smoothed solid black line represents the baseline average temperature (i.e., climatology) for each day during the 30-yr baseline period (1 Sept 1985–31 Aug 2014). The jagged solid black line is the observed (satellite-derived) sea surface temperature for each day. Dotted lines illustrate thresholds for increasing heatwave intensity categories (moderate, strong, severe, extreme). Colored portions indicate periods during which marine heatwaves occurred, with intensity increasing as colors darken.

Cumulative SST Anomalies

The persistent warmer than average (though typically cooler than heatwave status) conditions still yielded cumulative sea surface temperatures for 2021 that were warmer than average (Figure 30). Such cumulative warming may represent important conditions for the ecology of these systems in that the total thermal exposure for organisms was still higher than historically average conditions. Protracted warming may lead to elevated metabolic rates, higher growth rates, and higher prey demands.

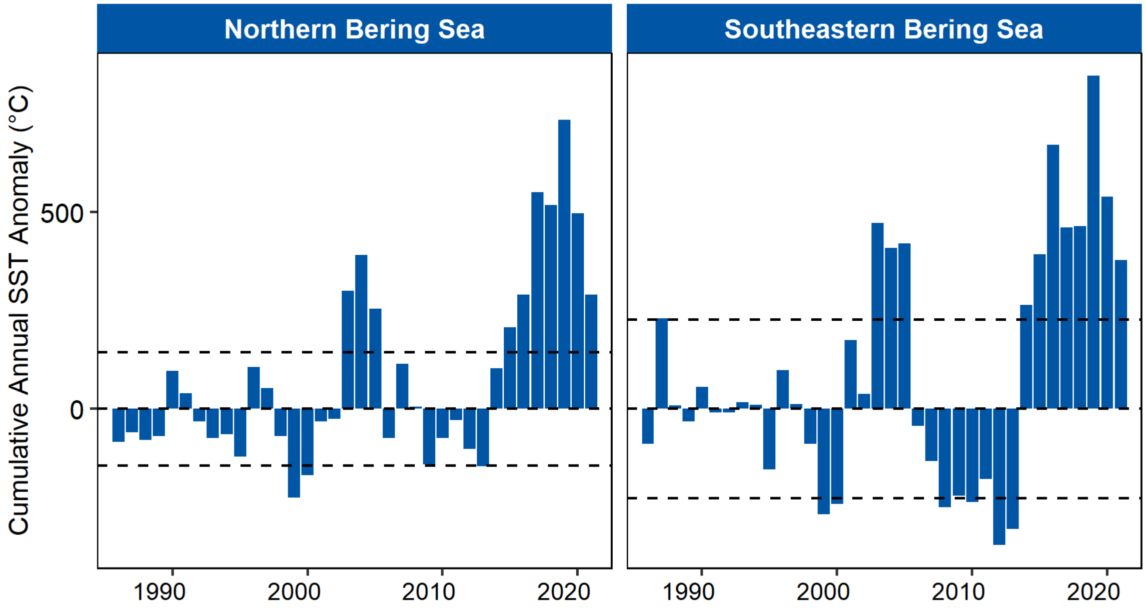


Figure 30: Cumulative annual sea surface temperature anomalies (sum of daily temperatures). Horizontal lines are ±1 SD from the mean during the 30-yr baseline period (1 Sept 1985–31 Aug 2014).

At the seasonal level, patterns of cumulative temperature exposure (degree heating days) demonstrated patterns more consistent with some of the recent warm stanza years than with cooler years of the past (Figure 31). Both the northern and southeastern regions experienced a shift to warmer thermal conditions in 2014.

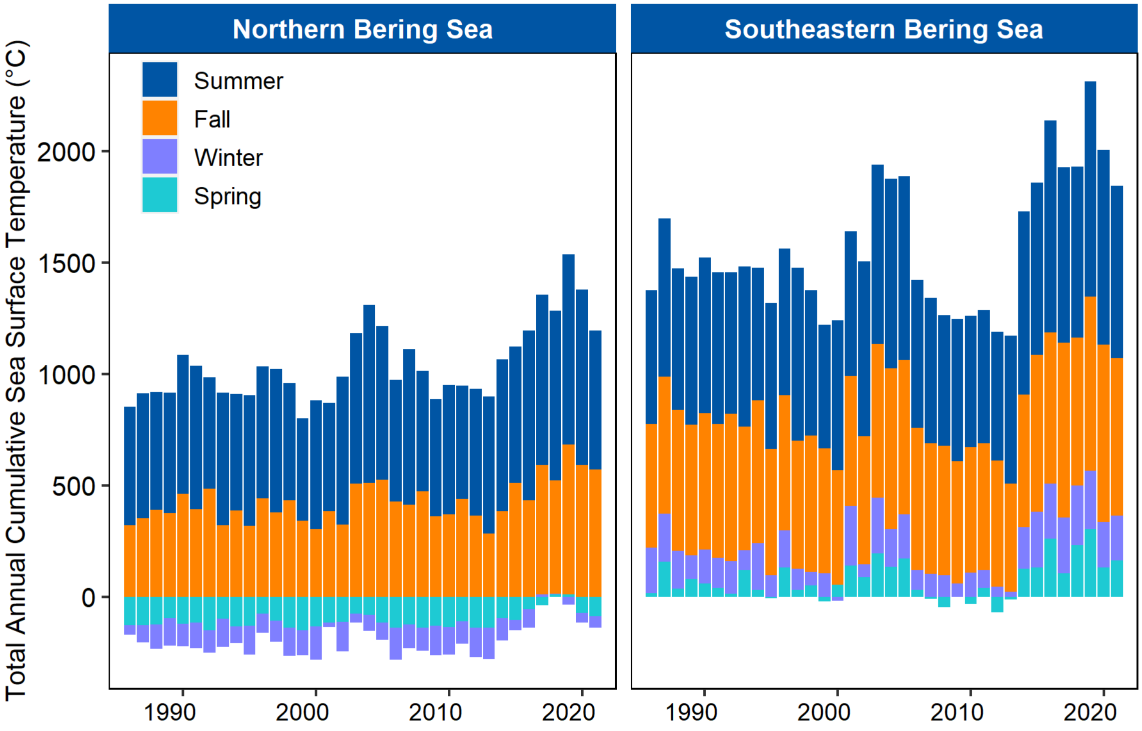


Figure 31: Cumulative sea surface temperatures (sum of daily temperatures) for each year, apportioned by season: summer (Jun–Aug), fall (Sept–Nov), winter (Dec–Feb), and spring (Mar–May). Negative values are the result of sea surface temperatures below zero.

St. Paul Island Temperature, Salinity, and Chlorophyll-a

Contributed by Seth Danielson, *sldanielson@alaska.edu*, Lauren Divine, *lmdivine@aleut.com*, Elizabeth Dobbins, Aaron Lestenkof, and Tyler Hennon

Community-led monitoring of temperature, salinity, and chlorophyll-a from North Dock on the St. Paul Island breakwater have been made since 2014 using CTD data loggers. Instrumentation used since 2015 also had a sensor for chlorophyll a fluorescence, which provides a measure of phytoplankton concentration. Water depth at the sample site is approximately 8m. Water column profiles are collected nominally weekly (Figure 32) and have been averaged into monthly means (Figure 33).

Trends

Water temperatures collected since 2014 from St. Paul Island indicate that 2016, 2018 (first half), and 2019 showed warmer water temperatures than the 7-year mean for most months while 2017, the latter half of 2018, and 2020 were relatively cool intervals. Although there is moderate variability, temperature in 2021 has remained near the 7-year mean. However, across the North Pacific as a whole, 2014 through 2021 has been appreciably warmer than the long-term average and the anomalies shown here all likely significantly underestimate the actual temperature offset relative to the climatology (e.g., Danielson et al. (2020)).

Salinity, however, shows an increasing trend over the time period. Contributing factors to salinity variability on the Bering Sea shelf include ice melt and advection, river discharge, precipitation, evaporation, inflows from the Gulf of Alaska, and cross-slope exchanges with the basin (Aagaard et al., 2006). Sensor drift has recently been determined to be unlikely, so the increased salinity likely represents a real long-term trend. Though the seasonal variability in water density is driven by changes in both temperature and salinity, the long-term increase in density at St. Paul Island is driven primarily by the increase in salinity (Figure 33).

Chlorophyll-a fluorescence measurements show year-to-year variations in the timing of the spring phytoplankton bloom (Figure 34). In particular, the bloom was not detected until May in 2019 and 2020, but the fluorescence did significantly increase above low winter values in April 2016, 2017, and 2018. The timing of phytoplankton bloom conditions has implications for zooplankton and microzooplankton blooms as well as grazing and growth rates.

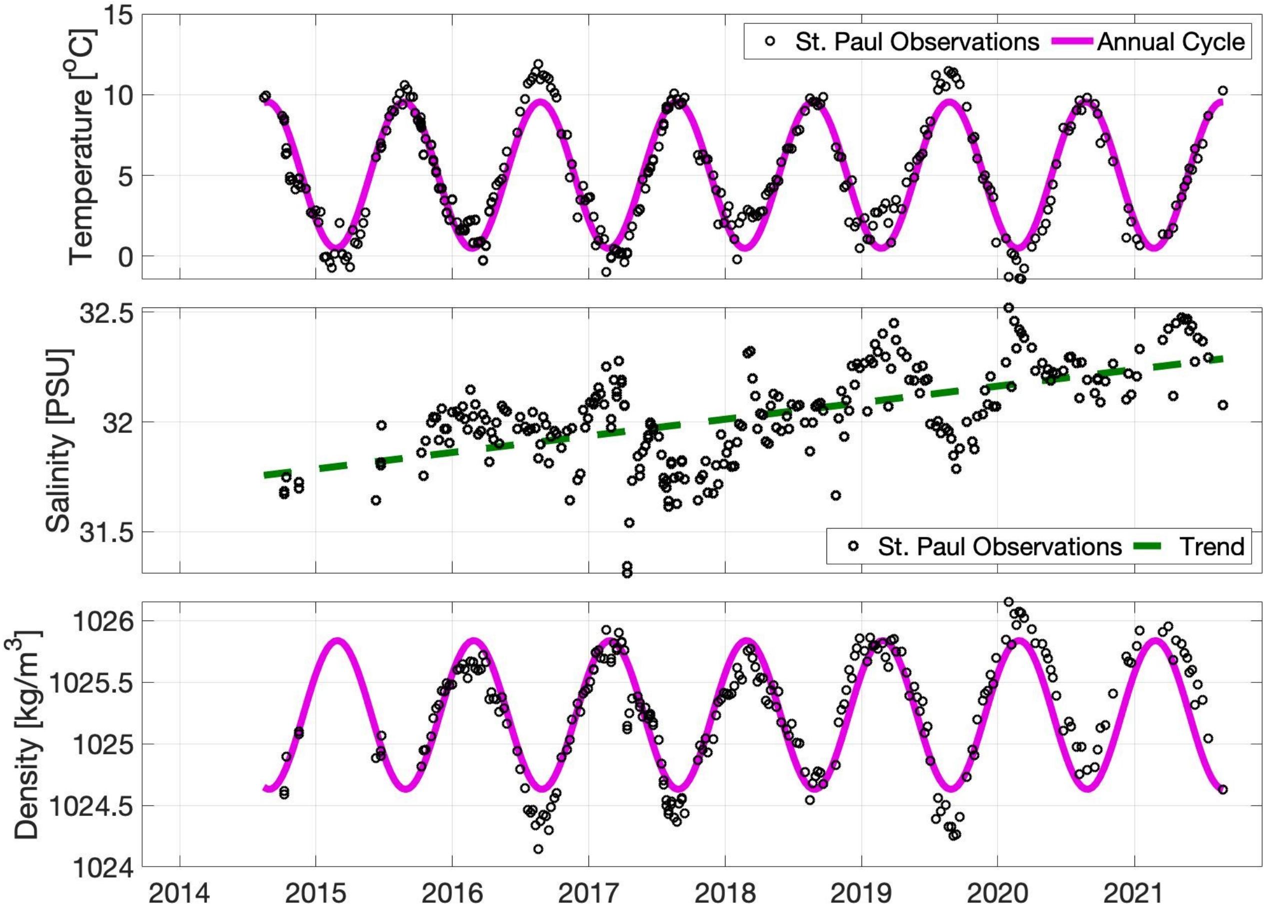


Figure 32: Observations of temperature (top), salinity (middle), and density (bottom) collected at St. Paul Island (black dots). Fitted annual cycles in temperature and density are in magenta and the long-term linear trend in salinity is represented by the dashed green line.

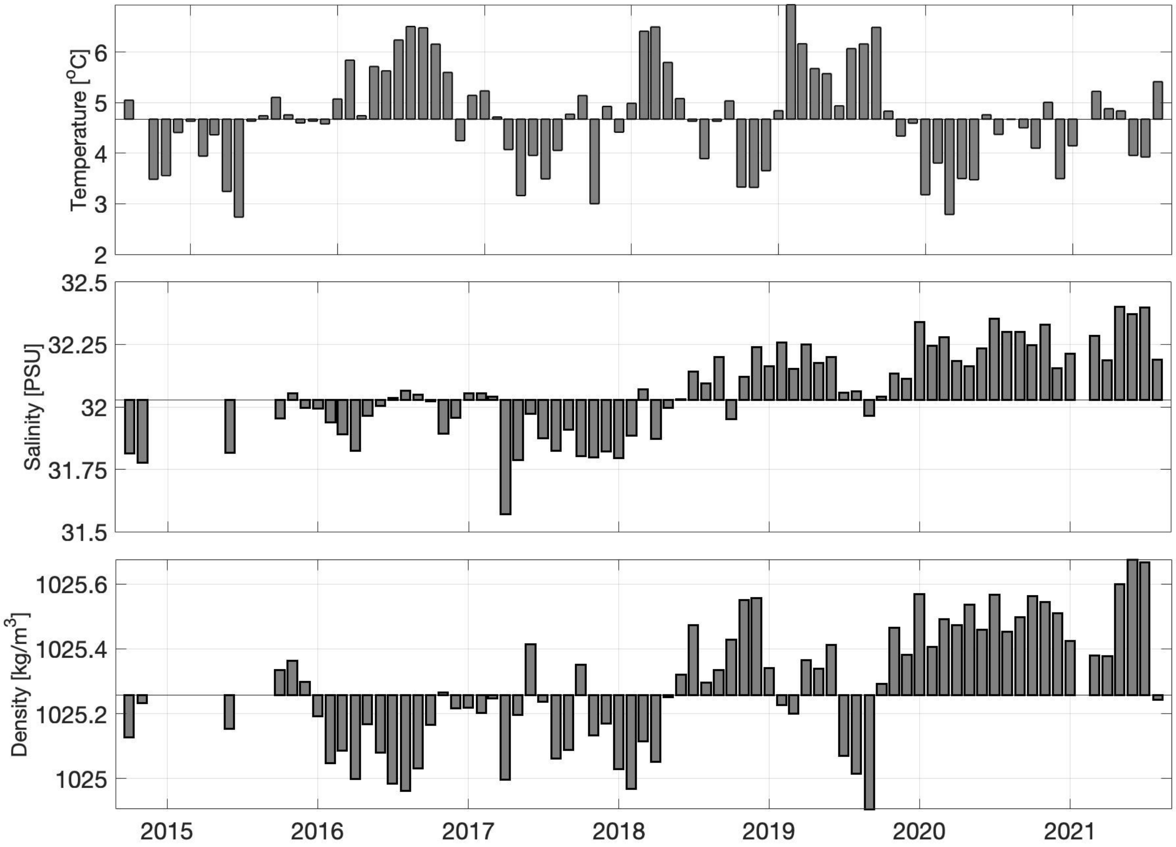


Figure 33: Monthly averages with the seasonal cycle removed for temperature (top), salinity (middle), and density (bottom).

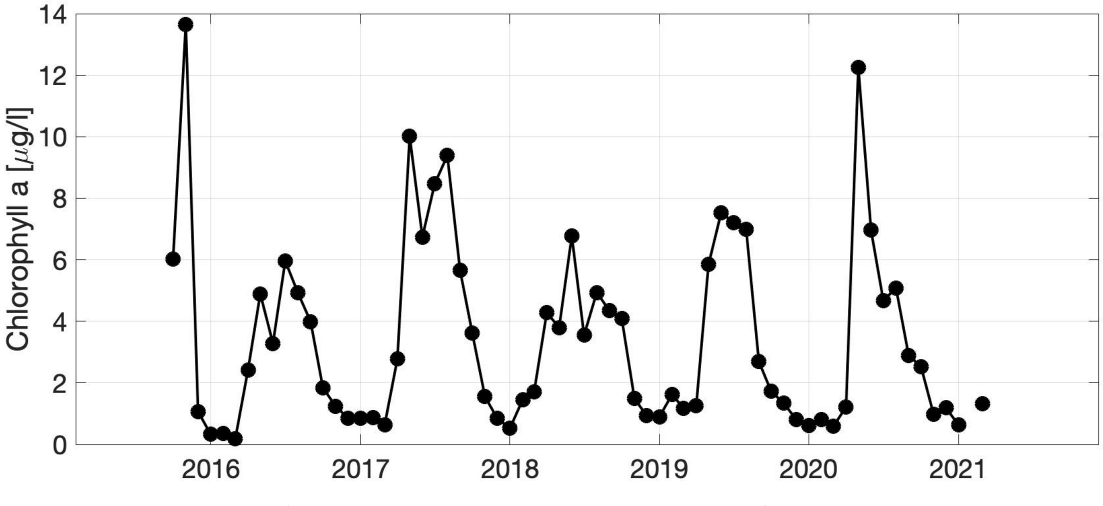


Figure 34: Monthly average of chlorophyll concentrations collected at St. Paul Island through March 2021.

Summer Surface and Bottom Temperatures Over the Bering Sea Shelf

Contributed by Sean Rohan, *sean.rohan@noaa.gov*, and Lewis Barnett, *lewis.barnett@noaa.gov*

In prior years, the mean temperature was calculated as the mean of observed temperatures weighted by stratum area, however this method can be sensitive to missing data. In comparing 10 different interpolation methods with leave-one-out-cross-validation, we found that ordinary kriging with Stein's parameterization of the Matérn semivariogram model produced the lowest prediction error in the majority of years. Therefore, in this and future years, this method will be used to calculate surface and bottom temperatures.

Trends

Mean surface and bottom temperatures were cooler than in the prior survey year (2019) on the shelf (Figure 35). The 2021 mean surface temperature was 7.2°C, which was 2.0°C lower than in 2019 yet 0.5°C higher than the grand mean of the time series (6.7°C). In 2021, the mean bottom temperature in the EBS was 3.3°C, the fourth highest on record after 2019, 2018, and 2016, and 0.9°C above the grand mean of the time series (2.5°C).

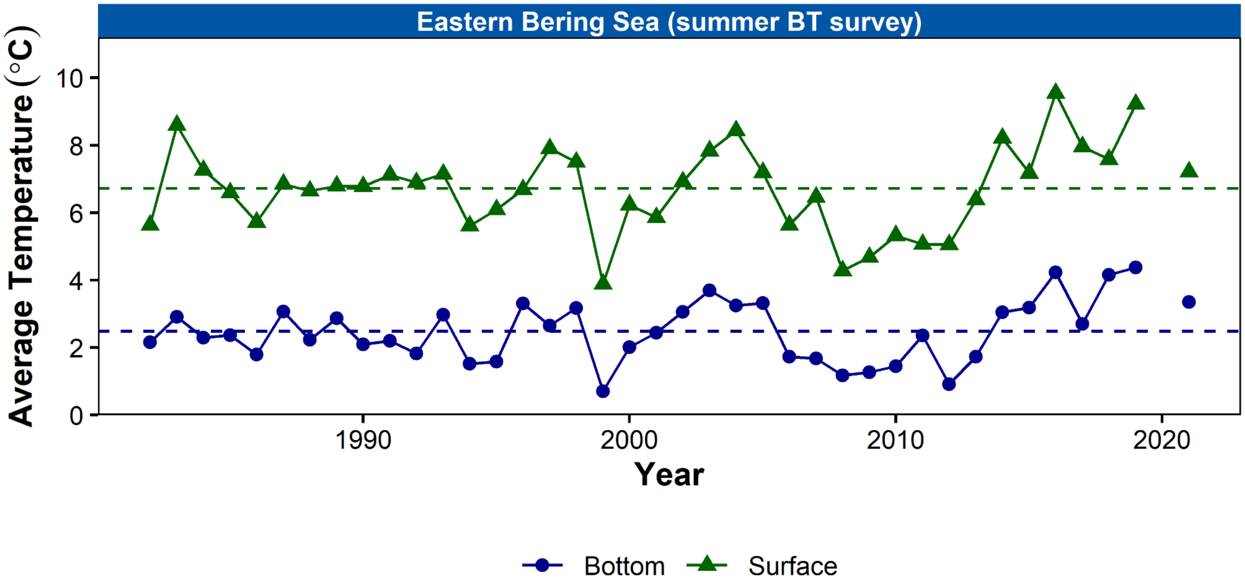


Figure 35: Average summer surface (green triangles) and bottom (blue circles) temperatures (°C) on the eastern Bering Sea (EBS) shelf based on data collected during standardized summer bottom trawl surveys from 1982–2021. Dashed lines represent the time series mean.

Cold Pool Extent Maps and Index Time Series

Contributed by Sean Rohan, *sean.rohan@noaa.gov*, and Lewis Barnett, *lewis.barnett@noaa.gov*

In prior years, the cold pool index was calculated based on the area within the 2°C bottom temperature isotherm derived from an inverse distance weighted interpolation, using a maximum of four observations in the weighting for each prediction. This year, we changed the interpolation method used to estimate this area, as described above for surface and bottom temperatures, to estimate cold pool extent for this and all prior years.

Trends

The cold pool extent has increased since 2018, yet the 2021 extent (58,975 km^2) was the fourth lowest on record and remains more than one standard deviation below the grand mean of the time series (see Figure 1). Estimates of cold pool area from 2018 and 2019 were the smallest on record, followed by 2003, which was only slightly smaller than in 2021. As is typical when the extent is small, the cold pool was restricted to the northern edge of the EBS shelf bottom trawl survey area (Figure 36). In general, the spatial extents of isotherms at all thresholds $\leq$1°C were similar, if slightly greater than prior record lows (Figure 36). The coldest bottom temperatures were restricted to the far northwest corner of the EBS shelf survey area, where temperatures were greater than -1°C, with an extremely small extent of waters $\leq$1°C (14,925 km^2) and $\leq$0°C (4,800 km^2). However, cooler bottom temperatures were observed in the NBS, including a substantial area with bottom temperatures $\leq$-1°C along the U.S.-Russia convention line to the west-southwest of St. Lawrence Island, while extremely warm bottom temperatures were observed on the northern inner shelf from Norton Sound to Nunivak Island (Figure 37). The temperature difference between the inner shelf in the NBS and inner shelf in the EBS is partially due to seasonal thermal heating owing to the NBS inner shelf being the last area sampled by the survey.

Fluctuations in the temperatures at the surface and bottom and the cold pool extent are the result of interannual variability in climatic conditions influencing the formation and retreat of sea ice on the EBS shelf during the prior winter (Stabeno et al., 2012; Stabeno and Bell, 2019). Less sea ice, persisting for less time, results in warmer temperatures and a smaller cold pool extent.

The cold pool has a strong influence on the thermal stratification, and overall, changes in surface and bottom temperature influence the spatial structure of the demersal community (Spencer, 2008; Kotwicki and Lauth, 2013; Thorson et al., 2020), trophic structure of the EBS food web (Mueter and Litzow, 2008; Spencer et al., 2016), and demographic processes of fish populations (Grüss et al., 2021). When the cold pool is small, species with warm water affinity (e.g., Arrowtooth flounder) are distributed more widely over the EBS shelf and expand across the shelf and to the north because there is no thermal barrier to migration. In contrast, the distribution of species with cold water affinity (e.g., Arctic cod, Bering flounder) contracts to the north when the cold pool is small.

While the cold pool area is defined based on the 2°C isotherm, recent studies suggest that a more ecologically relevant temperature for several subarctic fishes and crabs is the 1°C isotherm (Kotwicki and Lauth, 2013) or the 0°C isotherm for Walleye pollock and Pacific cod (Baker, 2021; Eisner et al., 2020). Considering the small extent of bottom temperatures cooler than 0°C and 1°C, it is likely that the bottom temperatures on the EBS shelf did not impose a major thermal barrier to migration for subarctic species in 2021. However, cooler bottom temperatures in the NBS (Figure 37) may have imposed some barrier to migration.

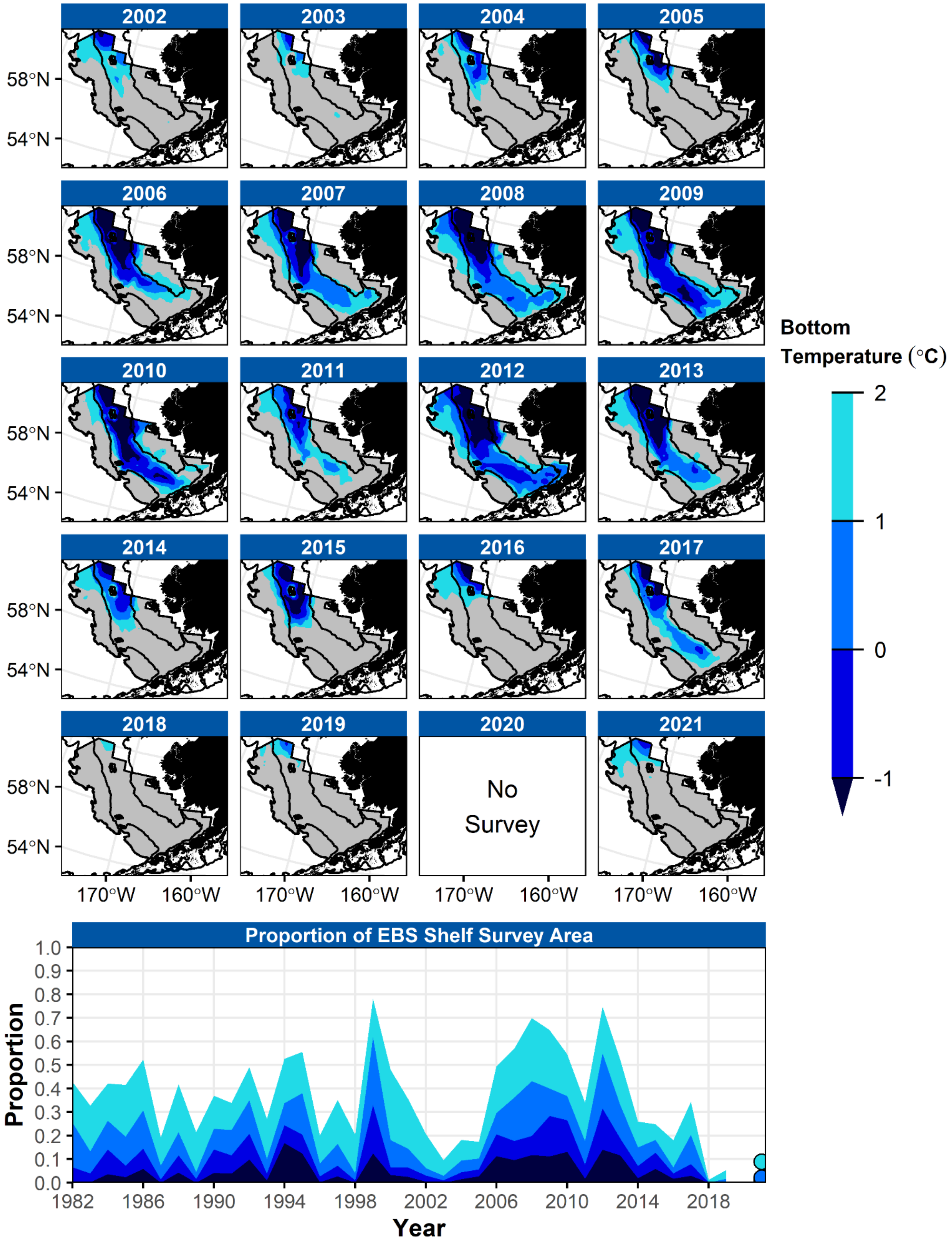


Figure 36: Cold pool extent in the eastern Bering Sea (EBS), as measured using observations from the EBS bottom trawl survey. Upper panels: Maps of cold pool extent in the EBS shelf survey area from 2002–2021. Lower panel: Extent of the cold pool in proportion to the total EBS shelf survey area from 1982–2021. Fill colors denote bottom temperatures ≤2°C, ≤1°C, ≤0°C, and ≤-1°C.

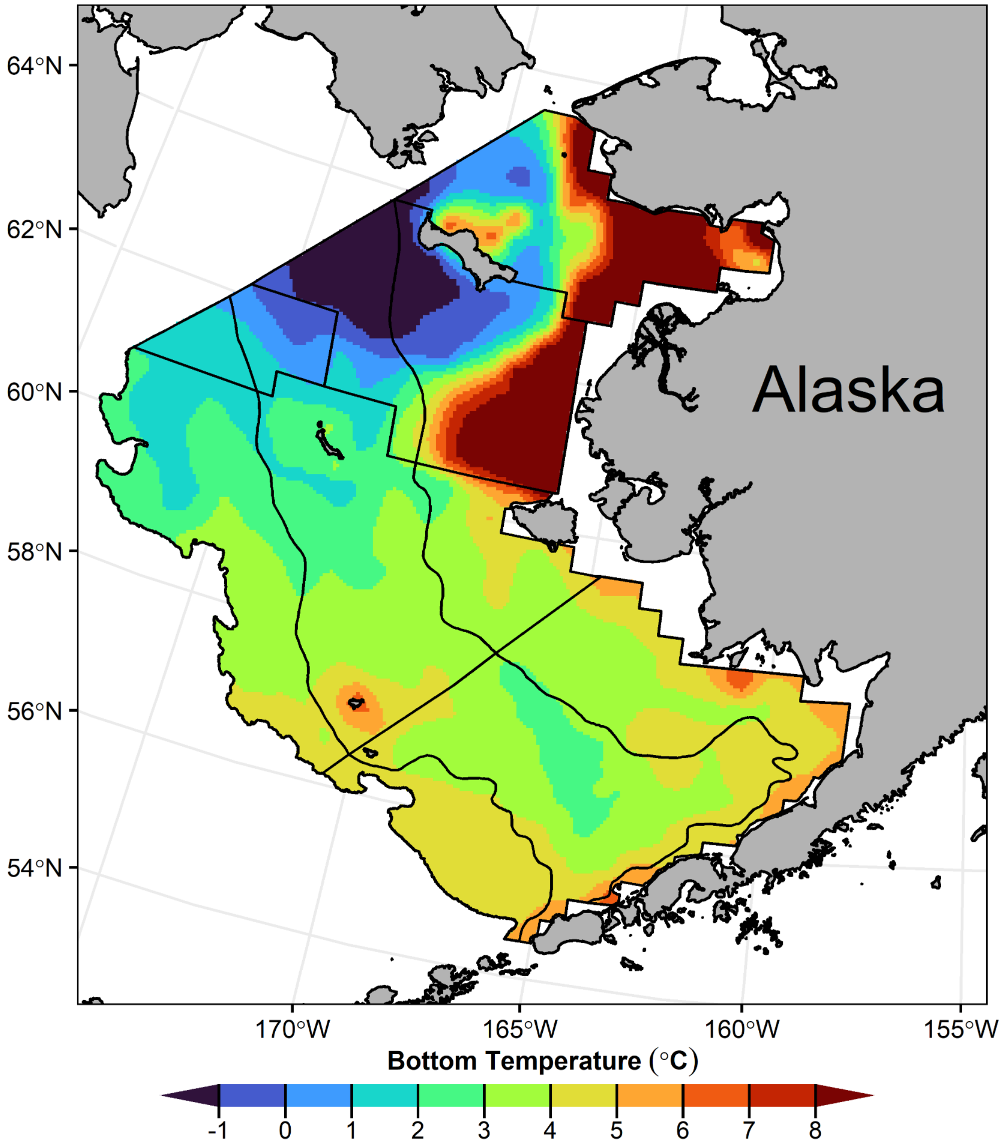


Figure 37: Contour map of bottom temperatures from the 2021 eastern and northern Bering Sea shelf bottom trawl surveys.

Bottom Temperature and Cold Pool Extent from ROMS
Contributed by Kelly Kearney, *kelly.kearney@noaa.gov*
The Bering 10K Regional Ocean Modeling System (ROMS) hindcast simulation was extended to the near-present, using reanalysis-based input forcing. This hindcast simulation now extends from Jan 15, 1970–Aug 18, 2021.

Trends
At 3.30°C, 2021 conditions were warmer than the average simulated southeastern Bering Sea (SEBS) mean bottom temperature between 1970–2021 (2.79°C), following slightly cooler than average conditions in 2020 (2.41°C) (Figure 38). In the summer, much of the SEBS region bottom water was very close to the 2°C threshold used to define the cold pool, with a resulting cold pool index indicating warm conditions (2021: 0.17, 1970–2021 mean: 0.35). As has been the case since 2018, no <0°C water remained in the summer. When compared to previous years, conditions most closely resemble 2004 and 1982 in terms of summer bottom temperature patterns and seasonal evolution of the cold pool indices. These years were all classified as warmer than average, but not extreme, with a spatial pattern showing patches of summer <2°C water in both the northern and southern parts of the southeast middle shelf, some <1°C water in the northern parts of the SEBS region, and no <0°C water.

Bottom Temperatures Along the Shelf Break
Contributed by Kevin Siwicke, *kevin.siwicke@noaa.gov*, and
Tyler Hennon, *tdhennon@alaska.edu*
Since 2005 bottom temperature surveys have been conducted on longline fishing vessels, generally between June and August (Figure 39). Thermistors are mounted to longline equipment, and remain on the bottom for several hours before recovery. Longline surveys are conducted on the Bering shelf break every odd year, and the bottom depths sampled there range between about 250m to 500m.

Trends
Though the period of record is relatively short for the Bering Sea shelf break, the average bottom temperature across all stations during the last four years of surveys (2015–2021) is markedly higher than the prior years (Figure 40). The 2017 summer bottom temperature was particularly high, which may have been a contributing factor leading to extremely low ice extent experienced in 2018. The bottom temperature in 2021 was lower than both 2017 and 2019, though still significantly above the averages from 2009–2013.

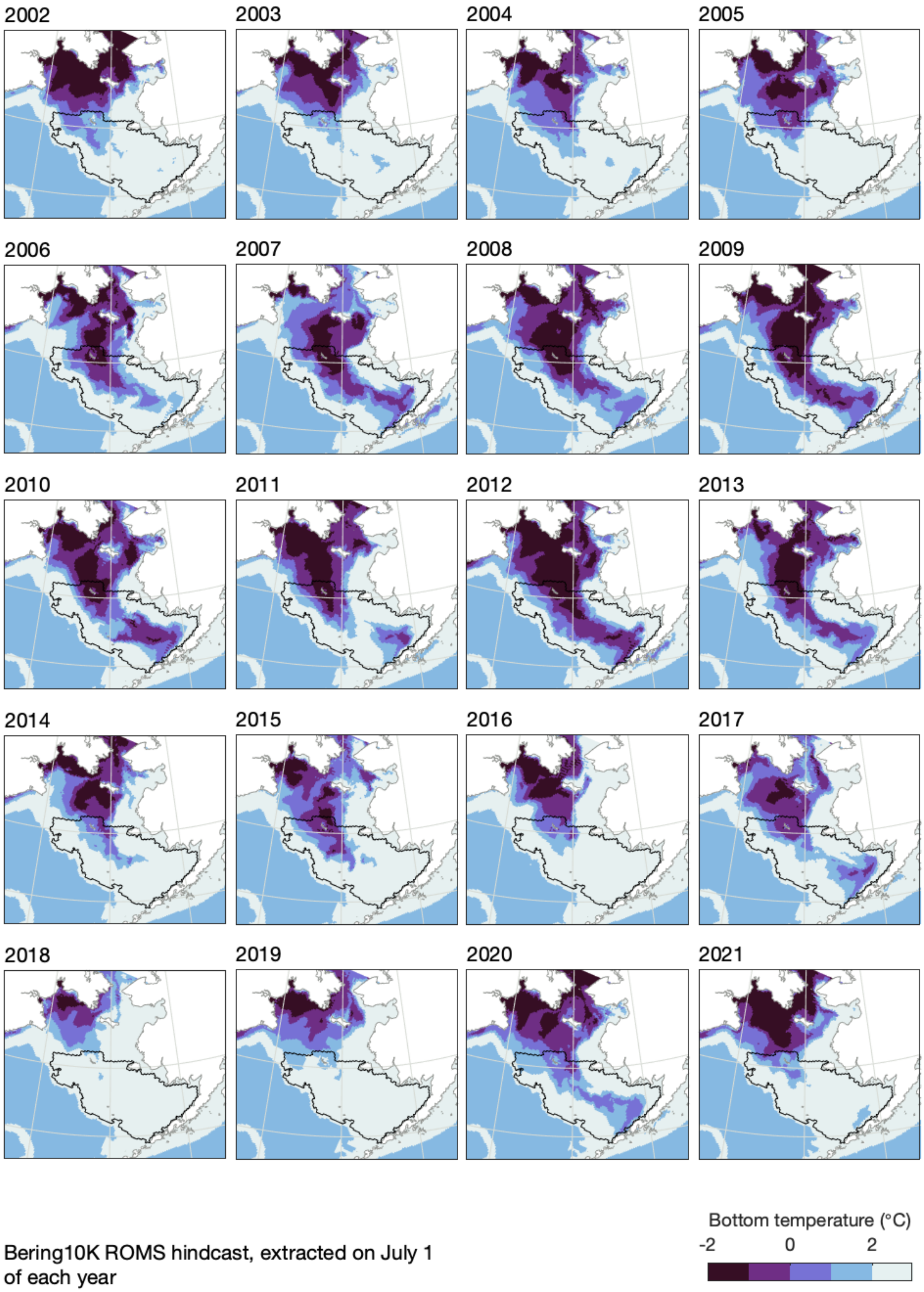


Figure 38: Bering 10K ROMS hindcast of cold pool extent, extracted on July 1 of each year, for the Bering Sea, 2002–2021. The black outline denotes the standard bottom trawl survey grid.

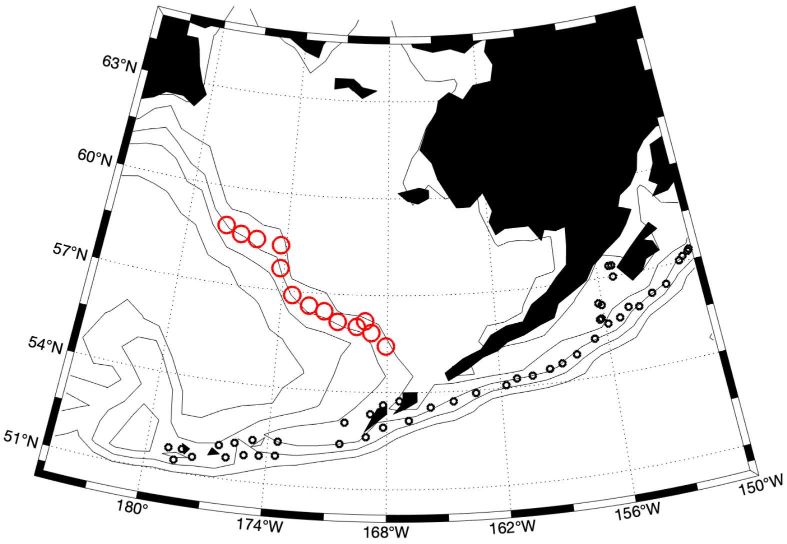


Figure 39: Map of longline survey sites (red circles) on the Bering Sea shelf break, 2009–2021. Black circles show locations of other longline sites across the Aleutian Islands and western Gulf of Alaska.

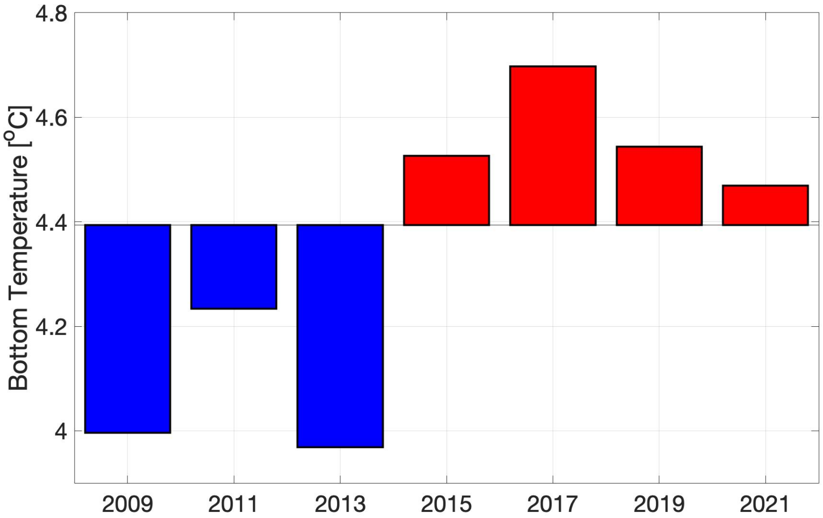


Figure 40: Bottom temperatures averaged across all longline surveys in the Bering Sea (red circles in Figure 39). Red bars indicate bottom temperatures were higher than the period-of-record average, whereas blue indicates they were below average.

6. Seasonal Projections from the National Multi-Model Ensemble (NMME)

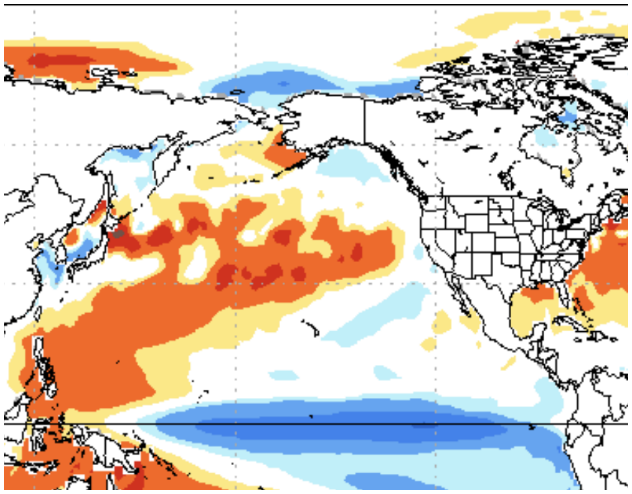
Contributed by Nick Bond, *nicholas.bond@noaa.gov*
Seasonal projections of SST from the National Multi-Model Ensemble (NMME) are shown in Figure 41. An ensemble approach incorporating different models is particularly appropriate for seasonal and longer-term simulations; the NMME represents the average of eight climate models. The uncertainties and errors in the predictions from any single climate model can be substantial. More detail on the NMME and projections of other variables are available at the following website: `http://www.cpc.ncep.noaa.gov/products/NMME/`.

The model projections from a year ago are reviewed. In general, the model forecasts from September 2020 for the following fall and winter indicated a continuation of positive SST anomalies across the North Pacific south of 50°N and in the NBS. For the spring of 2021, these forecasts included moderation in the magnitude of the warmer than normal temperatures in the Bering Sea and the development of slightly cooler than normal temperatures in the northern GOA. The model performance as a group was very good for the first period considered (Oct–Dec 2020). In particular, these forecasts showed near-normal temperatures in the vicinity of the Aleutian Islands separating relatively warm SSTs to the south and to the north, as observed. The predictions for the later period (Dec 2020–Feb 2021) were largely correct in a basin-scale sense, specifically relating to La Niña in the tropical Pacific and positive SST anomalies in the mid-latitude North Pacific, particularly in a localized region just east of Japan. From an Alaskan perspective, the models failed to predict the observed development of relatively cold conditions observed along the west coast of Alaska north of Nunivak Island into Norton Sound. The locations and nature of the better and worse model forecasts persisted into the longest time horizon considered (Feb-Apr 2021). The model predictions were quite good for the tropics and mid-latitude North Pacific, but failed with respect to a regional detail in terms of the presence of cool (warm) temperatures for the northern (southern) portion of the EBS shelf.

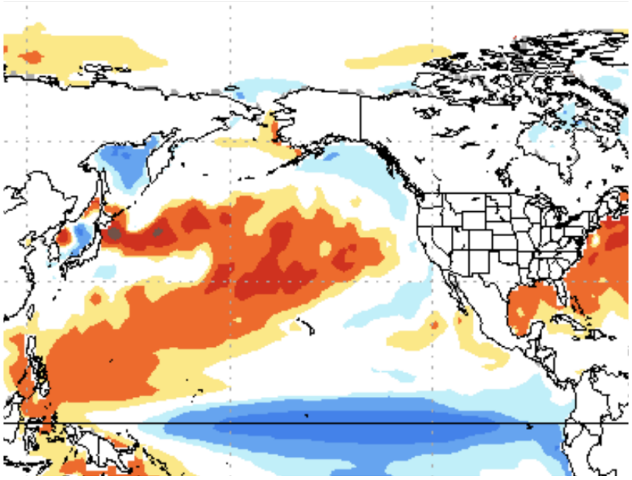
The NMME forecasts of three-month average SST anomalies indicate a continuation of a large region of relatively warm water in the central and western North Pacific south through the end of the calendar year (Oct-Dec 2021; Figure 41a). Positive anomalies are also predicted for the southeast Bering Sea shelf. Cold anomalies are projected north of Bering Strait, and to a lesser extent, for the GOA. The forecast of cool conditions in the northern waters of Alaska may seem curious given the long-term decline in summer sea ice in the Arctic. The model predictions may in part be attributable to the location of the ice edge during late summer 2021, which is not far displaced from its climatological position for the period of 1981–2010. The models also are indicating relatively high pressure centered south of the Aleutians near the dateline, which results in fewer storms of mid-latitude origin for the northern Bering and Chukchi Seas, and hence fewer incursions of mild, maritime air masses. It will be interesting to see if this scenario actually comes to pass.

The ensemble of model predictions for December 2021 through February 2022 includes anomalously high sea level pressure centered over the western Bering Sea resulting in a decrease in the positive temperature anomalies on the southeast Bering Sea shelf and continued cooling of the GOA (Figure 41b) as compared with climatological norms. These changes are consistent with what has occurred in past La Niña winters; the models as a group are predicting tropical Pacific temperatures commensurate with a moderate La Niña.

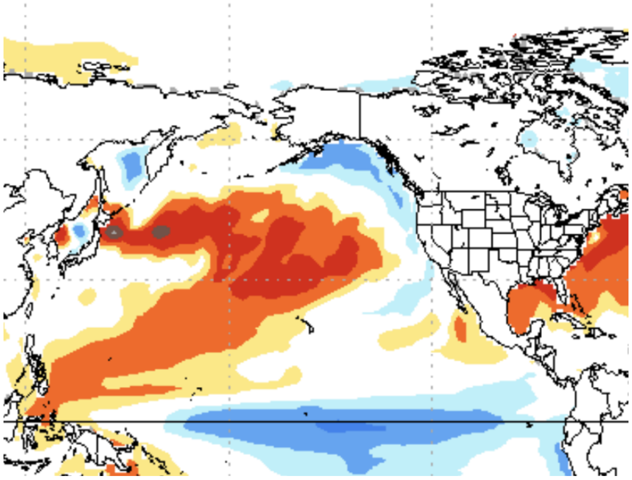
The distribution of SST anomalies predicted for February through April of 2022 (Figure 41c) shows that the trends of the previous 3-month period considered here are liable to be continued. If the models as a group are correct, the late winter and early spring of 2022 will bring near-normal temperatures to most of the Bering Sea and Aleutian Islands, and quite cold temperatures to the central GOA. The models also show a winding down of La Niña in the tropical Pacific. There is a fair amount of spread in the forecasts among the models. More specifically, 2 out of the 6 models forming the NMME are showing that the southeast Bering Sea shelf will remain warmer than normal into spring 2022, and 3 out of the 6 models are emphatic about the cool temperatures in the GOA with the others showing a more muted response. This variability/uncertainty also applies to the sea ice extent over the shelf in the EBS. Most but not all of the models suggest conditions that would result in ice extending south of 60°N perhaps all the way to M2, and as far south as Bristol Bay along the west coast of Alaska.



(a) Months Oct–Nov–Dec



(b) Months Dec–Jan–Feb



(c) Months Feb–Mar–Apr

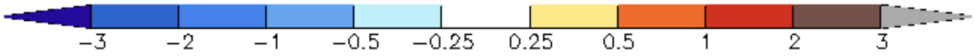


Figure 41: Predicted SST anomalies from the NMME model for Oct–Nov–Dec (1-month lead), Dec–Jan–Feb (3-month lead), and Feb–Mar–Apr (5-month lead) for the 2021–2022 season.

Habitat

Structural Epifauna - Eastern Bering Sea Shelf

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Last updated: October 2021

Description of indicator: Groups considered to be structural epifauna include: sea whips, corals, anemones, and sponges. Corals are rarely encountered on the eastern Bering Sea shelf so they were not included here. Relative CPUE by weight (kg per hectare) was calculated and plotted for each species group by year for 1982–2021. Relative CPUE was calculated by setting the largest biomass in the time series to a value of 1 and scaling other annual values proportionally. The standard error (±1) was weighted proportionally to the CPUE to produce a relative standard error.

Status and trends: Relative catch rates for sea anemones remained similar to estimates from 2016–2019, which were lower than the catch rates during 2010–2015. Sea whip estimates increased from 2019 to a catch rate similar to that observed 1999–2005 and 2013–2016. The catch rate of sponges dropped to the lowest level observed in the time series, but is similar to results observed intermittently during the early years of the time series, 1984–1992. These trends should be viewed with caution, however, because the consistency and quality of their enumeration have varied over the time series (Stevenson and Hoff, 2009; Stevenson et al., 2016). Moreover, the identification of trends is uncertain given the large variability in relative CPUE (Figure 42).

Factors influencing observed trends: Further research in several areas would benefit the interpretation of structural epifauna trends including systematics and taxonomy of Bering Sea shelf invertebrates; survey gear selectivity; and the life history characteristics of the epibenthic organisms captured by the survey trawl.

Implications: Understanding the trends as well as the distribution patterns of structural epifauna is important for modeling habitat to develop spatial management plans for protecting habitat, understanding fishing gear impacts, and predicting responses to future climate change (Rooper et al., 2016); however, more research on the eastern Bering Sea shelf will be needed to determine if there are definitive links.

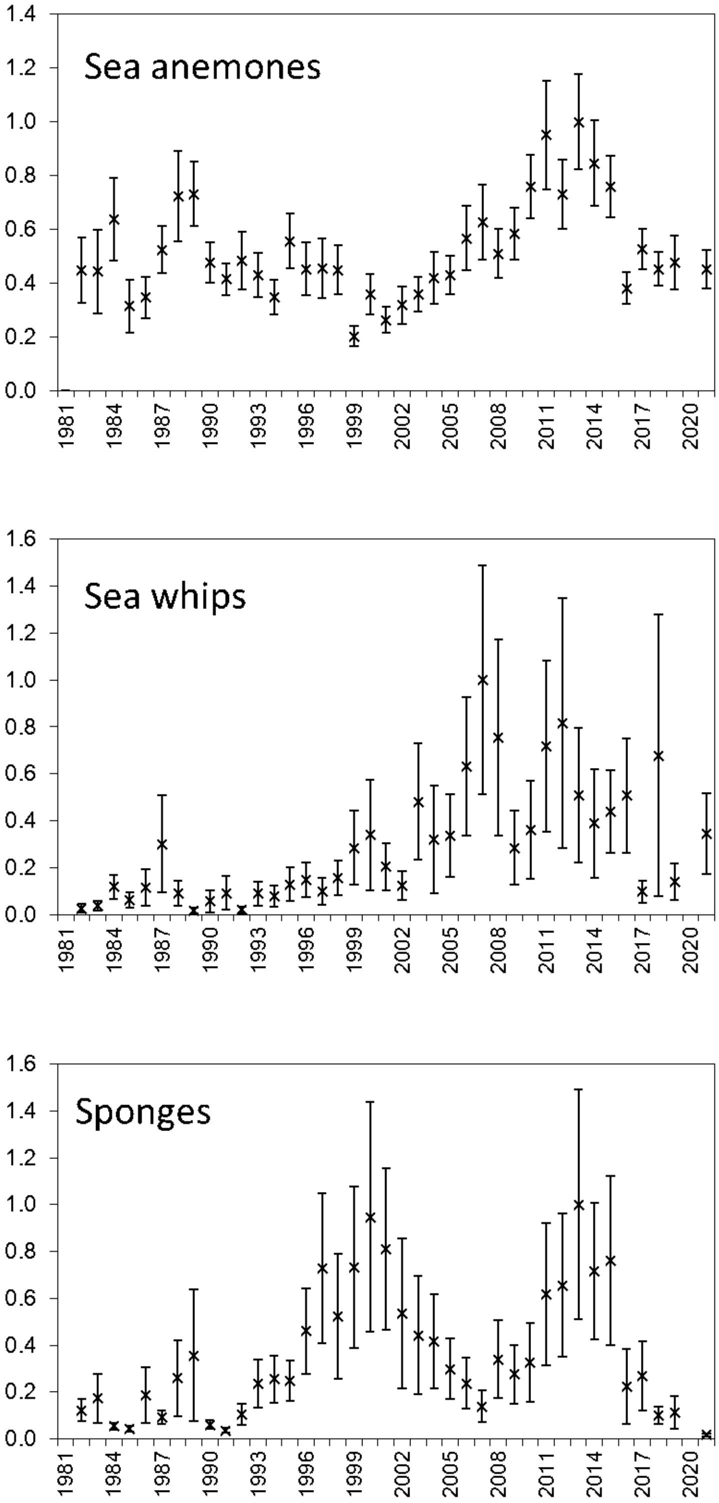

Figure 42: AFSC eastern Bering Sea shelf bottom trawl survey relative CPUE for benthic epifauna during the May to August time period from 1982–2021.

Primary Production

Spring Satellite Chlorophyll-a Concentrations in the Eastern Bering Sea

Contributed by Jens M. Nielsen[1,2], Lisa Eisner[3], Jordan Watson[3], Jeanette C. Gann[3], Matt W. Callahan[4], Calvin W. Mordy[2,5], Shaun W. Bell[2,5], and Phyllis Stabeno[5]
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[3]Auke Bay Laboratories, Alaska Fisheries Science Center, NOAA Fisheries
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Last updated: October 2021

Description of indicator: In subarctic systems, such as the eastern Bering Sea, the timing and magnitude of the spring bloom can have large and long-lasting effects on biological production with subsequent impacts on higher trophic levels including commercial fish stocks (Platt et al., 2003). The fate of the spring bloom (pelagic grazing or sinking to benthos), and it's timing also impact benthic feeders in the Bering Sea (Hunt et al., 2002). Recent climatic changes in the Bering Sea have included reduced sea ice and warming ocean temperatures (Stabeno and Bell, 2019), with consequent changes to the food web (Duffy-Anderson et al., 2019; Hunt et al., 2020). Understanding annual changes in spring phytoplankton biomass and peak timing dynamics are thus important metrics for depicting ecosystem changes. Here, we used ocean color satellite data from 2003–2021 available from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite at a 4x4 km resolution composites[9] to estimate: 1) average spring (Apr–Jun) chlorophyll-a concentrations (chl-a, an estimate of phytoplankton biomass in the surface layer), and 2) peak timing of the spring open water bloom for major regions in the eastern Bering Sea. In the southeastern Bering Sea, sustained observations at the M2 mooring (56.9°N, -164.1°W) provide good representation of the south middle shelf biophysical conditions. Thus, the long-term chl-a fluorescence mooring measurements were compared to the bloom peak timing estimates calculated from the satellite data.

We focus on the spring period as this is an important time for providing basal resources for zooplankton and thus energy for higher trophic level species. The April–June time-period was chosen as this period consistently includes the pelagic spring bloom peak. We further divided the eastern Bering Sea into 8 distinct regions split between approximately north and south of 60°N and defined by oceanographic fronts and water mass characteristics based on Ortiz et al. (2012) (Figure 43). There are several advantages of satellite data, including high spatial and temporal coverage. However, these products are also limited to measurements within the surface ocean and also have missing data due to ice and cloud cover, particularly in high latitude systems such as the Bering Sea. We used 8-day composite data for the biomass estimates, while 1-day composites were used to assess the spring bloom peak timing.

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[9] `coastwatch.pfeg.noaa.gov/erddap/griddap/erdMBchla8day.html`

Open water spring bloom peak timing was estimated from data binned to 0.5° latitude x 1° longitude spatial grid cells. We then calculated the average and standard deviation of all estimated bloom peaks within a specific region, which allowed for calculation of variability for each of the 8 areas. Grid cells with less than 66% seasonal coverage were excluded.

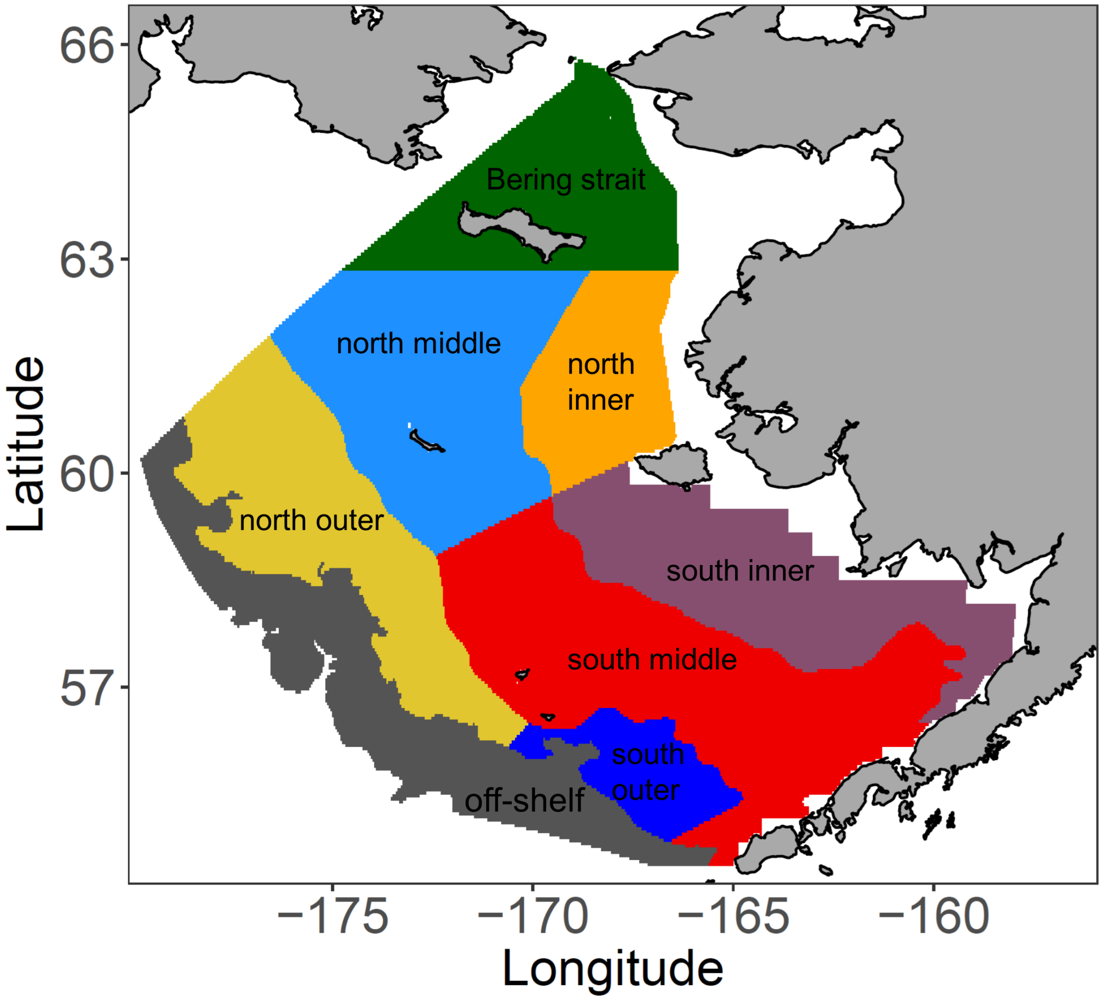

Figure 43: Map of the 8 shelf regions used for satellite chl-a analyses: south inner (purple), south middle (red), south outer (dark blue), off-shelf (dark grey), north inner (orange), north middle (light blue), north outer (yellow), and the Bering Strait (dark green). Off-shelf denotes regions on the shelf break and slope deeper than 200m Ortiz et al. (2012)

.

Status and trends: There was a high degree of interannual variability in satellite chl-a from 2003–2021. Both the south inner (<50m), south middle (50–100m), and south outer shelf (100–180m) had below average values in 2021, similar to values in the period 2016–2019. Values in the north inner and north middle shelf region were close to median. Values along the shelf–break (off-shelf region) were low in 2021, continuing an apparent decreasing trend since 2014 (Figure 44). Data coverage in the southern regions was generally good across all years, however further north, in some years data from April were particularly scarce due to extended ice coverage (Figure 45, blank spaces). Consequently, estimates in spring should be considered with caution during the years when coverage was limited.

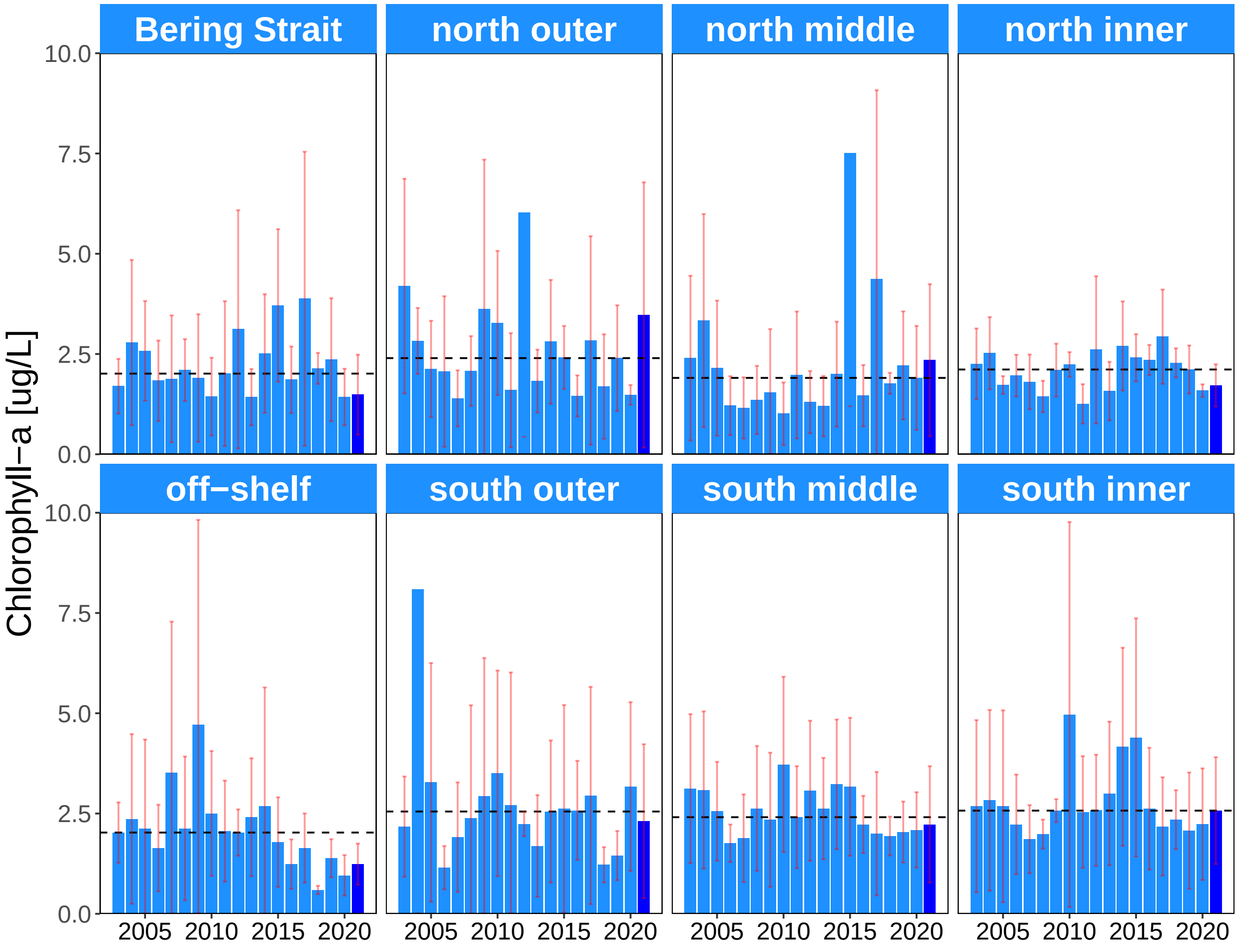

Figure 44: Average and standard deviation (SD) from spring (Apr–Jun) chl-a concentrations for 8 regions in the eastern Bering Sea. Dotted black line denotes the long-term (2003–2021) median for each region. **Note:** For plotting purposes, the minimum error bar is set at 0.01 and the maximum at 9.99. In a few cases, the +standard deviation was >10 (south outer in 2004 was 18.9; north middle in 2015 was 13.8; south outer in 2012 was 11.6).

Preliminary analyses of the pelagic spring bloom peak timing suggest that 2021, which was ice-free, was similar to the long term average in the south inner, south middle, and south outer shelf regions (Figure 46). For the south middle shelf region, peak bloom timing estimated from the satellite data generally concurred well with estimates from the M2 mooring fluorescence data (note: mooring peak timing in 2021 was estimated from the M2 profiling crawler). Exceptions are 2013 and 2016 during which the mooring data showed a much earlier peak than the average peak satellite chl-a timing, though few satellite data was available in that period when the peaks in fluorescence were observed. A second peak in fluorescence was visible in 2013 and 2016 close to the estimates from the satellite peak estimates (data not shown), indicating that some years experience two spring bloom periods. In the off-shelf region, the bloom peak in 2021 was about 1 week earlier than the long-term average but later than 2020, one of the earliest blooms recorded. However, the magnitude of off-shelf spring chll-a concentrations were low overall (Figure 44). Due to lack of consistent data coverage, no bloom satellite peak estimates were done for the northern regions.

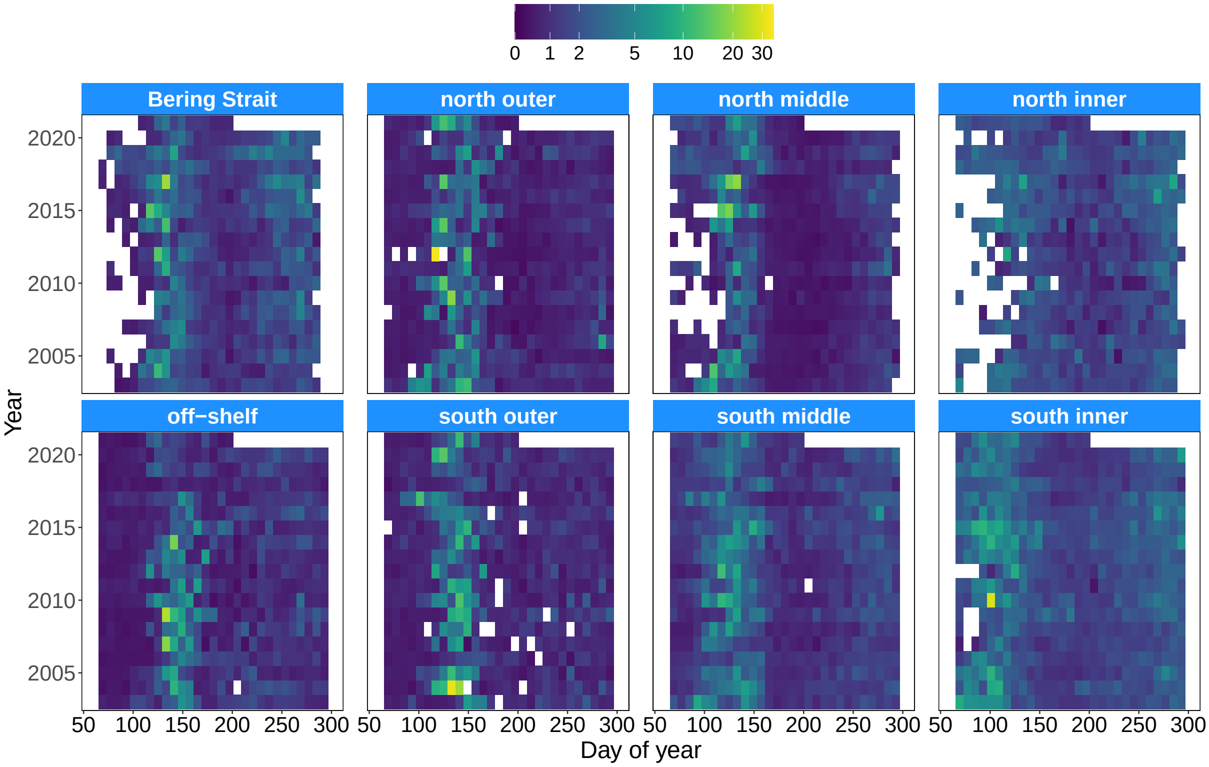

Figure 45: Heatmap of satellite 8-day composite chl-a concentrations for each year and region. Color scale is logged.

Factors influencing observed trends: Previous studies have highlighted the strong coupling between temperature and sea ice dynamics and spring bloom timing. For example, in the southern Bering Sea, ice present after mid-march commonly results in an early and prominent ice-associated bloom, while lack of ice normally results in a delayed open water bloom in mid- to late-May (Hunt et al., 2002, 2011; Sigler et al., 2014). On the southern middle shelf, we observed an earlier spring bloom in the cold years of 2007–2012 (excluding 2009) and in the average years of 2013 and 2017. However, spring bloom timing varied considerably in recent warm years (2018–2021), suggesting that the timing of the bloom was impacted by other factors besides ice. In 2021 bloom timing was average for an open water bloom, which tend to be slightly later (∼1–2 weeks) than blooms associated with ice retreat. For open water blooms, variations in springtime winds may influence the setup of stratification (e.g., higher winds can delay stratification, Stabeno et al. (2016)), which in turn affects light availability and the timing of the bloom. Analysis of chl-a biomass, though informative in depicting spring bloom timing, does not directly provide information of primary productivity (growth rates), though biomass levels in spring generally align well with the timing of production peak estimates. Since biomass is a balance between production and losses, lower biomass levels could also indicate enhanced grazing by microzooplankton and mesozooplankton or sinking to the benthos.

Implications: Primary producers provide fundamental energy and nutrients for zooplankton grazers and higher trophic level species. Understanding how climatic perturbations, and particularly the recent warm period, influence phytoplankton dynamics is a critical component in understanding ecosystem dynamics in the Bering Sea. Large, lipid-rich copepods, *Calanus* spp. were in higher

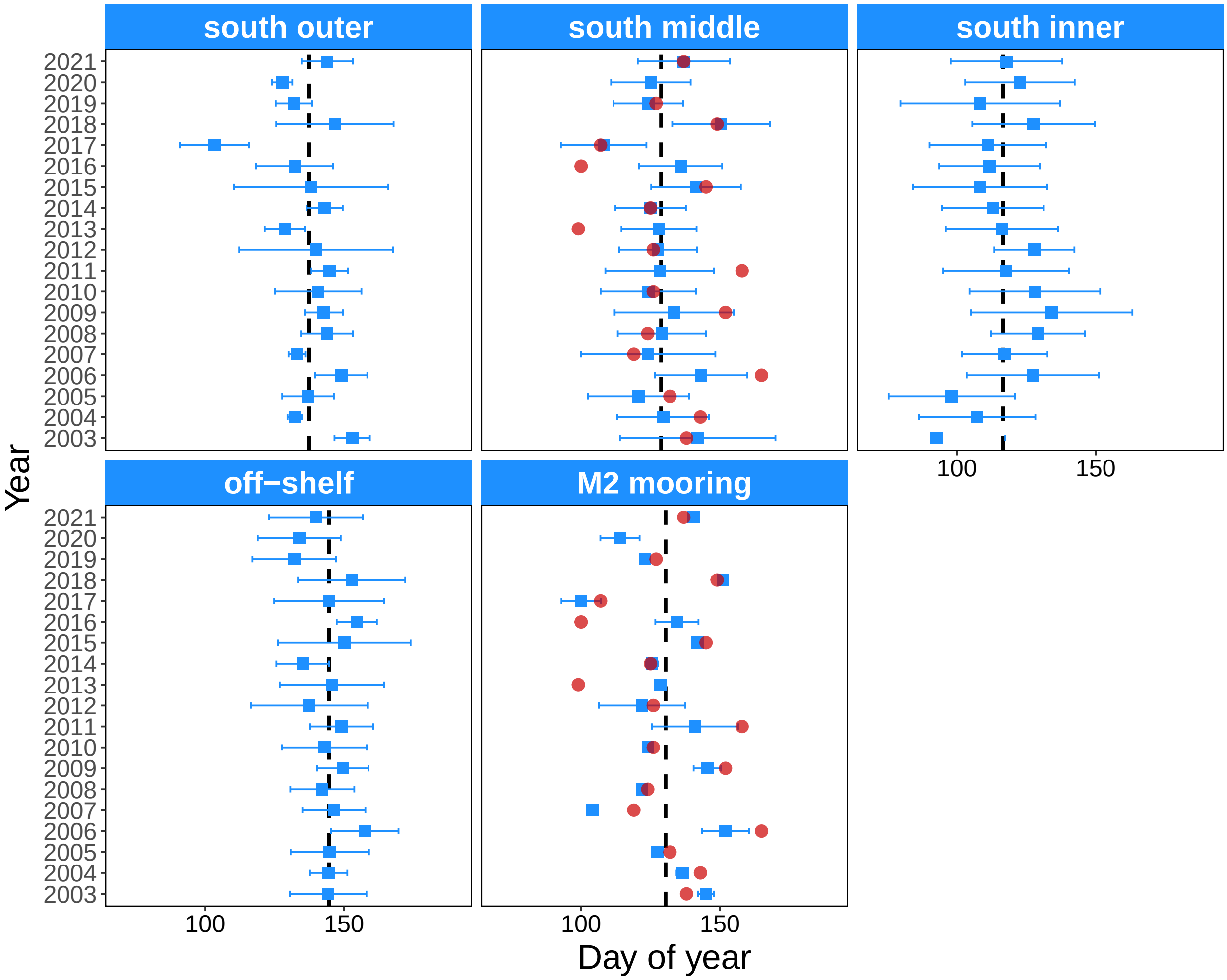

Figure 46: Average and SD of peak spring bloom timing estimated from areas within 4 southern regions in the eastern Bering Sea. Red dots are the M2 fluorescence peak timing estimates, which are compared to both the south middle shelf data and specifically to satellite data near M2 [1° latitude x 1° longitude].

abundance in summer 2017 (see p. 94), a year with an early spring bloom (and average ice cover), which may have offered an early food resource for zooplankton reproduction and survival. Our analyses also showed no significant long-term change in the bloom peak timing among low and high ice years combined. However if warming temperatures during winter and spring accelerate development rates of zooplankton (Coyle and Gibson, 2017) it may also reduce the duration of diapause leading to earlier emergence (Pierson et al., 2013). Thus the timing of the spring bloom has important implications for consumers such as zooplankton, and in turn their predators such as fish larvae. Reduction of sea ice, and thus lack of ice associated phytoplankton blooms also shifts the community composition in favor of pelagic phytoplankton over ice algae; changes that likely have strong impacts on benthic-pelagic energy fluxes (Hunt et al., 2002) and the nutritional composition of basal resources for consumers. The declining trends in chl-a biomass observed along the shelf-break in recent warm years (2016–2021) deserves further investigation. This area includes the "greenbelt", known for high production (Springer et al., 1996), and it will be important to understand the mechanism behind these apparent changes.

Gross Primary Production at the M2 Mooring Site

Contributed by Jens M. Nielsen[1,2], Shaun W. Bell[3], Noel E. Pelland[1,3], Calvin W. Mordy[2,3], Phyllis Stabeno[3], and Lisa Eisner[4]
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Last updated: October 2021

Description of indicator: The eastern Bering Sea shelf is a highly productive seasonal system with a dominant spring bloom that has long-lasting effects on the biological production of both pelagic and benthic consumers (Springer et al., 1996; Sigler et al., 2016). Here, we categorize seasonal primary production dynamics from 2016 to the present using a high resolution Profiling Crawler (Prawler) attached to a mooring line that collects physical and biological data in the upper 50 meters in combination with other *in situ* data. Specifically, we use dissolved oxygen data to estimate gross primary production (GPP). GPP is the amount of energy (often expressed in carbon units) produced by primary producers (e.g., phytoplankton, ice algae) during a given time (Cassar et al., 2015).

A production indicator using Prawler oxygen measurements was used to better capture the inter-annual dynamics and seasonal of primary production in the eastern Bering Sea. In the southeastern Bering Sea, the long term monitoring buoy "M2" (56.9°N, -164.1°W) provides good representation of the middle Bering Sea shelf biophysical conditions (Stabeno et al., 2001). Starting in 2016, the Prawler continuously collected vertical profiles of physical and biological data, including chlorophyll (chl-a) and dissolved oxygen, in the upper 50 m (data was not available in 2020). From the M2 Prawler we estimated weekly averaged rates of GPP using dissolved oxygen for 2016–2019 and 2021 using a Fourier GPP analysis method (Cox et al., 2015). Currently, GPP estimates are provided as an average estimate based on surface to mixed layer oxygen concentrations. The peak timing of the bloom was estimated as the peak of the 5-day rolling average of the daily GPP estimates. We calculated GPP production estimates for a 2-week period centered around the spring bloom peak, and for the summer period (July–August).

Status and trends: In 2021, the seasonal GPP cycle showed a substantial bloom peak in spring of above >400 mg C m^{-3} day^{-1} (Figure 47). Low production occurs during most of the summer except for smaller increases, commonly induced by increased winds which mix the water column and bring nutrients to the surface. Average GPP in 2021 during the 2-week period around the bloom reached ∼350 mg C m^{-3} day^{-1} (Table 2). Those values were similar to values reached during the bloom in 2019 but higher than 2018. The Prawler deployments in 2016 and 2017 only partially covered the bloom and thus those values were not considered. Summer averaged GPP was ∼125 mg C m^{-3} day^{-1} which was higher than both 2016 and 2017 but lower than 2018 (141 mg C m^{-3} day^{-1}).

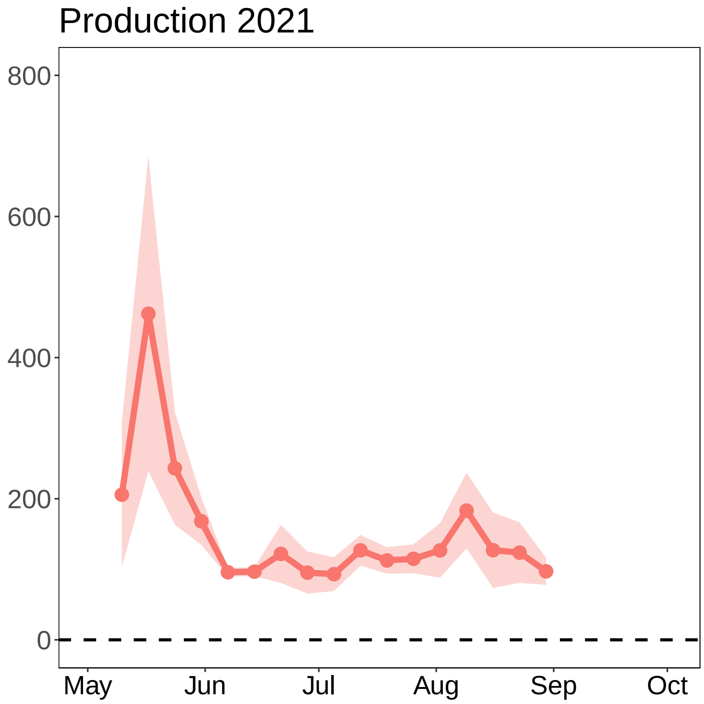

Figure 47: Seasonal cycle of weekly averaged gross primary production in the upper mixed layer from the M2 Prawler in 2021 as determined from dissolved oxygen.

Table 2: M2 Prawler gross primary production (GPP) estimates ± standard deviation (SD) (mg C m^{-3} day^{-1}) during the 14 and 21 days centered around the spring bloom peak, and during mid-summer (July–August). Note that the bloom peak was only partially captured in 2016 and missed entirely by the Prawler in 2017. Data was not available for mid-summer 2019 and all of 2020. Estimates from 2021 are preliminary. The bloom in 2018 was late compared to historical data (see p. 80). Initial gross primary production estimates in O_2 were converted to C units, using a C:O conversion of (106:138).

Year	**Peak bloom timing**	**Bloom GPP**		**Mid-summer GPP**	
		14 day (centered around peak)		July-August	
	day of year	mean	±SD	mean	±SD
2016	129	215.8	61.8	81.1	31.7
2017	107	NA	NA	56.9	14.2
2018	152	302.9	142.6	141.5	53.7
2019	139	322.5	212.7	NA	NA
2020	NA	NA	NA	NA	NA
2021	135	351.2	191	124.8	41.6

Factors influencing observed trends: The bloom peak timing appears to be average for an ice-free winter in southeastern Bering Sea (see p. 80). The 2021 GPP seasonal dynamics and bloom magnitude may provide good baseline information for average conditions in this region. Previous estimates from the Prawler (2016–2019) were mostly from warm years, except for 2017. However, the year 2017 deserves more attention as this was a highly abnormal year with a very early bloom peak and a subsequent subsurface chl-a max that persisted through the spring and into early summer. Since the Prawler was deployed after the bloom initiation, no GPP spring bloom estimate was possible for the year 2017.

Implications: In 2021, during the 2–3 weeks of the spring bloom peak GPP was >2x the total summer production. Summer production in 2021 appeared to be higher than most previous years (2016, 2017, 2019), but lower than 2018. Nonetheless, production during summer is commonly low, except during wind events that may enhance production during shorter periods (Sambrotto et al., 1986). Reduced production in summer is likely a combination of nutrient limitation and shifts in phytoplankton community composition (Lomas et al., 2020).

Coccolithophores in the Bering Sea

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Last updated: October 2021

Description of indicator: Blooms of coccolithophores, a unicellular calcium carbonate-producing phytoplanktonic organism, are easily observed by satellite ocean color instruments due to their high reflectivity. Coccolithophores produce calcium carbonate plates (coccoliths) that contribute to particulate inorganic carbon (PIC) in the ocean (Matson et al., 2019). Blooms are most commonly observed and cloud cover is typically lower during September than other months allowing for better quantification (Iida et al., 2012). An interannual index of the average area (km^2) covered by coccolithophores during the month of September is calculated with monthly average mapped PIC data (Balch et al., 2005; Gordon et al., 2001) from satellite. The indices are calculated from MODIS-Aqua satellite data (2002–2020) and from the VIIRS-SNPP satellite (2012–2021) provided by NASA Goddard Space Flight Center, Ocean Ecology Laboratory (MODIS-Aqua, 2018) are highly correlated and both are presented here for continuity.

PIC>0.0011 mol/m^3 was used to estimate the location of the influence of coccolithophore blooms. This threshold was derived by Matson et al. (2019). Highly reflective waters in shallow water near the coast can be due to re-suspended diatom frustules rather than coccoliths (Broerse et al., 2003). Thus, the index is calculated from the region south of 60°N and deeper than 30m depth to avoid contamination by shallow regions around St. Matthew and St. Lawrence islands and along the Alaskan coast, as well as sediment associated with the Yukon River. Because blooms are often largely confined to either the middle shelf or the inner shelf (Ladd et al., 2018), two indices are calculated, one for the middle shelf (50–100m depth) and one for the inner shelf (30–50m depth).

Note that the methodology for calculating the index has changed since the 2017 contribution. Because the index represents only a monthly estimate of spatial area influenced by coccolithophore blooms (and not more rigorous biomass or other biogeochemical estimates), it was determined that PIC provided the necessary information and is easily available data. Correlation with the previous index is $R^2=0.98$. In addition, the index calculations were updated in 2021, resulting in some changes to the overall estimates (mean change 13% higher for middle shelf and 26–35% higher for the inner shelf), however, the inteannual patterns from previous years are still present.

Before 1997, coccolithophore blooms in the eastern Bering Sea were rare. A large bloom (primarily *Emiliania huxleyi*) occurred in 1997 (Napp and Hunt, 2001; Stockwell et al., 2001) and for several years thereafter. During the 1997 bloom, the bloom was associated with a die-off of short-tailed shearwaters (*Puffinus tenuirostris*), a seabird commonly seen in these waters (Baduini et al., 2001). It was thought that the bloom may have made it difficult for the shearwaters to see their zooplankton prey from the air (Lovvorn et al., 2001). Since then, coccolithophore blooms in the eastern Bering Sea have become more common. Satellite ocean color data suggest that blooms are only found where water depths are between 20 and 100m. Blooms typically peak in September and interannual variability is related to both very weak and strong stratification (Iida et al., 2012; Ladd et al., 2018).

Status and trends: Annual images (Figure 48) show the spatial and temporal variability of coccolithophore blooms in September. Annual indices are obtained from satellite data by averaging spatially over the inner and middle shelf (Figure 49). Coccolithophore blooms were particularly large during the early part of the record, 1997–2000 (not shown). At the start of the MODIS-Aqua record, the index was low and remained low ($<$50,000 km^2) through 2006. In 2007, the index rose to almost double that observed in 2006 ($\sim$102,000 km^2). A higher index ($>$50,000 km^2) was observed in 2007, 2009, 2011, 2014, 2016, 2020, and 2021 for the middle shelf and in 2011 and 2014 ($>$20,000 km^2) for the inner shelf. Commonly for years with high index values (e.g., 2014, 2016, 2020) blooms are also observed in August (data not shown). September 2017 exhibited the lowest index of the record. The bloom index remained below average in 2018 and 2019, but increased, particularly on the middle shelf, in 2020 and was again high in 2021.

Factors influencing observed trends: It has been suggested that the strength of density stratification is the key parameter controlling variability of coccolithophore blooms in the eastern Bering Sea (Iida et al., 2012; Ladd et al., 2018). Stratification influences nutrient supply to the surface layer. Stratification in this region is determined by the relative properties (both temperature and salinity) of two water masses formed in different seasons, the warm surface layer formed in summer and the cold bottom water influenced by ice distributions the previous winter. Thus, the strength of stratification is not solely determined by summer temperatures and warm years can have weak stratification and vice versa (Ladd and Stabeno, 2012).

Implications: Coccolithophore blooms can have important biogeochemical implications. The Bering Sea can be either a source or a sink of atmospheric CO_2, with the magnitude of coccolithophore blooms and the associated calcification playing a role (Iida et al., 2012). In addition, variability in the dominant phytoplankton (diatoms vs. coccolithophores) is likely to influence trophic connections with the smaller coccolithophores resulting in longer trophic chains. Coccolithophores may be a less desirable food source for microzooplankton in this region (Olson and Strom, 2002). As noted previously, the striking milky aquamarine color of the water during a coccolithophore bloom can also reduce foraging success for visual predators.

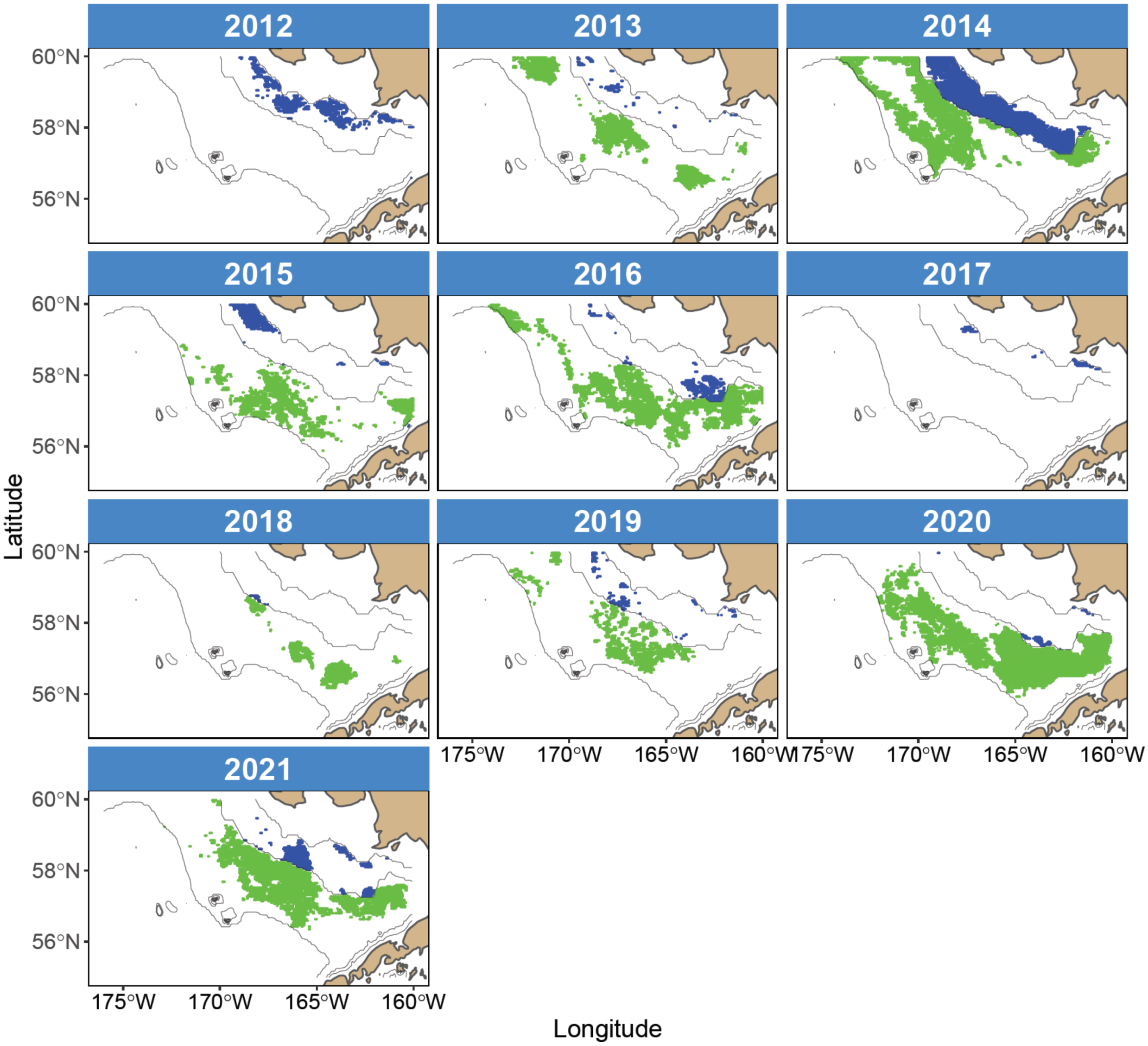

Figure 48: Maps illustrating the location and extent of coccolithophore blooms in September of each year from VIIRS-SNPP data. Color: satellite ocean color pixels exceeding the threshold (PIC>0.0011 mol/m^3) indicating coccolithophore bloom conditions. Blue: inner shelf (30–50 m depth), Green: middle shelf (50–100 m depth). These data are used to calculate the areal index in Figure 49.

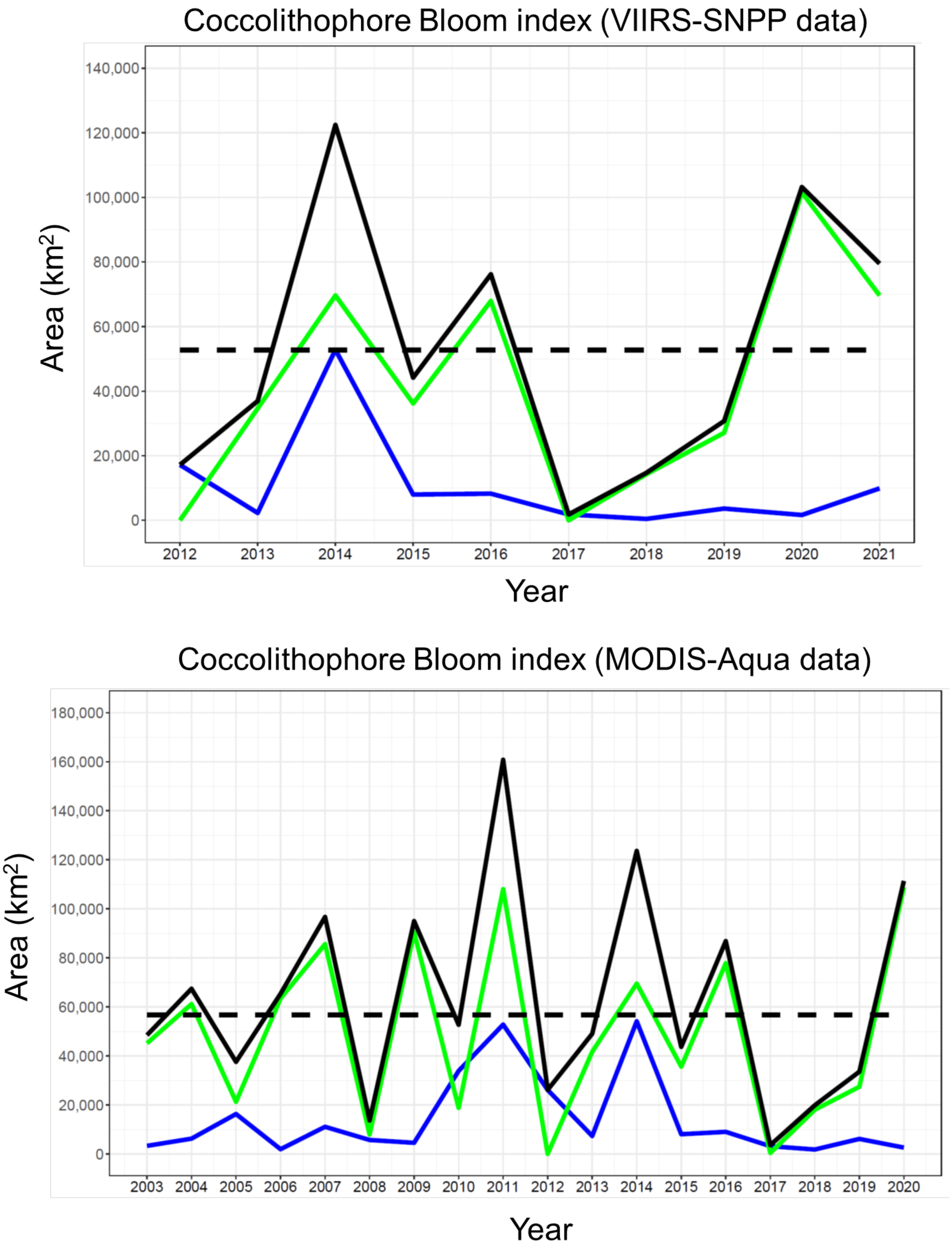

Figure 49: Coccolithophore index for the southeastern Bering Sea shelf (south of 60°N). Top panel shows index calculated from VIIRS-SNPP satellite; Bottom panel shows index calculated from MODIS-Aqua satellite. Blue: average over the inner shelf (30–50 m depth), Green: average over the middle shelf (50–100 m depth), Black: total. The black dotted line is the long-term average. At the time of writing MODIS-Aqua data for 2021 were not yet available.

Zooplankton

Continuous Plankton Recorder Data from the Eastern Bering Sea

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Description of indicator: Continuous Plankton Recorders (CPRs) have been deployed in the North Pacific routinely since 2000. Two transects are sampled seasonally, both originating in the Strait of Juan de Fuca, one sampled monthly (∼April–September) which terminates in Cook Inlet, the second sampled 3 times per year (in spring, summer, and autumn) which follows a great circle route across the Pacific terminating in Asia. Several indicators are now routinely derived from the CPR data and updated annually.

As well as the regular Pacific CPR sampling, the icebreaker the *Sir Wilfrid Laurier* (SWL) has now sampled a transect through the Bering Strait, and the western Chukchi and Beaufort Seas during the summer months of 2018, 2019, and 2020. The SWL is currently towing a CPR in the same region for 2021, however we do not (at present) have the funds to complete the sample analysis for the year 2021. These Arctic routes have been funded via annual research bursary schemes that have now come to an end; we are therefore looking for long-term funding to continue sampling in these areas in the future, as they provide important information on this transition area.

In this report we highlight this Arctic route that started in 2018 and transects the Bering Strait during the summer months of July through September. We present CPR data from the eastern Bering Sea region (Figure 50) as the following indices: the abundance per sample of large diatoms (the CPR only retains large, hard-shelled phytoplankton so while a large proportion of the community is not sampled, the data are internally consistent and may reveal trends), mean Copepod Community Size (see Richardson et al. (2006) for details but essentially the length of an adult female of each species is used to represent that species and an average length of all copepods sampled calculated) as an indicator of community composition and mesozooplankton biomass (estimated from taxon-specific weights and abundance data). Annual anomaly time series of each index have been calculated using a standard z-score calculation: z-score = $(x - \mu)/\sigma$ where x is the value and μ is the mean, and σ is the standard deviation (Glover et al., 2011). Scores of zero are equal to the mean, positive scores signify values above the mean, and negative scores values below the mean.

Status and trends: Figure 51 shows that the copepod community size and mesozooplankton biomass anomalies for 2020 were negative, where they had been positive in 2019. The mean diatom abundance anomaly was also negative in 2020.

Factors influencing observed trends: As there are only 3 years of consistent data, it is difficult to determine any trend. Analysis of summer CPR data in this region has revealed a general alternating (and opposing) pattern of high and low abundance of diatoms and large copepods in 2018 and 2019. This is a similar finding to the analysis from Batten et al. (2018), which was carried out in the southern Bering Sea and Aleutian Islands, and concluded that this was the result of a

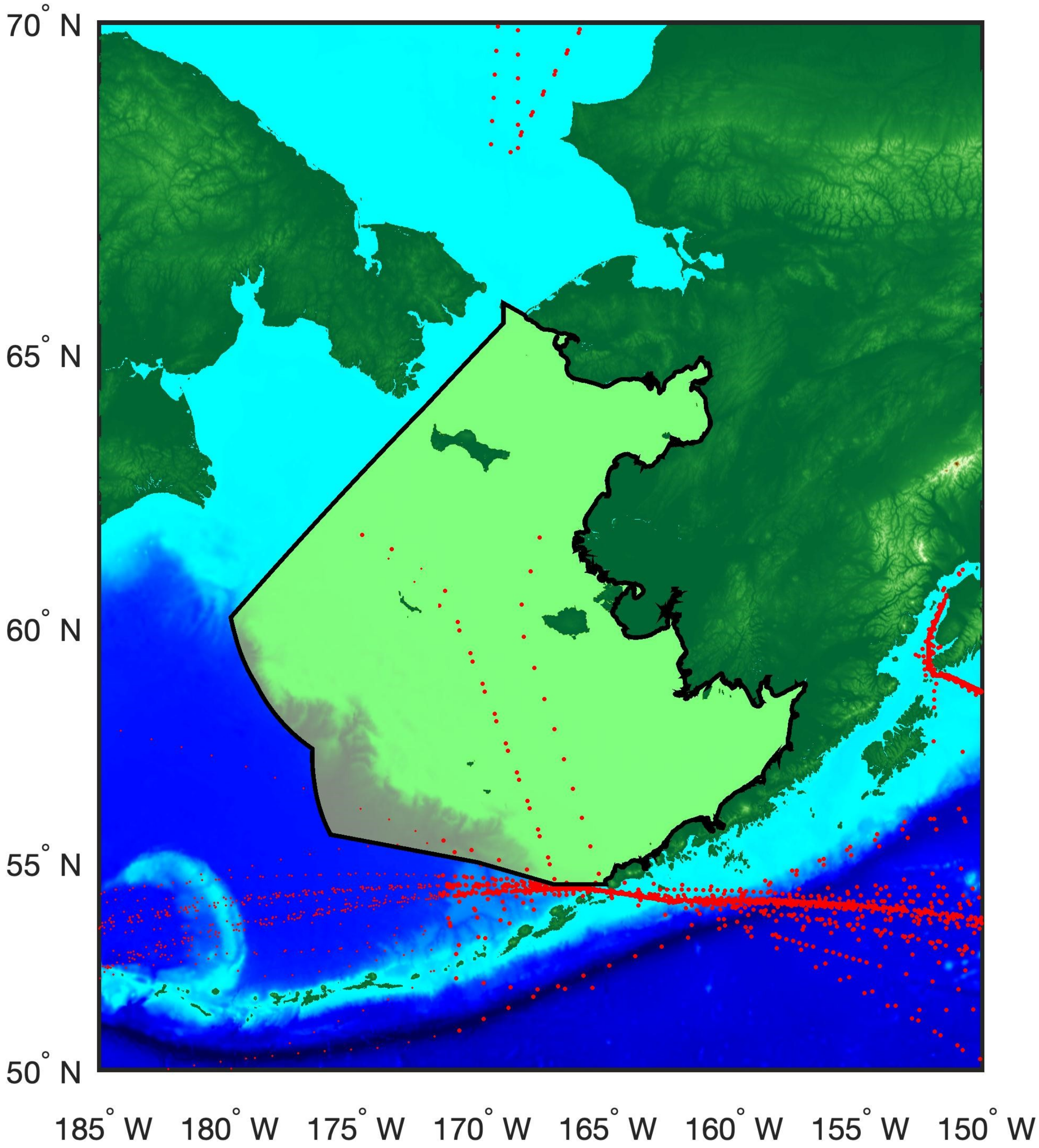

Figure 50: Location of CPR data, the region selected for analysis in this report is highlighted by a yellow rectangle. Red dots indicate actual sample positions and may overlay each other.

trophic cascade caused by maturing pink salmon present in the region. The zooplankton data in Figure 51 consist of more taxa than just large copepods but it is likely that there is some top-down influence of the pink salmon also present in these data.

Implications: This region appears to be subjected to top-down influence by pink salmon as well as bottom-up forcing by ocean climate, which is particularly challenging to interpret. Changes in community composition (e.g., abundance and composition of large diatoms, prey size as indexed by mean copepod community size) may reflect changes in the nutritional quality of the organism to their predators. Changes in abundance or biomass, together with size, influences availability of prey to predators.

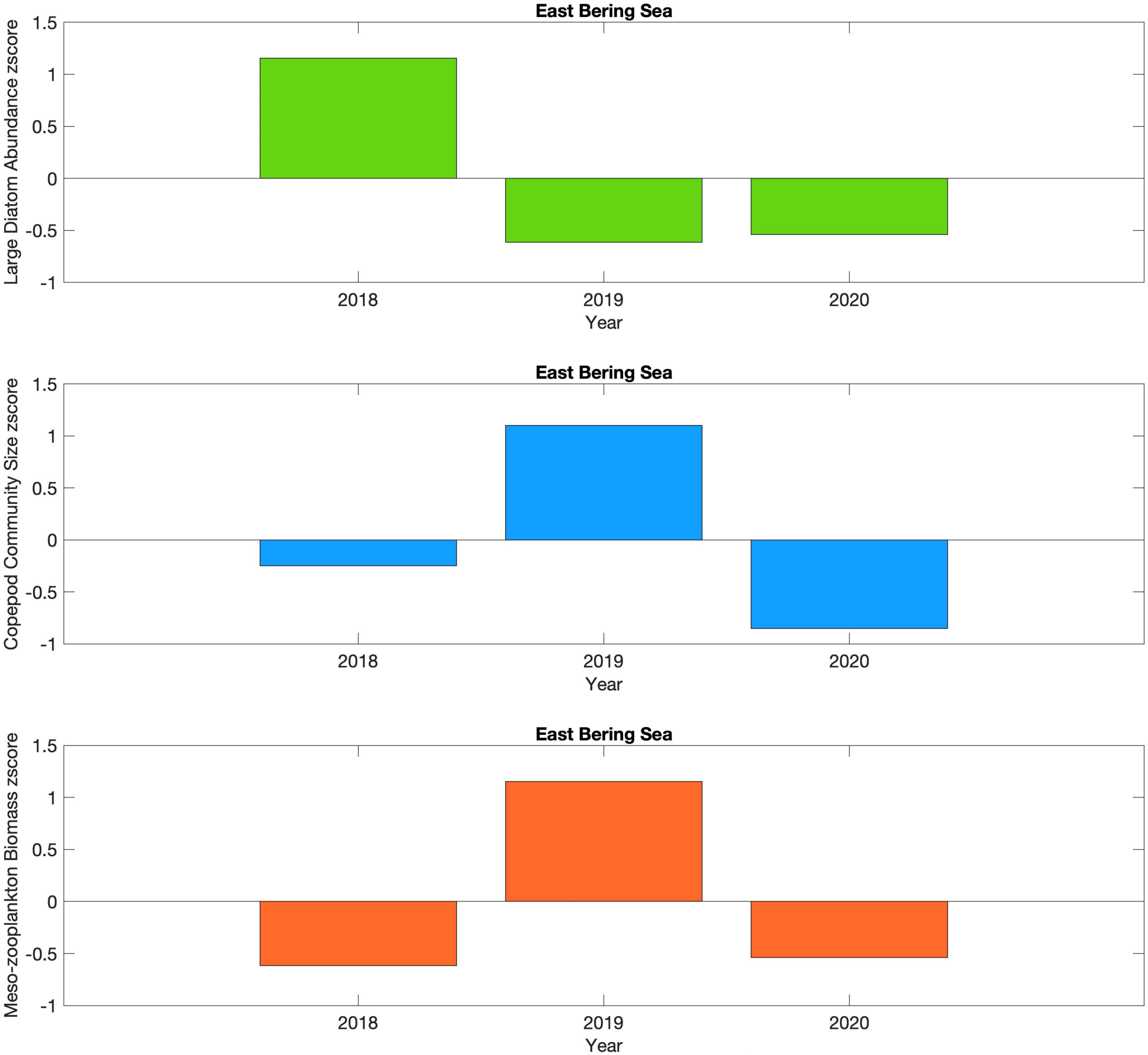

Figure 51: Annual anomalies of three indices of lower trophic levels (see text for description and derivation) for the region shown in Figure 2.

Current and Historical Trends for Zooplankton in the Bering Sea

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Last updated: October 2021

Description of indicator: In 2015, NOAA's Alaska Fisheries Science Center (AFSC) implemented a method for an at-sea Rapid Zooplankton Assessment (RZA) to provide leading indicator information on zooplankton composition in Alaska's Large Marine Ecosystems. The rapid assessment, which is a rough count of zooplankton (from paired 20/60 cm oblique bongo tows from 10 m from bottom or 300 m, whichever is shallower), provides preliminary estimates of zooplankton abundance and community structure. The method employed uses coarse categories and standard zooplankton sorting methods (Harris et al., 2000). The categories are small copepods ($\leq$2 mm; example species: *Acartia* spp., *Pseudocalanus* spp., and *Oithona* spp.), large copepods (>2 mm; example species: *Calanus* spp. and *Neocalanus* spp.), and euphausiids (<15 mm; example species: *Thysanoessa* spp.). Small copepods were counted from the 153 μm mesh, 20 cm bongo net. Large copepods and euphausiids were counted from the 505 μm mesh, 60 cm bongo net. Other, rarer zooplankton taxa were present but were not sampled effectively with the on-board sampling method.

RZA abundance estimates may not closely match historical estimates of abundance as methods differ between laboratory processing and ship-board RZA, particularly for euphausiids which are difficult to quantify accurately (Hunt et al., 2016). Rather, RZA abundances should be considered estimates of relative abundance trends. Detailed information on these taxa is provided after in-lab processing protocols have been followed (1 year post survey). Here, we show updated long-term time-series for the middle shelf of the southeastern Bering Sea for the spring 70 m isobath survey and northern Bering Sea. The mean abundance of each RZA category was plotted for the southern middle shelf of the Bering Sea (Ortiz et al., 2012) and represent primarily April and May in spring as the months with the greatest sampling frequency. The 2021 survey occurred from 1 May to 20 May. The northern Bering Sea survey represents late summer (August and September) in the inner and middle shelf region. The 2021 NBS survey occurred from 27 August to 20 September. Plots show the historical, archived abundance estimates from laboratory processed samples and on-board RZA estimates.

The total lipid content from RZA samples were performed on the designated zooplankton categories of large copepods and euphausiids, which were collected separately in glass vials from each station, stored frozen, and analyzed at NOAA's Auke Bay Laboratories. Briefly, the measured lipid content was compared to the respective wet-weight for the zooplankton in each vial. Lipid analysis was performed via a rapid colorimetric technique employing a modified version of the sulfo-phospho-vanillin (SPV) assay (Fergusson et al., 2020). This method was proven to be highly accurate for analyzing zooplankton lipids in a recent inter-laboratory cross validation study (Pinger et al., in prep).

Status and trends:

Southeastern Bering Sea

We did not detect high abundances of large-sized (>2 mm) *Calanus* spp. copepods along the middle shelf (Figure 52a) in spring and estimates were low compared to historical values as well (Figure 53a). Abundances were similar to the last cold year with significant ice coverage that we sampled, 2017. Small copepods (≤2mm) were similar along the 70 m isobath (Figure 52b) and similar to abundances measured in recent years (Figure 53b). Euphausiids (<15 mm) were very low in abundance, particularly in the southern Bering Sea where they were largely absent (Figure 52c). This was also reflected in the time-series, where euphausiid values were near zero (Figure 53c). However, large euphausiids (> 15 mm) were abundant (data not shown). Lipid content in large copepods (*Calanus* spp.) was low overall in spring, with a few stations showing elevated values in the southern portion of the 70 m isobath (Figure 54a). Lipid content in euphausiids was low overall, measuring less than 1% of total wet weight across the 70 m line (Figure 54b).

Northern Bering Sea

In 2021, abundances of large copepods (>2 mm) in the northern Bering Sea were low across the sampling grid, with the exception of some stations in the north (Figure 55a). Average abundances of large copepods estimated by the RZA were higher than 2018 and 2019, but low compared to the colder years of 2011–2013 (Figure 56a). Small copepod (<2 mm) abundances were higher in the northern portion and lower in the southern portion of the sample area (Figure 55b). Numbers of small copepods remained fairly consistent with values measured over the last 7 years (Figure 56b). In contrast, euphausiid abundances were slightly higher in the southern portion of the northern Bering Sea (Figure 55c) with numbers slightly higher compared to recent estimates (Figure 56c). Lipid content in large copepods (>2 mm; *Calanus* spp.) was elevated compared to spring values and highest near the southern, middle shelf portion of the survey (Figure 57a). Lipid content in euphausiids was also higher than that observed during spring with two stations in the northern portion of the sampling grid having the highest percent lipid observed (Figure 57b).

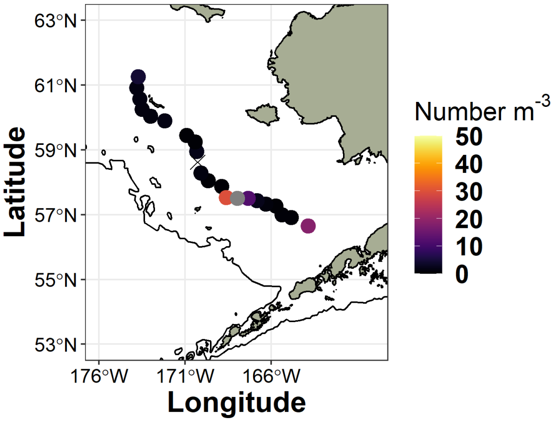
Factors influencing observed trends:

Southeastern Bering Sea

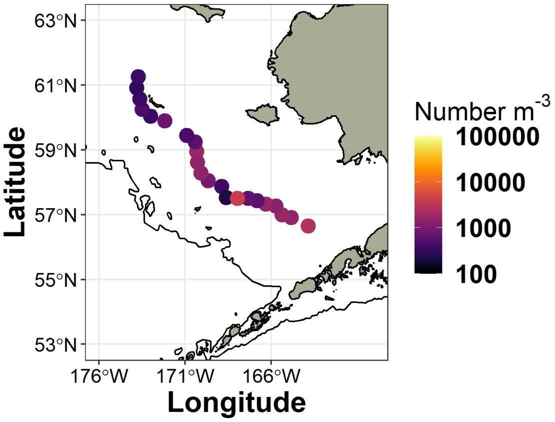
Based on observations made during the spring survey, we began sampling prior to the spring phytoplankton bloom at M2 (see p. 80). Ice had only recently retreated and we were able to approach the ice edge which was approximately 10 nm north of St. Matthew Island. Large copepods (*Calanus* spp.) respond strongly to sea ice dynamics in the Bering Sea (Eisner et al., 2018; Kimmel et al., 2018; Hunt et al., 2020). We noted low numbers of *Calanus* spp. in the larger net; however, we did see evidence of smaller stages of *Calanus* spp. (<2 mm) that were present in the 20 cm net and counted as small copepods. This suggests that *Calanus* spp. individuals were mostly in earlier copepodite stages, thus large copepod abundances were low.

The lower temperatures likely also caused a reduction in small copepod numbers, though not to the same degree as with the larger sized copepods. Small copepods showed little interannual variability in the Bering Sea (Figure 52 and Figure 53). These small, continuously reproducing copepods have growth rates that are more strongly related to temperature than food supply or body size (Hirst and Bunker, 2003). This can be seen in the lower relative abundances during colder years (2009–2012) and the elevated abundances in the more recent warm period (Figure 53).

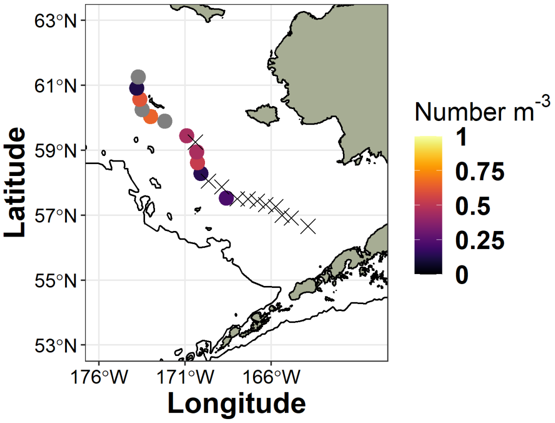
The very low abundances of euphausiids (<15 mm) may also be related to the colder temperatures. Normally, larger sized (>15 mm) euphausiids are in very low abundance in our surveys; however, we found higher abundances of >15 mm euphausiids on average compared to <15 mm euphausiids.



(a) Large copepods (>2 mm)

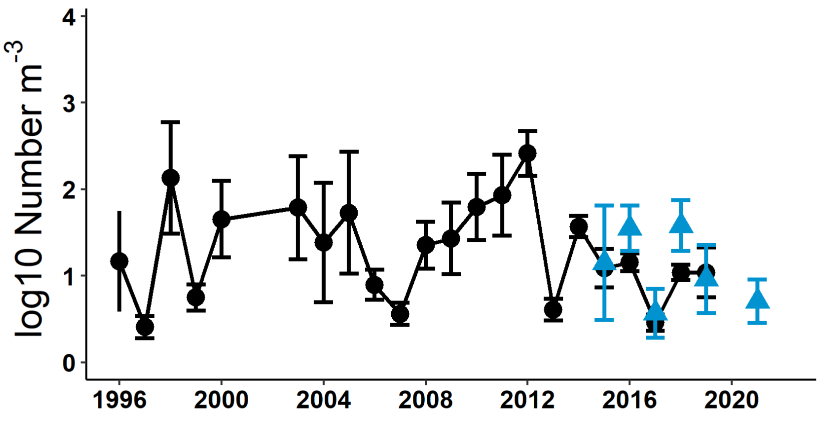


(b) Small copepods (≤2 mm)

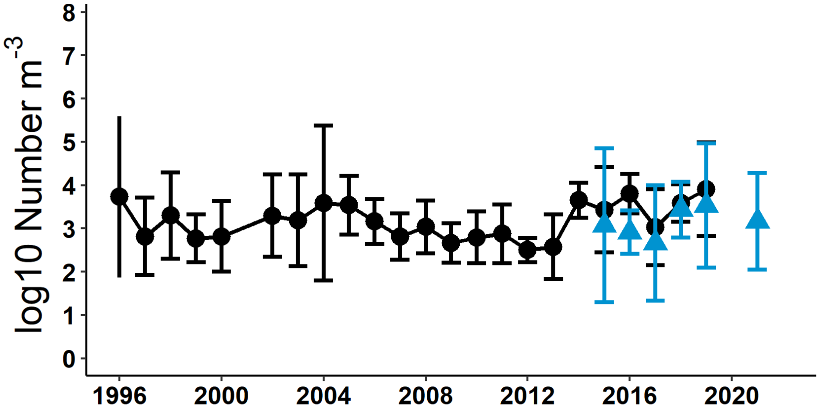


(c) Euphausiids (<15 mm)

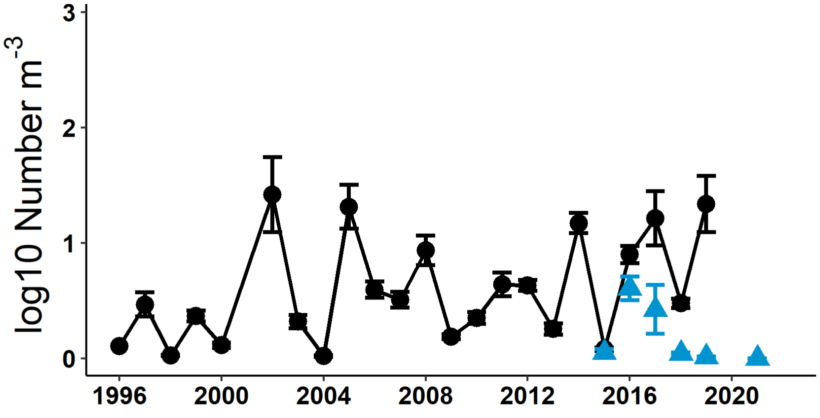
Figure 52: Maps show the spring abundance of large copepods (>2 mm), small copepods (≤2 mm), and euphausiid larvae/juveniles (<15 mm) in the southeastern Bering Sea estimated by the rapid zooplankton assessment. Note all maps have a different abundance scales (Number m^3). X indicates a sample with abundance of zero individuals m^3.



(a) Large copepods (>2 mm)

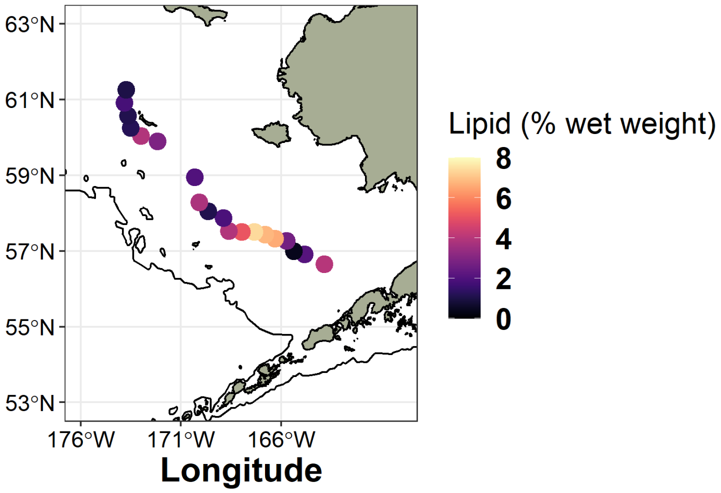


(b) Small copepods (≤2 mm)

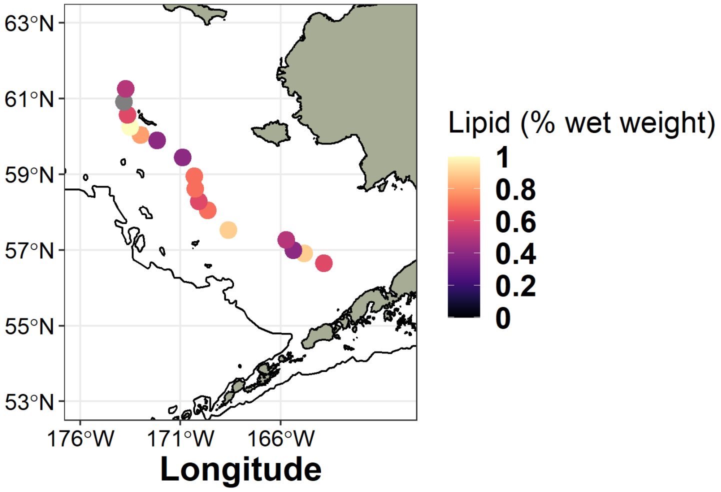


(c) Euphausiids (<15 mm)

Figure 53: Mean abundance of large copepods (>2 mm), small copepods (≤2 mm), and euphausiids (<15 mm) along the 70 m isobath during spring. Black circles represent archived data, blue triangles represent RZA data. Note differences in scale.



(a) Large copepods (>2 mm)



(b) Euphausiids

Figure 54: Lipid content (% wet weight) for large copepods (>2 mm; *Calanus* spp.) and euphausiids (>15 mm) along the 70 m isobath during spring.

Furthermore, it should be noted that the RZA and processed estimates of abundances often differ (Figure 52 and Figure 53). This is expected due to the patchy nature of euphausiid distribution and the difficulty in accurately estimating euphausiid abundances (Hunt et al., 2016).

The lipid content of *Calanus* spp. would be low compared to *Calanus* C5 copepodite stage individuals preparing for diapause, but did indicate that at least, at some locations, *Calanus* spp. was accumulating lipids. This suggests that the *Calanus* spp. population was able to begin lipid accumulation as summer approached. Lipid values in euphausiids were much lower compared to *Calanus* spp. and these large (>15 mm) adults may have not had a chance to accumulate much lipid if caught prior to the spring bloom or not near the ice edge.

Northern Bering Sea
The northern Bering Sea had slightly higher abundances of large copepods compared to the recent low-ice years, though numbers remained low despite some areas with higher abundances in the

northern portion of the survey area. Large copepods such as *Calanus* spp. are relatively less abundant along the inner shelf area sampled in this survey and it appears that *Calanus* spp. only becomes widespread in this region during cold years (Eisner et al., 2018), thus the low numbers along the inner shelf were not surprising.

The neritic zooplankton community primarily consists of small copepods (e.g., *Acartia* spp., *Centropages* spp.) and meroplankton (data not shown) and these numbers appeared similar to those in past surveys. This community remains ubiquitous and present along the inner shelf and is associated with the Alaska Coastal Water (Pinchuk and Eisner, 2017). The peak abundances seen during 2018 appear to have reduced slightly and this is likely related to cooler temperatures.

Euphausiid abundances were low overall and this was not different from the low overall numbers reported in the time-series (Figure 56). Overall, total lipids in both *Calanus* spp. and euphausiids from the northern Bering Sea in summer/fall showed higher values to those observed from the southern survey in the spring. This is consistent with C5 stage *Calanus* spp. accumulating lipid values that are higher later in the year and the greater frequency of occurrence for this species on the inner shelf. In contrast, euphausiids tended to have higher values to the north, albeit with lower sample numbers for euphausiids (Figure 57). These results suggest that euphausiids caught later in the year were able to accumulate a higher proportion of lipids compared to spring.

Implications:

Southeastern Bering Sea

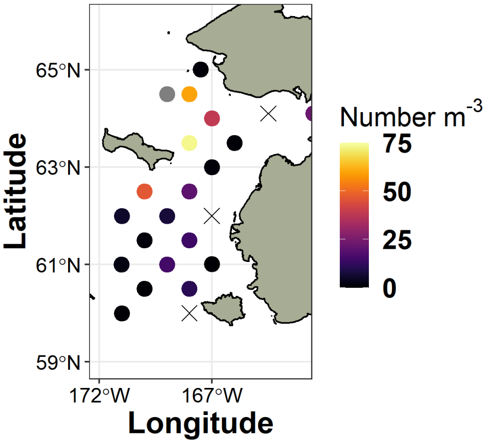
Smaller copepods and their early life history stages form the prey base for larval to early juvenile Walleye pollock, as well as other fish species, during spring (Figure 52 and Figure 53) on the eastern Bering Sea middle shelf. The slight reduction in smaller copepod abundance compared to warmer years was unlikely to impact food availability for larval fish as the observations were within historical ranges (Figure 53). Low abundances of large copepods are less critical in the spring, but very important later in the year (Hunt et al., 2011). Our observations of early life-history stages of *Calanus* spp. suggest that the annual cohort for this species was developing more slowly due to the colder temperatures. This was also reflected in the low lipid values in the spring. This would result in an increase in lipid-rich *Calanus* spp. available to age-0 fish later in the year and this relates to increased overwinter success for pollock (Siddon et al., 2013; Eisner et al., 2020). Observations from the fall survey would have placed this prediction into greater context; however, the survey was canceled.

The low abundances recorded for smaller euphausiids (<15 mm) must be understood in the context of the higher abundances of larger euphausiids (>15 mm) observed (data not shown). Given that the bongo nets are prone to underestimation of larger sized euphausiids, this likely indicated that large euphausiids were active and reproducing along the middle shelf. This observation suggests that euphausiids will persist along the middle shelf later in the year; however, confirming this prediction was difficult due to a lack of a summer acoustic survey in the Bering Sea during 2021. If euphausiids persisted and became abundant along the middle shelf in the fall, they would have represented a significant food source for forage fish (Hunt et al., 2016).

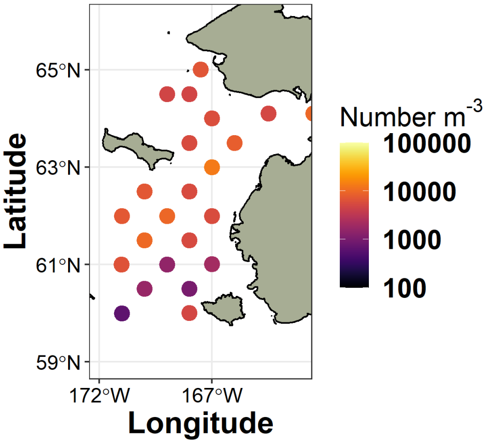
Northern Bering Sea

In the northern Bering Sea, the observed zooplankton abundances remained similar to those observed in recent years, with a slight increase in large copepod and euphausiid numbers. This continues to support the notion that the inner shelf region is an area that is dominated by smaller sized and more diverse plankton community relative to the middle shelf.

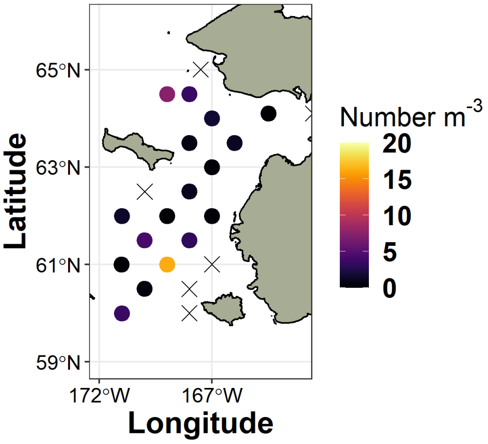
The lipid content of zooplankton from the northern survey, which was later in summer, was significantly higher than in spring, indicating the accumulation of lipids prior to diapause and their value as an energy-rich food source for young-of-year fish. While a direct comparison between the southeastern and northern Bering Sea was not possible for the late summer time-period, the accumulation of lipids in large *Calanus* spp. in the northern Bering Sea suggests the same could have occurred in the southeastern Bering Sea. In a recent paper, less spatial variability in *Calanus* spp. lipid content existed along the 70 m isobath than was expected given the strong difference in north ($> 60^{\circ}$N) vs. south temperature observed during 2015 (Tarrant et al., 2021). This suggests that copepods and euphausiids along the middle shelf in 2021 were likely to be storing lipids, if present and available as prey for forage fish.



(a) Large copepods (>2 mm)

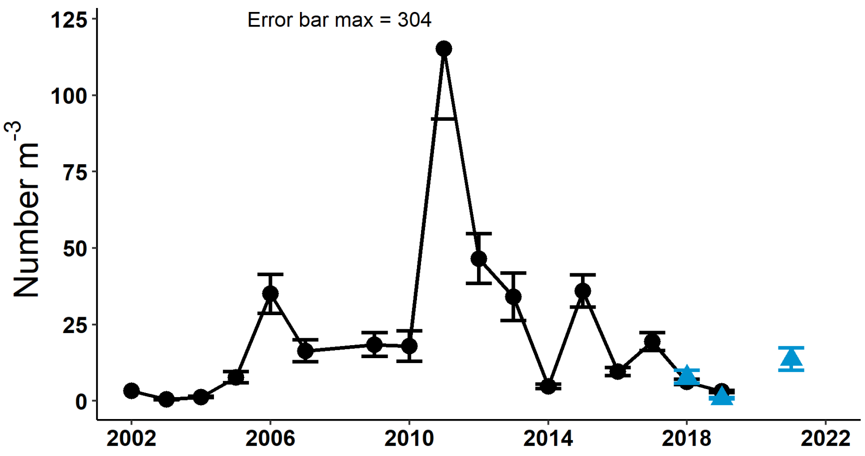


(b) Small copepods (≤2 mm)

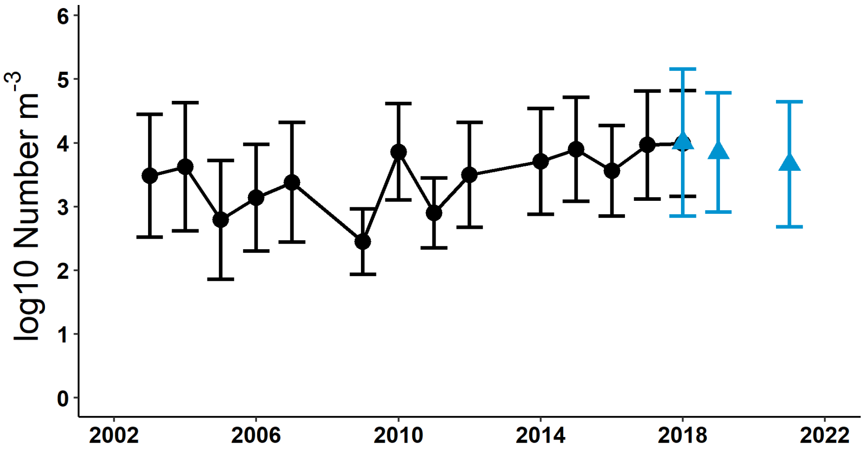


(c) Euphausiids (<15 mm)

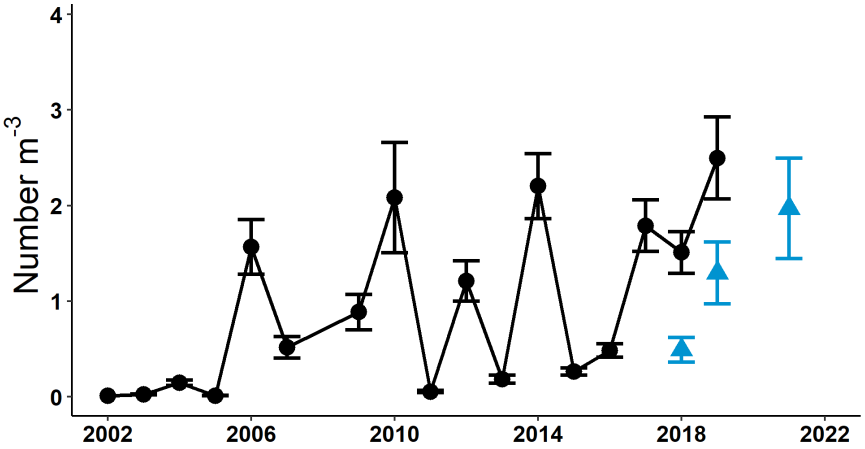
Figure 55: Maps show the summer/fall abundance of large copepods (>2 mm), small copepods (≤2 mm), and euphausiid larvae/juveniles (<15 mm) in the northern Bering Sea estimated by the rapid zooplankton assessment. Note all maps have a different abundance scales (Number m^3). X indicates a sample with abundance of zero individuals m^3.



(a) Large copepods (>2 mm)

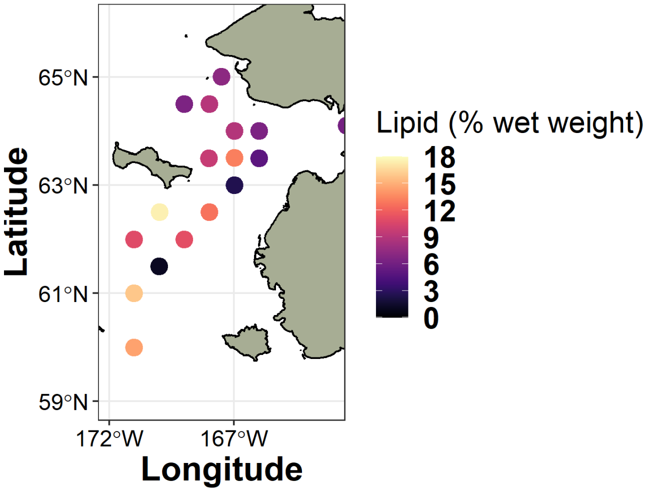


(b) Small copepods (≤2 mm)

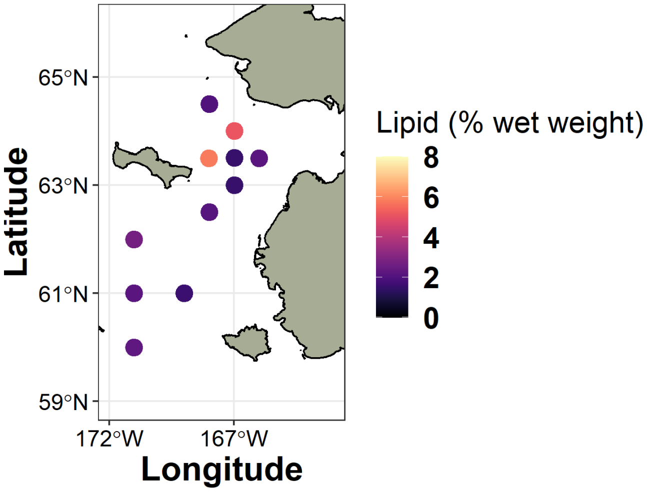


(c) Euphausiids (<15 mm)

Figure 56: Mean abundance of large copepods (>2 mm), small copepods (≤2 mm), and euphausiids (<15 mm) in the NBS during summer/fall. Black circles represent archived data, blue triangles represent RZA data. Note differences in scale.



(a) Large copepods (>2 mm)



(b) Euphausiids

Figure 57: Lipid content (% wet weight) for large copepods (>2 mm; *Calanus* spp.) and euphausiids (>15 mm) in the NBS during summer/fall.

Jellyfish

Jellyfishes - Eastern Bering Sea Shelf

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Last updated: October 2021

Description of indicator: The time series for jellyfishes (primarily *Chrysaora melanaster*) relative CPUE by weight (kg per hectare) was updated for 2021 (Figure 58). Relative CPUE was calculated by setting the largest biomass in the time series to a value of 1 and scaling other annual values proportionally. The standard error (±1) was weighted proportionally to the CPUE to produce a relative standard error.

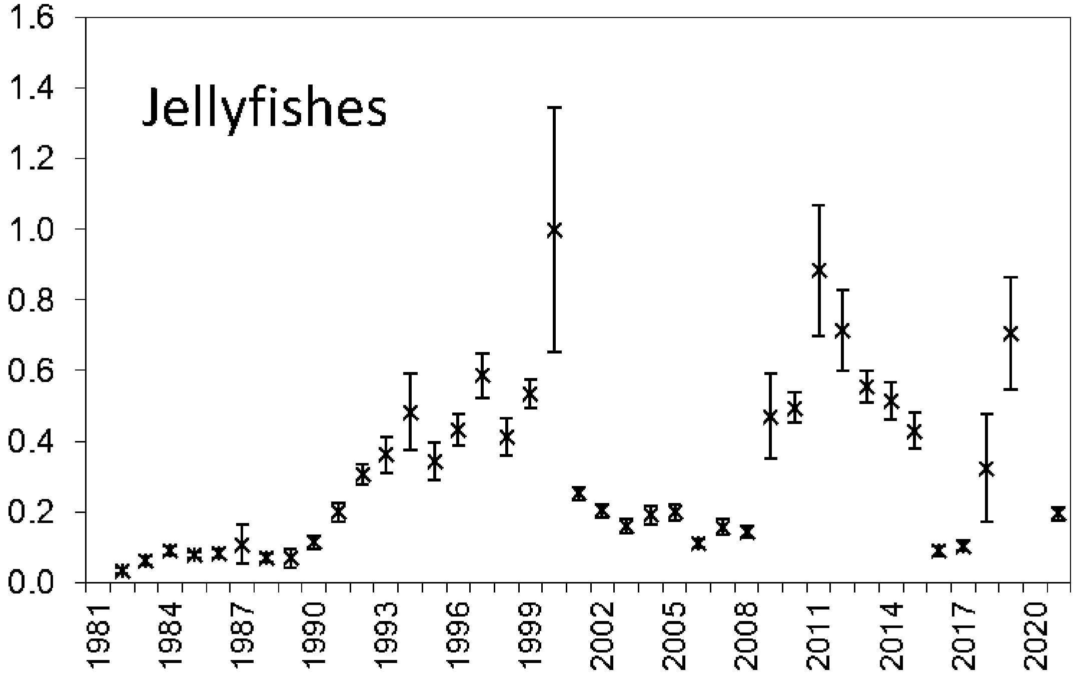

Figure 58: AFSC eastern Bering Sea shelf bottom trawl survey relative CPUE for jellyfish during the May to August time period from 1982–2021.

Status and trends: The relative CPUE for jellyfishes in 2021 decreased 73% from 2019 survey estimates, similar to the catch rates observed 2001–2008 and 2016–2017. These low CPUE values are also similar to those observed during the first nine years of the time series (1982–1991). There was a period of increasing biomass of jellyfishes throughout the 1990's (Brodeur et al., 1999) followed by a second period of relatively low CPUE's from 2001 to 2008 and then a second period with relatively higher CPUE values from 2009 to 2015.

Factors influencing observed trends: The fluctuations in jellyfish biomass and their impacts on forage fish, juvenile Walleye pollock (*Gadus chalcogrammus*), and salmon in relation to other biophysical indices were investigated by Cieciel et al. (2009) and Brodeur et al. (2002, 2008). Ice cover, sea-surface temperatures in the spring and summer, and wind mixing all have been shown to influence jellyfish biomass, and affect jellyfish sensitivity to prey availability (Brodeur et al., 2008).

Implications: Jellyfish are pelagic consumers of zooplankton, larval and juvenile fishes, and small forage fishes. A large influx of pelagic consumers such as jellyfish can decrease zooplankton and small fish abundance, which in turn can affect higher trophic levels causing changes to the community structure of the ecosystem.

Ichthyoplankton

There are no updates to Ichthyoplankton indicators in this year's report. See the contribution archive for previous indicators at: `http://access.afsc.noaa.gov/reem/ecoweb/index.cfm`.

Forage Fish

Highlights of the 2021 Bering Sea and Aleutian Islands Forage Report

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Last updated: September 2021

The abundance of forage species (e.g., fishes, squids, euphausiids, and other invertebrates) in the eastern Bering Sea (EBS) is difficult to measure. There are no dedicated surveys for these species, and the existing surveys are limited in their ability to assess forage species due to gear selectivity (e.g., mesh size) or catchability (e.g., vertical distribution).

Nevertheless, these surveys can be used to discern general trends in abundance. The trawl survey-based aggregate forage index (which does not include juvenile pollock or Pacific herring) suggests that forage abundance has declined substantially since 2015 (see Report Card, Figure 1). This is supported by the reduced abundance and frequency of occurrence observed for individual species as described in the 2021 Forage Report. The surface trawl survey in the northern Bering Sea (NBS) indicates a similar decline in capelin and age-0 pollock. Trends in herring abundance are more complicated, with results varying between the EBS bottom trawl survey, the NBS surface trawl survey, and the Togiak District spawner biomass and recruitment indices (see p. 108). The herring data do seem to suggest an increase in herring abundance throughout the Bering Sea in recent years. Temporal patterns of juvenile salmon abundance in the NBS are similarly complex, although the abundance of small salmon, herring, and forage species as a whole were substantially lower in 2021 relative to 2019.

Taken together, the available information suggests that the EBS and NBS are experiencing a decline in the availability of forage species for predators. Because many forage species are sensitive to their environment, particularly changes in temperature, it is likely that recent warm years in this region have contributed to this decline. A decline in forage availability may have contributed to other substantial changes in the Bering Sea.

Vertical Distribution of Age-0 Pollock in the Southeastern Bering Sea

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Last updated: September 2021

Description of indicator: Vertical distribution of age-0 pollock was estimated through the calculation of an abundance-weighted mean depth during two cold years (2011, 2012) and two warm years (2014, 2016). The abundance of age-0 pollock in the southeastern Bering Sea was estimated using acoustic-trawl methods. The process involved assigning trawl-catch data to acoustic-backscatter data that was measured along a transect line. The trawl catch information was manually assigned to backscatter from a single surface, oblique, or midwater-trawl depending on proximity, tow depth, and backscatter characteristics. Scrutinized backscatter was echo-integrated into 0.5 nautical mile (nmi) by 5 m bins, and output as nautical area scattering coefficient, m^2/nmi^2 (NASC). The species-specific compositions from each catch were used to convert NASC to species-specific abundance (individuals/nmi^2) using published measurements of the acoustic properties of these species. Age-0 pollock abundance was summed over each depth bin to calculate the weighted mean depth over the entire survey area. Here, we show yearly abundance-weighted mean depths during the late summer over the southeastern Bering Sea.

Status and trends: Age-0 pollock were deeper in the water column during the cold years of 2011 and 2012, and closer to the surface during the warm years of 2014 in 2016 (Figure 59).

Factors influencing observed trends: Within the years analyzed, 2011 and 2012 represented colder years while 2014 and 2016 represented warmer years in the southeastern Bering Sea. These two oceanographic temperature phases resulted in a change in the vertical distribution of age-0 pollock. Energy densities of age-0 pollock collected in trawls from these surveys showed that pollock collected in cold years had higher energy densities than those collected in warm years, suggesting improved feeding and provisioning conditions at depth in colder thermal conditions. Colder years have greater abundances of larger lipid-rich prey which result in higher dietary percentages of lipid and energy densities of age-0 pollock (Coyle et al., 2011; Heintz et al., 2013; Kimmel et al., 2018). This is partially explained given that larger lipid-rich prey vertically migrate deeper in the water column during the day.

Implications: Vertical distribution shifts may impact predator-prey overlap between age-0 pollock and their lipid-rich prey (e.g., calanoid copepods, euphausiids), resulting in different feeding conditions that ultimately define fish body condition prior to the onset of winter. As the climate warms further, or these warm phases potentially lengthen in time, there may be a compounding problem of poor condition and recruitment, thus significantly reducing the standing stock of pollock.

Figure 59: Annual abundance-weighted mean depth of age-0 pollock during late summer in the south-eastern Bering Sea.

Herring

Togiak Herring Population Trends

Contributed by Greg Buck, Sherri Dressel, Sara Miller, and Caroline Brown
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Last updated: October 2021

Description of indicator: A time-series of catch-at-age model estimates of mature Pacific herring (*Clupea pallasii*) biomass (1980–2020) spawning in the Togiak District of Bristol Bay serves as an index of mature population size. Togiak herring are an important prey species for piscivorous fish, seabirds, and marine mammals, and serve as an important resource for subsistence harvesters and commercial fisheries. The forecast size of the Togiak Bay herring spawning stock is used for the purpose of setting the State of Alaska commercial guideline harvest level for the following year's Togiak spring sac roe fishery and Dutch Harbor bait fishery. The forecasted size of the Togiak Bay herring spawning stock, combined with the size of other eastern Bering Sea (EBS) herring stocks, serves as the basis for setting the annual prohibited species catch (PSC) limit for EBS groundfish fisheries per Amendment 16A of the Bering Sea/Aleutian Islands Groundfish Fishery Management Plan. The annual PSC limit is set at 1% of the annual biomass of mature EBS herring and is apportioned among trawl fishery categories. Attainment of any apportionment may trigger closure of Herring Savings Areas to that fishery. The Togiak Bay herring stock is the largest herring spawning stock in Alaskan waters and is thought to comprise approximately 70% of the EBS herring spawning biomass that occurs along the coastline from Port Heiden/Port Moller to Norton Sound. Due to reduced commercial market demands for herring and State of Alaska budget cuts, Togiak Bay herring is the only mature herring stock in the EBS area that is currently and consistently monitored, surveyed, and assessed for stock size on an annual basis.

The biomass of mature Pacific herring occurring in the Togiak District of Bristol Bay has been tracked through aerial surveys since the late 1970s using methods described by Lebida and Whitmore (1985). Generally, the peak aerial survey biomass estimate occurs while the commercial fishery is open. Typically, the harvest prior to the peak, along with the peak aerial survey biomass and an aerial survey biomass around the time commercial fishery ends, are combined to provide a survey estimate of mature herring biomass. A statistical catch-at-age model is then used to forecast Pacific herring biomass in the Togiak District of Bristol Bay (Funk et al., 1992; Funk and Rowell, 1995). The data used in the model include aerial survey estimates of biomass weighted by a confidence score (confidence depends primarily on visibility conditions, aerial survey coverage, and number of surveys), age composition and weight-at-age information collected from the fishery, and harvest from the purse seine and gillnet fisheries. Recruitment of Togiak herring to the fishery begins around age-4 and fish are believed to be fully recruited into the fishery around age-8.

Status and trends: Mature Togiak herring biomass, as estimated by the model, increased steeply from 1980 to 1983 (Figure 60), due to large age-4 recruitments in 1981 and 1982 (Figure 61). The biomass then declined through the late-1990s and has remained stable since that time. The large annual biomasses estimated by the model during the late 1980s have considerable uncertainty due to the poor aerial survey conditions and confidence scores during that time.

The 2021 biomass forecast for Togiak was based on aerial survey estimates, annual age composition and weight-at-age data collected from the fishery, and harvest data. The forecast for 2021 (236,742 short tons) was a 25% increase from the model hindcast of 2020 mature biomass (189,375 short tons) is the largest forecast since integrated catch-age models have been used for forecasting (first forecast was made for 1993) and is greater than model hindcasts since 1987 (Figure 60). The increase in the forecast is primarily due to the estimated age-4 recruitment in 2020, which is the highest estimated recruitment since 1982, but is also highly uncertain as the recruit class has only been observed once (2020 data). While the magnitude of the estimated 2020 estimated recruitment is uncertain due to first being observed in 2020 (only one observation of this year class), the high PSC catch in the EBS pollock fishery in 2020 supports the likelihood of a strong increase in young EBS herring (Siddon et al., 2020), as does preliminary Togiak herring data from 2021. The 2020 mature population was estimated to be predominantly age-4 and-6 fish as the population continues to be supported by the 2014 and now also the 2016 year classes (age-4 recruits in 2018 and 2020, Figure 61).

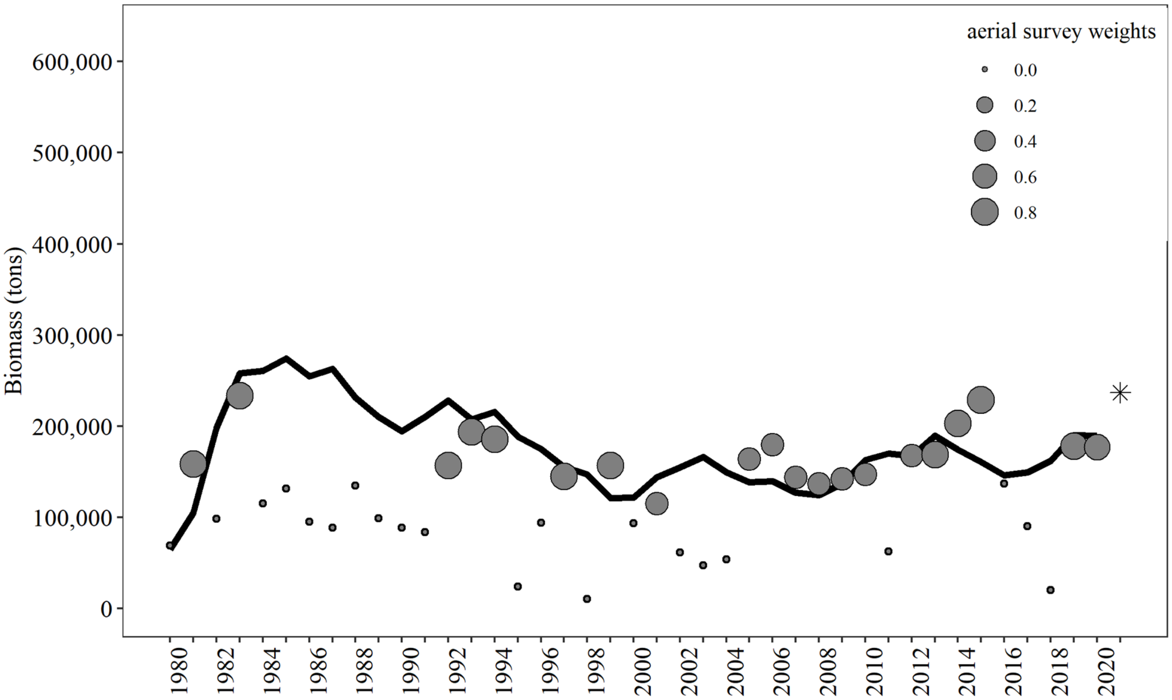

Figure 60: Aerial survey-estimated biomass plus pre-peak catch that were included in the model (grey points), model-estimated mature biomass (black solid line), and model-estimated mature biomass forecast (black asterisk). The size of the grey points reflects the confidence weighting of each aerial survey estimate in the model based on weather, number of surveys, quality of surveys, and timing of surveys relative to the spawn (ranging from 0=no confidence to 1=perfect confidence).

An active commercial sac roe fishery is conducted on this population with gillnet and purse seine gear. A small spawn on kelp quota is allowed but has not been utilized since 2003. The sac roe fishery has harvested an average of 19,081 short tons annually over the last 10 years (2011–2020).

Residents of Togiak have relayed to Alaska Department of Fish & Game staff that they do not participate in the Togiak herring commercial fishery as they once did primarily due to a concern about abundance of herring needed for subsistence uses, as well as competition with commercial

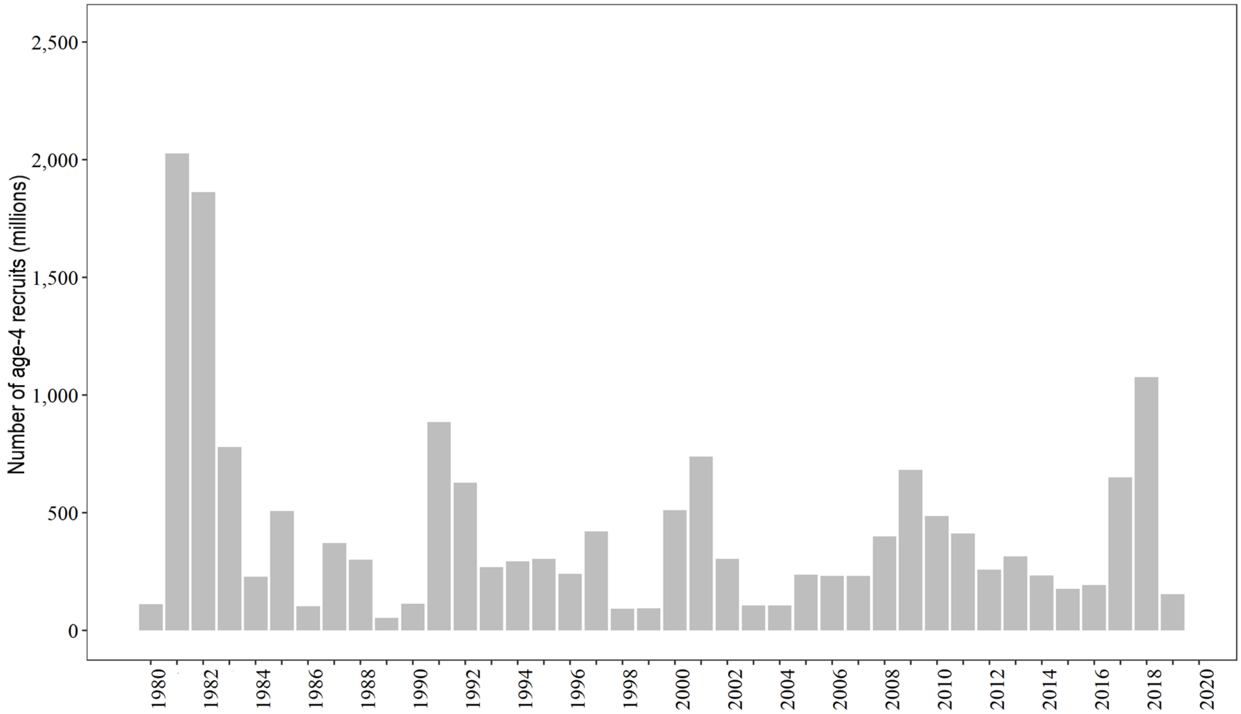

Figure 61: Model estimates of age-4 recruit strength (numbers of age-4 mature and immature fish).

fishers from outside the state. ADF&G has conducted two comprehensive subsistence surveys in Togiak – in 1999 (Coiley-Kenner et al., 2003) and 2008 (Fall et al., 2012), as well as a study designed to address proposals coming before the 2017 Board of Fisheries and a more recent non-salmon fish harvest survey in 2019 (Jones et al., 2021). Harvests of herring and/or herring spawn on kelp were measured in all four years. Harvests of herring declined by 22% between 1999 and 2008 while the harvest of spawn on kelp increased by 146%, from 8 lbs per capita to 20 lbs per capita. During the 2017 study, Togiak households reported harvesting only 3 lbs of spawn on kelp per capita. Many residents expressed concern about the herring stocks in 2008 and in 2017, especially about their ability to harvest spawn on kelp. In 2019, Togiak residents reported harvesting 13.7 lbs of herring roe per capita. Despite lower harvests of herring and herring roe in 2019 than 2008, Togiak respondents noted that the quantity of herring spawn on kelp was improved in 2019 in comparison to resource availability over the previous 10 years. An anecdotal report suggests that the 2020 harvest was also good.

Factors causing observed trends: Togiak herring biomass trends are dependent upon recruitment and are influenced by the environment. Pacific herring recruitment is both highly variable and cyclic with large recruitment events (age-4) occurring roughly every 8–10 years. Biomass trends are greatly influenced by recruitment, with the highest biomasses in 1983–1987 resulting from the largest age-4 recruitments in 1981 and 1982. The substantial recruitment in 2020 suggests the population will increase in 2021 (Figure 60). Williams and Quinn (2000) demonstrate that Pacific herring populations in the North Pacific are closely linked to environmental conditions, particularly water temperature. Tojo et al. (2007) demonstrate how the complex reproductive migration of EBS herring is related to temperature and the retreat of sea ice and how it has changed since the 1980s. Wespestad and Gunderson (1991) suggest that recruitment variation in the EBS relates to the degree of larval retention in near-coastal nursery areas where temperatures and feeding conditions are optimal for rapid growth. Specifically, they indicate that above average year-classes occur in years with warm sea surface temperatures when the direction of transport is north to northeast (onshore) and wind-driven transport velocity is low, whereas weak year classes occur in years when sea-surface temperature is cold, wind-driven transport is west to northwest (offshore), and wind-driven transport velocity is high. It is possible that the shift to anomalously warm sea surface temperatures from 2014 to 2020 (Watson, 2020) have positively impacted herring recruitment. Continued examination of environmental conditions such as sea surface temperature, air temperature, surface winds, and EBS ice coverage may increase our understanding of the recruitment processes at play in this population.

Elders and Togiak residents have expressed concern that commercial purse seine fishing for sac roe has influenced Togiak herring biomass trends. They describe changes in the density and spatial extent of herring spawn and decreases in herring abundance since approximately the 1990s. However, reports of improved quantity of spawn on kelp in 2019, relative to the last 10 years, is hopeful. As is beginning to be explored for other herring stocks in the North Pacific, closer examination of the spatial distribution of herring spawn and the spatial distribution of commercial fishing effort may increase our understanding of the potential impacts of commercial fishing on herring spawning populations and subsistence harvest.

Implications: Togiak herring are an important prey species for piscivorous fish, seabirds, and marine mammals. Togiak herring are also an important resource for subsistence harvesters, as well as the basis for a directed Togiak commercial herring sac roe fishery and a directed commercial Dutch Harbor bait fishery, as well as being PSC in the EBS groundfish fisheries. The cyclic nature of recruitment into this population has implications for predators and prey of Pacific herring as well as fisheries. The stable trend of this stock since the mid-1990's, despite cyclic recruitment, has allowed for directed commercial fisheries to open and has contributed to approximately stable PSC levels for EBS groundfish fisheries since 1992. Togiak residents express considerable concern about declines in the subsistence fishery since the early 1990s, but subsistence reports from 2019 suggest a positive change. Data in upcoming years will help define the magnitude and impact of the 2020 recruitment on the Togiak herring population and the implications for subsistence harvest, commercial fisheries, and PSC limits in the EBS groundfish fisheries.

Salmon

Trends in Alaska Commercial Salmon Catch – Bering Sea

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Last updated: September 2021

Description of indicator: This contribution provides commercial catch information for salmon of the Bering Sea. This contribution summarizes data and information available in Alaska Department of Fish & Game (ADF&G) reports (e.g., Brenner et al. (2021)) and on their website[10].

Pacific salmon in Alaska are managed in four regions based on freshwater drainage basins[11]: Southeast/Yakutat, Central (encompassing Prince William Sound, Cook Inlet, and Bristol Bay), Arctic-Yukon-Kuskokwim, and Westward (Kodiak, Chignik, and Alaska peninsula). ADF&G prepares harvest projections for all areas rather than conducting run size forecasts for each salmon run. There are five Pacific salmon species with directed commercial fisheries in Alaska; they are sockeye (*Oncorhynchus nerka*), pink (*O. gorbuscha*), chum (*O. keta*), Chinook (*O. tshawytscha*), and coho (*O. kisutch*) salmon.

Status and trends:
Statewide
Catches from directed fisheries on the five salmon species have fluctuated over recent decades but in total have been generally strong statewide (Figure 62). The commercial harvests from 2020 totaled 118.3 million fish, which was 14.4 million less than the preseason forecast of 132.7 million fish. Preliminary data from ADF&G for 2021 indicates a statewide total commercial harvest of about 222.2 million fish (as of 20 September 2021), which is well above the preseason projection of 190.1 million fish. The 2021 harvest was bolstered by the catch of 151.6 million pinks, primarily from Prince William Sound, and 55.8 million sockeye, primarily from Bristol Bay.

Bering Sea
Salmon harvests in the Bering Sea are numerically dominated by the catch of sockeye in Bristol Bay (Figure 63). The 2020 Bristol Bay sockeye run of 58.3 million is the fourth largest ever, and the harvest of 39.6 million was the fifth highest ever. Escapement goals for sockeye in 2020 were met or exceeded in every drainage in Bristol Bay where escapement was defined. Preliminary data for 2021 from ADF&G indicates that the commercial harvest of Bristol Bay sockeye is strong again, at nearly 42 million fish (for more information on 2021 Bristol Bay sockeye salmon, see p. 115).

Chinook abundance in the Arctic-Yukon-Kuskokwim region has been low since the mid-2000s and remains low. From 2008 to 2020 no commercial periods targeting Chinook were allowed in the Yukon Management Area. Preliminary data for 2021 indicate that Chinook escapement goals will not likely be met for the Yukon Area. In 2020, Chinook did meet the drainage-wide escapement goal for the Kuskokwim Area.

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[10] `https://www.adfg.alaska.gov/`
[11] `https://www.adfg.alaska.gov/index.cfm?adfg=commercialbyfisherysalmon.salmonareas`

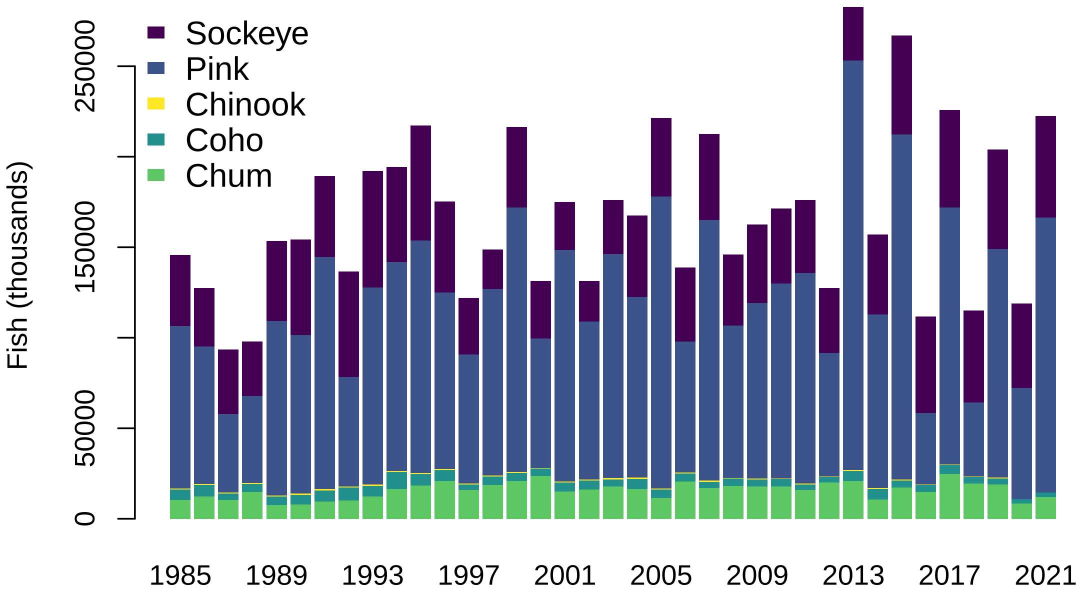

Figure 62: Alaska statewide commercial salmon catches, 2021 values are preliminary. Source: ADF&G; `http://www.adfg.alaska.gov`. ADF&G not responsible for the reproduction of data, subsequent analysis, or interpretation.

The 2020 commercial harvest of summer chum in the Yukon Area was the lowest since 2003. There were no commercial harvests for salmon during fall 2020 in the Yukon Management Area due to the low run size for fall chum and coho salmon. According to ADF&G, the 2021 Yukon fall chum run has not met the minimum escapement goal needed to allow commercial harvests[12].

For more information on 2021 Arctic-Yukon-Kuskokwim salmon abundance estimates, see p. 26.

Factors influencing observed trends: Salmon have complex life histories and are subject to stressors in the freshwater and marine environments, as well as anthropogenic pressures. These forces do not affect all species and stocks equally or in the same direction, and resolving what is driving the population dynamics of a particular stock is challenging (Rogers and Schindler, 2011). Interannual variation in statewide total salmon abundance is partly due to the even-year, odd-year cycle in pink salmon, particularly production from the Prince William Sound stock of pink salmon, which typically have larger runs in odd years. Chinook runs have been declining statewide since 2007. Size-dependent mortality during the first year in the marine environment is thought to be a leading contributor to low Chinook run sizes (Beamish and Mahnken, 2001; Graham et al., 2019). Additionally, rising sea temperatures and loss of sea ice may lead to slower growth for juvenile Chinook in the eastern Bering Sea (Yasumiishi et al., 2020).

Salmon are also caught as bycatch in Bering Sea groundfish trawl fisheries, most of which are Chinook and chum. The North Pacific Fishery Management Council has implemented management measures and incentives that have largely been successful at reducing Chinook bycatch in groundfish trawl fisheries since their peak in 2007 (Stram and Ianelli, 2015). However, the bycatch of non-Chinook (i.e., chum) has trended upward since 2012 and in 2021 is at its highest level since 2005[13].

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[12] `https://www.adfg.alaska.gov/static/applications/dcfnewsrelease/1335706319.pdf`

[13] `https://www.npfmc.org/wp-content/PDFdocuments/bycatch/BeringSeaSalmonBycatchFlyer.pdf`

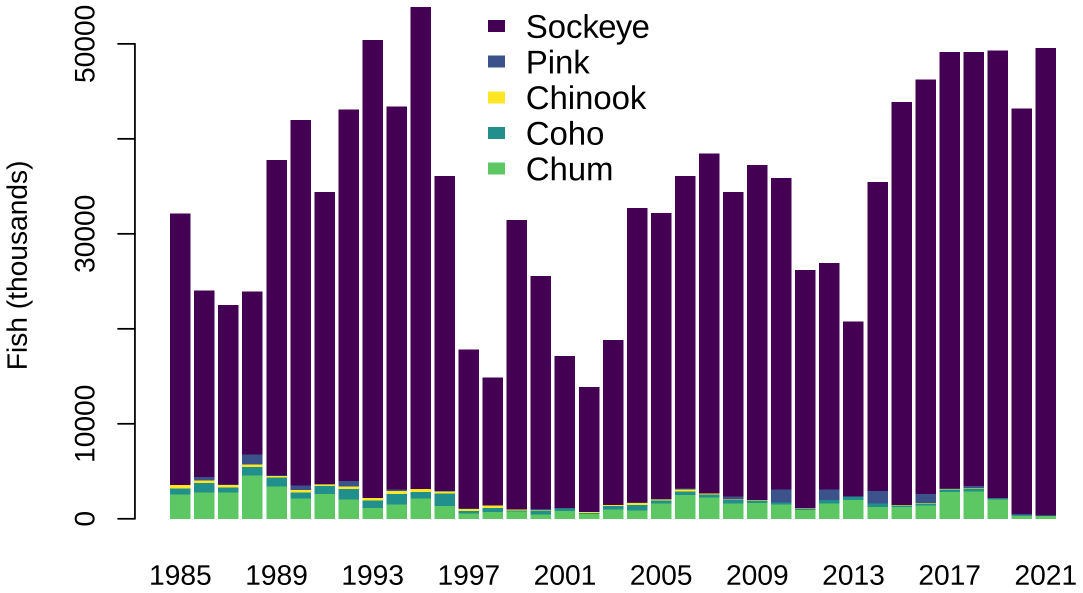

Figure 63: Commercial salmon catches in the eastern Bering Sea, 2021 values are preliminary. Source: ADF&G; `http://www.adfg.alaska.gov`. ADF&G not responsible for the reproduction of data, subsequent analysis, or interpretation.

In the Bering Sea, sockeye are the most abundant salmonid, and since the early 2000s they have had consistently strong runs, which have supported large harvests. Bristol Bay sockeye display a variety of life history types. For example, their spawning habitat is highly variable and demonstrates the adaptive and diverse nature of sockeye in this area (Hilborn et al., 2003). Therefore, productivity within these various habitats may be affected differently depending upon varying conditions, such as climate (Mantua et al., 1997), so more diverse sets of populations provide greater overall stability (Schindler et al., 2010). The abundance of Bristol Bay sockeye may also vary over centennial time scales, with brief periods of high abundance separated by extended periods of low abundance (Schindler et al., 2006).

Implications: Salmon have important influences on Alaska marine ecosystems through interactions with marine food webs – as predators on lower trophic levels and as prey for other species such as Steller sea lions. In years of great abundance, salmon may exploit prey resources more efficiently than their competitors. A negative relationship between seabird reproductive success and years of high pink salmon abundance has been demonstrated (Springer and van Vliet, 2014). Directed salmon fisheries are economically important for the state of Alaska. The trend in total statewide salmon catch in recent decades has been for generally strong harvests, despite annual fluctuations.

Measures to reduce salmon bycatch can affect the spatial distribution of groundfish trawl fisheries through area closures and incentives to avoid bycatch. When the aggregate Chinook salmon run size in the Kuskokwim, Unalakleet, and Upper Yukon Rivers is less than 250,000, a lower limit to Chinook bycatch is imposed on the pollock fishery.

Temporal Trend in the Annual Inshore Run Size of Bristol Bay Sockeye Salmon (*Oncorhynchus nerka*)

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Last updated: October 2021

Description of indicator: The annual abundance of adult sockeye salmon (*Oncorhynchus nerka*) returning to Bristol Bay is enumerated by the Alaska Department of Fish and Game (ADF&G). The total inshore run in a given year is the sum of catches in five terminal fishing districts plus the escapement of sockeye to nine major river systems. Total catch is estimated based on the mass of fishery offloads and the average weight of individual sockeye within time and area strata. Escapement is the number of fish successfully avoiding fishery capture and enumerated during upriver migration toward the spawning grounds, or through post-season aerial surveys of the spawning grounds (Elison et al., 2018). Although there have been slight changes in the location and operation of escapement enumeration projects and methods over time, these data provide a consistent index of the inshore return abundance of sockeye to Bristol Bay since 1963.

Status and trends: The 2021 Bristol Bay salmon inshore run of 67.7 million sockeye is the largest on record since 1963 and is 43.5% higher than the recent 10-year average of 47.2 million sockeye, and 99.6% higher than the 1963–2020 average of 33.9 million sockeye (Figure 64). The temporal trend in Bristol Bay sockeye indicates a large increase during the recent 7-year period, with inshore run sizes in 2015–2021 all exceeding 50 million salmon and above recent and long-term averages. The current period of high Bristol Bay sockeye production now exceeds the previous high production stanza that occurred 1989–1995.

Note: *At the time of printing, the 2021 Bristol Bay inshore run size numbers are preliminary and subject to change.*

Factors influencing observed trends: The return abundance of Bristol Bay sockeye is positively correlated with the Pacific Decadal Oscillation (Hare et al., 1999), specifically with Egegik and Ugashik district run sizes increasing after the 1976/1977 regime shift (Figure 65). However, recent research has highlighted that relationships between salmon population dynamics and the PDO may not be as consistent as once thought, and may in fact vary over time (Litzow et al., 2020*a*,*b*). The abundance and growth of Bristol Bay sockeye has also been linked to the abundance of pinks (*Oncorhynchus gorbuscha*) in the North Pacific (Ruggerone and Nielsen, 2004; Ruggerone et al., 2016).

Implications: The high inshore run of Bristol Bay sockeye in 2021 and the preceding 6-year period indicate positive survival conditions for these stocks while in the ocean. Given evidence that the critical period for sockeye survival occurs during the first summer and winter at sea (Beamish and Mahnken, 2001; Farley et al., 2007, 2011) and the predominant age classes observed for Bristol Bay stocks are 1.2, 1.3, 2.2, and 2.3 (European designation: years in freshwater–years in the ocean), the large 2021 Bristol Bay sockeye inshore run suggests these stocks experienced positive conditions at entry into the eastern Bering Sea in the summers of 2018 and 2019, and winters of 2018–2019 and 2019–2020.

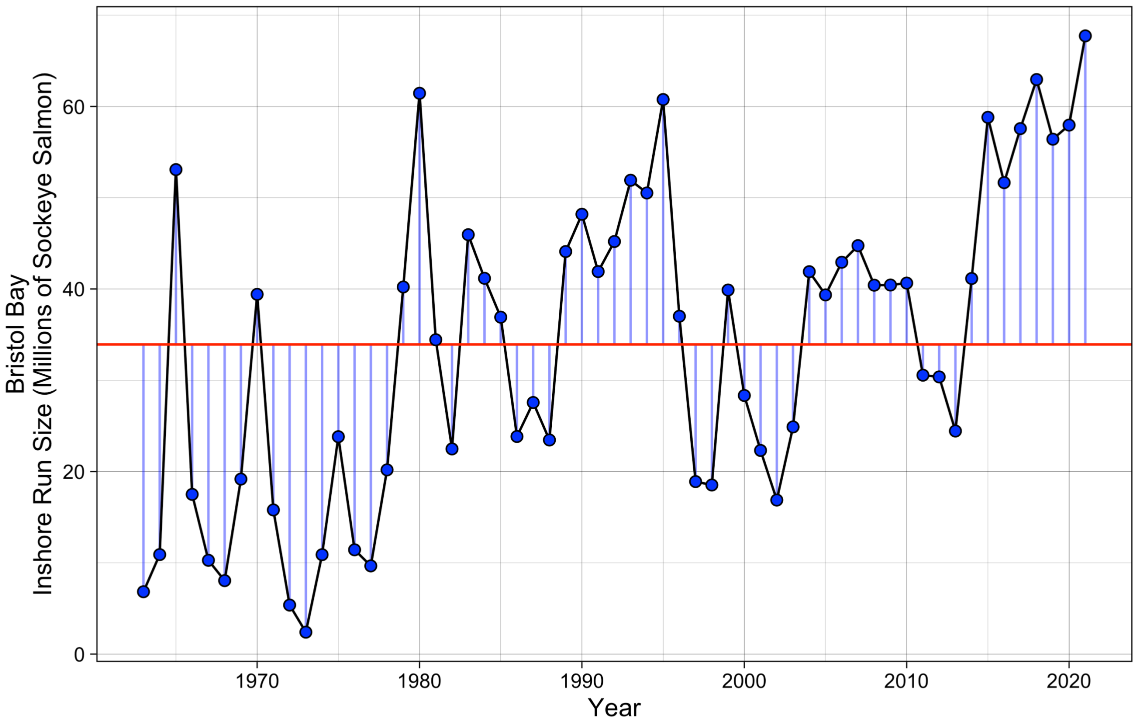

Figure 64: Annual Bristol Bay sockeye salmon inshore run size 1963–2021. Red line is the time series average of 33.9 million sockeye.

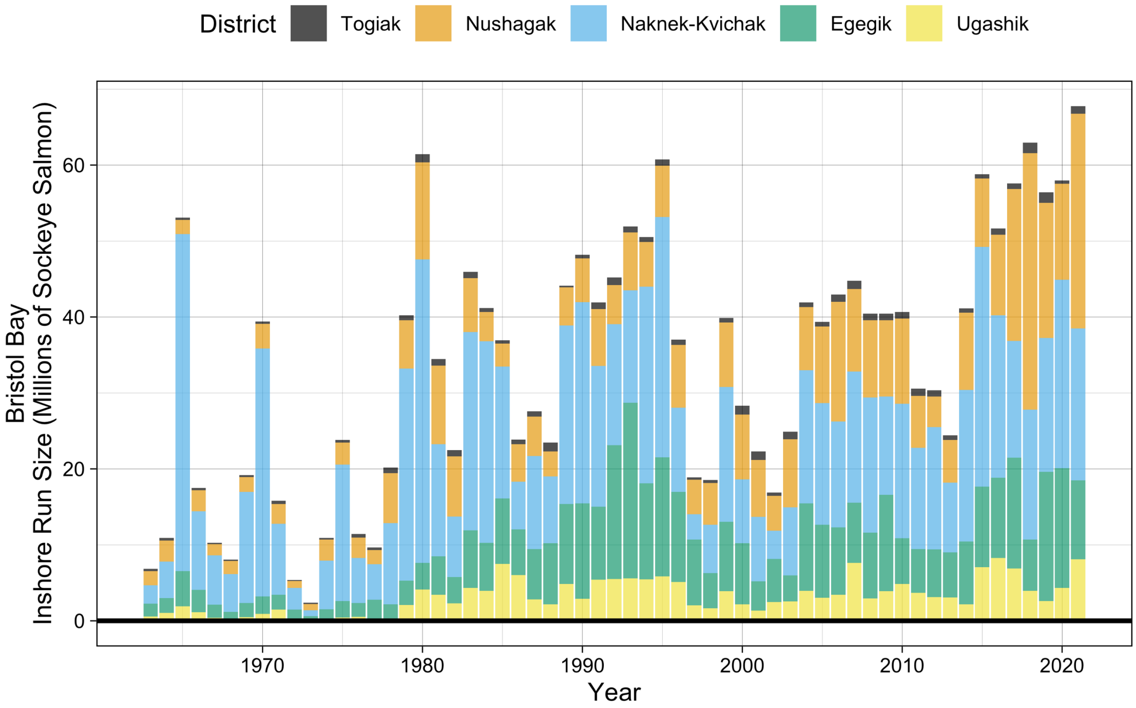

Figure 65: Annual Bristol Bay sockeye salmon inshore run size 1963–2021 by commercial fishing district.

Northern Bering Sea Juvenile Chinook Salmon Abundance Index

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Last updated: October 2021

Description of indicator: A mixed-stock juvenile (first year at sea) Chinook salmon (*Oncorhynchus tshawytscha*) abundance index is estimated from surface trawl catch and effort data in the northern Bering Sea (NBS). The NBS surface trawl and ecosystem survey was initiated by NOAA's Alaska Fisheries Science Center (AFSC) in 2002 as part of the Bering-Aleutian Salmon International Survey (BASIS), and has continued to support research objectives on the marine ecology of salmon and to improve our understanding of how the NBS ecosystem is changing in response to warming climate and loss of Arctic sea ice.

This index is based on late summer (September) surface trawl catch-per-unit-effort (CPUE) data expanded to the survey area and adjusted for mixed layer depth (MLD). Stock-specific abundance of Chinook salmon has been used to provide insight into the survival of Yukon River Chinook salmon (Murphy et al., 2017; Howard et al., 2020; Murphy et al., 2021) and has become a key part of their pre-season assessment (JTC, 2021). Stock-specific abundance indices will be available once stock compositions have been estimated for the survey. This mixed-stock index follows a similar pattern to the stock-specific indices as stock compositions have tended to be relatively stable over time (with the exception of 2019) (Murphy et al., 2021). The mixed-stock abundance index for juvenile Chinook salmon in the northern Bering Sea ranged from 1.4 million to 5.6 million juveniles with an average of 3.0 million, 2003–2019 (Figure 66).

Status and trends: The mixed-stock abundance of juvenile Chinook salmon in the northern Bering Sea was below average in 2021 and has been below average since 2017. Juvenile abundance has steadily declined from its latest peak in 2013.

Factors influencing observed trends: Early life-history (freshwater and early marine) survival of Yukon River Chinook salmon is the primary factor influencing juvenile abundance in the northern Bering Sea. On average, 87% of the juvenile Chinook salmon in the northern Bering Sea are from the Yukon River (Howard et al., 2019; Murphy et al., 2021). Although spawning abundance varies from year to year, juvenile abundance is most closely related to juvenile survival or the number of juveniles-per-spawner.

Implications: The abundance of juvenile Chinook salmon in the NBS is significantly correlated with adult returns (Murphy et al., 2017; Howard et al., 2019, 2020; Murphy et al., 2021). Below average juvenile abundance is expected to contribute to below average adult returns three to four years in the future (juveniles typically remain at sea for three to four years before returning to freshwater to spawn). Below average returns will result in subsistence fishery restrictions in the NBS (Yukon River and Norton Sound Chinook salmon) and contribute to reduced Chinook salmon bycatch caps in the eastern Bering Sea pollock fisheries. Yukon River and Norton Sound (Unalakleet River) Chinook salmon are two of the three stock groups used to define abundance-based bycatch caps in the eastern Bering Sea pollock fishery.

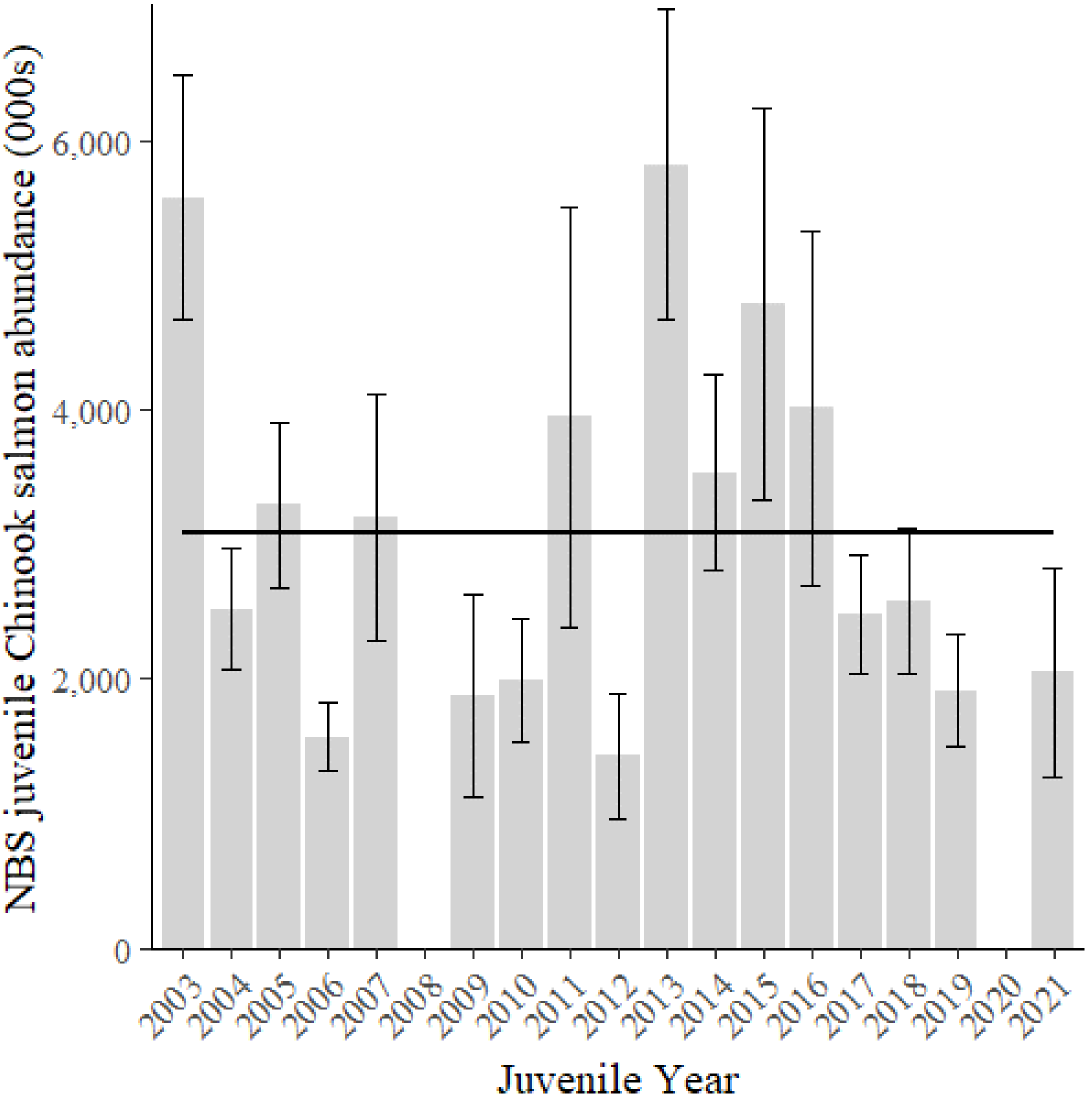

Figure 66: Juvenile Chinook salmon abundance estimates in the northern Bering Sea, 2003–2021. Error bars are one standard deviation above and below juvenile abundance estimates.

Juvenile Pink Salmon Abundance in the Northeastern Bering Sea

Contributed by Ed Farley[1], Jim Murphy[1], Kathrine Howard[2], and Sabrina Garcia[2]
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Last updated: October 2021

Description of indicator: A relative index of abundance of juvenile (first year at sea) pink salmon (*Oncorhynchus gorbuscha*) was constructed from late-summer (typically September) surface trawl and oceanographic surveys in the northeastern Bering Sea (NBS). The index is based on trawl catch-per-unit-effort data (log) and mixed layer depth, and has ranged from 0.9 to 5.4 with an overall average of 3.0 from 2003 to 2021 (no surveys in 2008 and 2020) (Figure 67). The juvenile index is significantly correlated with an index of pink salmon returns to Yukon and Norton Sound rivers and provides an informative tool to forecast adult returns to these regions (Figure 68). The preliminary index for 2021 is 0.9, which forecasts an adult return of approximately 500,000 pink salmon to these regions during 2022.

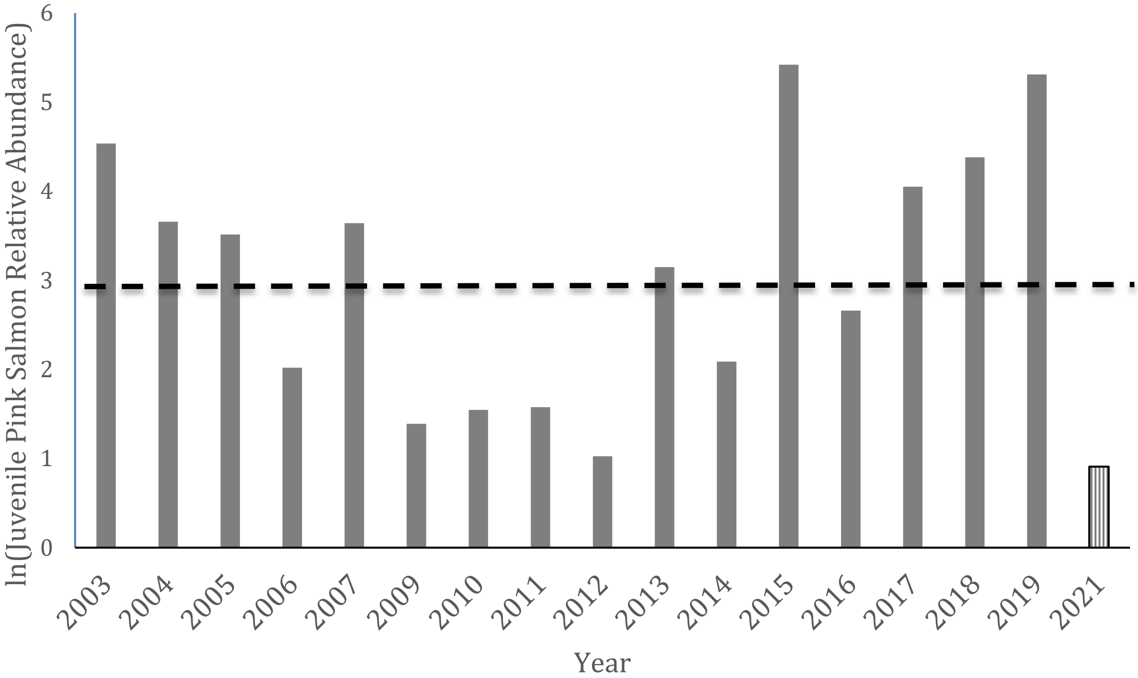

Figure 67: Juvenile pink salmon relative abundance index for the northeastern Bering Sea, 2003–2021. Dashed line indicates the average relative abundance index from 2003 to 2021. The dashed bar is the preliminary juvenile pink salmon relative abundance index for 2021. No surveys were conducted in 2008 or 2020.

Status and trends: The juvenile pink salmon index has varied over time, and was generally higher in warmer years (2003–2005; 2015–2019), but decreased dramatically during 2021.

Factors influencing observed trends: The NBS is experiencing significant warming and extremes in seasonal ice extent and thickness that may benefit pelagic production during summer months and improve the growth and survival of local pink salmon stocks in early marine life history stages. It is unclear at this time why juvenile pink salmon relative abundance declined abruptly during the 2021 NBS survey.

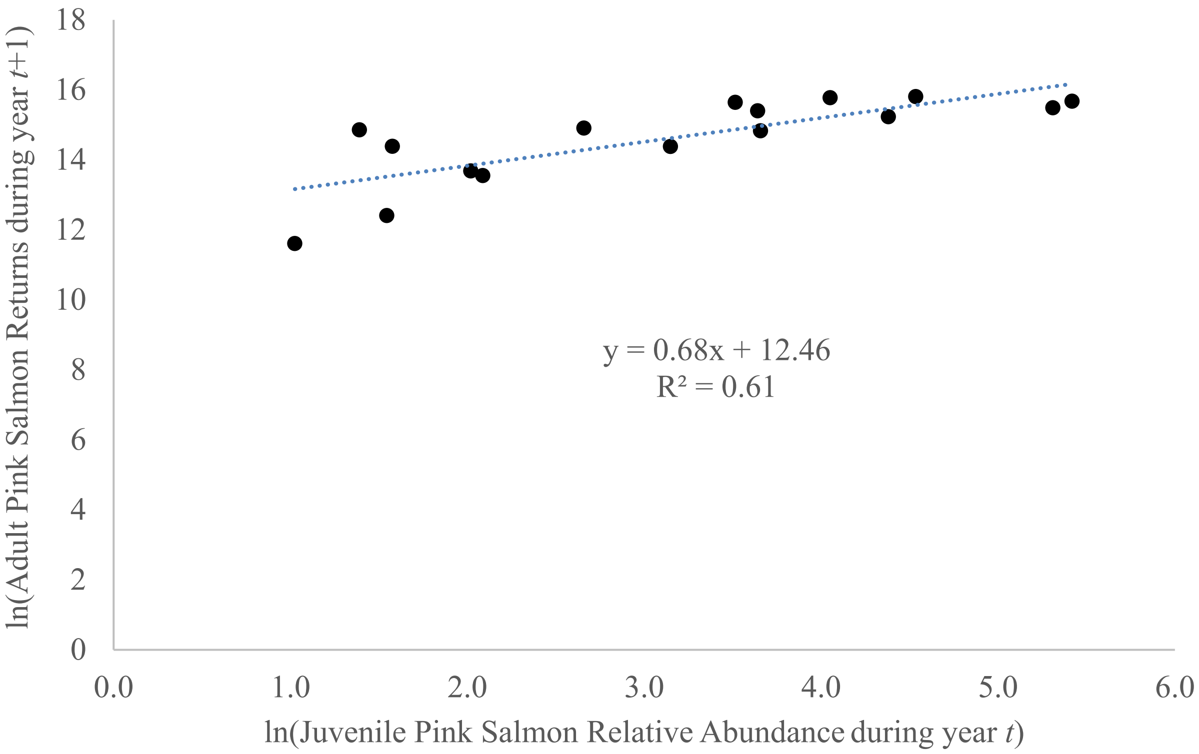

Figure 68: The relationship between juvenile pink salmon relative abundance index (2003–2019) and the index of pink salmon returns (2004–2020) to Yukon and Norton Sound rivers the following year.

Implications: In general, pink salmon appear to be taking advantage of warming freshwater and marine environments of the NBS and may portend further changes in the NBS region as a result of ongoing warming. Higher pink salmon production in the NBS region may be linked to the northward movement of salmon into the Arctic as pink salmon seek other areas to colonize. However, there is still high variability in numbers of juvenile pink salmon, even during warm years, as indicated by their dramatic decline during fall 2021.

Juvenile Abundance Index for Yukon River Fall Chum Salmon

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Last updated: October 2021

Description of indicator: Stock-specific abundance indices of juvenile (first year at sea) chum salmon (*Oncorhynchus keta*) in the eastern Bering Sea are estimated for the Upper Yukon River stock group, which is comprised of stocks in both the U.S. and Canada (hereafter, fall chum salmon). These abundance indices are available for all years from 2003 to 2021 (except 2008 and 2020). Given that the abundance indices for juvenile chum salmon are in the early phases of model development, caution should be exercised when interpreting results as they are subject to change as the model is refined over time.

Abundance indices are based on surface trawl catch-per-unit-effort (CPUE, #/km^2) from surveys operating between 58°N and 63°N and east of 172.5°W. These boundaries were chosen as they encompass the area of the eastern Bering Sea where genetic analyses indicate fall chum salmon in their first year at sea are encountered in high proportions. Annual CPUEs were then expanded by the proportion of fall chum salmon to generate an annual stock-specific CPUE for the eastern Bering Sea. The 2021 abundance index was generated using the average genetic stock proportion from 2015–2019 and will change once stock compositions from 2021 become available. From 2003–2021, the index of abundance for the fall chum salmon stock group ranged from a low of 14 in 2006 to a high of 169 in 2019, with an average CPUE of 50 (Figure 69).

Fall chum salmon caught as juveniles in eastern Bering Sea surveys are assumed to be age-1 (one winter spent in the gravel before migrating to the sea). Therefore, the stocks of juvenile fall chum salmon encountered will primarily return as adults to the Yukon River three years later as age-4 and four years later as age-5. Between juvenile years 2003–2015 (brood years 2002–2014), the relationship between the juvenile fall chum salmon index in the eastern Bering Sea and the adult returns from those juveniles showed a strong, positive trend. However, the addition of the most recently completed brood year (2015 brood year, 2016 juvenile year) does not follow this trend (Figure 70).

Status and trends: While the 2016 juvenile fall chum salmon index was above average, the adult returns from that juvenile year were lower than expected based on the juvenile to adult relationship (Figure 70). Juvenile fall chum salmon caught in 2016 predominantly returned to the Yukon River as age-4 in 2019 and age-5 in 2020. The other juvenile years that would have predominantly contributed to the poor adult run abundances in 2020 and 2021 were the 2017 juvenile cohort (returning as age-4 in 2020 and age-5 in 2021) and the 2018 juvenile cohort (returning as age-4 in 2021 and age-5 in 2022). While the 2017 juvenile fall chum salmon abundance index in the eastern Bering Sea was below average, the index has been above average since 2018 (Figure 70). Although the above-average juvenile abundance indices in 2018, 2019, and 2021 suggest improved adult run sizes over the next few years, uncertainty in the juvenile to adult relationship precludes our ability to reliably forecast future run sizes. Additional years of adult return data are needed to see how future years affect the juvenile to adult relationship.

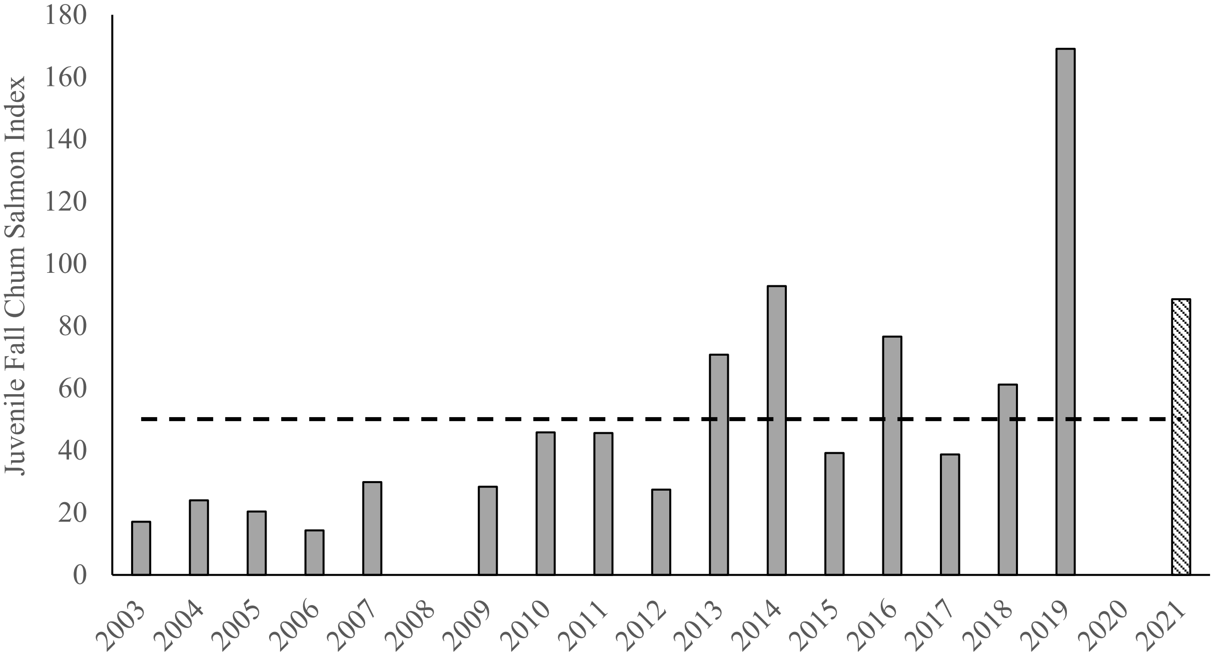

Figure 69: Juvenile chum salmon abundance indices (#/km^2) for the Upper Yukon River (fall chum) stock group, 2003–2021. No surveys occurred in 2008 and 2020. The 2021 abundance index was generated using the average genetic stock proportion from 2015–2019 and will change once stock compositions from 2021 become available. Dashed line indicates the average juvenile chum salmon index across years 2003–2019.

Factors influencing observed trends: The strong, positive relationship between the juvenile abundance index and adult returns from juvenile years 2003–2015 (brood years 2002–2014) suggests that the strength of adult returns is determined sometime before the end of the first summer in the ocean. However, the weakening of this relationship with the addition of the 2016 juvenile year (2015 brood year) suggests that changes in later-stage marine mortality in recent years may be disproportionately affecting the productivity of fall chum salmon returns. Whether the current trend will continue in recent years is unknown and additional years of adult return data are needed.

Implications: A primary objective of estimating a juvenile fall chum salmon abundance index is to determine if a reliable adult forecasting tool can be developed for fall chum salmon, similar to the forecasting tool created for Yukon River Chinook salmon (Murphy et al., 2017; Howard et al., 2020; Murphy et al., 2021). Chum salmon mortality following the first summer in the ocean must be relatively stable before juvenile abundance can be used to reliably forecast future adult returns. While preliminary model results were promising, fluctuations in marine mortality, likely driven by rapid changes in the marine environment, may complicate the development of an accurate tool to predict adult returns. Future iterations of model development may require environmental covariates (e.g., sea surface temperature) to account for natural mortality that occurs during later life-history stages.

Fall chum salmon from the Yukon River are an important subsistence resource and are increasingly important when Chinook salmon runs are low, especially for the people of the Upper Yukon River. The ability to predict changes in productivity for this stock group would be beneficial to fishery managers and stakeholders in the region and would allow them to plan for anticipated run sizes up

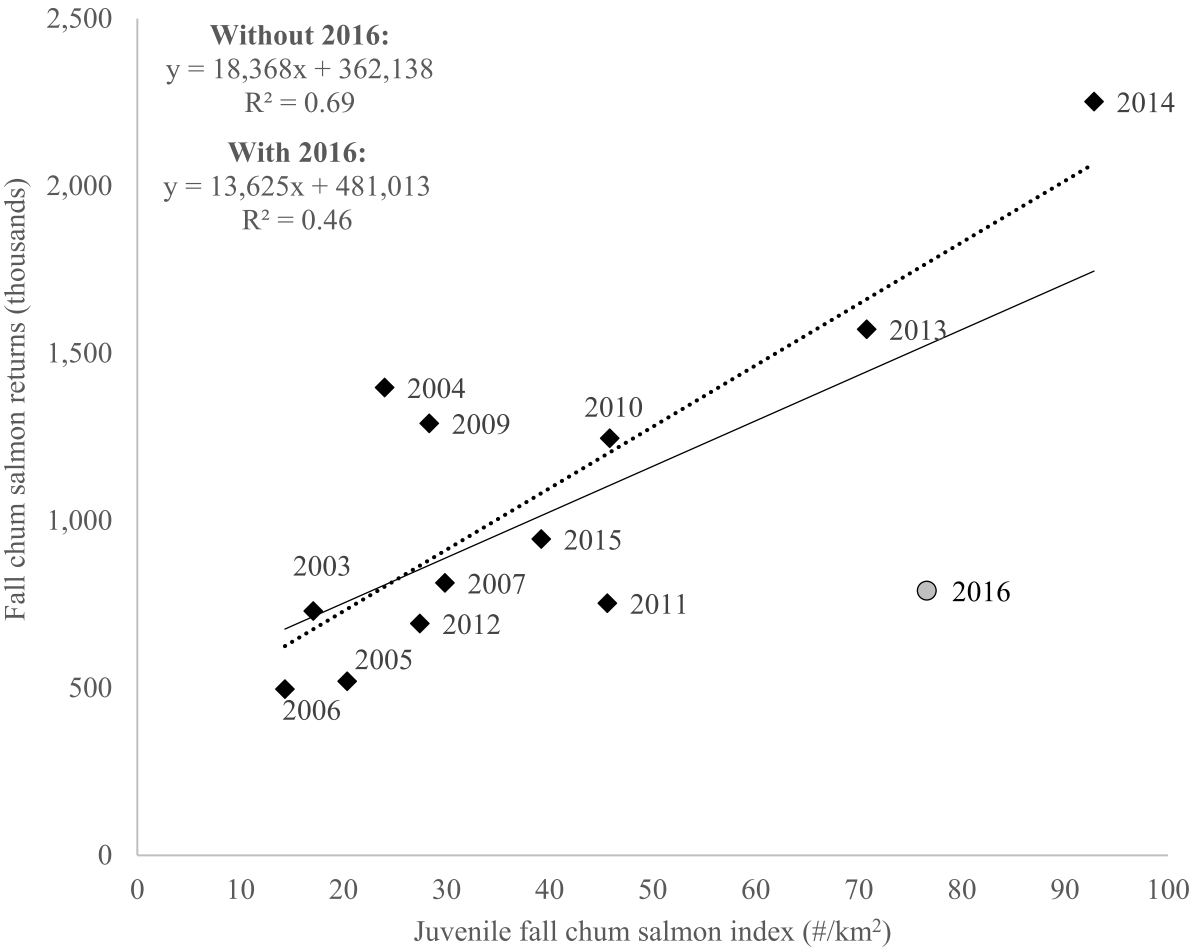

Figure 70: Relationships between juvenile abundance and adult abundance for Upper Yukon River (fall chum salmon) for juvenile years 2003–2016. Adult abundance is the number of returning adults and only includes years where all juveniles from a cohort have returned to the Yukon River. The dashed regression line excludes juvenile year 2016 and the solid black line includes all years. Labels indicate juvenile year (juvenile year is equal to brood year + 1).

to three years in the future. More work is needed to refine the juvenile model, such as determining a core area that is consistently sampled year to year. Similarly, continued marine research on juvenile salmon is necessary to understand how rapid changes to the marine environment affect chum salmon population dynamics.

Groundfish

Eastern and Northern Bering Sea Groundfish Condition

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Description of indicator: Length-weight residuals represent how heavy a fish is per unit body length and are an indicator of somatic growth variability (Brodeur et al., 2004). Therefore, length-weight residuals can be considered indicators of prey availability, growth, general health, and habitat condition (Blackwell et al., 2000; Froese, 2006). Positive length-weight residuals indicate better condition (i.e., heavier per unit length) and negative residuals indicate poorer condition (i.e., lighter per unit length) (Froese, 2006). Fish condition calculated in this way reflects realized outcomes of intrinsic and extrinsic processes that affect fish growth, which can have implications for biological productivity through direct effects on growth and indirect effects on demographic processes such as reproduction and mortality (Rodgveller, 2019; Barbeaux et al., 2020).

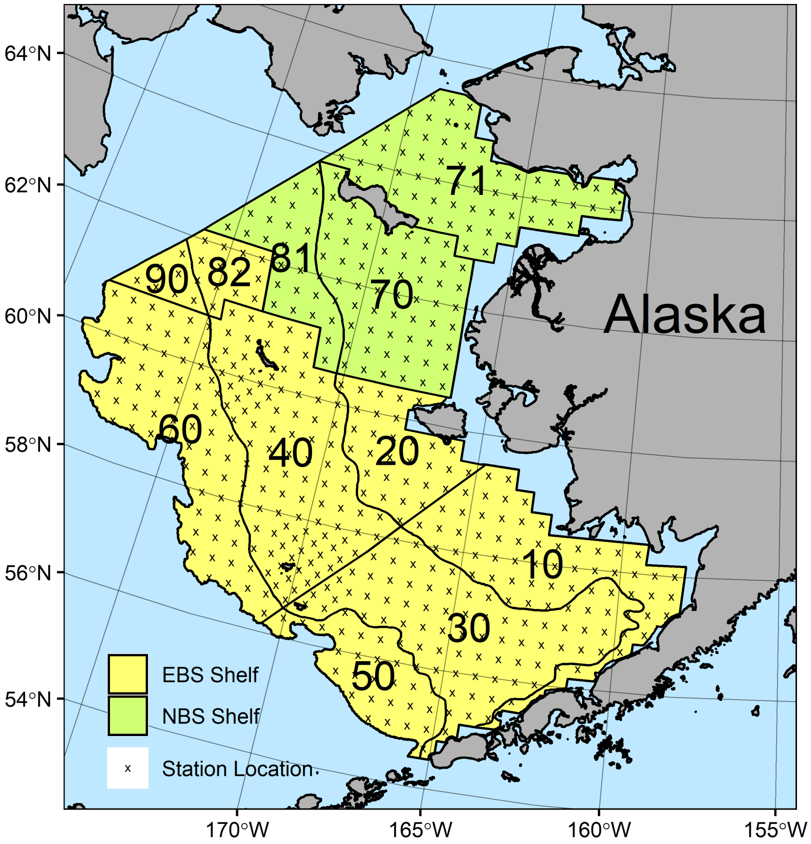

Figure 71: NOAA Alaska Fisheries Science Center summer bottom trawl survey strata (10–90) and station locations (x) on the eastern Bering Sea (EBS) shelf and in the northern Bering Sea (NBS).

The groundfish morphometric condition indicator is calculated from paired fork lengths (mm) and weights (g) of individual fishes that were collected during bottom trawl surveys of the eastern Bering Sea (EBS) shelf and northern Bering Sea (NBS) which were conducted by the Alaska Fisheries Science Center's Resource Assessment and Conservation Engineering (AFSC/RACE) Groundfish Assessment Program (GAP). Fish condition analyses were applied to Walleye pollock (*Gadus chalcogrammus*), Pacific cod (*G. macrocephalus*), Arrowtooth flounder (*Atheresthes stomias*), Yellowfin sole (*Limanda aspera*), Flathead sole (*Hippoglossoides elassodon*), Northern rock sole (*Lepidopsetta polyxystra*), and Alaska plaice (*Pleuronectes quadrituberculatus*) collected in bottom trawls at standard survey stations (Figure 71). For these analyses and results, survey strata 31 and 32 were combined as stratum 30; strata 41, 42, and 43 were combined as stratum 40; and strata 61 and 62 were combined as stratum 60. Northwest survey strata 82 and 90 were excluded from these analyses.

To calculate indicators, length-weight relationships were estimated from linear regression models based on a log-transformation of the exponential growth relationship, $W = aL^b$, where W is weight (g) and L is fork length (mm) for all areas for the period 1997–2021 (EBS: 1997–2021, NBS: 2010, 2017–2019, 2021). A unique slope (b) was estimated for each survey stratum to account for spatial-temporal variation in growth and bottom trawl survey sampling. Length-weight relationships for 100–250 mm fork length pollock (corresponding with ages 1–2 years) were calculated separately from adult pollock (> 250 mm).

Residuals for individual fish were obtained by subtracting observed weights from bias-corrected weights-at-length that were estimated from regression models. For the EBS shelf, individual length-weight residuals were averaged for each stratum and weighted based on the proportion to total biomass in each stratum from area-swept expansion of bottom trawl survey catch per unit effort (CPUE; i.e., design-based stratum biomass estimates). Variation in fish condition was evaluated by comparing average length-weight residuals among years. Analysis for the NBS was conducted separately from the EBS because of the shorter time series and the NBS was treated as a single stratum. To minimize the influence of unrepresentative samples on indicator calculations, combinations of species, stratum, and year with sample size <10 were used to fit length-weight regressions but were excluded from calculating length-weight residuals for both the EBS and NBS.

Methodological Changes: Length-weight data from corner stations were included in analyses. This change was made because length-weight samples from corner stations are collected within stratum boundaries following regular sampling protocols.

Status and trends: Fish condition, based on length-weight residuals, has varied over time for all species examined (Figures 72 and 73). In 2019, an upward trend in condition was observed for most species relative to 2017–2018 with positive weighted length-weight residuals relative to historical averages for large pollock (>250 mm), Northern rock sole, Yellowfin sole, Arrowtooth flounder, and Alaska plaice. In 2021, mean weighted length-weight residuals in the EBS were negative for large pollock (>250 mm) and Arrowtooth flounder (Figure 72). Mean weighted length-weight residuals were negative for Pacific cod, Northern rock sole, Alaska plaice, and Flathead sole, although 95% confidence intervals for these species included the historical mean. Weighted length-weight residuals were near the historical averages for small pollock (100–250 mm) and Yellowfin sole (Figure 72).

In 2021, negative length-weight residuals were observed for large pollock (>250 mm), Pacific cod, Yellowfin sole, and Alaska plaice in the NBS (Figure 73). The only species with a positive length-weight residual in the NBS in 2021 was small pollock (100–250 mm) (Figure 73).

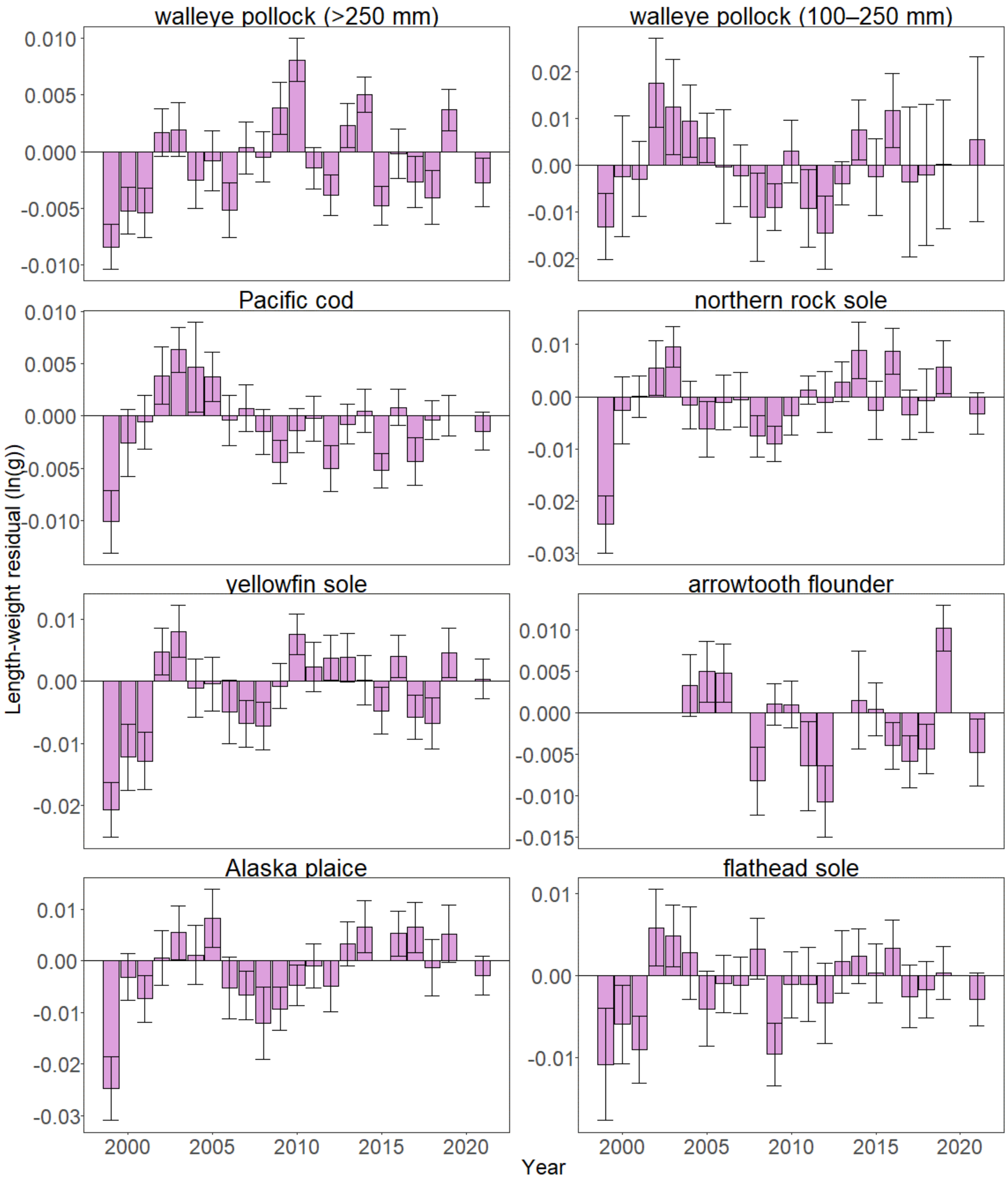

Figure 72: Weighted length-weight residuals for seven groundfish species and age 1–2 Walleye pollock (100–250 mm) collected during AFSC/RACE GAP standard summer bottom trawl surveys of the eastern Bering Sea shelf, 1999–2021. Filled bars denote weighted length-weight residuals using this year's indicator calculation. Error bars denote two standard errors.

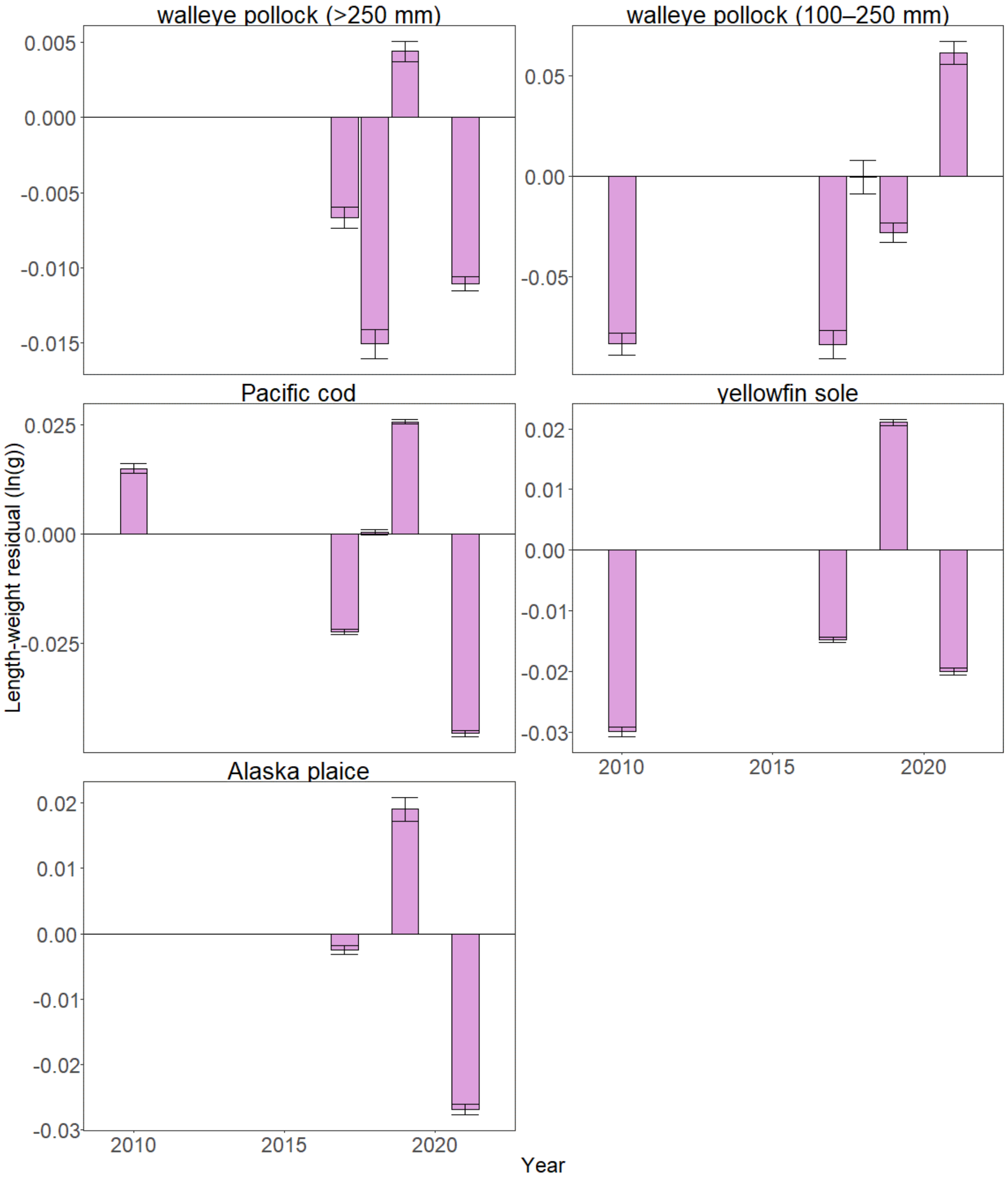

Figure 73: Length-weight residuals for groundfish species and age 1–2 Walleye pollock (100–250 mm) collected during AFSC/RACE GAP summer bottom trawl surveys of the northern Bering Sea, 2010 and 2017–2021. Error bars denote two standard errors.

In 2021, similar to 2010–2019, Pacific cod condition was generally negative on the middle and outer northern shelf and outer southern shelf (strata 40, 50, and 60); however, condition was also negative on the inner southern shelf and inner northern shelf (strata 10, 20 and 30), indicating a decline in condition on these strata since 2019 (Figure 74). Large pollock (>250 mm) condition was primarily negative on all strata in 2021, which is consistent with the observed condition on the inner shelf since 2015. In 2021, small pollock (100–250 mm) condition was generally positive, and consistent with observed condition on the inner shelf since 2014. In 2021, negative condition was observed in all EBS strata for Northern rock sole, Alaska plaice, Flathead sole, and Arrowtooth flounder. The remaining species, Yellowfin sole, had positive residuals on the outer shelf (stratum 40) (Figure 74).

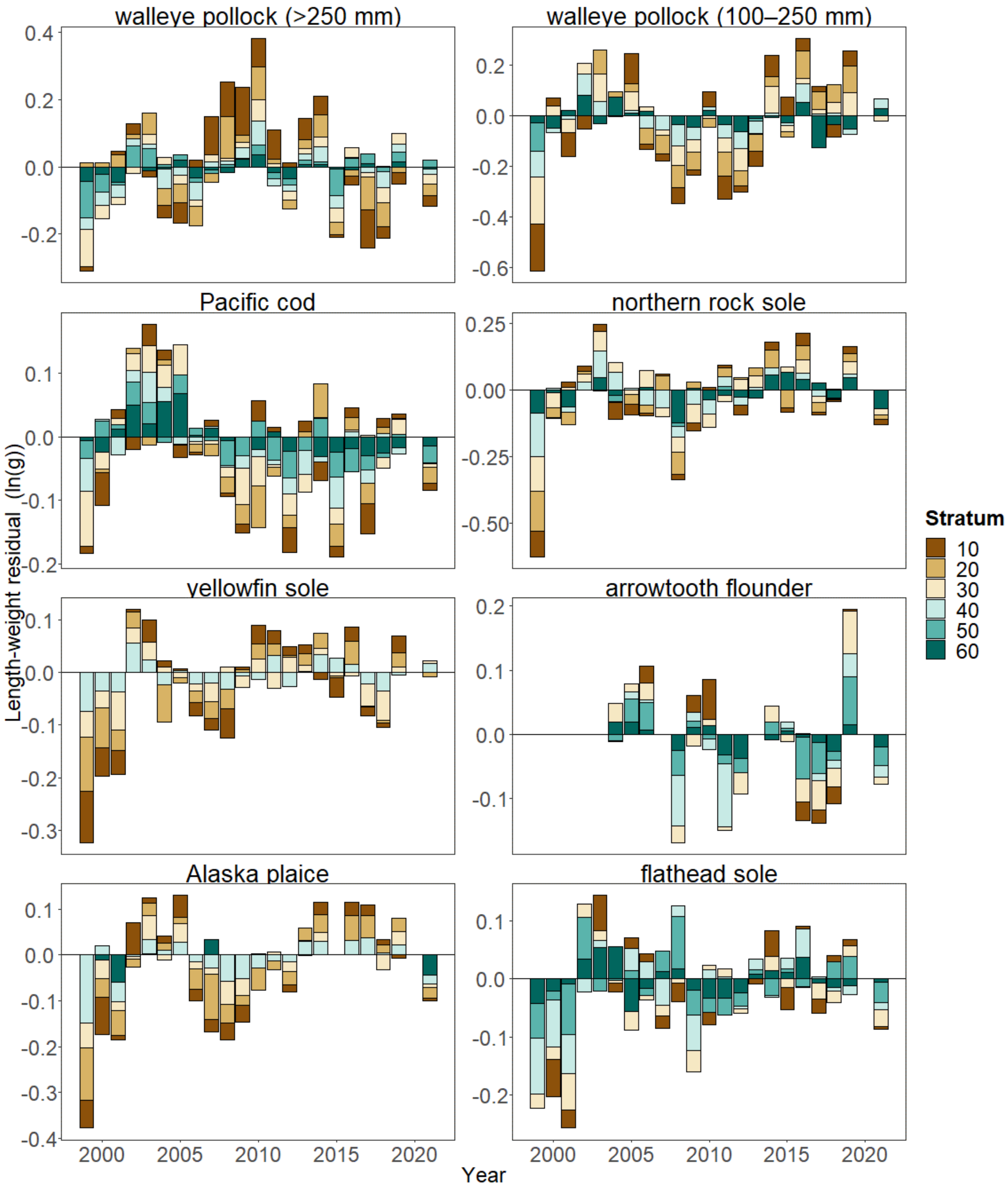

Figure 74: Length-weight residuals by survey stratum (10–60) for seven eastern Bering Sea shelf groundfish species and age 1–2 Walleye pollock (100–250 mm) sampled in the AFSC/RACE GAP standard summer bottom trawl survey, 1999–2021. Length-weight residuals are not weighted by stratum biomass.

Factors influencing observed trends: Several factors may influence the observed temporal and spatial patterns in fish condition in the EBS and NBS. Water temperature could explain some of the spatial and temporal variability in length-weight residuals. Historically, particularly cold years tend to correspond with negative condition, while particularly warm years tend to correspond with positive condition. For example, water temperatures during the 1999 survey were particularly cold in the Bering Sea and this corresponded to a year of negative condition for all groundfish for which data exist. In addition, spatial temporal factor analyses suggest the morphometric condition of age-7 pollock is strongly correlated with cold pool extent in the EBS (Grüss et al., 2021). In recent years, continuing warm temperatures across the Bering Sea shelf since the record low seasonal sea ice extent in 2017–2018 and historical cold pool area minimum in 2018 (Stabeno and Bell, 2019) may have influenced the positive trend in fish condition from 2016 to 2019. Although warmer conditions also occurred in 2021, with the fourth smallest cold pool area and fifth warmest mean bottom temperature in the 39-year survey time series, the majority of species had negative or neutral conditions in 2021.

Although warmer temperatures may increase growth rates if there is adequate prey to offset temperature-dependent increases in metabolic demand, growth rates may also decline if prey resources are not adequate to offset temperature-dependent increases in metabolic demand. For example, elevated temperatures during the 2014–2016 marine heatwave in the Gulf of Alaska led to lower growth rates of Pacific cod and lower condition because prey resources were not sufficient to make up for increased metabolic demand (Barbeaux et al., 2020). The influence of temperature on growth rates depends on the physiology of predator species, prey availability, and the adaptive capacity of predators to respond to environmental change through migration, changes in behavior, and acclimatization. Thus, the factors underpinning the negative or neutral condition remain unclear.

Other factors that could affect length-weight residuals include survey timing, stomach fullness, fish movement patterns, sex, and environmental conditions (Froese, 2006). The starting date of annual length-weight data collections has varied from late May to early June and ended in late July-early August in the EBS, and mid-August in the NBS. Although we account for some of this variation by using stratum-specific regression coefficients, variation in condition could relate to the timing of collection within survey strata. Survey timing can be further compounded by seasonal fluctuations in reproductive condition with the buildup and depletion of energy stores (Wuenschel et al., 2019). Another consideration is that fish weights sampled at sea are typically inclusive of stomach content weight so gut fullness may influence the length-weight residuals. Since feeding conditions likely change over space and time, how much the fish ate at its last meal and the proportion of its total body weight attributable to the gut weight could be an important factor influencing the length-weight residuals. We can also expect some fish to exhibit seasonal or ontogenetic movement patterns during the survey months. Although the condition indicator characterizes spatial and temporal variation of length-weight residuals for important fish species in the EBS and NBS, they do not inform the mechanisms or processes behind the observed patterns.

Implications: Fish morphometric condition can be considered an indicator of ecosystem productivity with implications for fish survival, maturity, and reproduction. For example, in Prince William Sound, the pre-winter condition of herring may determine their overwinter survival (Paul and Paul, 1999), differences in feeding conditions have been linked to differences in morphometric condition of pink salmon in Prince William Sound (Boldt and Haldorson, 2004), variation in morphometric condition has been linked to variation in maturity of sablefish (Rodgveller, 2019), and lower morphometric condition of Pacific cod was associated with higher mortality and lower growth rates during the 2014–2016 marine heat wave in the Gulf of Alaska (Barbeaux et al., 2020). Thus, the condition of EBS and NBS groundfishes may provide insight into ecosystem productivity as well as fish survival, demographic status, and population health. However, survivorship is likely affected by many factors not examined here. We also must consider that, in these analyses, fish condition was computed for all sizes of fishes combined, except in the case of pollock. Examining condition of early juvenile stage fishes not yet recruited to the fishery, or the condition of adult fishes separately, could provide greater insight into the value of length-weight residuals as an indicator of individual health or survivorship (Froese, 2006), particularly since juvenile and adult pollock exhibited opposite trends in condition in both the EBS and NBS this year.

The negative trend in fish condition observed during the 2021 AFSC/RACE GAP EBS and NBS bottom trawl surveys (i.e., increasingly negative length-weight residuals) could be related to concurrent trends in other ecosystem components and needs to be examined further. Furthermore, this denotes a shift in a general positive trend in fish condition in the previous two to three survey years. Trends such as prolonged warmer water temperatures following the marine heat wave of 2014–2016 (Bond et al., 2015) and reduced sea ice and cold pool area extent in the eastern Bering Sea (Stabeno and Bell, 2019) may affect fish condition in ways that have yet to be determined. As we continue to add years of length-weight data and expand our knowledge of relationships between condition, growth, production, survival, and the ecosystem, these data may increase our understanding of the health of fish populations in the EBS and NBS.

Research priorities: Due to programmatic constraints, we did not transition the groundfish condition indicator to use a spatio-temporal model with spatial random effects (VAST) in 2021. For next year's ESR, we aim to transition to VAST, which should allow more precise biomass expansion, improve estimates of uncertainty, and better account for spatial-temporal variation in length-weight samples from bottom trawl surveys. Revised indicators will be presented alongside a retrospective analysis to compare the current condition indicator to a VAST-based condition indicator in 2022. Furthermore, there is an ongoing Essential Fish Habitat project within the AFSC Groundfish Assessment Program to validate the morphometric condition indicator in Pacific cod and pollock using a physiological metric. Finally, the Condition Congress Steering Committee provided four recommendations for the future of fish condition research at AFSC: inter-calibration of existing condition indices, development of projects to link physiological measurements of condition to demographic outcomes, management-directed research, and standardizing formulation and description of metrics (Hurst et al., 2021). Future research priorities should consider this guidance.

Patterns in Foraging and Energetics of Walleye pollock, Pacific cod, Arrowtooth flounder, and Pacific halibut

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Description of indicator: We report trends in metabolic demand from an adult bioenergetics model for groundfish in SEBS (Ciannelli et al., 1998; Holsman et al., 2019; Holsman and Aydin, 2015) and patterns in diet composition from the NOAA Fisheries Alaska Fisheries Science Center's Food Habits database of fish diets collected during summer bottom trawl surveys in the eastern Bering Sea (EBS). This work is part of an in prep manuscript and the authors request that the images and data reported herein not be duplicated or shared outside of this reprot until the publication is complete in 2022. Bioenergetics-based indices were calculated for individual predator stomach samples using bioenergetic models. Samples were averaged by 5-cm predator bins across stations within a strata and then extrapolated to the population level using annual proportional biomass for each bin in each strata based on bottom trawl surveys (see Ciannelli et al. (1998); Holsman et al. (2019); Holsman and Aydin (2015), and Livingston et al. (2017) for more information).

Bioenergetic diet indices collectively indicate changes in foraging and growing conditions; relative foraging rate (RFR) reflects the ratio of observed food consumption (specific consumption rate; C_ggd) to a theoretical temperature and size-specific maximum consumption rate from laboratory feeding experiments. Declines in this index can reflect decreases in prey availability or prey switching to more energetically valuable prey. Therefore we also present mean diet energy density (mnEDJ_g) which reflects the average energetic density of prey in stomachs sampled from across the EBS in a given year. Less favorable foraging patterns would be reflected in declines in RFR when mnEDJ_g remains the same or also declines in a given year. Metabolic demand (R_ggd) generally increases with temperature and indicates the basal energetic requirements of the fish. Finally, scope for growth (G_ggd) integrates metabolic demand, prey energy, and relative consumption rates to indicate how changes in temperature and foraging collectively influence (potential) growth.

Status and trends: We observe directional trends in consumption and potential growth that reflect climate driven changes to metabolic demand and trophic interactions and which indicate declining conditions for groundfish in the southeastern Bering Sea (SEBS) in recent years. All five indices suggest continued poor conditions for Walleye pollock (*Gadus chalcogrammus*; hereafter "pollock") and Pacific cod (*Gadus macrocephalus*) in recent years relative to historical rates (1982–2010).

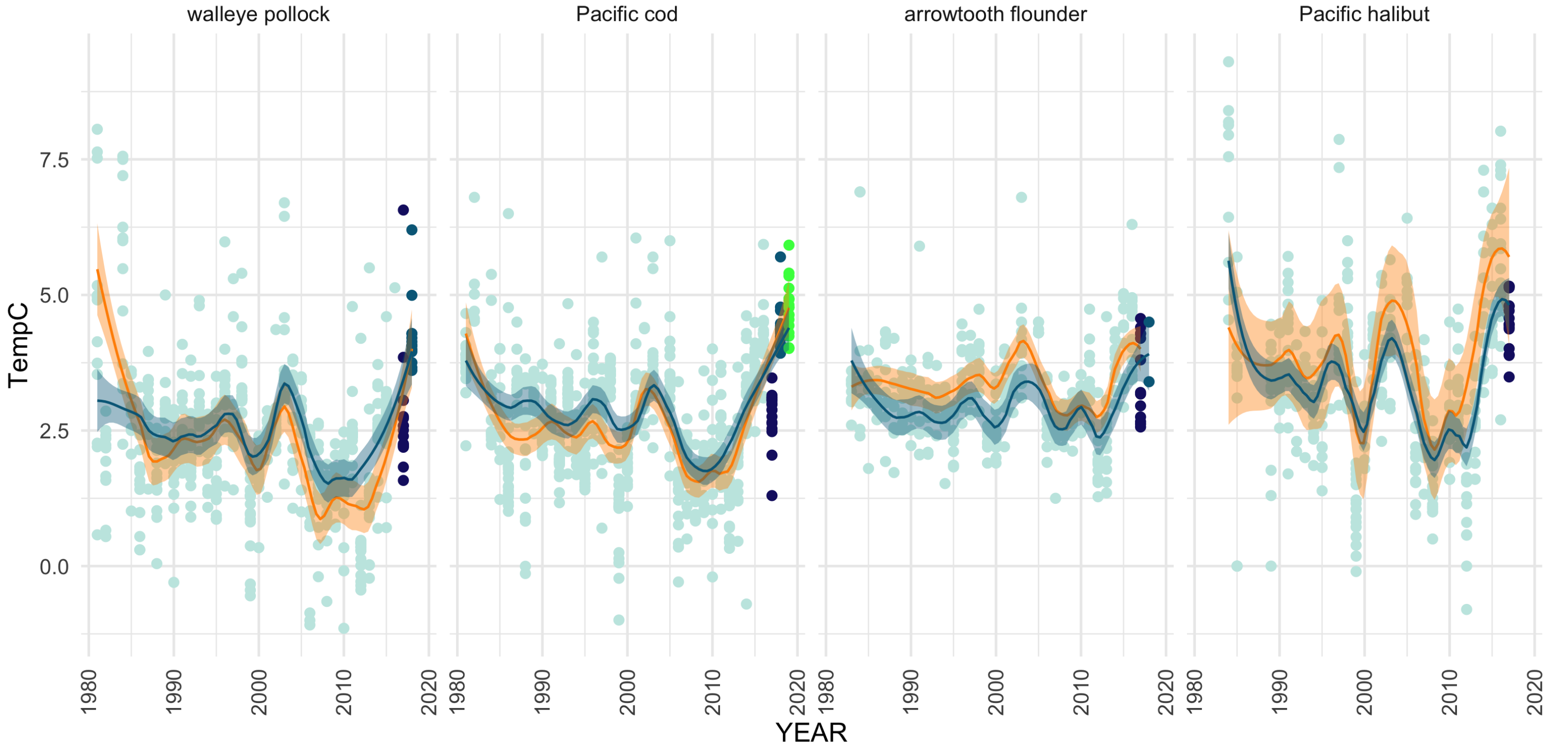

Figure 75: Average thermal experience (TempC) for 5-cm size bins of groundfish species in SEBS (light blue dots), with 2016 (dark blue), 2017 (dark teal), and 2018 (bright green) highlighted for reference. The spline represents a loess smoother for juvenile (orange) and adult (teal) fish. Data is based on biomass-weighted bottom temperature for samples collected during NOAA AFSC summer bottom trawl surveys.

Thermal experience (biomass weighted bottom temperature) of all four groundfish species in the SEBS has increased in recent years (Figure 75), with Pacific cod recent thermal experience the highest in the 30+ year time series. Relative energetic demand of pollock, Pacific cod, and Pacific halibut (*Hippoglossus stenolepis*; hereafter "halibut") reflect climate-driven changes to metabolic demand with marked increases in metabolic demand since 2005–2010 ("R_ggd" for respiration). Accordingly, metabolic demand for (juvenile and adult) pollock and Pacific cod continues to increase relative to historical (1982–2010) rates with 2015–2019 rates approximately 64%, 5%, and 7% higher than historical values for pollock, Pacific cod, and halibut (respectively).

Meanwhile relative foraging rates for juvenile pollock and Pacific cod declined markedly in recent years (2015–2019) relative to historical rates (1982–2010) by -41% and -18%, respectively (Figure 76).

The mean energetic value of sampled diets dropped in 2000 (pollock) and 2005 (Pacific cod) relative to previous years and has generally remained lower than 1982–2000 values. Mean energetic density of prey for pollock and Pacific cod is approximately -5% lower than prior to 2000. The integrated outcome of these changes is an overall decline in scope for growth for both pollock and juvenile Pacific cod in recent years, especially for juvenile Pacific cod, where (2015–2019) juvenile Pacific cod scope for growth remains well below the long-term average (1982–2010; Figure 77).

Factors influencing observed trends: Metabolic demands for ectothermic fish like pollock, Pacific cod, Arrowtooth flounder, and halibut are largely a function of thermal experience and body size and tend to increase exponentially with increasing temperatures. Fish can minimize metabolic costs through behaviors, such as movement to thermally optimal temperatures, or can increase consumption of food energy to meet increasing metabolic demands. The latter requires sufficient access to abundant or high energy prey resources.

Implications: For pollock and Pacific cod in the EBS, during recent anomalously warm years, metabolic demands were elevated while foraging rates and scope for growth were reduced (Figures 75 and 76). This pattern was most pronounced for juvenile and adult pollock, and juvenile Pacific cod (Figure 77). This has important implications; in order to offset metabolic demands these fish would have had to (1) consume more food or more energetically rich food, (2) access energetic reserves leading to net body mass loss, or (3) move to more energetically favorable foraging grounds. There are a few lines of evidence to support all three of these potential responses to climate-driven changes in the EBS, including observations of large numbers of Pacific cod in the northern Bering Sea surveys in 2017–2021.

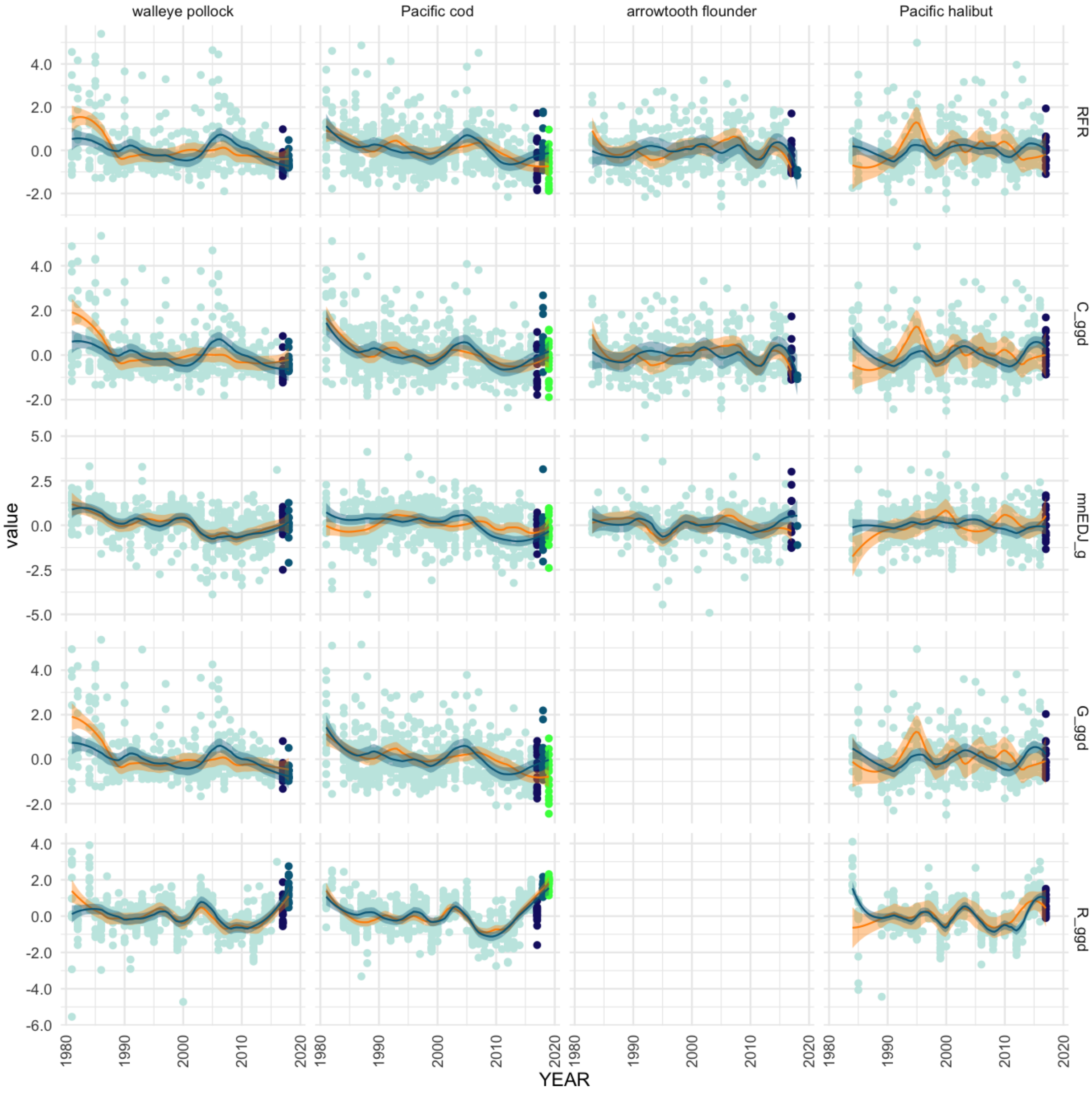

Figure 76: Normalized (i.e., Z-score scaled) bioenergetic diet indices for groundfish species over time including relative foraging rate (RFR), specific consumption rate (C_ggd), mean diet energy density (mnEDJ_g), scope for growth (G_ggd), and metabolic demand (R_ggd). Mean values for each year and bin are shown as light blue dots, while 2016 (dark blue), 2017 (dark teal), and 2018 (bright green) are highlighted for reference. The spline represents a loess smoother for juvenile (orange) and adult (teal) fish. Data is based on biomass-weighted indices for samples collected during NOAA AFSC summer bottom trawl surveys.

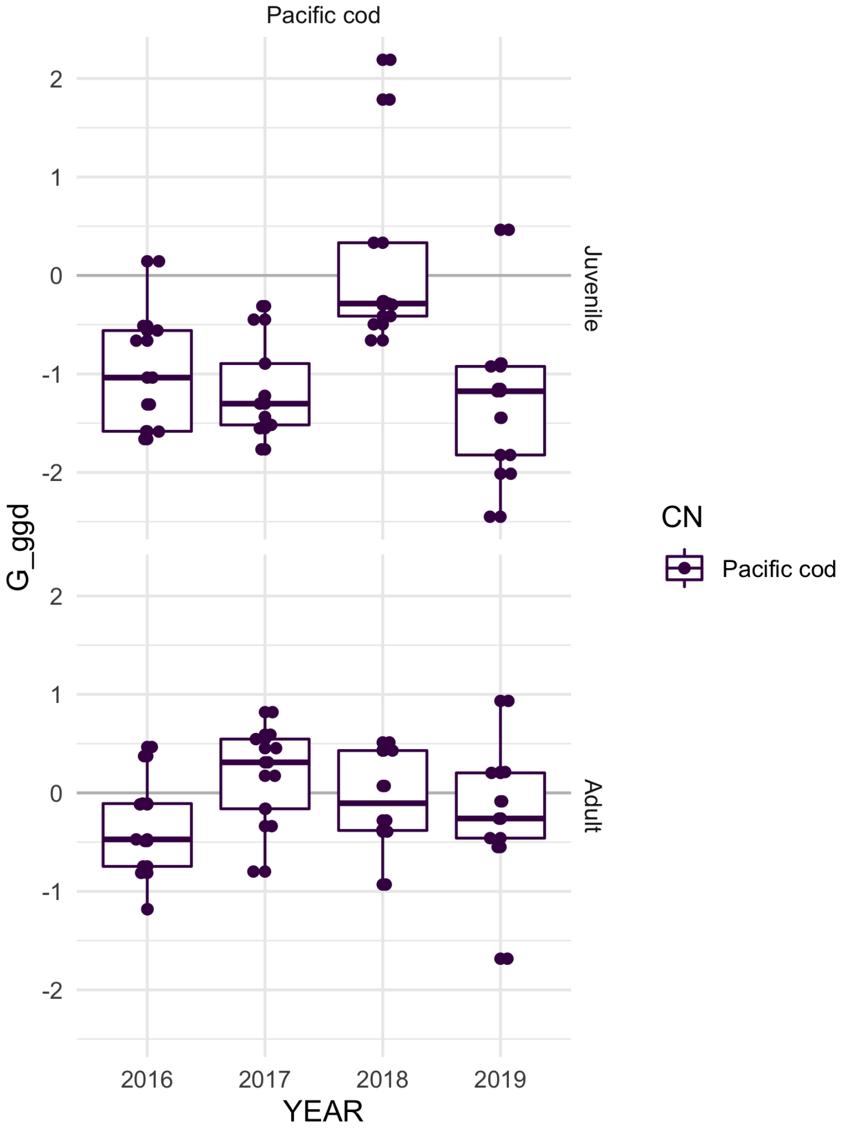

Figure 77: Normalized (i.e., Z-score scaled) bioenergetic (potential) scope for growth (G_ggd) for juvenile and adult fish from 2015–2019. Data is based on biomass-weighted indices for samples collected during NOAA AFSC summer bottom trawl surveys.

Multispecies Model Estimates of Time-varying Natural Mortality

Contributed by Kirstin K. Holsman, Jim Ianelli, Kerim Aydin, Kalei Shotwell, Grant Thompson, Kelly Kearney, Ingrid Spies, Steve Barbeaux, and Grant Adams
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Last updated: October 2021

Description of indicator: We report trends in age-1 total mortality for Walleye pollock (*Gadus chalcogrammus*, 'pollock'), Pacific cod (*Gadus macrocephalus*, 'P. cod') and Arrowtooth flounder (*Atheresthes stomias*, 'Arrowtooth') from the eastern Bering Sea. Total mortality rates are based on residual mortality inputs (M1) and model estimates of annual predation mortality (M2) produced from the multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics). See Appendix 1 of the BSAI pollock stock assessment for 2021 as well as Holsman et al. (2016), Holsman and Aydin (2015), Ianelli et al. (2016), and Jurado-Molina et al. (2005) for more information.

Status and trends: The CEATTLE model estimates of age-1 natural mortality (i.e., M1+M2) for pollock, P. cod, and Arrowtooth continue to decline from the 2016 peak mortality. For all three species, age-1 predation mortality rates have remained similar to 2020 and are well below the long-term mean. At 1.3 yr^{-1}, age-1 mortality estimated by the model was greatest for pollock and lower for P. cod and Arrowtooth, with total age-1 natural mortality at around 0.71 and 0.68 yr^{-1}. The 2021 age-1 natural mortality across species is 11% to 46% lower than in 2016 and is below average for pollock (relative to the long-term mean) (Figure 78). Similarly, P. cod and Arrowtooth age-1 mortality are well below the long-term mean.

Patterns in the total biomass of each species consumed by all three predators in the model (typically 1–3 yr old fish) is similar to patterns in age-1 natural mortality but with slight differences in 2021. Pollock and Arrowtooth biomass consumed by all predators in the model is approximately equal to the long-term average, while P. cod biomass consumed is well below average (Figure 79).

Factors influencing observed trends: Temporal patterns in natural mortality reflect annually varying changes in predation mortality that primarily impact age-1 fish (and to a lesser degree ages 2 and 3 fish in the model). Pollock are primarily consumed by older conspecifics, and pollock cannibalism accounts for 57% (on average) of total age-1 predation mortality, with the exception of the years 2006–2008 when predation by Arrowtooth exceeded cannibalism as the largest source of predation mortality of age-1 pollock; Figure 80). The relative proportion of age-1 pollock consumed by older pollock and Arrowtooth increased slightly in 2021, while the relative proportion consumed by P. cod declined slightly.

Combined annual predation demand (annual ration) of pollock, P. cod, and Arrowtooth in 2021 was 5.59 million tons, down slightly from the 6.8 million t annual average during the warm years and large maturing cohorts of 2014–2016. Pollock represent approximately 79% of the model estimates of combined prey consumed with a long term average of 5.76 million tons of pollock consumed annually by all three predators in the model. Individual annual rations remain well above average for all three predator species, driven by anomalously warm water temperatures in the Bering Sea during recent years (Figure 81).

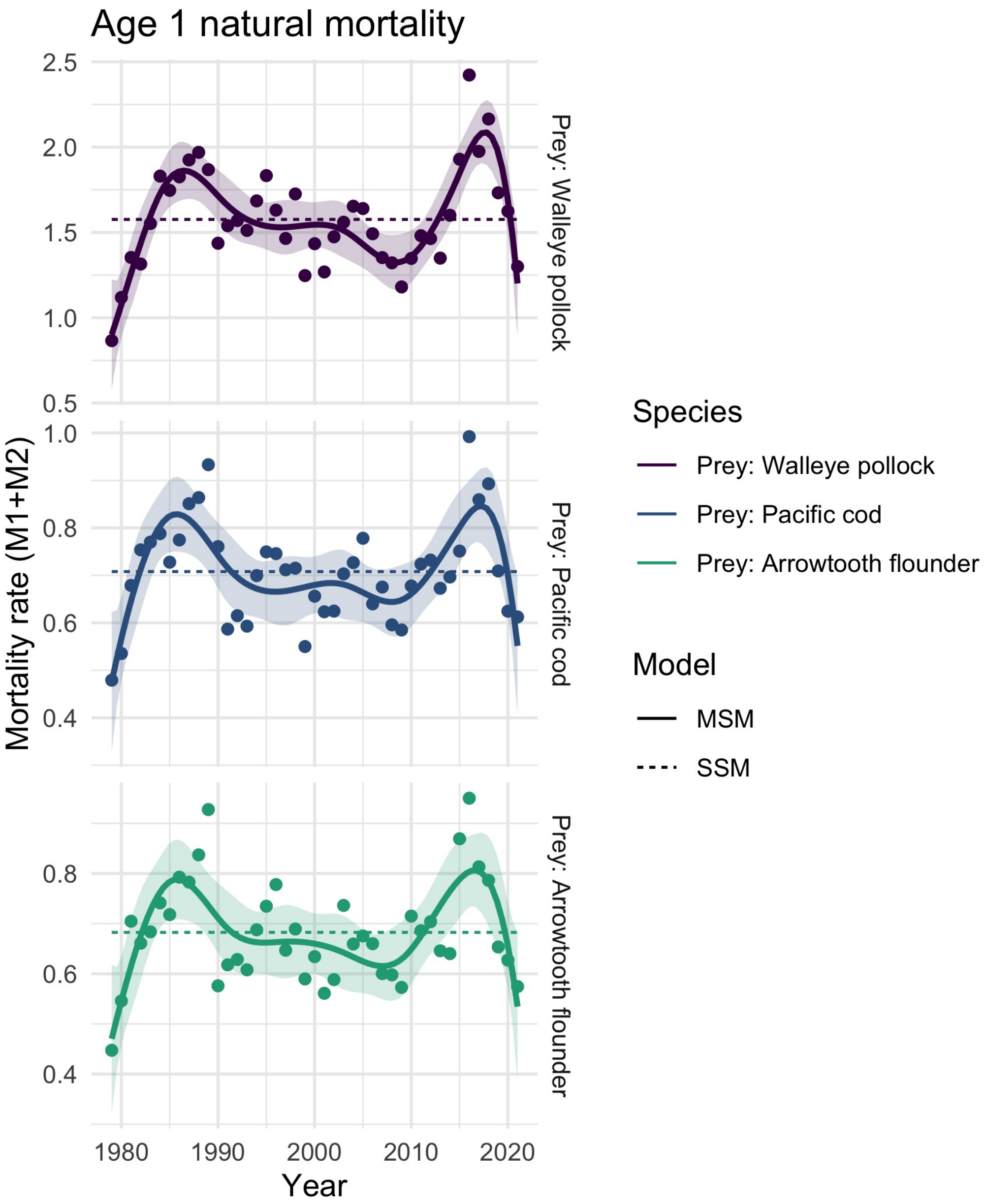

Figure 78: Annual variation in total mortality ($M1_{i1} + M2_{i1,y}$) of age-1 pollock (as prey) (a), age-1 P. cod (as prey) (b), and age-1 Arrowtooth (as prey) (c) from the single-species models (dashed gray line) and the multi-species models with temperature (black line). Updated from Holsman et al. (2016); more model detail can be found in Appendix 1 of the BSAI pollock stock assessment for 2021.

Implications: We find evidence of continued declines in predation mortality of age-1 pollock, P. cod, and Arrowtooth relative to recent high predation years (2014–2016). While warm temperatures continue to lead to high metabolic (and energetic) demand of predators, declines in total predator biomass are contributing to a net decrease in total consumption (relative to 2016) and therefore reduced predation rates and mortality in 2019–2021. This pattern indicates improving top-down conditions for juvenile groundfish survival in 2020 through predator release due to declining biomass of groundfish.

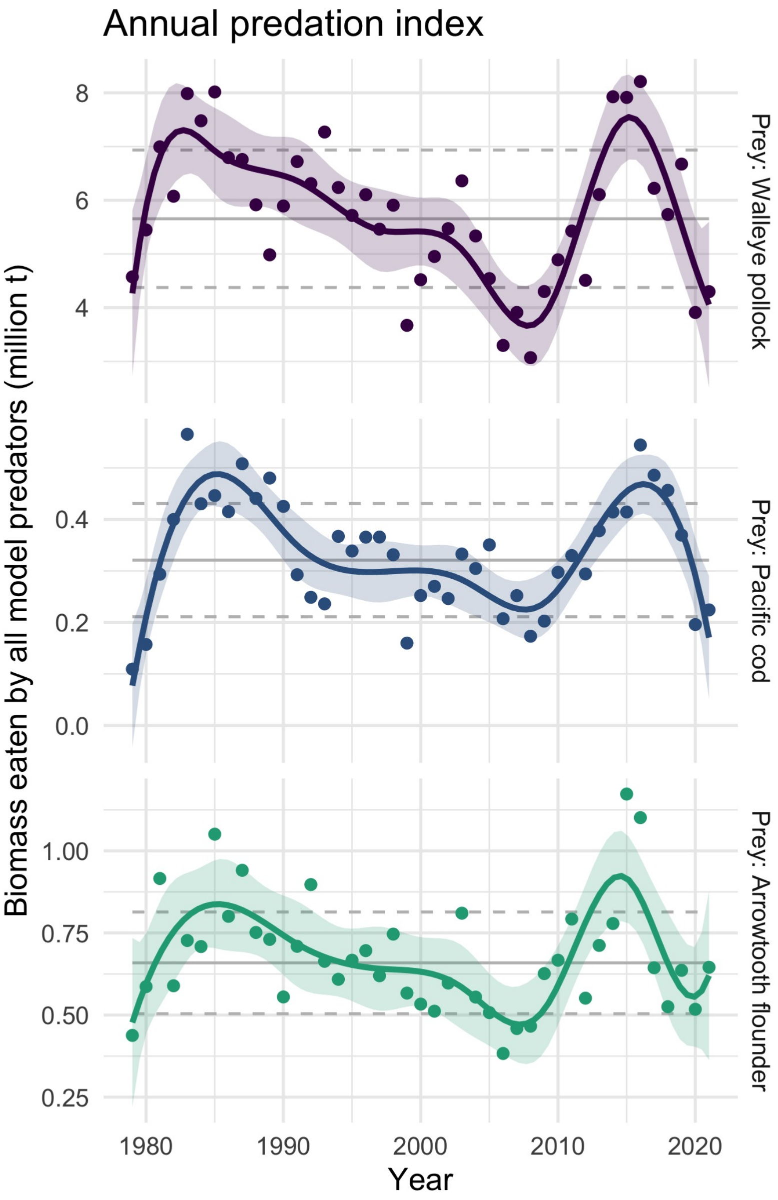

Figure 79: Multispecies estimates of prey species biomass consumed by all predators in the model: a) total biomass of pollock consumed by predators annually b) total biomass of P. cod consumed by predators annually, c) total biomass of Arrowtooth consumed by predators annually. Gray lines indicate 1979–2021 mean estimates for each species.

Between 1980 and 1993, relatively high natural mortality rates reflect patterns in combined annual demand for prey by all three predators that was highest in the mid 1980's (collectively 9.13 million t per year), and in recent years (collectively 6.5 million t per year). The peak in predation mortality of age-1 pollock in 2006 corresponds to the maturation of a large age class of 5-7 year old pollock and 2 year old P. cod that dominated the age composition of the two species in 2006. Similarly, the recent peaks in mortality in 2016 reflect anomalously warm water temperatures combined with the maturation of the large 2010–2012 year class of pollock.

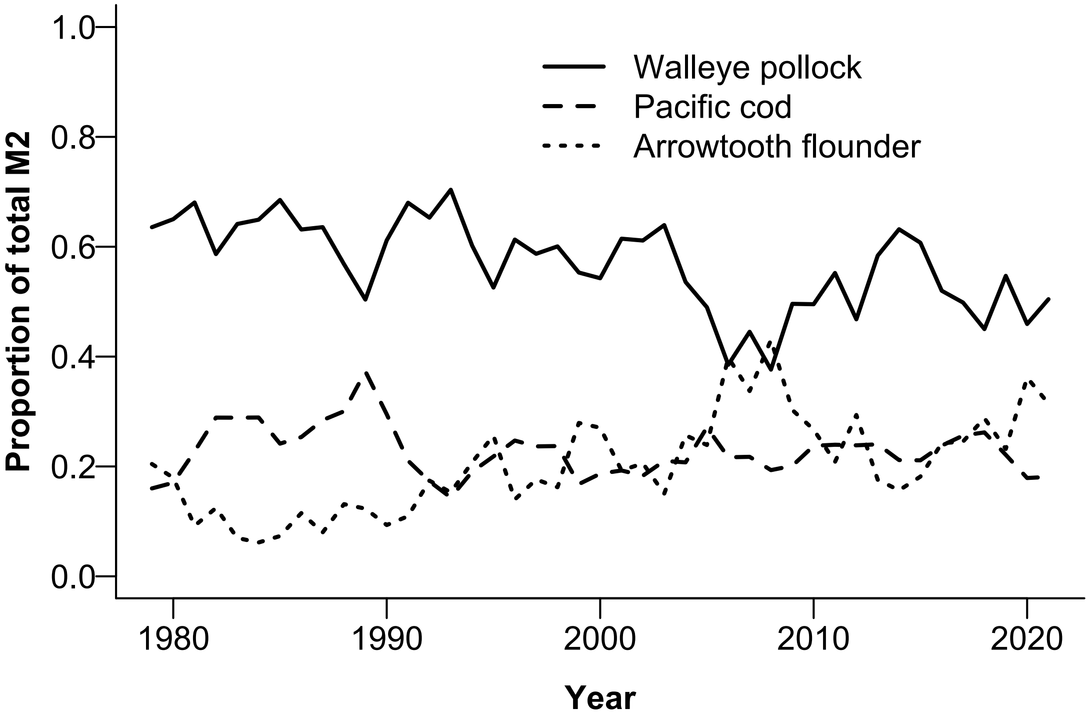

Figure 80: Proportion of total predation mortality for age-1 pollock from pollock (solid), P. cod (dashed), and Arrowtooth (dotted) predators across years. Updated from Holsman et al. (2016); more model detail can be found in Appendix 1 of the BSAI pollock stock assessment for 2021.

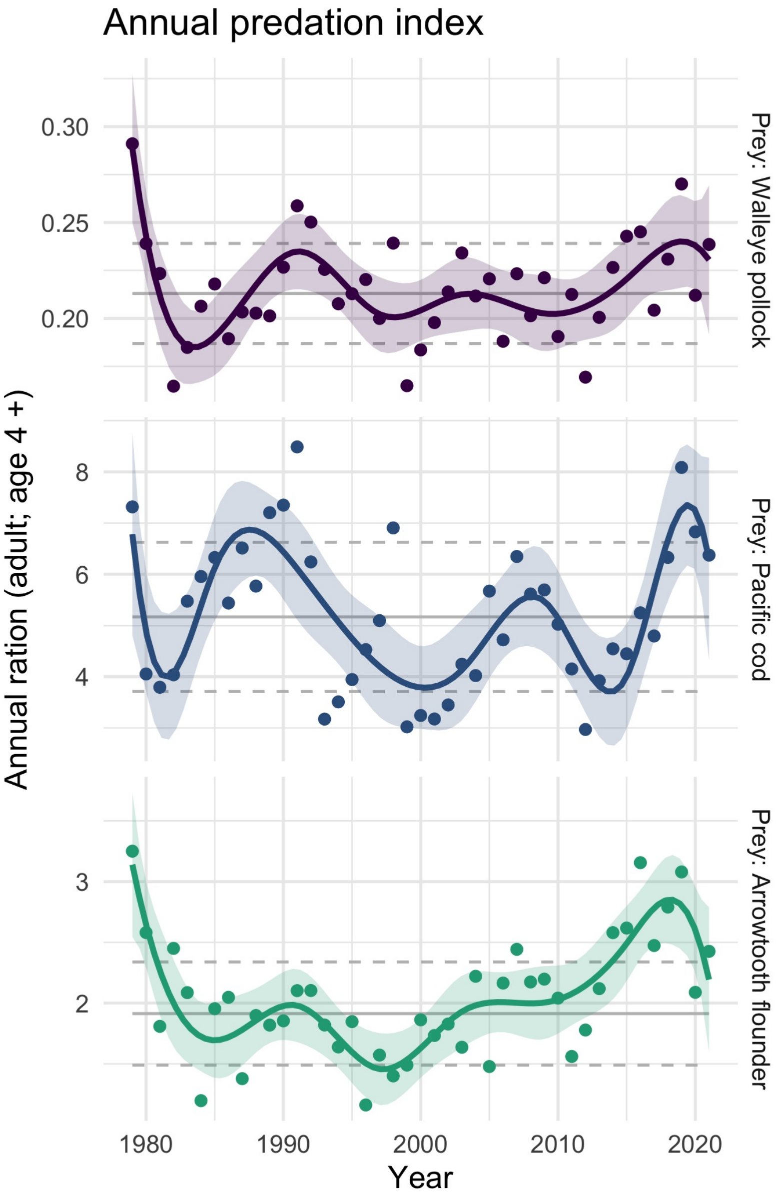

Figure 81: Multispecies estimates of annual ration (kg consumed per individual per year) for adult (age-4+) predators: a) pollock, b) P. cod, and c) Arrowtooth. Gray lines indicate 1979–2021 mean estimates and 1 SD for each species; orange line is a 10-y (symmetric) loess polynomial smoother indicating trends in ration over time.

Groundfish Recruitment Predictions

Pre- and Post-Winter Temperature Change Index and the Recruitment of Bering Sea Pollock

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Last updated: September 2021

Description of indicator: The temperature change (TC) index is a composite index for the pre- and post-winter thermal conditions experienced by Walleye pollock (*Gadus chalcogrammus*) from age-0 to age-1 in the southeastern Bering Sea (Martinson et al., 2012). The TC index (year t) is calculated as the difference in the average monthly sea surface temperature in June (t+1) and August (t) (Figure 82) in an area of the southern region of the eastern Bering Sea (56.2°N to 58.1°N by 166.9°W to 161.2°W). Time series of average monthly sea surface temperatures were obtained from the NOAA Earth System Research Laboratory Physical Sciences Division website. Sea surface temperatures were based on NCEP/NCAR gridded reanalysis data (Kalnay et al. (1996), data obtained from `http://www.esrl.noaa.gov/psd/cgi-bin/data/timeseries/timeseries1.pl` (accessed Sept., 14, 2021)). Less negative values represent a cool late summer during the age-0 phase followed by a warm spring during the age-1 phase for pollock.

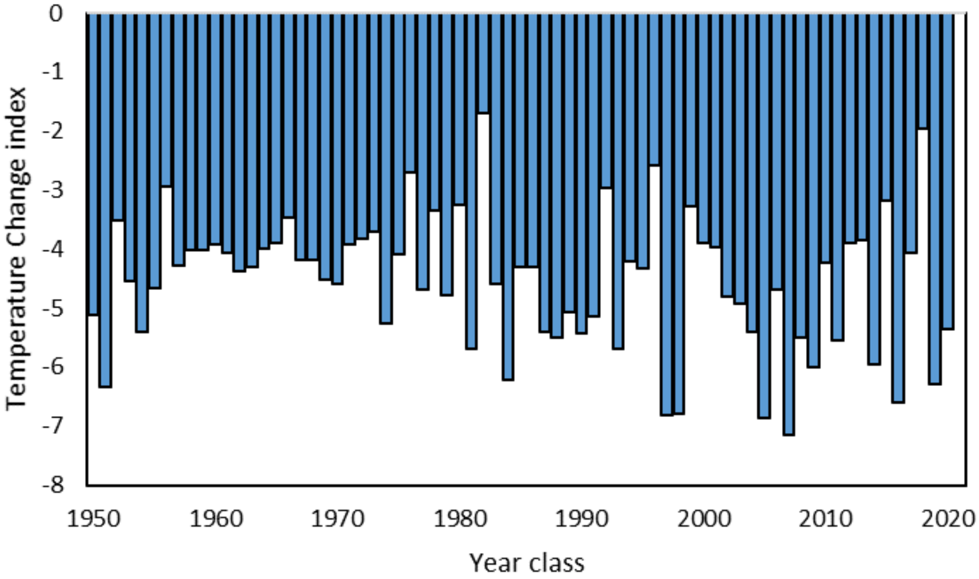

Figure 82: The Temperature Change index values for the 1950 to 2020 year classes of pollock. Values represent the differences in sea temperatures on the southeastern Bering Sea shelf experienced by the 1950–2020 year classes of pollock. Less favorable conditions (more negative values) represent a warm summer during the age-0 life stage followed by a relatively cool spring during the age-1 life stage. More favorable conditions (less negative values) represent a cool summer during the age-0 life stage followed by a relatively warm spring during the age-1 life stage.

Status and trends: The 2020 year class TC index value is -5.37, higher than the 2019 year class TC index value of -6.30, indicating slightly improved conditions for pollock survival from age-0 to age-1 from 2020 to 2021 than from 2019 to 2020. The low expected survival is due to the larger difference in sea temperature from late summer (warm) to the following spring (warm). The late summer sea surface temperature (August 11.6°C) in 2020 was 1.7°C higher than the longer term average (9.9°C) and spring sea temperature (June 6.2°C) in 2021 was warmer than the long-term average of 5.3°C in spring since 1949.

Factors causing observed trends: According to the original Oscillating Control Hypothesis (OCH), warmer spring temperatures and earlier ice retreat led to a later oceanic and pelagic phytoplankton bloom and more food in the pelagic waters at an optimal time for use by pelagic species (Hunt et al., 2002). The revised OCH indicated that age-0 pollock were more energy-rich and have higher overwintering survival to age-1 in a year with a cooler late summer (Coyle et al., 2011; Heintz et al., 2013). Therefore, the warmer later summers during the age-0 phase followed by warmer spring temperatures during the age-1 phase are assumed unfavorable for the survival of pollock from age-0 to age-1. The 2020 year class of pollock experienced above average summer temperatures during the age-0 stage and a warm spring in 2021 during the age-1 stage indicating below average conditions for overwintering survival from age-0 to age-1.

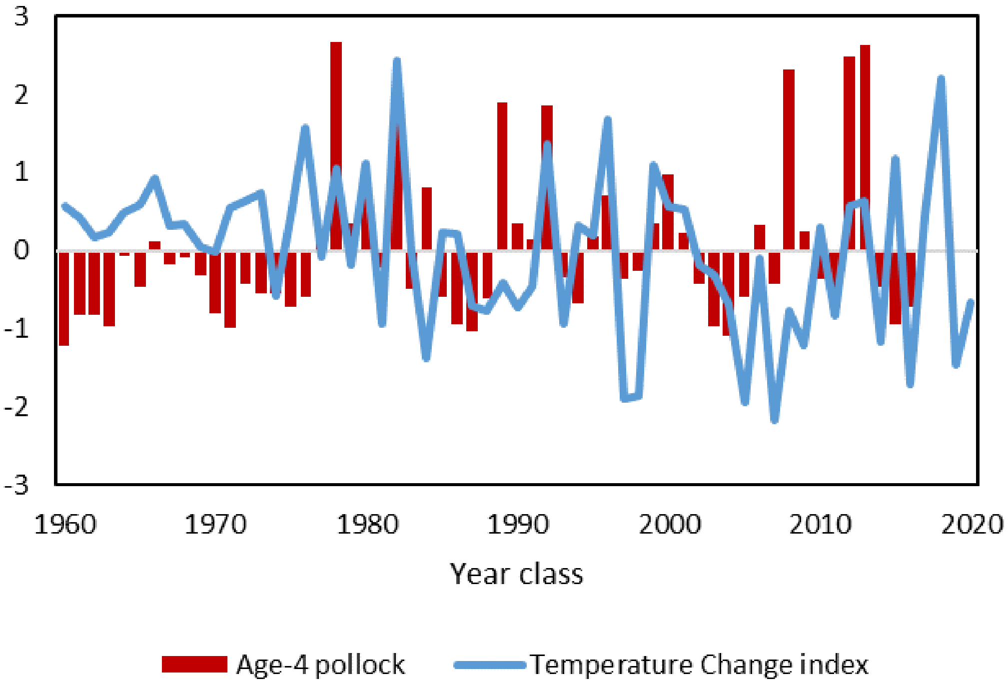

Figure 83: Normalized time series values of the temperature change index indicating conditions experienced by the 1960–2020 year classes of pollock during the summer age-0 and spring age-1 life stages. Normalized values of the estimated abundance of age-4 pollock in the southeastern Bering Sea from 1964–2020 for the 1960–2016 year classes. Age-4 pollock estimates are from Table 29 in Ianelli et al. (2020). The TC index indicates below average conditions for the 2020 year classes of pollock.

Implications: The 2020 TC index value of -5.37 was below the long-term average of -4.58, therefore we expect below average recruitment of pollock to age-4 in 2024 from the 2020 year class (Figure 83).

Benthic Communities and Non-target Fish Species

Miscellaneous Species - Eastern Bering Sea Shelf

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Last updated: October 2021

Description of indicator: "Miscellaneous" species fall into three groups: eelpouts (Zoarcidae), poachers (Agonidae), and sea stars (Asteroidea). The three species comprising the eelpout group are the wattled eelpout (*Lycodes palearis*) and shortfin eelpout (*L. brevipes*) and to a lesser extent the marbled eelpout (*L. raridens*). The biomass of poachers is dominated by a single species, the sturgeon poacher (*Podothecus acipenserinus*) and to a lesser extent the sawback poacher (*Leptagonus frenatus*). The composition of sea stars in shelf trawl catches are dominated by the purple-orange sea star (*Asterias amurensis*), which is found primarily in the inner/middle shelf regions, and the common mud star (*Ctenodiscus crispatus*), which is primarily an inhabitant of the outer shelf. Relative CPUE by weight (kg per hectare) was calculated and plotted for each species or species group by year for 1982–2021. Relative CPUE was calculated by setting the largest biomass in the time series to a value of 1 and scaling other annual values proportionally. The standard error (±1) was weighted proportionally to the CPUE to produce a relative standard error.

Status and trends: The 2021 relative CPUE for eelpouts remained about the same as in 2019 (6% increase), just above the average of the estimates over the last 10 years. The poacher group CPUE increased by 40% from 2019, continuing an increasing trend following an annual decrease observed from 2015 to 2018. The 2021 poacher estimate is still 10% lower than the average for the time series. The sea stars, as a group, increased by 8% from 2019 to 2021, and the 2021 CPUE ranked as the 3$^{\text{rd}}$ highest since 1982 and continues an overall increasing trend that started in 2013 (Figure 84).

Factors causing observed trends: Determining whether these trends represent real responses to environmental change or are simply an artifact of standardized survey sampling methodology (e.g., temperature dependent catchability) will require more specific research on survey trawl gear selectivity relative to interannual differences in bottom temperatures and on the life history characteristics of these epibenthic species.

Implications: Eelpouts have important roles in the energy flow within benthic communities. For example, eelpouts are a common prey item of Arrowtooth flounder (*Atheresthes stomias*). However, it is not known at present whether these changes in CPUE are related to changes in energy flow.

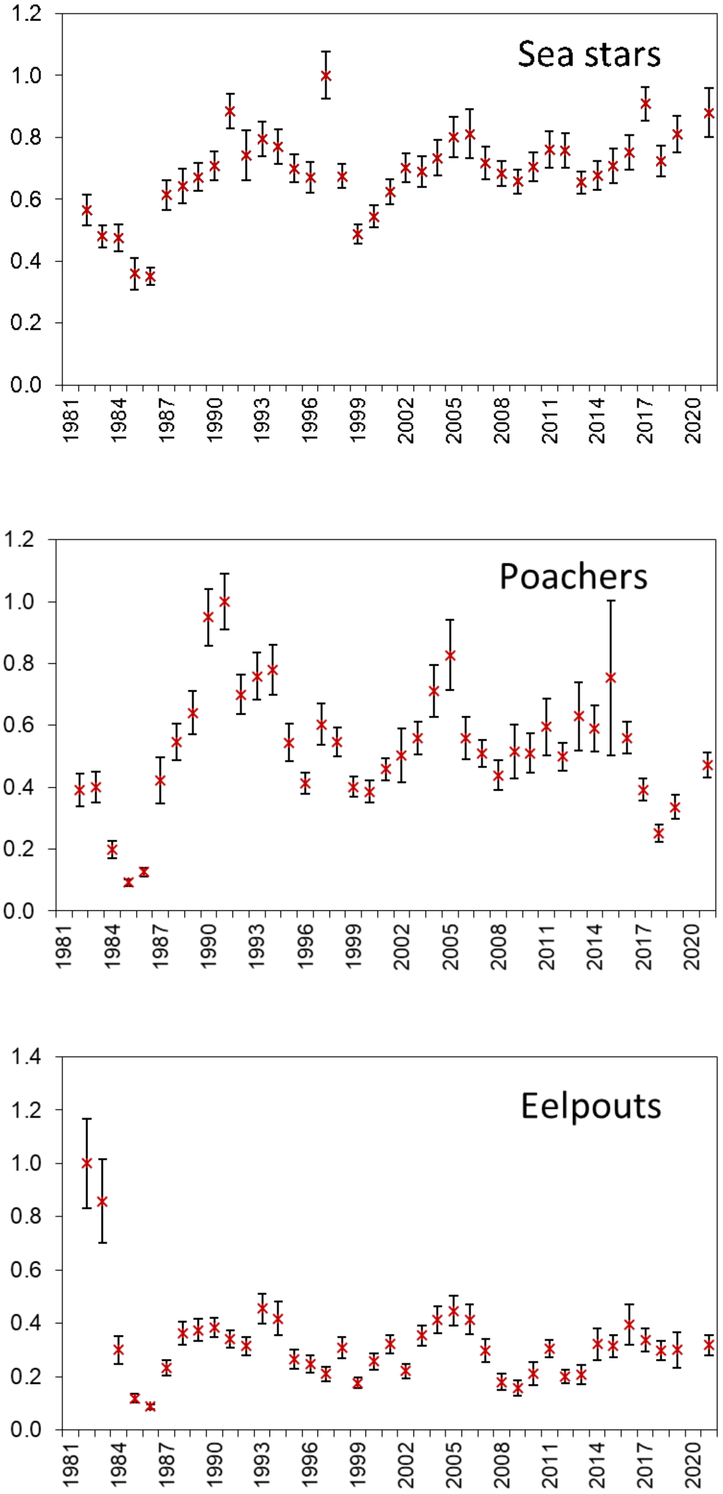

Figure 84: AFSC eastern Bering Sea shelf bottom trawl survey relative CPUE for miscellaneous fish species during the May to August time period from 1982–2021.

Eastern Bering Sea Commercial Crab Stock Biomass Indices

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Last updated: September 2021

Description of indicator: This indicator is the commercial crab species biomass time series in the eastern Bering Sea. The eastern Bering Sea bottom trawl survey has been conducted annually since 1975 by the Resource Assessment and Conservation Engineering Division of the Alaska Fisheries Science Center. The purpose of this survey is to collect data on the distribution and abundance of crab, groundfish, and other benthic resources in the eastern Bering Sea. The data provided here include the time series of results from 1998 to the present. In 2021, 375 standard stations were sampled on the eastern Bering Sea shelf from 31 May to 22 July. The observed trends in crab biomass may be indicative of trends in either benthic production, or benthic response to environmental variability. The commercial crab biomass is also indicative of trends in exploited resources over time.

Status and trends: The historical trends of commercial crab biomass and abundance are highly variable (Figure 85). In 2021, Bristol Bay mature male red king crab biomass increased by 28% relative to 2019 estimates, which while a slight rebound, continues a -66% decline since 2014. Mature female red king crab biomass declined by 24%, although abundance decreased similarly, due to remaining females being larger, with this being the lowest estimate since 1995. St. Matthew blue king crab adult males declined by -44%, marking a return to a declining trend observed since 2014. Female blue king crab biomass is not adequately sampled during this survey due to a nearshore distribution around St. Matthew Island. Mature male Tanner crab biomass declined by -21 to -39%. The -39% decline in western district mature males marks a dramatic departure from recent stable/increasing trends, but continues a decline observed in 2019. Mature females increased in the western district (+36%) and increased substantially (+332%) in the eastern district. Total snow crab biomass declined by 77% relative to 2019, and 86% relative to 2018, with this being driven by across the board declines in immature female (-94%), mature female (-72%), immature males (-83%), legal males (-66%), mature males (-55%), and industry preferred males (-57%). Pribilof Islands crab stocks remain extremely depressed with highly variable survey biomass estimates due to trawl survey limitations related to crab habitat and patchy crab distribution.

Factors influencing observed trends: Environmental variability and exploitation affect trends in commercial crab biomass over time. Recent modeling analyses suggest that environmental variability is largely driving inter-annual variability in crab stock recruitment, although a mortality event may be occurring with opilio, the direct driver of which is unknown.

Implications: The implications of the observed variability in crab stocks are dramatic inter-annual and inter-decadal variability in benthic predators and ephemeral (seasonal) pelagic prey resources when crab are in larval stages in the water column or as juveniles on the benthic substrates. Although it is unclear at what life stage crab stock variability is determined, it is likely that environmental variability affecting larval survival and changes in predation affecting juvenile survival are important factors. As such, the environmental conditions affecting larval crab may also be important for larval demersal groundfish and the availability of crab as prey may be important for demersal fish distributions and survival. Disease may also be a factor, although this is speculative.

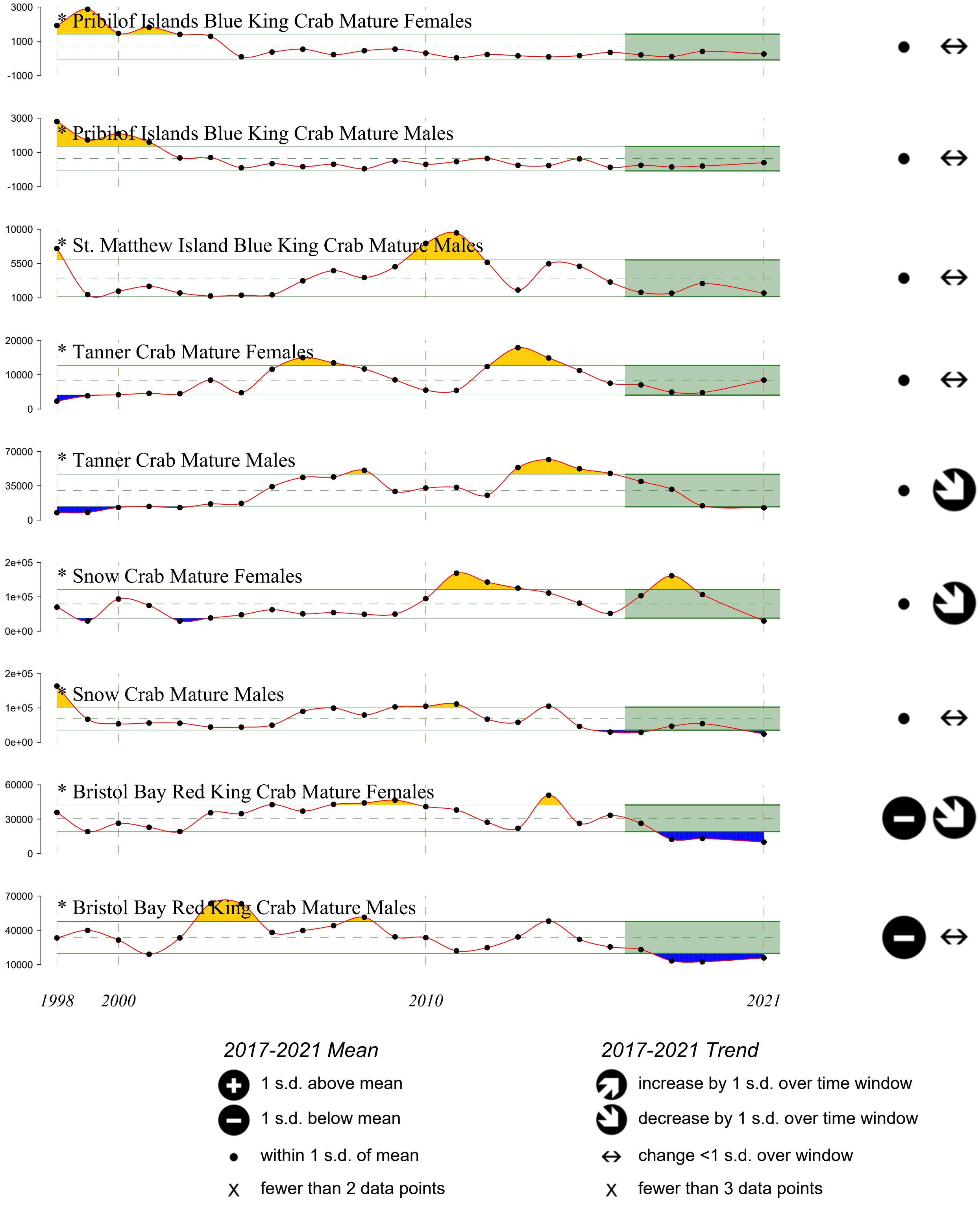

Figure 85: Historical biomass for commercial crab stocks caught on the National Marine Fisheries Service eastern Bering Sea bottom trawl survey, 1998–2021.

Seabirds

Integrated Seabird Information

This integration is in response to ongoing collaborative efforts within the seabird community and contains contributions from (in alphabetical order):

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Last updated: October 2021

Summary Statement

Migrant short-tailed shearwaters, predominately plankton-eating surface-feeders with some diet variation, experienced a significant mortality peak in August–September 2021. Most carcasses were found along the northern Bering Sea coastline, indicating a widespread lack of euphausiid prey or small fish alternatives (e.g., age-0 fish, sand lance). Other species observed through opportunistic reports of beached birds in 2021 included fish-eating birds (puffins and kittiwakes) and plankton-eating auklets in June, suggesting impacts across trophic levels. However, from July through September, the main species affected other than shearwaters (eating predominantly euphausiids) were fish-eating birds, primarily murres, horned puffins, and black-legged kittiwakes. Mortality was highest in the northern Bering Sea during August–September. Multi-species marine bird die-off events potentially reflect important changes in the biophysical oceanographic conditions in the region and the availability of prey resources.

Southeastern Bering Sea
On St. Paul Island, although long-term quantitative surveys were not conducted, the timing of breeding and abundance at colonies of fish-eating birds (murres, kittiwakes, puffins) appeared average, while plankton-eating bird abundance was lower than average, based on local observations.

Offshore surveys were minimal in 2021, due to COVID-19 travel restrictions, but those surveys that were conducted indicated average or slightly above average seabird densities across the southeastern Bering Sea.

Northern Bering Sea
On St. Lawrence Island, the colony attendance of fish-eating species (i.e., black-legged kittiwakes, common murres) sharply decreased in 2021, compared to 2020. Broadly, all fish-eating birds had poor reproductive success or complete reproductive failure, on both St. Lawrence Island and Hall Island. The plankton-eating birds had mixed reproductive success – least auklets did well on both Hall Island and St. Lawrence Island, but crested auklets (on St. Lawrence Island) had poor reproductive success. There were few offshore surveys, but those that were conducted indicated average densities of seabirds in the region.

Introduction: Seabirds can be viewed as indicators of ecosystem changes; therefore population-level responses can signal shifts in prey availability that may similarly affect commercial fish populations. In this Integrated Seabird Information section, we synthesize information and observations from a variety of sources (including tribal members, community members, and researchers) to provide an overview of environmental impacts to seabirds and what that may indicate for ecosystem productivity as it pertains to fisheries management. We merge across information sources to derive regional summaries within the southeastern and northern Bering Sea and interpret changes in seabird dynamics with respect to understanding ecosystem productivity.

Approach: We focused on three attributes of seabirds that may serve as broader ecosystem indicators important to fisheries managers. We interpret these attributes as reflective of seabirds' life history and how they sample the ecosystem, either as fish-eating or planktivorous species.

Life History:
Reproductive success reflects feeding conditions in the environment for breeding birds and has implications for seabird population trajectories and food security (i.e., subsistence egging practices). Timing (phenology) of seabird reproductive stages (i.e., lay or hatch) at colonies can reflect ecosystem conditions encountered by birds during the months preceding the breeding season or local weather conditions at the colony when they arrive (e.g., snow cover). Long-lived seabirds may delay or skip breeding if foraging conditions limit their ability to build up energy reserves to support energetic demands during the breeding season. Widespread reproductive failure during the breeding season, such as abandonment of nest sites or widespread egg or chick loss, may indicate that foraging conditions deteriorated rapidly or the presence of disturbance at the colony such as from land-based predators. Differences in reproductive success within a season among plankton-eating, fish-eating, and mixed plankton/fish-eating species may reflect differences among availability of prey resources including differences in abundance, distribution, and nutritional quality.

Colony attendance (numbers) can reflect population and survival trends, or differences in the proportion of birds attempting to breed. Non-breeders also attend the colony (e.g., murres), even in poor years, so attendance patterns must be interpreted with caution.

Colony attendance (timing) reflects local conditions (e.g., wind, presence of snow) as well as prey availability immediately preceding the breeding season. Earlier colony attendance may indicate that foraging conditions were favorable, such that birds were able to build enough energy reserves to prepare them for the breeding season. Later colony attendance may reflect poor winter foraging conditions or a mismatch in spring bloom timing and subsequent ocean productivity.

Mortality events may indicate broad ecosystem concerns such as harmful algal blooms (HABs) or large-scale decreases in prey location, quality, and/or quantity.

Sampling:
Fish-eating, surface feeding seabirds include kittiwakes, that feed on small schooling fish available at the surface (e.g., capelin, Arctic cod, juvenile pollock, and juvenile herring), thus making them potential indicators of processes affecting juvenile groundfish that migrate to the surface to feed. *Fish-eating, diving seabirds* include thick-billed and common murres that feed on small, schooling fish (e.g., age-0 and age-1 pollock) to depths up to 200m, thus they have access to fish throughout the water column and to the sea floor in shallow areas. Thick-billed murre adults also consume euphausiids at some locations, although both murre species require fish to raise their chicks. Few of these species are obligate fish-eaters; for example, murres are known to eat a large number of euphausiids and kittiwakes take a mix of zooplankton and squid, as well.

Plankton-eating seabirds include least and crested auklets that feed primarily on copepods and euphausiids. Shearwaters and thick-billed murres also consume euphausiids, along with larvae and small fish. All of these species are indicators of regional feeding conditions for planktivorous groundfish species, including the larvae and juveniles of fish-eating species.

Status and Trends

Southeastern Bering Sea (Pribilof Islands)

Reproductive success
Due to COVID-19 restrictions, U.S. Fish & Wildlife Service (USFWS) crews were not able to conduct a field season on St. Paul and St. George Islands. Therefore, standardized reproductive success, timing of breeding, abundance, and diet data are not available for the 2020 or 2021 season. Instead, information from St. Paul Island is provided by Island Sentinels, community members, and tribal members of the Aleut Community of St. Paul Island.

Black-legged kittiwakes and **red-faced cormorants** hatched at least some chicks at St. Paul Island in 2021 (no data on late-season chicks/fledging). **Common murres** laid eggs, but observations were not available past incubation to estimate hatching or chick fledging success. No subsistence harvesting of **thick-billed** or **common murre** eggs occurred in summer 2021 due to low attendance by adult murres and low egg production. Nesting was observed at the Tourist Point Cliff, located on the south facing coast of St. Paul Island, by tribal and community members. From photos taken in mid-July, the timing of **black-legged kittiwake** and **red-faced cormorant** hatching appeared normal, as was the timing of egg laying for **thick-billed murres**, even though numbers of eggs laid was low.

Subsistence fishermen at St. Paul Island reported sea surface temperatures of 8.9°C in early August, unusually warm, which raised concerns about local prey availability for all species, particularly surface feeders, during the chick-rearing period.

Colony attendance (numbers)
The abundance of multiple species nesting at the Tourist Point Cliff was assessed in July by Seabird Youth Network educators and St. Paul Island community members. **Murres** appeared to be slightly less numerous than in the past, but **black-legged kittiwake** and **tufted and horned puffin** numbers appeared average. At what was formerly a thriving, abundant colony at East Landing adjacent to the town of St. Paul, **least auklet** numbers appeared low, as has been the trend over at least the last decade. There were no data collected on the Zapadni colony, which was not observed in 2021.

Although once abundant, **parakeet auklets** have been apparently declining in abundance at St. Paul Island for several years. In fact, in 2020, no parakeet auklets were observed at St. Paul Island. In 2021, parakeet auklets were observed, but no information on abundance or timing was available.

Colony attendance (timing)
Least auklets were observed during their typical arrival period, late April–early May.

Mortality events
Despite ongoing die-offs in the north, beach-based surveys reflected a low-to-average encounter rate of carcasses at the Pribilof Islands in winter through summer 2021 (Figure 86). However, in late September, monitoring teams on St. Paul Island reported 11 shearwaters on Lukanin beach, 4 on Polovina beach, 5 on Benson beach, and 3 on North beach. This peak in September 2021 is significant, as it is greater than 5 times the month-averaged baseline (Figure 1). However, this peak is more than 6 times lower than the peak in shearwaters that occurred in 2019 (see Siddon et al. (2020)). The 2019 peak marked a mass mortality event for short-tailed shearwaters that reflected broader ecosystem-level stresses (i.e., 2$^{\text{nd}}$ winter of minimal sea ice, frequent and persistent marine heatwave conditions over the SEBS and NBS). Both the historical norms and recent unprecedented events are important to keep in mind when interpreting the events of 2021.

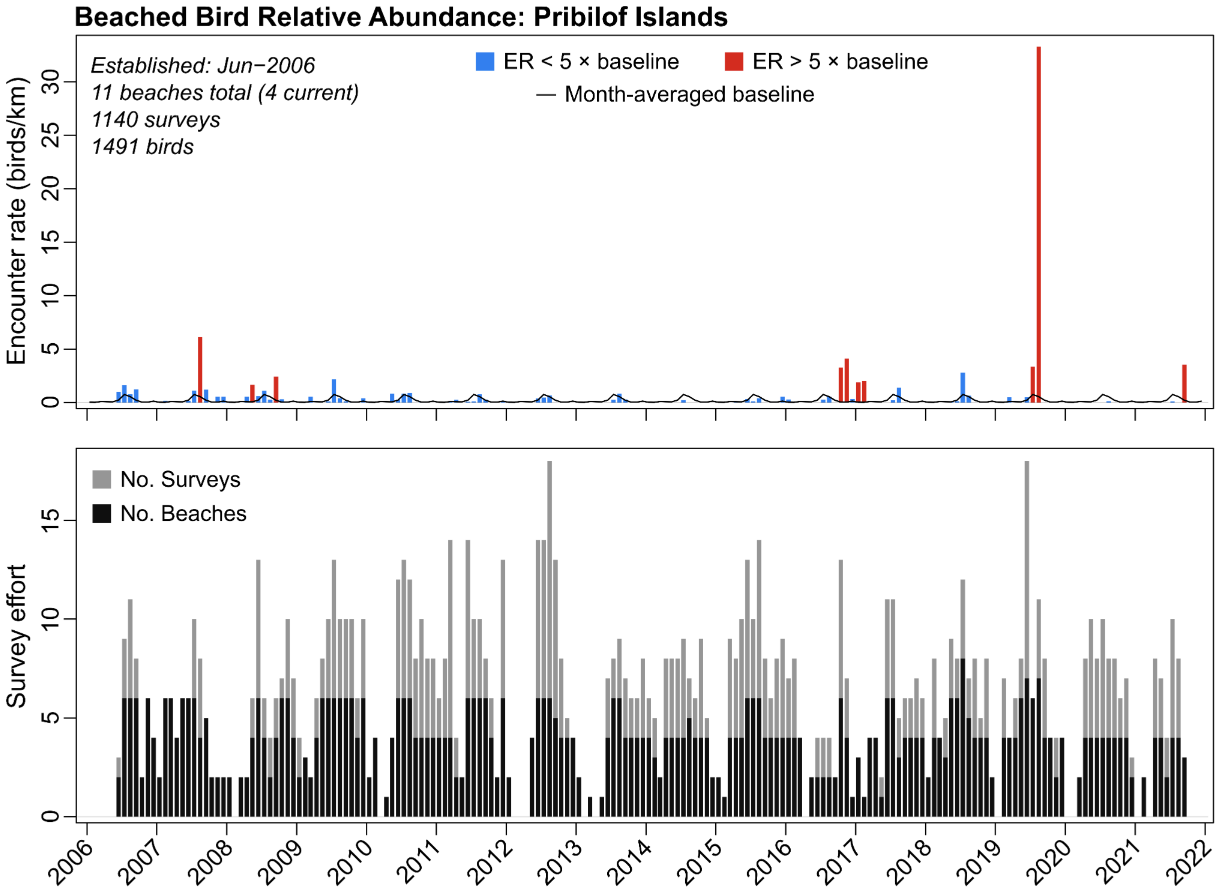
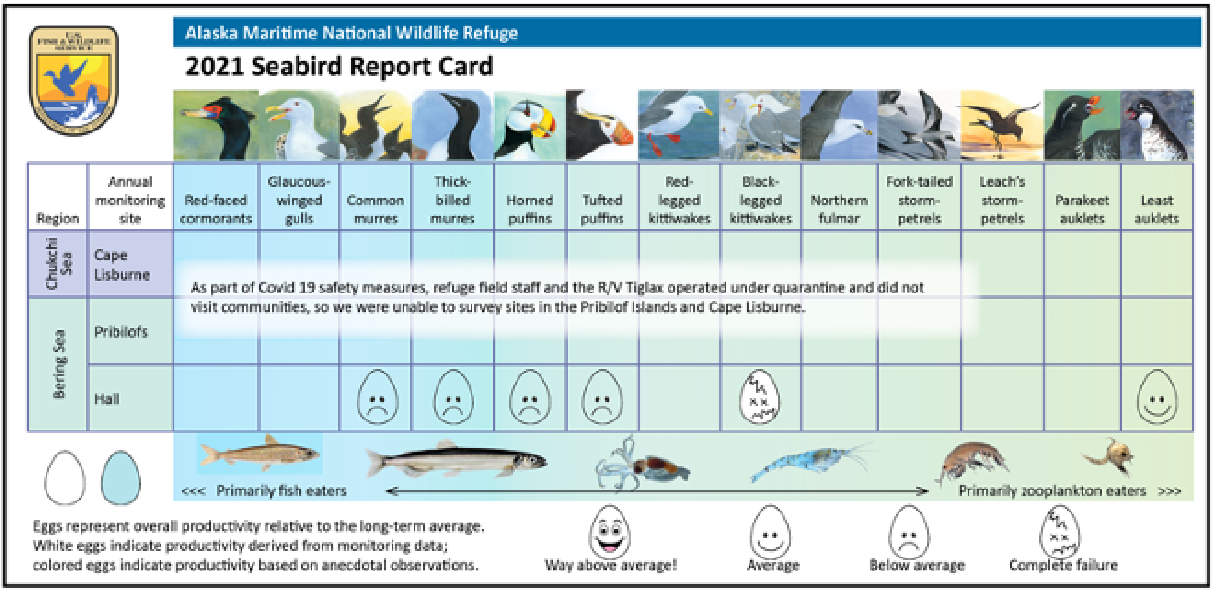


Figure 86: Month-averaged beached bird carcass abundance, standardized per km of survey effort, for the Pribilof Islands. The top panel shows the month-averaged encounter rate (ER: birds per km). The bottom panel shows survey effort at the monthly scale.



Alaska Maritime National Wildlife Refuge

2021 Seabird Report Card

Region	Annual monitoring site	Red-faced cormorants	Glaucous-winged gulls	Common murres	Thick-billed murres	Horned puffins	Tufted puffins	Red-legged kittiwakes	Black-legged kittiwakes	Northern fulmar	Fork-tailed storm-petrels	Leach's storm-petrels	Parakeet auklets	Least auklets
Chukchi Sea	Cape Lisburne													
Bering Sea	Pribilofs													
	Hall			☹	☹	☹	☹		✗					☺

As part of Covid 19 safety measures, refuge field staff and the R/V Tiglax operated under quarantine and did not visit communities, so we were unable to survey sites in the Pribilof Islands and Cape Lisburne.

<<< Primarily fish eaters ⟷ Primarily zooplankton eaters >>>

Eggs represent overall productivity relative to the long-term average.
White eggs indicate productivity derived from monitoring data;
colored eggs indicate productivity based on anecdotal observations.

Way above average! Average ☺ Below average ☹ Complete failure ✗

Figure 87: Reproductive success of seabird species in the northern Bering Sea. Quantitative data were collected for murres and kittiwakes, but no long term data were available for comparison. Kittiwakes exhibited complete reproductive failure. Data on puffins and auklets were qualitative.

Northern Bering Sea (including Hall Island, St. Lawrence Island, and the Bering Strait region)

Reproductive success

Hall Island, off the northwest end of St. Matthew Island, was visited by the USFWS in summer 2021. Both **murres** and **puffins** had low reproductive success (Figure 87) and **murre** nesting was very late at Hall Island. In fact, a small number of recently hatched chicks were still present when USFWS departed the island in late August 2021.

Murres at Kevipaq, St. Lawrence Island had near complete reproductive failure in 2021, similar to failures observed in 2018 following the marine heatwave and unprecedented low levels of sea ice. In 2021, snow remained on the cliffs through spring, even into late July in some places, and may have contributed to low breeding efforts of murres. Murres nearly abandoned the breeding cliffs in early August, despite having had relatively high adult attendance at study plots at the end of July (Figure 87, top left).

Black-legged kittiwakes on Hall Island experienced complete reproductive failure (Figure 87), and the same was true at Kevipaq, St. Lawrence Island where no chicks were produced (Figure 88, top right).

Least Auklets did well in 2021 at both Hall Island and St. Lawrence Island. At Hall Island, least auklets had an apparently average year (Figure 87). Although no quantitative data were collected on least auklets at Hall Island, the colony was well attended and adults were observed carrying food loads.

At the Kitnik site on St. Lawrence Island, **least auklets** had an average year. Least auklets hatched and fledged about 1 week earlier than 2016–2020 at St. Lawrence Island. **Crested auklets**, on the other hand, had a below average year reflecting variability in planktonic prey and/or competition between the two auklet species (Figure 88, bottom). Opportunistic observations of least auklet and crested auklet chick meals indicated both species continued to consume primarily euphausiids, a pattern observed since 2017.

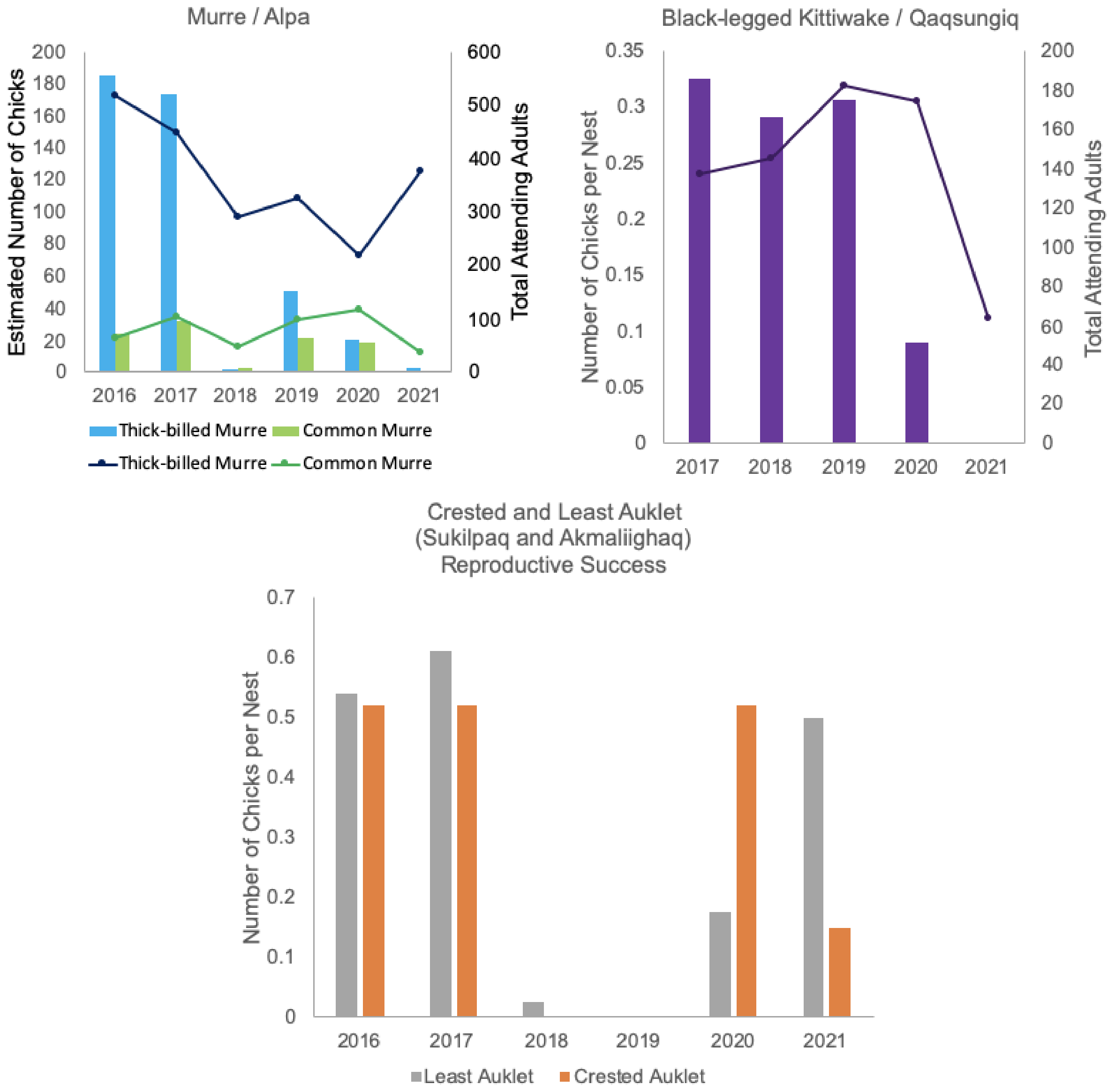


Figure 88: *Top left:* Murre reproductive success index (bars, left axis) and adult attendance counts (lines, right axis) at Kevipaq, St. Lawrence Island. *Top right:* Kittiwake reproductive success index (bars, left axis) and adult attendance counts (lines, right axis) at Kevipaq, St. Lawrence Island. *Bottom:* Auklet reproductive success index for least auklets (gray bars) and crested auklets (orange bars) at Kitnik, St. Lawrence Island.

Colony attendance (numbers)
At St. Lawrence Island, **black-legged kittiwakes** had low attendance at all observed cliffs with a 50% reduction in attendance in 2021 compared to 2020 (Figure 88, top right). Observers described **murre** cliffs at St. Lawrence Island as being free of guano; one ledge that had been abandoned by adult murres was littered with several dead chicks.

Colony attendance (timing)
Hunting for pelagic **cormorant** chicks began about a month earlier than normal at St. Lawrence Island.

Mortality events
During May–September 2021 in the Bering Strait/Chukchi Sea region, two beaches were surveyed for beached birds; each beach was surveyed twice. Observers saw an average deposition of beached birds compared to the time series average (Figure 89). Investigation of three common groups revealed **shearwaters** had a mortality peak in August 2021 (Figure 90), but standardized surveys did not reflect that **kittiwakes** or **murres** had elevated deposition in 2021.

In 2021, the northern Bering Sea was the location of several large mortality counts of over 100 carcasses each: predominantly **shearwaters** at the mouth of the Kuskokwim River in July, **shearwaters** near Wales and Nome, Alaska in August, and **shearwaters** and **murres** on St. Lawrence Island in September (Figure 91). Some (n=10) dead **crested auklets** were observed on beaches near breeding colonies near Savoonga on St. Lawrence Island in mid-August 2021, but these numbers were not unusual.

At the same time that **short-tailed shearwaters** began to show up in high numbers in the northern Bering Sea (Figure 91), British Columbia to northern California began seeing unprecedented numbers of short-tailed shearwaters, August–October 2021 (Figure 92, a and c). Southbound migrant short-tailed shearwaters departed the Bering Sea much earlier and presumably benefited from consistently productive waters of the California Current, especially the Columbia River plume (also a known stopover location for northward-migrating shearwaters). Sooty shearwaters, which range only as far north as Bristol Bay, did not show a mass migration from Alaska, and had average counts, August–October 2021 (Figure 92, b and d).

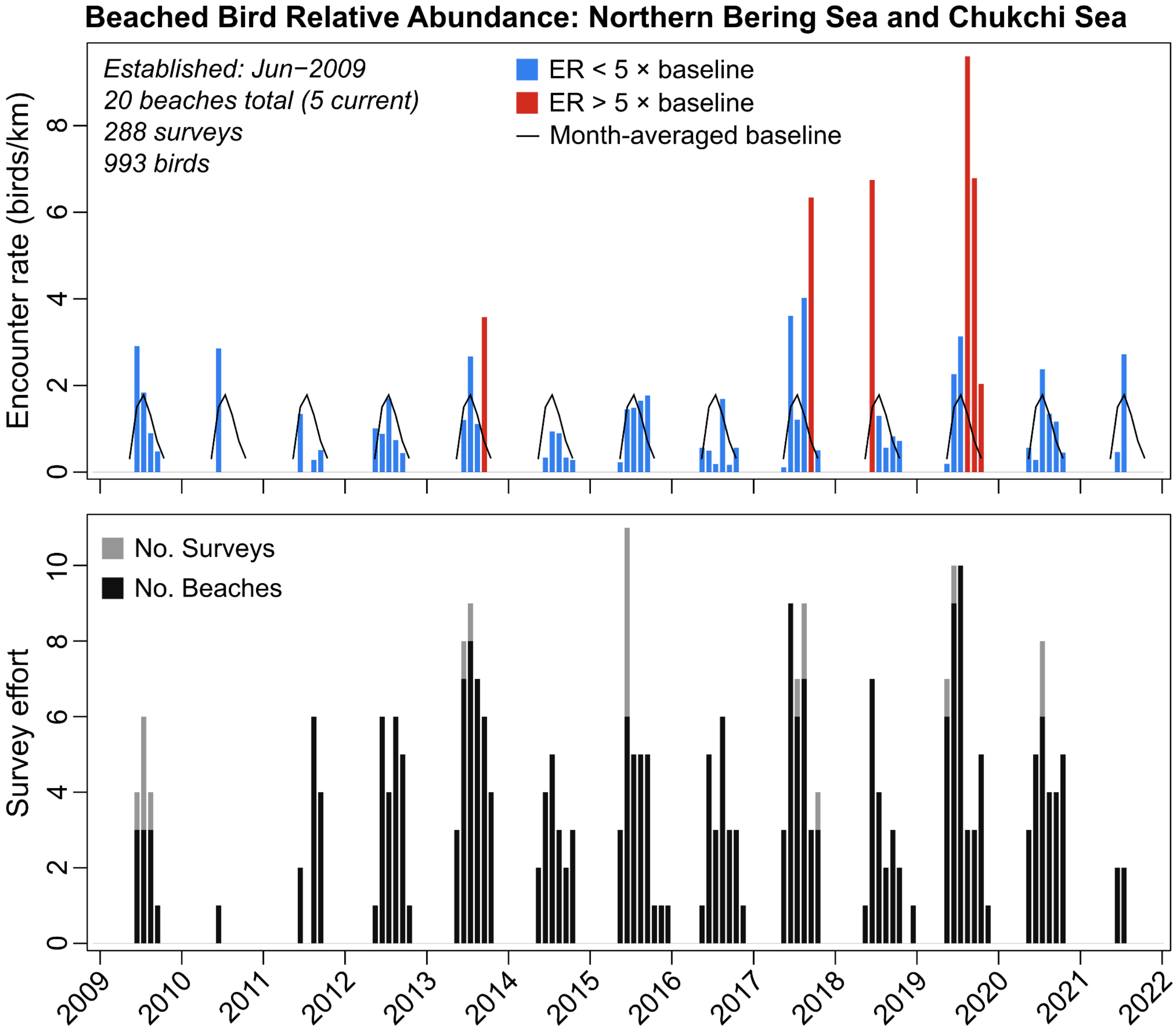


Figure 89: Month-averaged beached bird carcass abundance, standardized per km of survey effort, for the Bering Strait/Chukchi Sea. The top panel shows the month-averaged encounter rate (ER: birds per km). The bottom panel shows survey effort at the monthly scale.

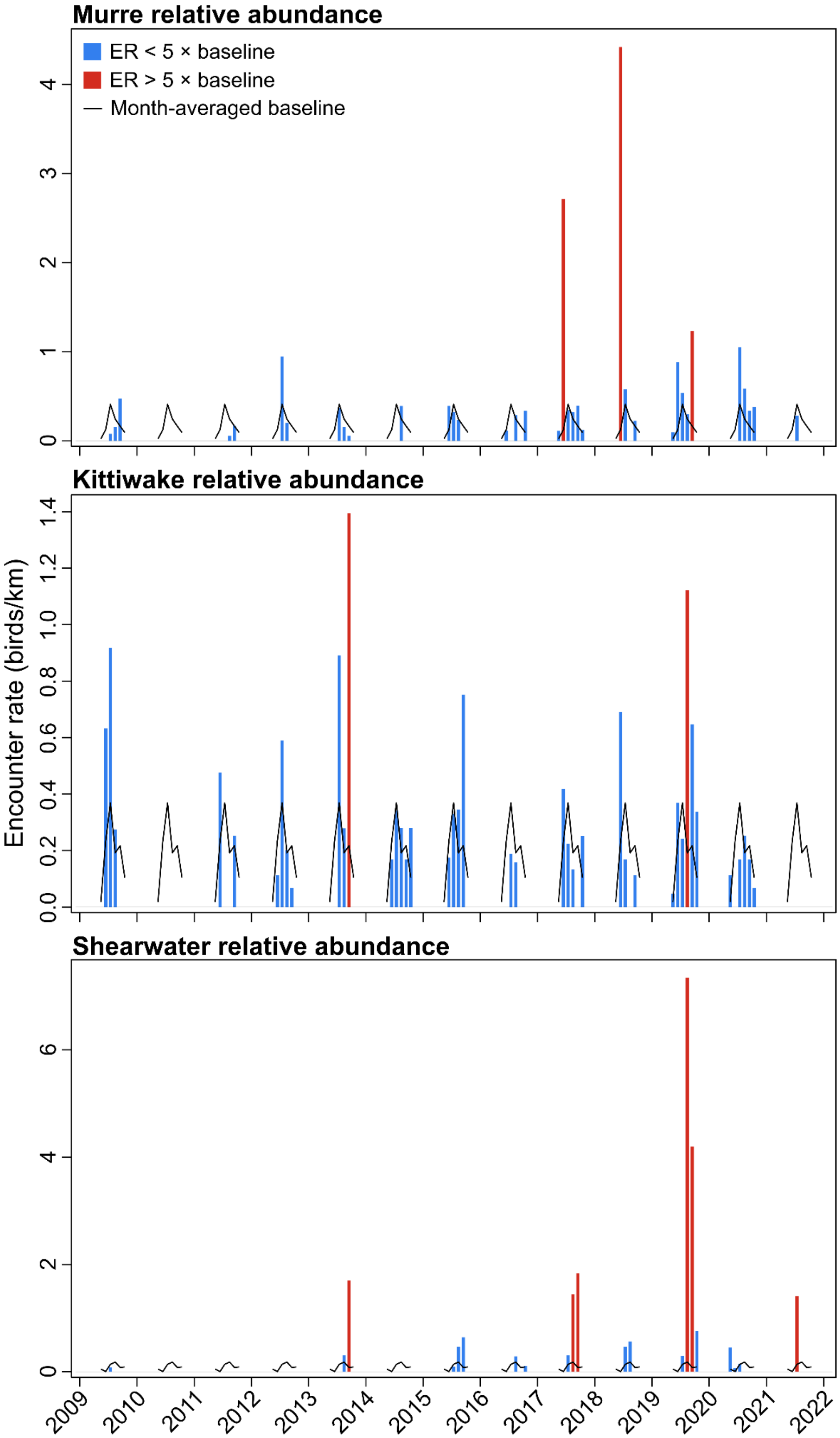


Figure 90: Month-averaged beached bird carcass abundance, standardized per km of survey effort, for the Bering Strait/Chukchi Sea for murres, kittiwakes, and shearwaters. Each panel shows the month-averaged encounter rate (ER: birds per km).

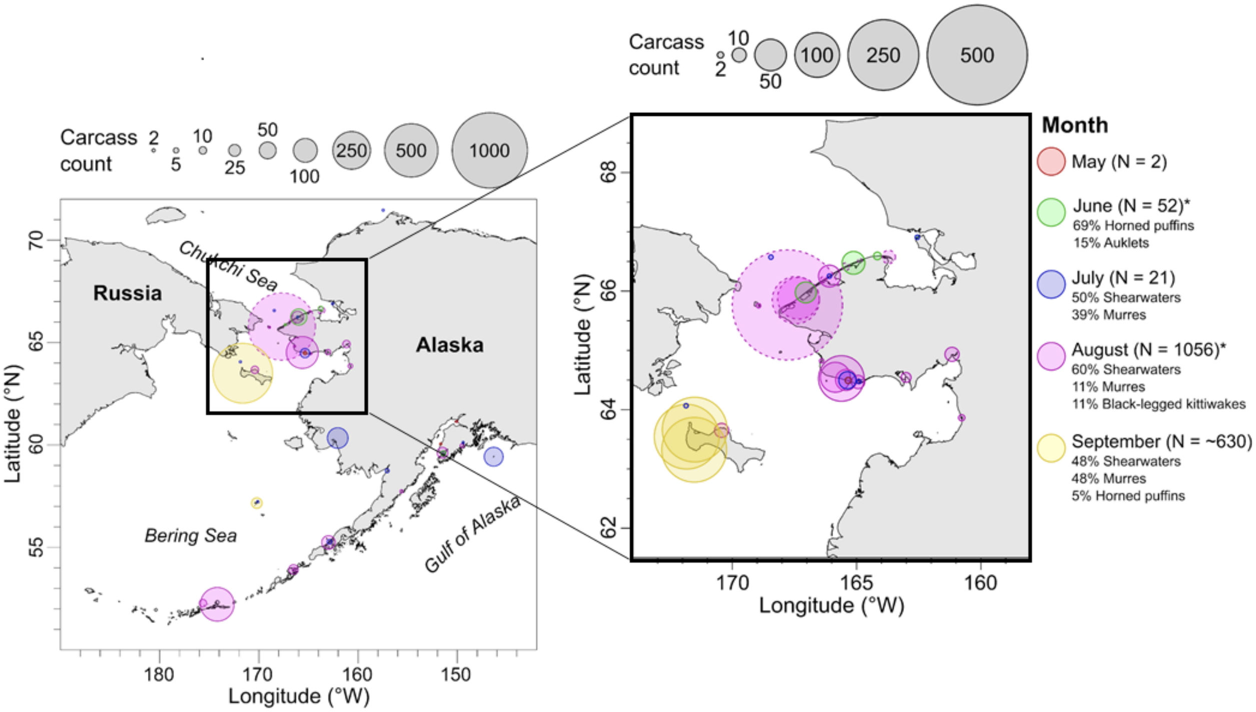
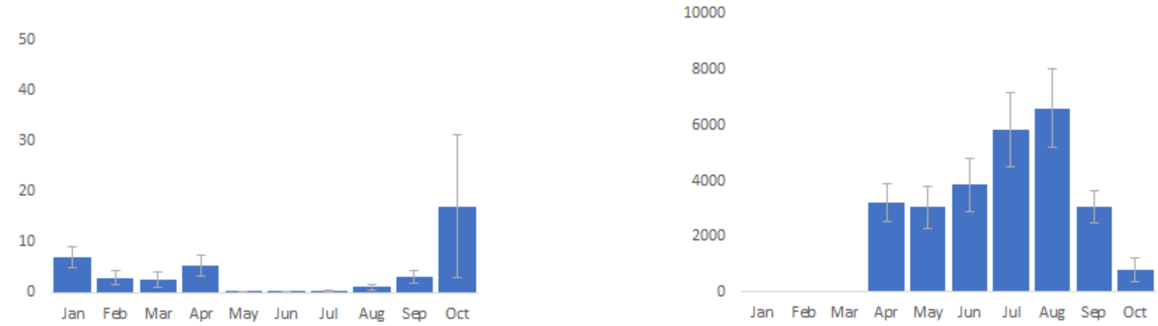


Figure 91: Seabird die-off map for Alaska during May–September 2021. Inset shows northern Bering Sea/Chukchi Sea carcass counts (**note** difference in scale). Data provided by National Park Service, Kawerak, Inc. staff, UAF Alaska Sea Grant faculty, as well as coastal community members reporting to ADF&G, COASST, Kawerak, Inc., UAF-Alaska Sea Grant, and USFWS. *: species composition is of birds identified to species/group. However, in August a large proportion (60%) of birds were not identified. Circles represent reports of seabird carcass abundance and are not standardized for variable observer effort among locations. The absence of reports in certain locations may indicate gaps in current knowledge OR an actual absence of bird carcasses. Reports from aerial surveys (dashed circles) are distinguished from other beach-based reports (solid circles) due to major differences in area observed.

(a) Short-tailed shearwater (1998-2020) (b) Sooty shearwater (1998-2020)



(c) Short-tailed shearwater 2021 vs 1998-2020 (d) Sooty shearwater 2021 vs 1998-2020

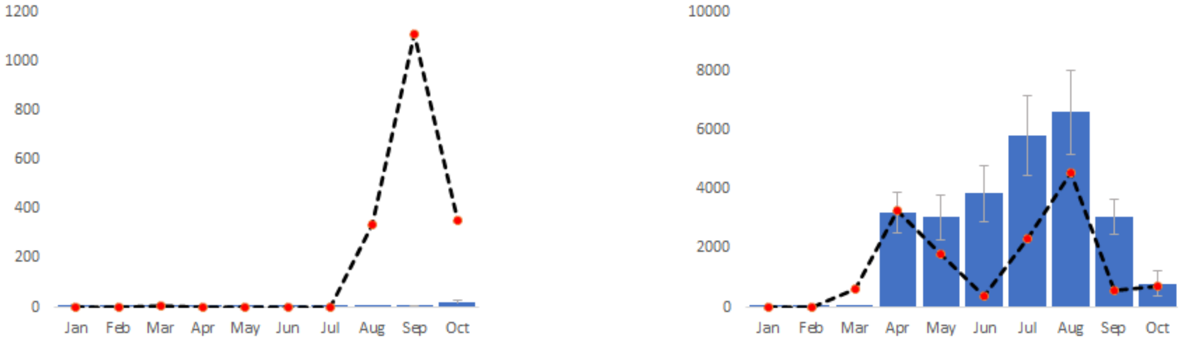


Figure 92: (a) Short-tailed shearwater counts on Westport Pelagic Seabird Cruises (WA), 1998–2020, error is standard error, note the Y axis; (b) Sooty shearwater counts on Westport Pelagic Seabird Cruises (WA), 1998–2020, error is standard error; (c) Short-tailed shearwater counts in 2021 (dotted line) compared to long-term average, 1998–2020, note the differences in the Y axes 10a, 10c; (d) Sooty shearwater counts on cruises in 2021 (dotted line) compared to long-term average, 1998–2020. Across the time series, cruises did not occur Nov–Dec. Data publicly available and retrieved from `https://westportseabirds.com/Oct2021`.

Marine Mammals

Marine Mammal Stranding Network: Eastern Bering Sea

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Last updated: September 2021

Description of indicator: Since 1985, members of the NMFS Alaska Marine Mammal Stranding Network (AMMSN) have collected and compiled reports on marine mammal strandings throughout the state. These reports are indices of events witnessed by members of the stranding network, the scientific community, and the general public, with varying degrees of knowledge regarding marine mammal biology and ecology. Over the last five years, the AMMSN has received over 1,600 reports of stranded marine mammals within Alaska. The causes of marine mammal strandings are often unknown but some causes are disease, exposure to contaminants or harmful algal blooms, ship strikes, entanglement in fishing gear, or ingestion of marine debris.

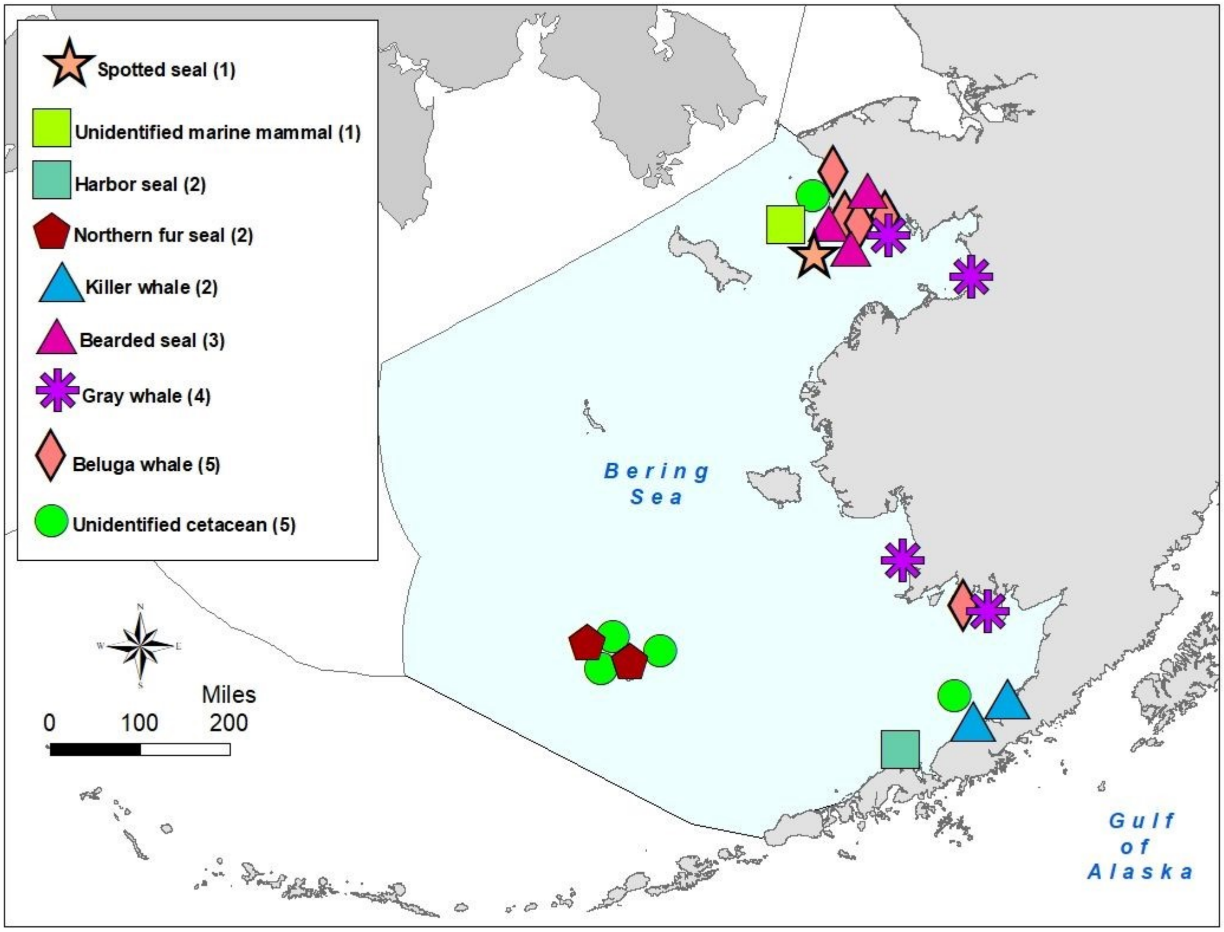

Figure 93: Reported stranded marine mammals between January 1, 2021 and September 18, 2021.

When a stranded marine mammal is reported, information is collected including species, location, age or size. In some cases, the initial photos and observations reported to AMMSN may be the only opportunity to collect information on the event. When possible, trained and authorized members respond and collect life history data and samples as part of a partial or full necropsy. Photos and carcasses are evaluated for potential human interactions such as vessel strikes. These responses are conducted under the Marine Mammal Protection Act authorization either under a 112c agreement issued by NMFS to AMMSN members through a Stranding Agreement or under 109(h) authority exercised by local, state, federal or tribal entities.

Status and trends: The number of reported strandings in Alaska has increased over time. So far in 2021, 25 stranded marine mammals have been reported (confirmed reports only) in the eastern Bering Sea region, the majority of reports being near more populated areas (Figure 93) where AMMSN members are located. Reported strandings in the eastern Bering Sea region since 2016 varied between years without an overall pattern or consistent increase in reports (Table 3). The 2021 stranding data includes confirmed strandings reported between Jan 1–Sept 18, 2021.

Factors influencing observed trends: It is important to recognize that stranding reports represent effort, which has varied substantially over time and location, and overall has increased over time and in areas with higher human population densities. Unusual Mortality Events (UMEs) including the 2018 ice seal and the 2019 gray whale UME can have a large influence on variability between years in this area (Table 3). Under the Marine Mammal Protection Act, an UME is defined as "a stranding that is unexpected; involves a significant die-off of any marine mammal population; and demands immediate response."

Implications: Other factors that may influence the number and species of marine mammals being reported include changing populations of some species including the increase in northern fur seals using Bogoslof Island for breeding. Further, the number of stranded marine mammals in an area can vary due to the potential conflict with fishery resources either directly through prey competition or indirectly through interactions with fishing gear such as increased whale entanglements in gear. Further, human population and activity in an area influences the potential for a carcass or stranded marine mammal to be observed and reported.

Table 3: Reported stranded NMFS marine mammal species for the last five years in the eastern Bering Sea by species and year.

	2016	2017	2018	2019	2020	2021
Beluga whale	18	12	11	14	13	5
Harbor porpoise		3	4	6	3	
Fin whale	1				2	
Gray whale	4	7	7	14	15	4
Humpback whale	1	2	4	3	1	
Minke whale				2	1	
Killer whale	5		2		1	2
Sperm whale						
Unidentified cetacean	3	8		1	2	1
Unidentified small cetacean	2	2				
Unidentified large whale	1	7	7	11	2	
Total Cetaceans	35	41	35	51	40	12
Harbor seal	2		1	4	2	2
Northern fur seal	10	6	10	18	2	2
Bearded seal		1	32	20	8	3
Ribbon seal				2		
Ringed seal	3	8	31	8	2	
Steller sea lion	1	3	1		4	
Spotted seal	1	5	17	14	4	1
Unidentified pinniped	2	3	19	26	8	
Unidentified marine mammal	3	7	5	2		1
Total Pinnipeds	22	33	116	94	30	9
Total Cetaceans and Pinnipeds	57	74	151	145	70	21

Ecosystem or Community Indicators

Aggregated Catch-Per-Unit-Effort of Fish and Invertebrates in Bottom Trawl Surveys on the Eastern and Northern Bering Sea Shelf, 1982–2021

Contributed by Franz Mueter[1] and Lyle Britt[2]
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[2]Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
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Last updated: October 2021

Description of indicator: The index provides a measure of the overall biomass of demersal and benthic fish and invertebrate species. We estimated annual mean catch-per-unit-effort (CPUE in kg ha) of all fish and major invertebrate taxa using all successful hauls completed during standardized bottom trawl surveys on the eastern Bering Sea shelf (EBS) from 1982—2021 and on the northern Bering Sea shelf (NBS) in 2010, 2017, 2019, and 2021. Total CPUE for each haul was computed as the sum of the CPUEs of all fish and major invertebrate taxa. To obtain an index of average CPUE by year for each survey region, we modeled log-transformed total CPUE (N = 14,466 hauls in the EBS, N = 572 hauls in the NBS) as a smooth function of Julian day and location (latitude/longitude), with year-specific intercepts, using an Additive Model. The CPUE index does not account for gear or vessel differences, which are confounded with interannual differences and may affect results prior to 1990. Therefore we only show trends from 1990–2021. To highlight differences between recent trends in the EBS and NBS, we also computed the mean CPUE by region and year for the four years with complete surveys in the NBS using an additive model to account for seasonal trends (smooth function of Julian day) and account for spatially correlated errors that were assumed to decrease exponentially with distance.

Status and trends: Total log(CPUE) in the EBS shows no significant trend (linear regression, adjusted for temporal autocorrelation, t=0.291, p=0.773)(Figure 94) but large fluctuations between 1990 and 2021. The highest observed value in the time series occurred in 2014 and total CPUE declined thereafter with a sharp and significant drop between 2017 and 2018. Total CPUE increased again in 2019, followed by another significant decrease between 2019 and 2021 to the lowest level since 2009. Total CPUE in the NBS increased between 2010 and 2019, and decreased substantially between 2019 and 2021 (Figure 95).

Factors influencing observed trends: Commercially harvested species accounted for approximately 95% of survey catches. Fishing is expected to be a major factor determining trends in survey CPUE, but environmental variability is likely to account for a substantial proportion of the observed variability in CPUE through variations in recruitment, growth, distribution, and catchability. The increase in survey CPUE in the early 2000s in the EBS primarily resulted from increased abundances of Walleye pollock (*Gadus chalcogrammus*) and a number of flatfish species (Arrowtooth flounder, *Atheresthes stomias*; Yellowfin sole, *Limanda aspera*; Rock sole, *Lepidopsetta bilineata*; and Alaska plaice, *Pleuronectes quadrituberculatus*) due to strong recruitments in the 1990s. Decreases in 2006–2009 and subsequent increases are largely a result of fluctuations in pollock recruitment and abundance. Models including bottom temperature suggest that, in the EBS, CPUE tends to be lower in years with low bottom water temperatures, as evident in reduced CPUEs in

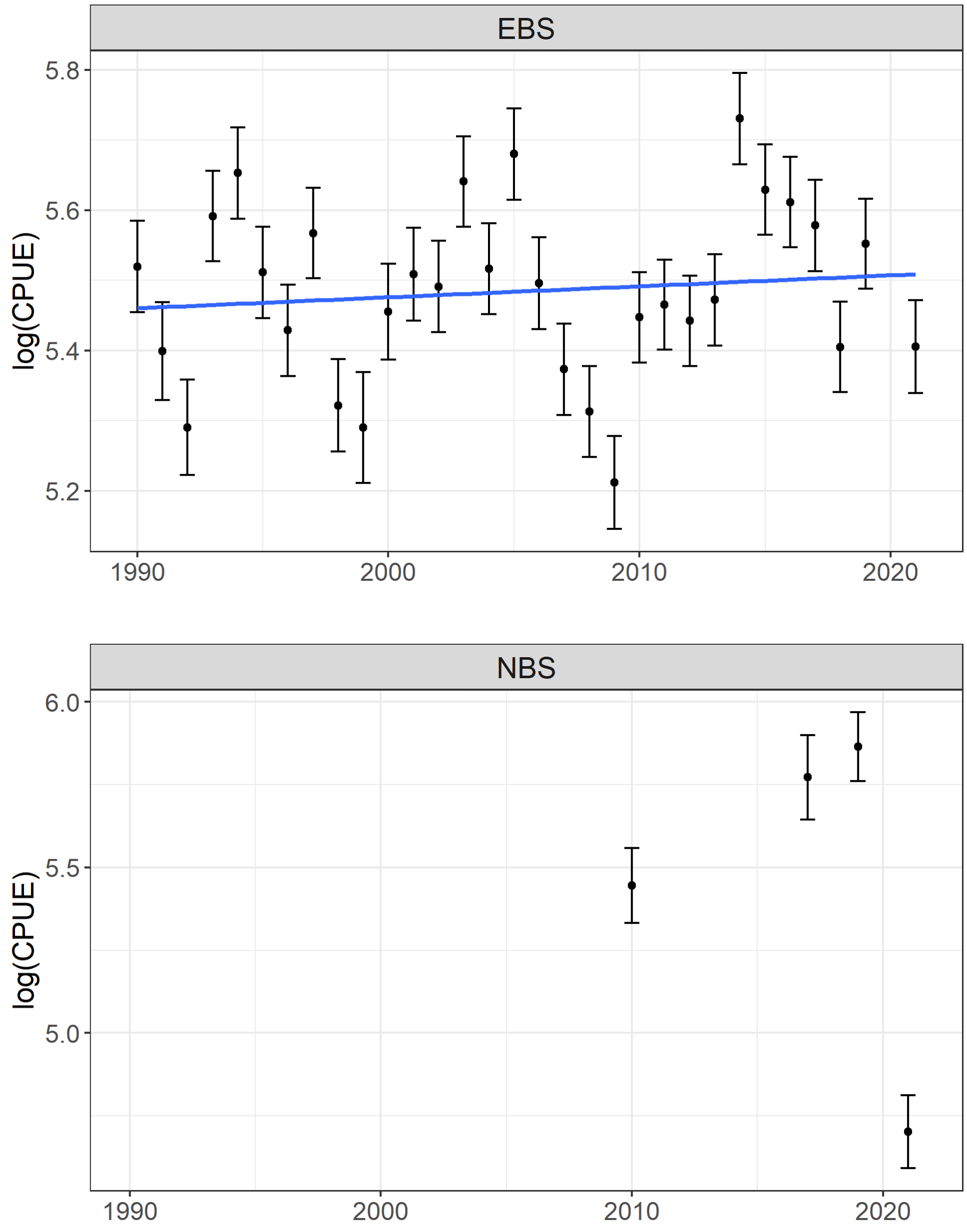

Figure 94: Model-based estimates of total log(CPUE) for major fish and invertebrate taxa captured in bottom trawl surveys from 1990 to 2021 in the eastern Bering Sea (EBS) and northern Bering Sea (NBS) with approximate pointwise 95% confidence intervals and linear time trend (EBS only). Estimates were adjusted for differences in day of sampling and sampling locations among years. The linear time trend was estimated using a generalized least squares regression assuming 1^{st} order auto-correlated residuals and was not statistically significant. Note differences in y-axis scales.

1999 and 2006–2013, when the cold pool covered a substantial portion of the shelf. Overall, there is a moderate positive relationship between average bottom temperatures and CPUE in the same year ($r=0.46$, $p=0.0087$), but not in the following years. Reduced CPUE during cold periods is likely due to a combination of temperature-dependent changes in catchability of certain species (e.g., flatfish, crab), changes in distribution as a result of the extensive cold pool displacing species

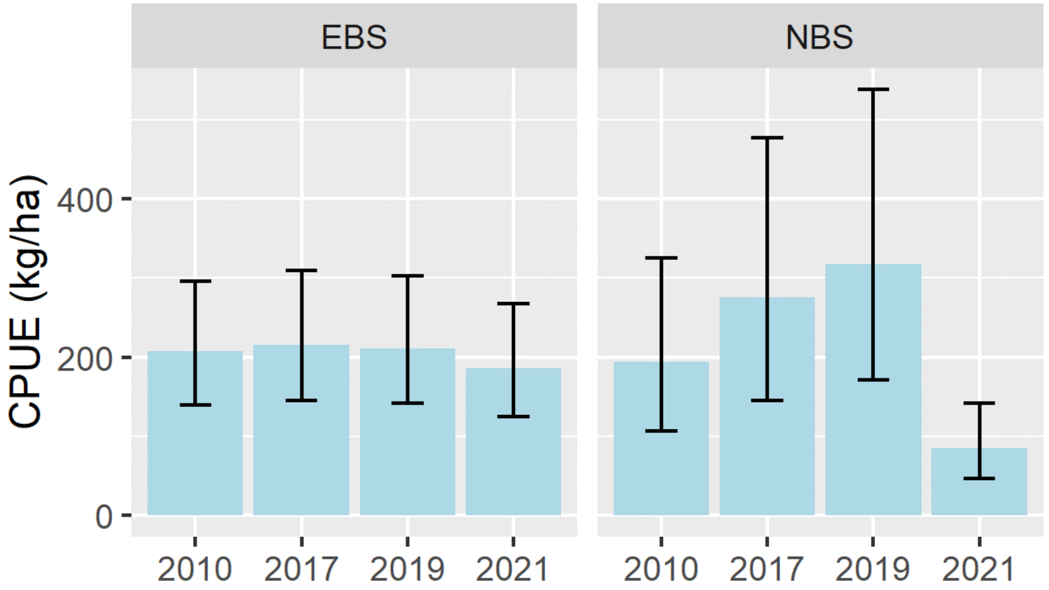

Figure 95: Mean CPUE of all macrofauna (fish and invertebrates) sampled during bottom trawl surveys in 2010, 2017, 2019, and 2021 with 95% confidence intervals. Estimates by region and year, adjusted for day of sampling, based on an additive model with spatially auto-correlated errors (exponential correlation structure).

into shallower (e.g., red king crab) or deeper (e.g., Arrowtooth flounder) waters, or changes in vertical distribution of semi-demersal species. The large decrease in the EBS in 2018 was primarily due to a decrease in the CPUE of pollock, as well as that of Pacific cod (*G. macrocephalus*) and most flatfish species, except Arrowtooth flounder. The subsequent increase in 2019 and decrease in 2021 were primarily due to changes in pollock catches, whereas the CPUE of other dominant species remained stable. In contrast, the drop in total CPUE in the NBS between 2019 and 2021 was much more pronounced (Figure 95) and reflected large decreases in all of the dominant species, including pollock, yellowfin sole, Alaska plaice, Pacific cod, snow crab, and skates. Of the 37 major taxa examined here, 28 decreased from 2019 to 2021 (Figure 96)

Implications: This indicator can help address concerns about maintaining adequate prey for upper trophic level species and other ecosystem components. Relatively stable or increasing trends in the total biomass of demersal fish and invertebrates suggest that the prey base has remained stable over recent decades, but displays substantial fluctuations over time, largely as a result of variability in pollock biomass.

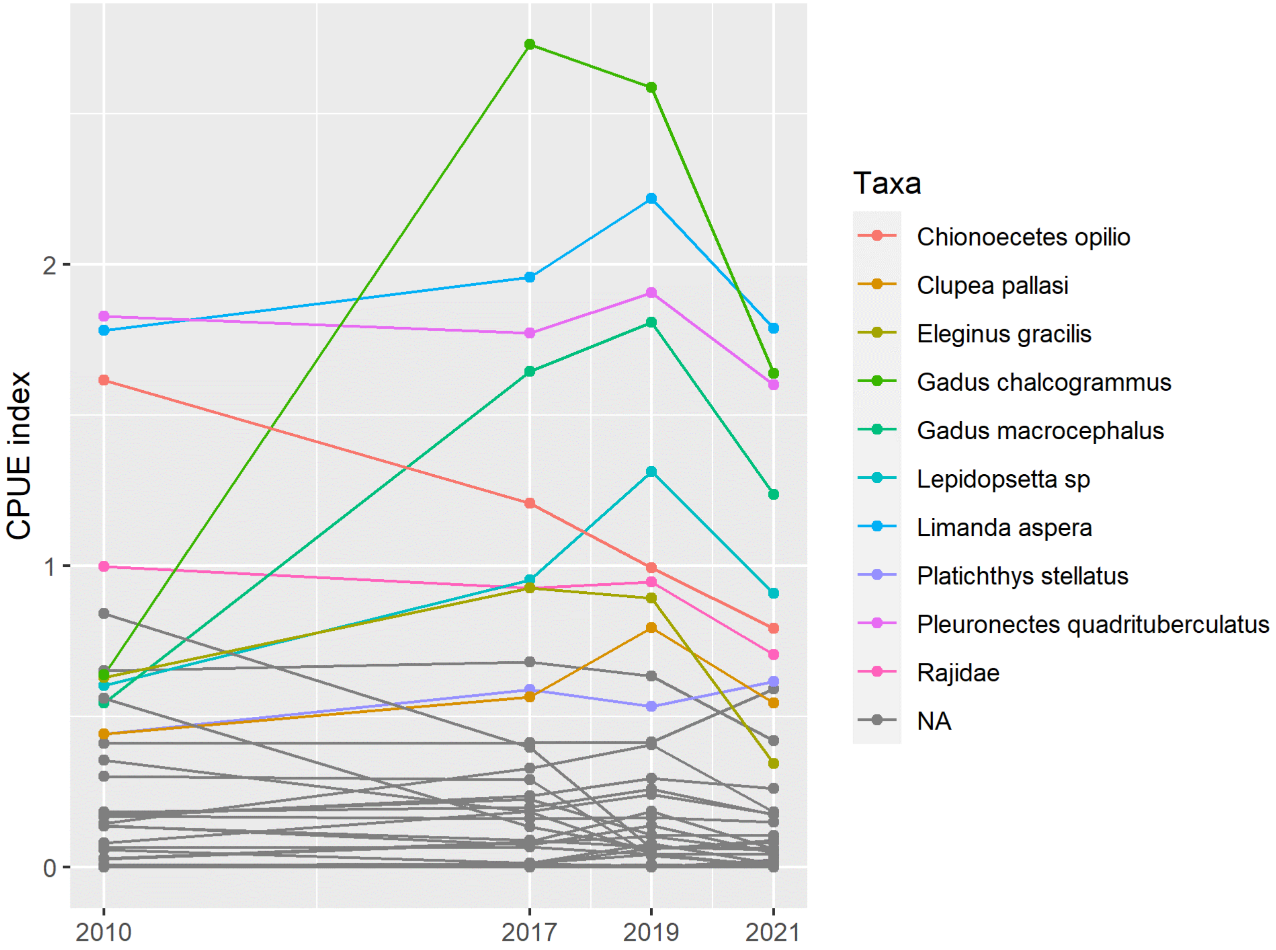

Figure 96: Changes in mean, fourth-root transformed CPUE of 41 major taxa in the northern Bering Sea based on surveys conducted in 2010, 2017, 2019, and 2021. 'NA' denotes all other taxa. A total of 28 taxa decreased between 2019 and 2021, with only 9 taxa increasing.

Average Local Species Richness and Diversity of the Eastern Bering Sea and Northern Bering Sea Groundfish Community

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Last updated: October 2021

Description of indicator: Indices of local species richness and diversity are based on standard bottom trawl surveys in the eastern Bering Sea (EBS) and northern Bering Sea (NBS). We computed the average number of fish and major invertebrate taxa per haul (richness) and the average Shannon index of diversity (Magurran, 1988) by haul based on CPUE (by weight) of each taxon. Indices for the EBS were based on 45 fish and invertebrate taxa that were consistently identified throughout all surveys since 1982 (Table 1 in Mueter and Litzow (2008), excluding Arctic cod *Boreogadus saida* because of unreliable identification in early years). Annual average indices of local richness and diversity were estimated by first computing each index on a per-haul basis, then estimating annual averages with confidence intervals across the survey area using an Additive Model that accounted for the effects of variability in sampling locations (latitude/longitude), depth, and date of sampling. In addition to trends over time, we mapped average spatial patterns for each index across the eastern Bering Sea survey region.

Status and trends: Species richness and diversity on the EBS shelf have undergone significant variations from 1982 to 2021 (Figure 97). The average number of species per haul increased by one to two species per haul from 1995 to 2004, remained relatively high through 2011 and both richness and diversity decreased through 2014, followed by a return to relatively high levels through 2021, with an unusually high Shannon diversity observed in 2018. Richness tends to be highest along the 100 m isobath, while diversity tends to be highest on the middle shelf (Figure 98). Local richness is lowest along the slope and in the northern part of the survey region, while diversity is lowest in the inner domain. Local richness was lower by 2–3 species on average in the NBS and varied little among the four survey years, whereas local Shannon diversity increased between 2010 and the most recent years (Figure 99).

Factors influencing observed trends: Local richness and diversity reflect changes in the spatial distribution, abundance, and species composition that may be caused by fishing, environmental variability, or climate change. If species are, on average, more widely distributed in the sampling area, the number of species per haul increases. Spatial shifts in distribution from year to year can cause high variability in local species richness in certain areas, for example along the 100m contour. These shifts appear to be the primary drivers of changes in species richness over time. Local species diversity is a function both of how many species are caught in a haul and how evenly CPUE is distributed among these species, hence time trends (Figures 97 and 99) and spatial patterns (Figure 98) in species diversity differ from those in species richness.

Implications: There is evidence from many systems that diversity is associated with ecosystem stability, which depends on differential responses to environmental variability by different species or functional groups (e.g., McCann (2000)). To our knowledge, such a link has not been established for marine fish communities. In the EBS, local species richness may be particularly sensitive to long-

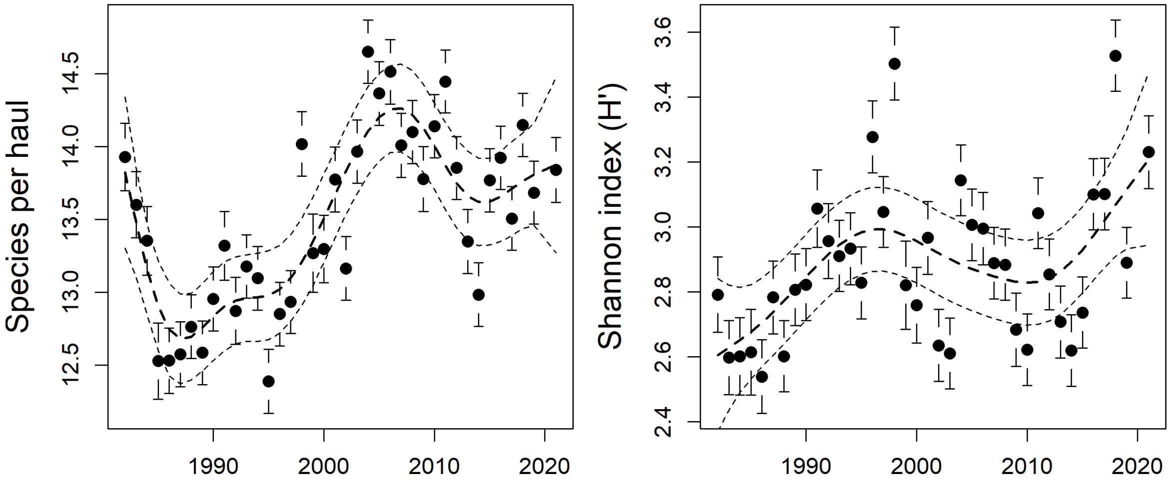

Figure 97: Model-based annual averages of local species richness (left, average number of species per haul), and species diversity (Shannon index, right) in the eastern Bering Sea, 1982–2021, based on 45 fish and invertebrate taxa collected by standard bottom trawl surveys with pointwise 95% confidence intervals (bars) and loess smoother with 95% confidence band (dashed/dotted lines). Model means were adjusted for differences in depth, date of sampling, and geographic location.

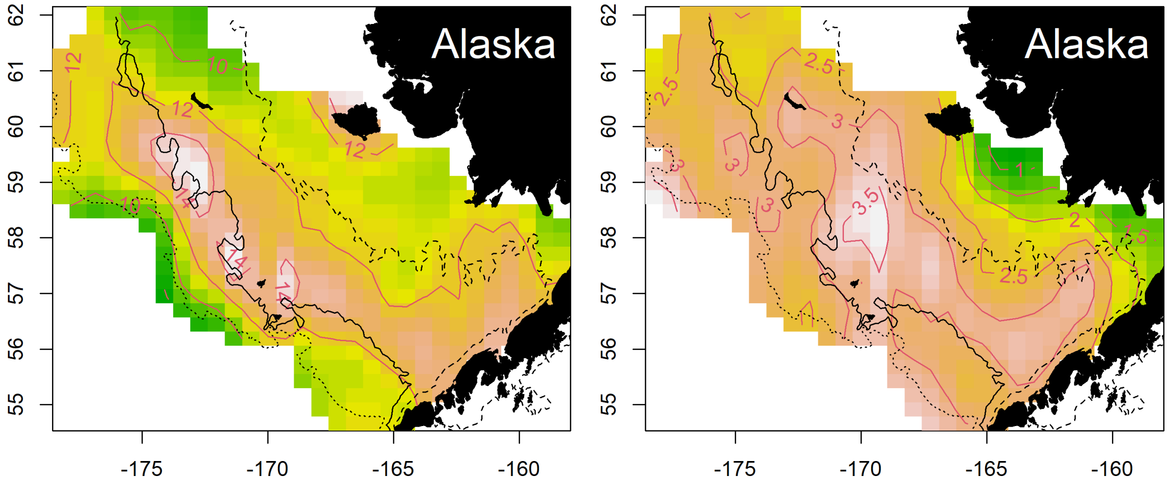

Figure 98: Average spatial patterns in local species richness (left, number of taxa per haul) and Shannon diversity in the eastern Bering Sea. The 50m (dashed), 100m (solid), and 200 m (dotted) depth contours are shown. Note highest richness along 100 m contour, highest diversity on middle shelf.

term trends in bottom temperature as the cold pool extent changes (Mueter and Litzow, 2008) and provides a useful index for monitoring responses of the groundfish community to projected climate warming (Alabia et al., 2020).

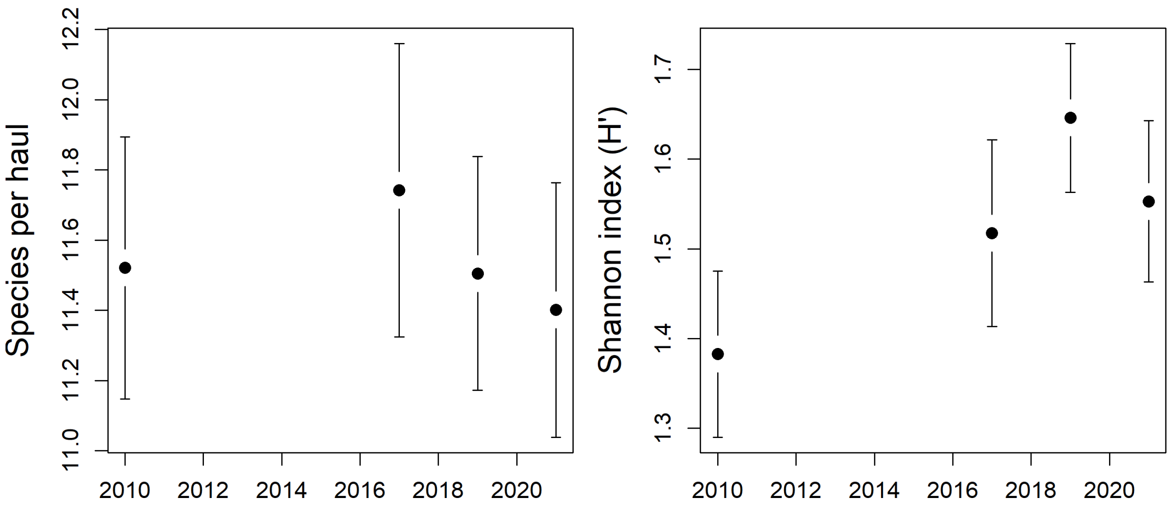

Figure 99: Model-based annual averages of local species richness (left, average number of species per haul), and species diversity (Shannon index, right) in the northern Bering Sea (2010, 2017, 2018, 2019) based on 45 fish and invertebrate taxa collected by standard bottom trawl surveys with pointwise 95% confidence intervals. Model means were adjusted for differences in depth, date of sampling, and geographic location.

Spatial Distribution of Groundfish Stocks in the Bering Sea

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Last updated: October 2021

Description of indicator: We provide indices of changes in the spatial distribution of groundfish on the eastern Bering Sea (EBS) shelf. The first index provides a simple measure of the average North-South displacement of major fish and invertebrate taxa from their respective centers of gravity (e.g., Woillez et al. (2009)) based on AFSC-RACE EBS bottom trawl surveys for the 1982–2021 period. Annual centers of gravity for each taxon were computed as the CPUE-weighted mean latitude across 285 standard survey stations that were sampled each year and an additional 58 stations sampled in all but one survey year. Each station (N=343) was also weighted by the approximate area that it represents. Initially, we selected 46 taxa as in Table 1 of Mueter and Litzow (2008). Taxa that were not caught at any of the selected stations in one or more years were not included, resulting in a total of 39 taxa for analysis. In addition to quantifying N-S shifts in distribution, we computed CPUE and area-weighted averages of depth to quantify changes in depth distribution. Because much of the variability in distribution is likely to be related to temperature variability, we removed linear relationships between changes in distribution and temperature by regressing distributional shifts on annual mean bottom temperatures. Residuals from these regressions are provided as an index of temperature-adjusted shifts in distribution.

Status and trends: Both the latitudinal and depth distribution of the demersal community on the EBS shelf show strong directional trends over the last four decades, indicating significant distributional shifts to the north and into shallower waters (Figure 100). The distribution shifted slightly to the south and deeper in recent cold years (2006–2013) and shifted back to the north and shallower from 2014 to 2019 with a substantial shift to the northwest in 2016. The distribution shifted slightly south in 2017, but remained near its northern maximum through 2019. Between 2019 and 2021, the mean distribution across species shifted back to the southeast. Strong shifts in distribution remain evident even after adjusting for linear temperature effects (Figure 100). The center of gravity of most individual species shifted to the northwest along the shelf or to the northeast onto the shelf in 2016, the warmest year in the survey time series (Figure 101). Cooler temperatures in 2017 appeared to result in an immediate and substantial southeastward shift, in contrast to a more moderate response to similar cooling in 2006. Following the return to higher bottom temperatures in 2018 and 2019, the overall center of gravity shifted slightly to the northwest, but in 2021 shifted back to the southeast. However, northern Bering Sea (NBS) surveys since 2017 suggest that much of the biomass of fishes in some recent years occurred in the NBS. The latitudinal gradient in overall density of all major fish and invertebrate taxa combined declined from south to north in 2010 but increased from south to north in 2021, with much higher estimated densities near Bering Strait than off the Alaska Peninsula (Figure 102). This trend reversed again in 2021, with mean densities near Bering Strait declining from ∼300 kg/ha in 2019 to <100 kg/ha in 2021. These patterns were primarily driven by changes in the distribution of pollock and Pacific cod (Figure 102, see also Stevenson and Lauth (2012); Thorson et al. (2020)).

Factors influencing observed trends: Many populations shift their distribution in response to temperature variability. Such shifts may be the most obvious response of animal populations to global warming (Parmesan and Yohe, 2003). However, distributional shifts of demersal populations in the Bering Sea are not a simple linear response to temperature variability (Mueter and Litzow (2008); Figure 100). The reasons for strong residual shifts in distribution that are not related to temperature changes remain unclear but could be related to density-dependent responses (Spencer, 2008) in combination with internal community dynamics (Mueter and Litzow, 2008). Unlike groundfish in the North Sea, which shift to deeper waters in response to warming (Dulvy et al., 2008), the Bering Sea groundfish community shifted to shallower waters during warm periods (Figure 100) because of the retreat of the cold pool from the middle shelf that allows subarctic species to expand from the outer shelf into shallower regions.

Implications: Changes in distribution have important implications for the entire demersal community, other populations dependent on these communities, the fishing industry, and for stock assessments. The demersal community is affected because distributional shifts change the relative spatial overlap of different species, thereby affecting trophic interactions (Hunsicker et al., 2013; Spencer et al., 2016) and, ultimately, the relative abundances of different species. Upper trophic level predators, for example fur seals and seabirds, are affected because the distribution and hence availability of their prey changes. Fisheries are directly affected by changes in the distribution of commercial species, which alters the economics of harvesting because fishing success within established fishing grounds may decline and travel distances to new fishing grounds may increase (Haynie and Pfeiffer, 2013). Finally, stock assessments are affected by shifts outside the standard survey area, such as the substantial redistribution of Pacific cod into the NBS in 2018 and the apparent redistribution of much of the overall biomass in the Bering Sea to the NBS shelf in 2019. This was followed in 2021 by substantial declines in mean density at most latitudes with the largest overall declines in the NBS (Figure 102).

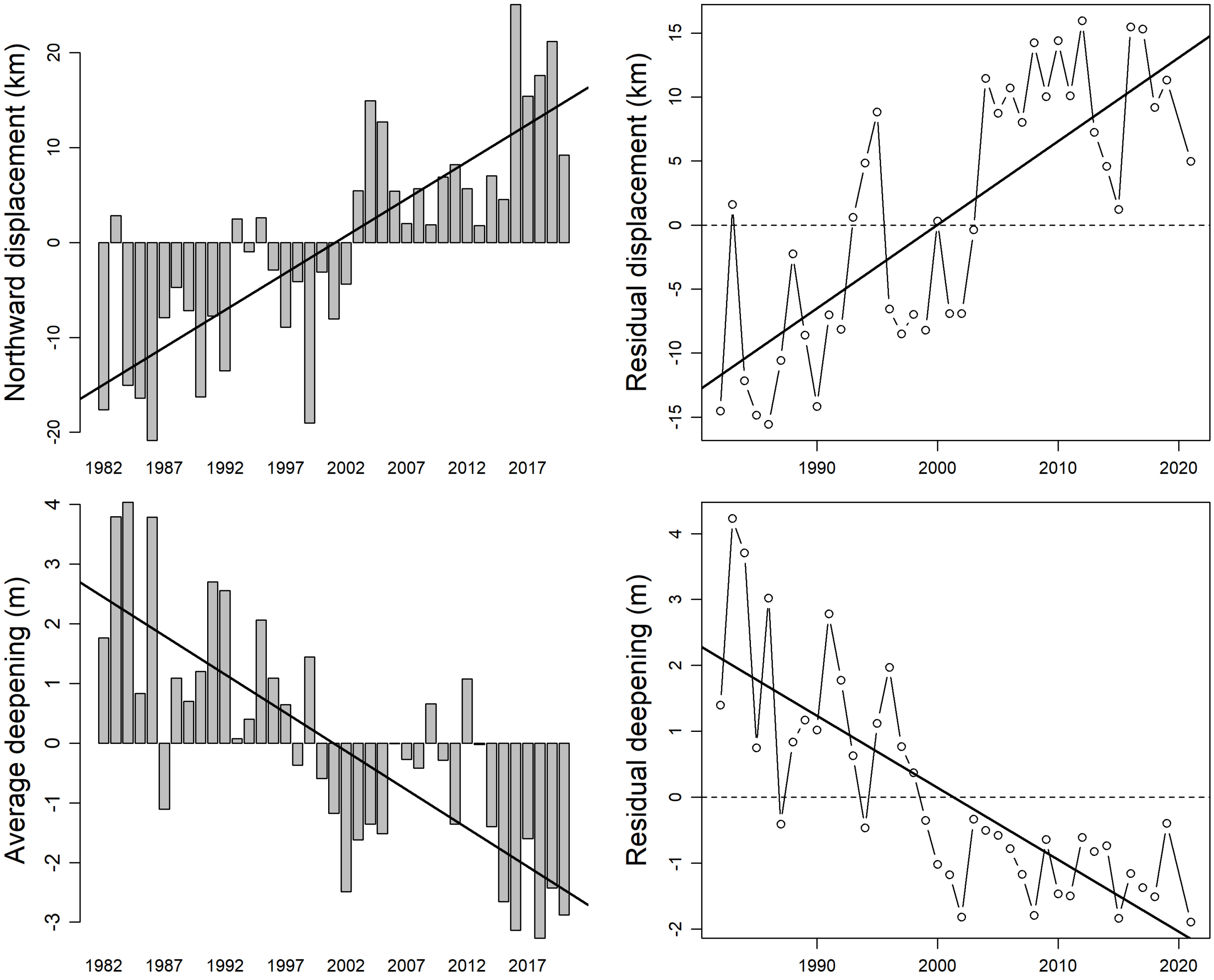

Figure 100: Left: Distributional shifts in latitude (average northward displacement in km from species-specific mean latitudes) and shifts in depth distribution (average vertical displacement in m from species-specific mean depth, positive indices indicate deeper distribution). Right: Residual displacement from species-specific mean latitude (top) and species-specific mean depth (bottom) after adjusting the indices on the left for linear effects of mean annual bottom temperature on distribution. Residuals were obtained by linear regression of the displacement indices on annual average temperature (Northward displacement: $R^2=0.22$, $t=4.74$, $p<0.001$; Deepening: $R^2=0.26$, $t=-4.89$, $p<0.001$). Solid trend lines denote linear regressions over time (Northward displacement: $R^2=0.62$, $t=6.31$, $p<0.001$; Residual northward displacement: $R^2=0.56$, $t=4.64$, $p<0.001$; Deepening: $R^2=0.87$, $t=-5.94$, $p<0.001$; residual deepening: $R^2=0.63$, $t=-7.87$, $p<0.001$).

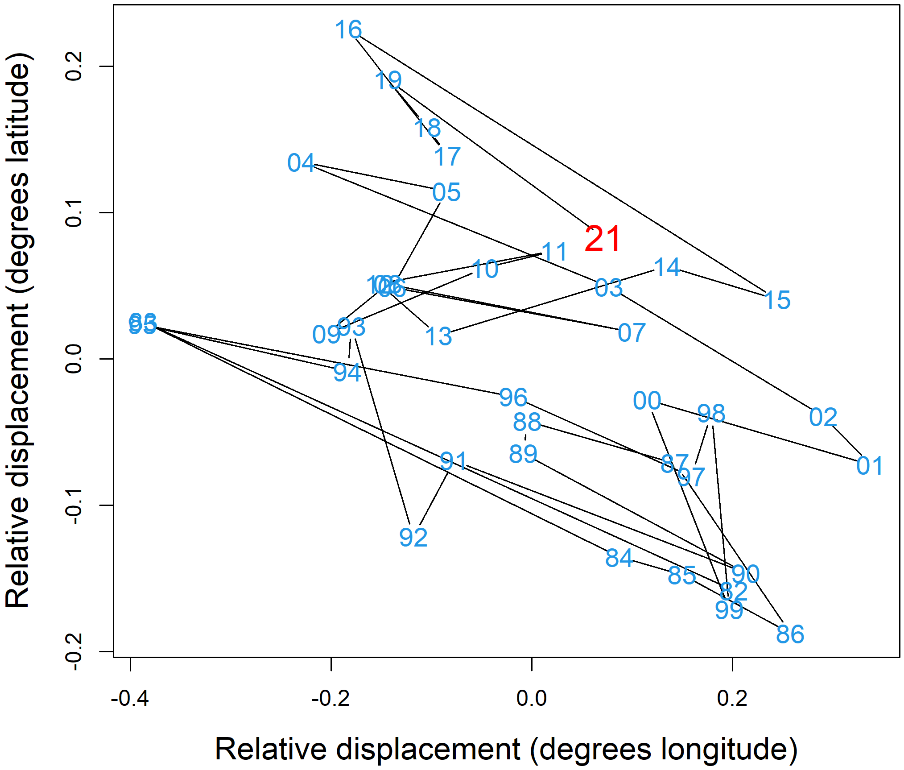

Figure 101: Average North-South and East-West displacement across 39 taxa on the eastern Bering Sea shelf relative to species-specific centers of distribution.

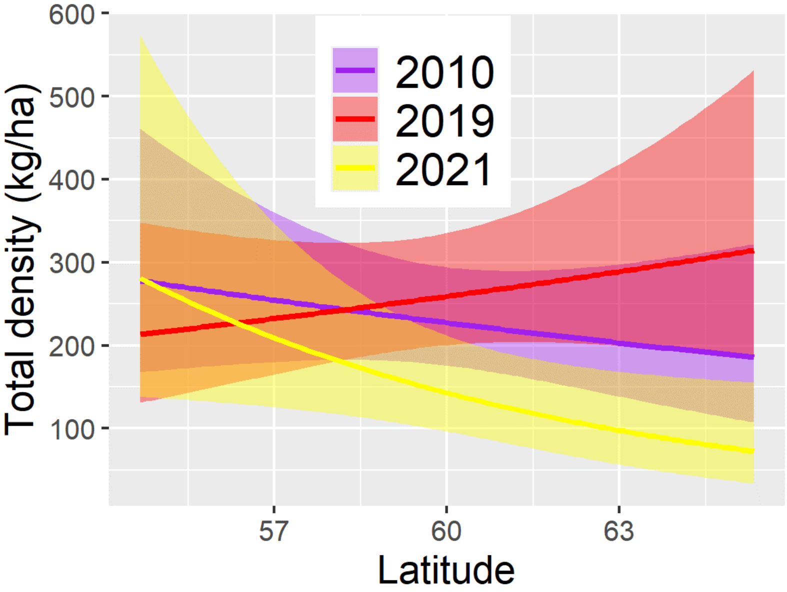

Figure 102: Estimated latitudinal trends in average macrofaunal density for all fish and invertebrate taxa combined from the Alaska Peninsula in the south to the Bering Strait in the North. Estimates are based on generalized additive models of log(catch-per-unit-effort) as a function of latitude and depth by year with an exponential spatial autocorrelation structure.

Mean Lifespan of the Fish Community

Contributed by George A. Whitehouse[1] and Geoffrey M. Lang[2]
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Description of indicator: The mean lifespan of the community is a proxy for the turnover rate of species and communities and reflects the resistance of the community to perturbations (Shin et al., 2010). The indicator for mean lifespan of the groundfish community is modeled after the method for mean lifespan presented in Shin et al. (2010). Lifespan estimates of groundfish species regularly encountered during the NMFS/AFSC annual summer bottom-trawl survey of the eastern Bering Sea were retrieved from the AFSC Life History Database[14]. The groundfish community mean lifespan is weighted by biomass indices calculated from the bottom-trawl survey catch data.

This indicator specifically applies to the portion of the demersal groundfish community that is efficiently sampled by the trawling gear used by NMFS during this survey at the standard survey sample stations (for survey details see Conner and Lauth (2016)). Species that are infrequently encountered or not efficiently caught by the bottom-trawling gear are excluded from this indicator (e.g., sharks, grenadiers, myctophids, pelagic smelts). The survey index used here is the same as that used for fish and invertebrate biomass indices on the report card (Figure 1).

Walleye pollock is a biomass dominant species in the eastern Bering Sea and may drive the value of community indicators. Therefore this indicator is presented as two time series, one that includes and one that excludes walleye pollock.

Status and trends:
With pollock included: The mean lifespan of the eastern Bering Sea demersal fish community in 2021 is 30.54 years and is the second highest over the time series (Figure 103, black circles), just up from 30.53 years in 2019. Mean groundfish lifespan has generally been stable over the time series with only a small amount of year-to-year variation, and shows no indication of a long-term trend.

Without pollock included: The mean lifespan of the eastern Bering Sea groundfish community without pollock in 2021 is 30.3 years (Figure 103, gray triangles). Over the times series, the patterns and trends are similar between the two series with the values being slightly lower for the series without pollock. The exception to this pattern was 1985 when the mean lifespan was 32.0 with pollock included and 32.9 without pollock.

Factors influencing observed trends: Fishing can affect the mean lifespan of the groundfish community by preferentially targeting larger, older fishes, leading to decreased abundance of longer-lived species and increased abundance of shorter-lived species (Pauly et al., 1998). Interannual variation in mean lifespan can be influenced by the spatial distribution of species and the differential selectivity of species and age classes to the trawling gear used in the survey. Strong recruitment events or periods of week recruitment could also influence the mean community lifespan by altering

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[14] `https://access.afsc.noaa.gov/reem/LHWeb/Index.php`

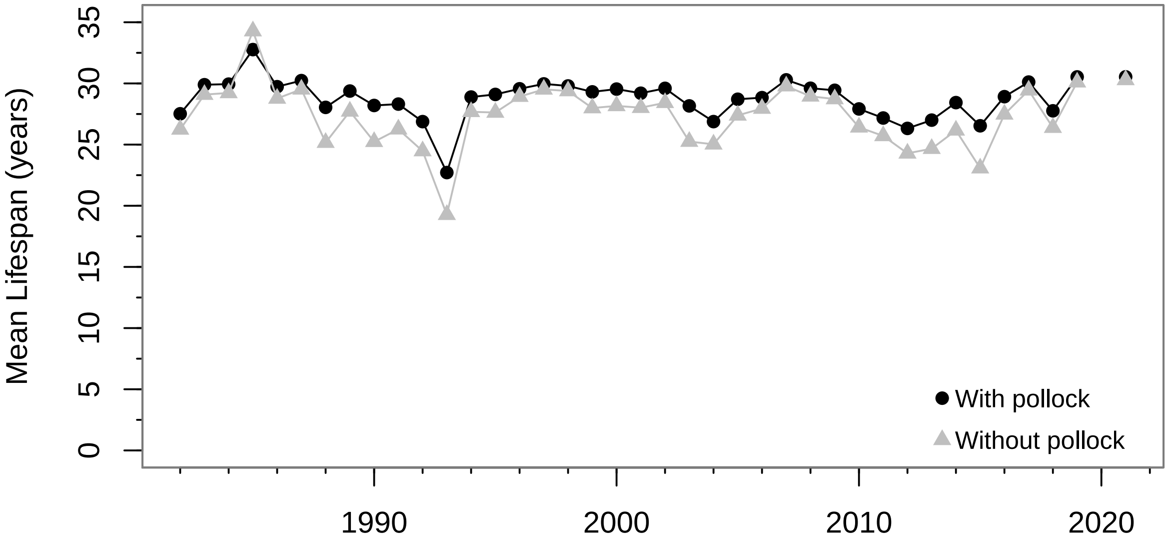

Figure 103: The mean lifespan of the eastern Bering Sea demersal fish community, weighted by biomass indices calculated from the NMFS/AFSC annual summer bottom-trawl survey. The black circles are the series with pollock included and the gray triangles are the series without pollock included.

the relative abundance of age classes and species. For example, the low value observed in 1993 reflects a year of peak biomass index for capelin, a shorter-lived species. The peak mean lifespan for both series in 1985 was in part elevated by high biomass indices for long-lived species, such as sablefish. The lifespan of pollock is slightly higher than the mean groundfish lifespan without pollock. When pollock are removed from this indicator, there is a small decrease in value but the same overall trend is followed.

Implications: The groundfish mean lifespan has been stable over the time series of the summer bottom-trawl survey. There is no indication longer-lived species have decreased in relative abundance or are otherwise being replaced by shorter lived-species. Species that are short-lived are generally smaller and more sensitive to environmental variation than larger, longer-lived species (Winemiller, 2005). Longer-lived species help to dampen the effects of environmental variability, allowing populations to persist through periods of unfavorable conditions and to take advantage when favorable conditions return (Berkeley et al., 2004; Hsieh et al., 2006).

Mean Length of the Fish Community

Contributed by George A. Whitehouse[1] and Geoffrey M. Lang[2]
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Last updated: October 2021

Description of indicator: The mean length of the groundfish community tracks fluctuations in the size of groundfish over time. This size-based indicator is thought to be sensitive to the effects of commercial fisheries because larger predatory fish are often targeted by fisheries and their selective removal would reduce mean size (Shin et al., 2005). This indicator is also sensitive to shifting community composition of species with different mean sizes. Fish lengths are routinely recorded during the NMFS bottom trawl survey of the eastern Bering Sea, which has occurred each year from 1982 to 2021, except in 2020. Mean lengths are calculated for groundfish species (or functional groups of multiple species; e.g., eelpouts) from the length measurements collected during the trawl survey. The mean length for the groundfish community is calculated with the species mean lengths, weighted by biomass indices (Shin et al., 2010) calculated from the bottom-trawl survey catch data.

This indicator specifically applies to the portion of the demersal groundfish community that is efficiently sampled with the trawling gear used by NMFS during the summer bottom-trawl survey of the EBS at the standard survey sample stations (for survey details see Conner and Lauth (2016)). Species that are infrequently encountered or not efficiently caught by the bottom-trawling gear are excluded from this indicator (e.g., sharks, grenadiers, myctophids, pelagic smelts). The survey index used here is the same as that used for fish and invertebrate biomass indices on the report card (Figure 1).

Species (or functional groups) infrequently sampled for lengths (less than five times over the time series) are excluded from this indicator (e.g., capelin, eulachon, greenlings). Twenty-two species are included in this indicator. Eleven species had their lengths sampled in all 39 years of the time series. Another eleven species were sampled between 11 and 36 times over the time series. In those years where lengths were not sampled for a species, we replaced it with a long-term mean for that species.

Walleye pollock is a biomass dominant species in the eastern Bering Sea and may drive the value of community indicators. Therefore this indicator is presented as two time series, one that includes and one that excludes walleye pollock.

Status and trends:
With pollock included: The mean length of the eastern Bering Sea groundfish community in 2021 is 35.7 cm, down from a peak value of 38.3 cm in 2018, but still above the long term mean of 32.4 cm (Figure 104, black circles). The mean length trended upward from 2012 to 2018 and has decreased each survey year since. The status in 2020 is unknown.

Without pollock included: The mean length of eastern Bering Sea groundfish without pollock is 34.5 cm in 2021, down from a peak value of 38.3 cm in 2018 (Figure 104, gray triangles). This series trended upward from 2012 to 2018, but has declined in 2019 and 2021 although it remains above the long term mean of 29.4 cm.

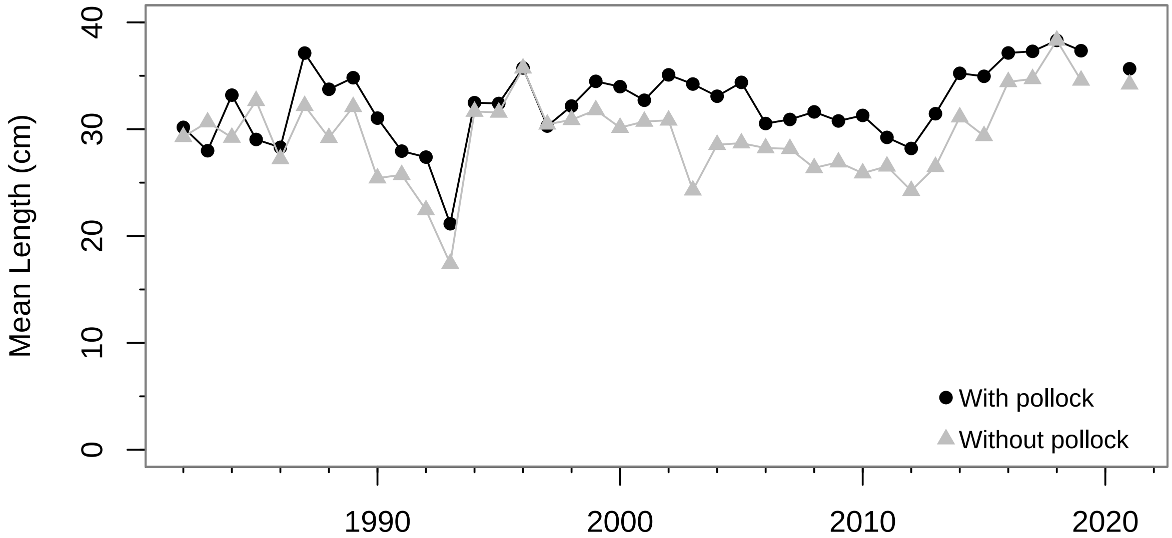

Figure 104: Mean length of the groundfish community sampled during the NMFS/AFSC annual summer bottom-trawl survey of the eastern Bering Sea (1982–2021). The groundfish community mean length is weighted by the relative biomass of the sampled species. The black circles are the mean length with pollock included and the gray triangles are the series without pollock.

Factors influencing observed trends: This indicator is specific to the fishes that are routinely caught and sampled during the NMFS summer bottom-trawl survey. The estimated mean length can be biased if specific species-size classes are sampled more or less than others, and is sensitive to spatial variation in the size distribution of species. Changes in fisheries management or fishing effort could also affect the mean length of the groundfish community. Modifications to fishing gear, fishing effort, and targeted species could affect the mean length of the groundfish community if different size classes and species are subject to changing levels of fishing mortality. The mean length of groundfish could also be influenced by fluctuations in recruitment, where a large cohort of small forage species could reduce mean length of the community. Environmental factors could also influence fish growth and mean length by effecting the availability and quality of food or by direct temperature effects on growth rate.

Walleye pollock is a biomass dominant component of this ecosystem and year-to-year fluctuations in their mean size and biomass have a noticeable effect on this indicator. In 1993, their biomass index was above average but their mean size was the fifth lowest of the time series. Additionally, 1993 was a pronounced peak in the biomass index of capelin. This reduced the proportional contribution of other species to the total groundfish biomass index, thus reducing the indicator value (i.e., mean length) in 1993. Years where this indicator attained its highest values (1987, 2016–2019) generally correspond to years of above average mean size and/or biomass index for pollock, except 2018 where pollock mean size was average but their biomass index was below average.

The series without pollock mirrored the overall trends in the series with pollock included, but was generally lower. This was because the mean length of pollock was generally a few cm greater than the mean length of the rest of the groundfish community. Exceptions occurred in 1983, 1985, and 2018 when the mean length of pollock was less than the mean of the rest of the groundfish community. In these three instances, the indicator value was higher for the series without pollock.

Implications: The mean length of the groundfish community in the eastern Bering Sea has been stable over the bottom-trawl time series (1982–2021) with some interannual variation. The collective stability of the combined biomass of relatively larger groundfish species has helped to maintain this indicator at its recent high values. Previous dips in this indicator were in part attributable to spikes in abundance of smaller forage species (e.g., capelin) as opposed to a sustained shift in community composition or reductions in species mean length.

Stability of Groundfish Biomass

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Last updated: October 2021

Description of indicator: The stability of the groundfish community total biomass is measured with the inverse biomass coefficient of variation (1 divided by the coefficient of variation of total groundfish biomass (1/CV[B])). This indicator provides a measure of the stability of the ecosystem and its resistance to perturbations. The variability of total community biomass is thought to be sensitive to fishing and is expected to increase with increasing fishing pressure (Blanchard and Boucher, 2001). This metric is calculated following the methods presented in Shin et al. (2010). The CV is the standard deviation of the groundfish biomass index over the previous 10 years divided by the mean over the same time span. The biomass index for groundfish species was calculated from the catch of the NMFS/AFSC annual summer bottom-trawl survey of the eastern Bering Sea (EBS). Since 10 years of data are required to calculate this metric, the indicator values start in 1991, the tenth year in the trawl survey time series (1982–2021). This metric is presented as an inverse, so as the CV increases the value of this indicator decreases, and if the CV decreases the value of this indicator increases.

This indicator specifically applies to the portion of the demersal groundfish community that is efficiently sampled by the trawling gear used by NMFS during the annual summer survey at the standard survey sample stations (for survey details see Conner and Lauth (2016)). Species that are infrequently encountered or not efficiently caught by the bottom-trawling gear are excluded from this indicator (e.g., sharks, grenadiers, myctophids, pelagic smelts). The survey index used here is the same as that used for fish and invertebrate biomass indices on the report card (Figure 1).

Walleye pollock is a biomass dominant species in the eastern Bering Sea and may drive the value of this community indicator. Therefore this indicator is presented as two time series, one that includes and one that excludes pollock.

Status and trends:
With pollock included: The state of this indicator in 2021 is 6.18, which is down from the series high of 8.54 in 2019 (Figure 105, black circles). The previous high of 7.90 was observed in 1992,

which was followed by a steady decrease to a low of 3.84 in 2002. Since then it gradually increased to a value of 5.84 in 2018 before sharply increasing to its new high in 2019. The status in 2020 is unknown. This indicator is currently above the long term mean of 5.2.

Without pollock included: This indicator has dropped to 7.05 in 2021 from a high value of 9.78 in 2019 (Figure 105, gray triangles). This indicator dropped sharply from 7.49 in 1992 to 3.41 in 1993, and remained below four until 2003, where the value increased to 5.44. The indicator value remained relatively stable until 2010, when the indicator began a steady upward trend to the series high value in 2019.

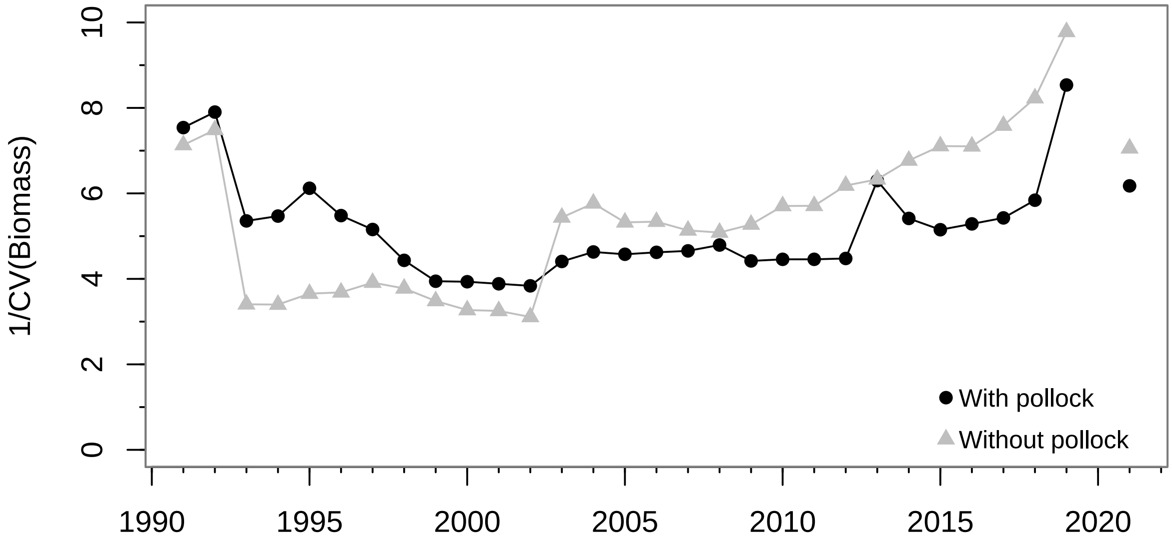

Figure 105: The stability of groundfish in the eastern Bering Sea represented with the inverse biomass coefficient of variation of total groundfish biomass (1/CV[B]). Ten years of data are required to calculate this metric, so this time series begins in 1991 after the tenth year of the NMFS/AFSC annual summer bottom-trawl survey. The black circles are the series with pollock included in the index, and the gray triangles are the same series but with pollock excluded.

Factors influencing observed trends: Fishing is expected to influence this metric as fisheries can selectively target and remove larger, long-lived species affecting population age structure (Berkeley et al., 2004; Hsieh et al., 2006). Larger, longer-lived species can become less abundant and be replaced by smaller shorter-lived species (Pauly et al., 1998). Larger, longer-lived individuals help populations to endure prolonged periods of unfavorable environmental conditions and can take advantage of favorable conditions when they return (Berkeley et al., 2004). A truncated age-structure could lead to higher population variability (CV) due to increased sensitivity to environmental dynamics (Hsieh et al., 2006). Interannual variation in this metric could also be influenced by interannual variation in species abundance in the trawl survey catch, patchy spatial distribution for some species, or species distribution shifts (Stevenson and Lauth, 2019; Thorson, 2019). This metric, as calculated here with trawl-survey data, reflects the stability of the portion of the groundfish community that is represented in the catch data of the annual summer bottom-trawl survey. Both sharp increases or decreases in species index values can increase variability and reduce the indicator value.

The high values for this indicator in 2019 and at the start of the time series are indicative of stable groundfish biomass with a relatively low CV during the previous ten years. The CVs for both time series in 2019 were the lowest over their respective time series resulting in their highest indicator values. The sharp drop in total biomass in 2021, particularly for pollock, increased the CV resulting in lower indicator values in 2021. Previously, both series (with and without pollock) dropped sharply from 1992 to 1993. This was because the index for capelin in 1993 was anomalously high which increased variability and reduced the indicator value. In 2003, both series increased, which was in part due to the high capelin value in 1993 no longer being a part of the most recent 10 years.

In 2009, the series without pollock began a steady increase towards its high value in 2019. The series with pollock included has a more modest positive trend over the same span, with high values in 2013 and 2019. Pollock is a biomass dominant species in the eastern Bering Sea and interannual fluctuations in their biomass are sufficient to increase variability for the total groundfish community and thus, reduce the indicator value. The series without pollock is more sensitive to fluctuations of other species, such as capelin. The sharp increase in the capelin index in 1993 kept this series lower than the series with pollock included from 1993–2002.

Implications: The measure 1/CV[B] indicates that the eastern Bering Sea groundfish community has been generally stable over the time period examined here. While the drop in biomass from 2019 to 2021 has reduced both indicators, with and without pollock, both remain above long term mean levels.

Emerging Stressors

Ocean Acidification

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Last updated: October 2021

Description of indicator: The oceanic uptake of anthropogenic CO_2 is decreasing ocean pH and carbonate saturation states in a process known as ocean acidification (OA). The cold, carbon rich waters of the Bering Sea are already naturally more corrosive than other regions of the global ocean, making this region more vulnerable to rapid changes in ocean chemistry. Ship-based sampling has already identified subsurface waters corrosive to aragonite (a soluble form of calcium carbonate used by many marine shell-building organisms), denoted by aragonite saturation states (Ω_{arag})<1 (Mathis et al., 2011). The projected areal expansion and shallowing of these waters with continued absorption of anthropogenic CO_2 from the atmosphere poses a direct threat to marine calcifiers and an indirect threat to other species through trophic interactions. These OA risks demonstrate a clear need to track and forecast the spatial extent of acidified waters in the Bering Sea.

Here, we present carbonate chemistry output from the Bering Sea ROMS model (Bering10K; Pilcher et al. (2019)), consisting of the current hindcast that runs from 2003 to August 15, 2021. We show spatial plots for Bering Sea bottom water conditions, including both the hindcast 2003–2020 average and the 2021 anomaly (Figure 106). We focus on bottom waters and the late summer timeframe because this is where we expect the most acidic waters to develop, due to seasonal biological respiration. This is also when temperatures are close to their highest and are thus most likely to have synergistic negative effect on crabs (Swiney et al., 2017). This model output is used to develop indices for both pH and the aragonite saturation state (Ω_{arag}) using threshold values of biological significance (Figure 107). Negative effects to the condition index and survival of red king and tanner crab have previously been found at pH<7.8 (Long et al., 2013), and $\Omega_{\text{arag}}<1$ represents when the dissolution of aragonite becomes favorable. The goal of this index time series, along with the spatial anomaly plot, is to provide a quick assessment of the summer water pH and Ω_{arag} conditions compared to previous years.

Status and trends: pH and Ω_{arag} in bottom waters for 2021 are near average for most of the inner and middle shelf, with some slightly more acidic areas in the southeastern shelf and some slightly less acidic waters in the northern Bering Sea near St. Lawrence Island (Figure 106). Notably, outer shelf waters are relatively more acidic (warmer colors) than average, particularly in bottom waters southwest of St. Matthew Island where pH conditions are 0.3–0.5 units lower than average. This continues a multi-year pattern of anomalously more acidic waters for the outer shelf domain that emerged in 2018, though the magnitude of this anomaly decreased this year for the southeastern

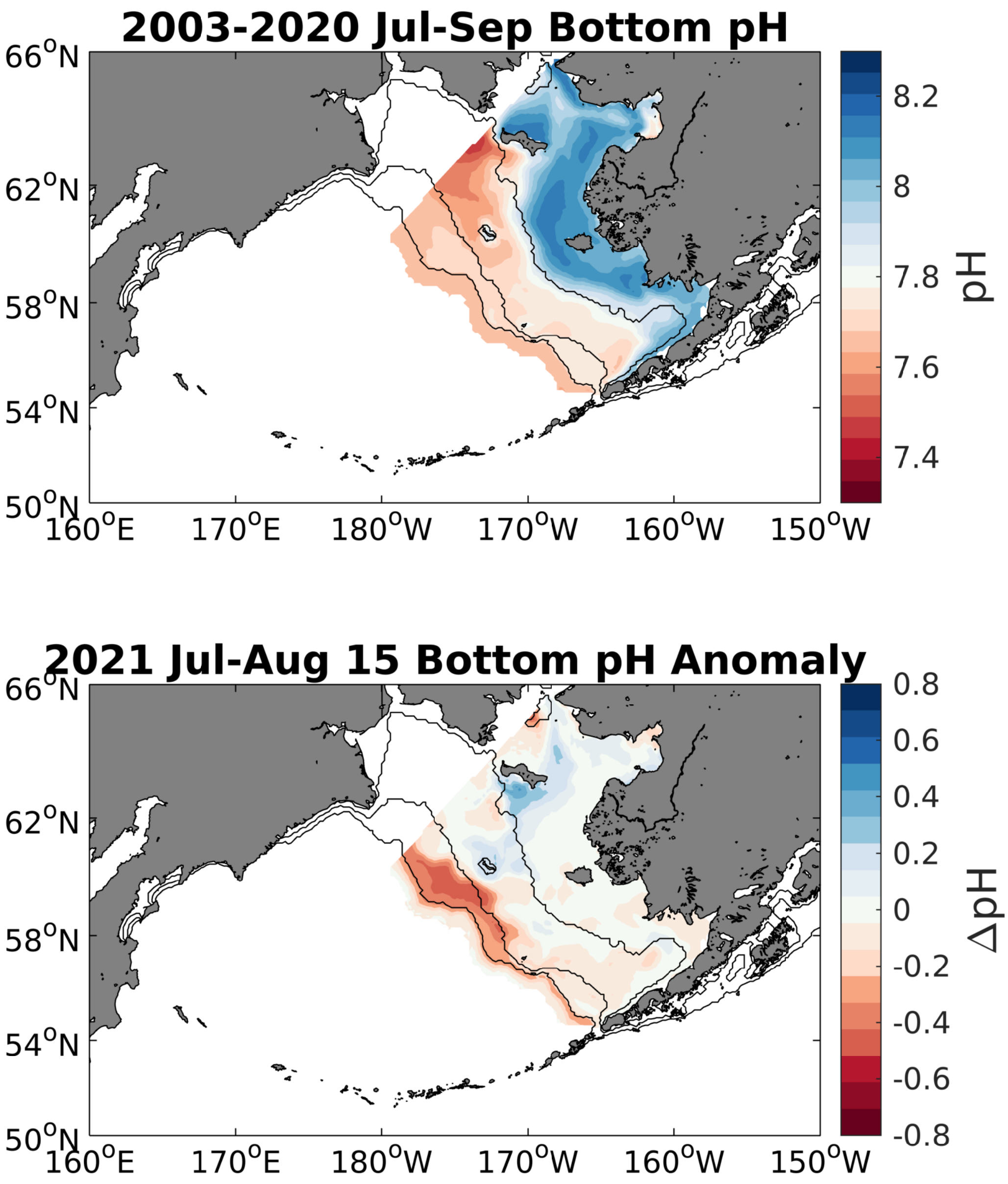

Figure 106: Model spatial maps of July–September averaged bottom water pH for the (top) 2003–2020 hindcast and (b) the 2021 nowcast (updated through August 15) anomaly compared to the 2003–2020 average. Contour lines denote the 50m, 100m, and 200m isobaths. Regions that are outside of the eastern Bering Sea management region are omitted.

outer shelf. Both index values suggest slightly less acidic conditions overall than 2020 and are near the 2003–2020 average.

Factors influencing observed trends: It is likely that the persistent region of lower pH located on the outer shelf is ultimately a result of changes in circulation and not ocean acidification. This water mass is also relatively high in salinity and nutrients, with relatively low dissolved oxygen concentrations. Analysis of the modeled water dissolved inorganic carbon and total alkalinity concentrations suggests that the source of this water is upwelling of deep water from the Bering Sea basin. This is consistent with the anomalously strong southerly winter winds in recent years, which have also greatly reduced sea ice extent (Stabeno and Bell, 2019).

Implications: Based on the sensitivity of red king crab to pH, previous work suggests that OA may have significant negative impacts to the red king crab fishery (Seung et al., 2015; Punt et al., 2016). However, these effects are not expected to emerge at present, as other environmental variables (e.g., temperature) are better predictors of red king crab movements. Modeled pH and Ω_{arag} water conditions in Bristol Bay for 2021 are near average and the shallower inner shelf waters that serve as habitat for juvenile red king crab are relatively well buffered. Although outer shelf bottom waters are substantially lower in pH in 2021 than the 2003–2020 mean, these waters are relatively more acidic at baseline. Furthermore, this region serves as habitat for snow crab populations, which may be more resilient to OA based on initial biological experiments (C. Long, unpublished data). At this time, there is no evidence that OA can be linked to recent declines in surveyed snow crab and red king crab populations.

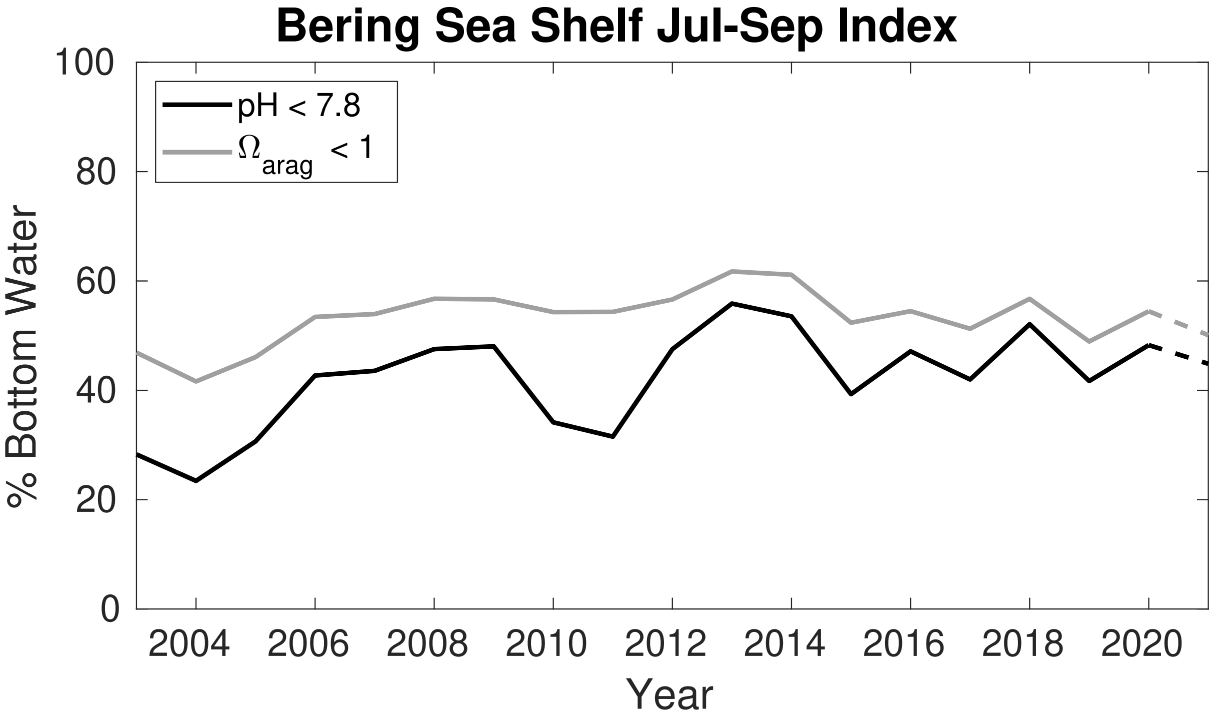

Figure 107: Model time series of the July–September (black line) pH index and (grey line) Ω_{arag} undersaturation index. Each index is calculated as the percent of spatial area of the Eastern Bering Sea region (Figure 106) where bottom waters have a July–September average below the denoted value. The dashed portion at the end represents the incomplete 2021 value, which is run up through August 15.

Harmful Algal Blooms

Contributed by Thomas Farrugia[1], Darcy Dugan[1], Kathi Lefebvre[2], Don Anderson[3], Evangeline Fachon[3], Natalie Rouse[4], and Emma Pate[5].

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[2] NOAA Northwest Fisheries Science Center, Seattle, WA
[3] Woods Hole Oceanographic Institution, Woods Hole, MA
[4] Alaska Veterinary Pathologist Services, Eagle River, AK
[5] Norton Sound Health Corporation, Nome, AK

Contact: farrugia@aoos.org
Last updated: September 2021

Sampling Partners:

Alaska Ocean Observing System
Alaska Veterinary Pathologists
Aleutian Pribilof Island Association
Central Council of Tlingit and Haida*
Chilkoot Indian Association*
Craig Tribal Association*
Hoonah Indian Association*
Hydaburg Cooperative Association*
Kachemak Bay NERR
Ketchikan Indian Association*
Klawock Cooperative Association*
Knik Tribe of Alaska
Kodiak Area Native Association
Metlakatla Indian Community*
NOAA Kasitsna Bay Lab
NOAA WRRN-West
North Slope Borough
Organized Village of Kake*
Organized Village of Kasaan*
Petersburg Indian Association*
Qawalangin Tribe of Unalaska
Sitka Tribe of Alaska*
Skagway Traditional Council*
Southeast Alaska Tribal Ocean Research
Sun'aq Tribe of Kodiak*
UAF-Alaska Sea Grant
USGS Alaska Science Center
Woods Hole Oceanographic Institution
Wrangell Cooperative Association*
Yakutat Tlingit Tribe*

**Partners of Southeast Alaska Tribal Ocean Research (SEATOR)*

Description of indicator: Alaska's most well-known and toxic harmful algal blooms (HABs) are caused by *Alexandrium* spp. and *Pseudo-nitzschia* spp. *Alexandrium* produces saxitoxin which can cause paralytic shellfish poisoning (PSP) and has been responsible for five deaths and over 100 cases of PSP in Alaska since 1993 (see DHSS fatality report[15]). Analyses of paralytic shellfish toxins are commonly reported as of toxin/100 g of tissue, where the FDA regulatory limit is 80/100g. Toxin levels between 80–1000/100 g are considered to potentially cause non-fatal symptoms, whereas levels above 1000/100g (∼ 12x regulatory limit) are considered potentially fatal.

Pseudo-nitzschia produces domoic acid which can cause amnesic shellfish poisoning and inflict

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[15] `http://www.dhss.alaska.gov/News/Documents/press/2020/DHSS_PressRelease_PSPFatality_20200715.pdf`

permanent brain damage. *Pseudo-nitzschia* has been detected in 13 marine mammal species and has the potential to impact the health of marine mammals and birds in Alaska. No human health impacts of domoic acid have been reported in Alaska.

The State of Alaska tests all commercial shellfish harvest, however there is no state-run shellfish testing program for recreational and subsistence shellfish harvest. Regional programs, run by Tribal, agency, and university entities, have expanded over the past five years to provide test results to inform harvesters and researchers and reduce human health risk (Figure 108). All of these entities are partners in the Alaska Harmful Algal Bloom Network which was formed in 2017 to provide a statewide approach to HAB awareness, research, monitoring, and response in Alaska. More information on methods can be found on the Alaska HAB Network website[16] or through the sampling partners listed above.

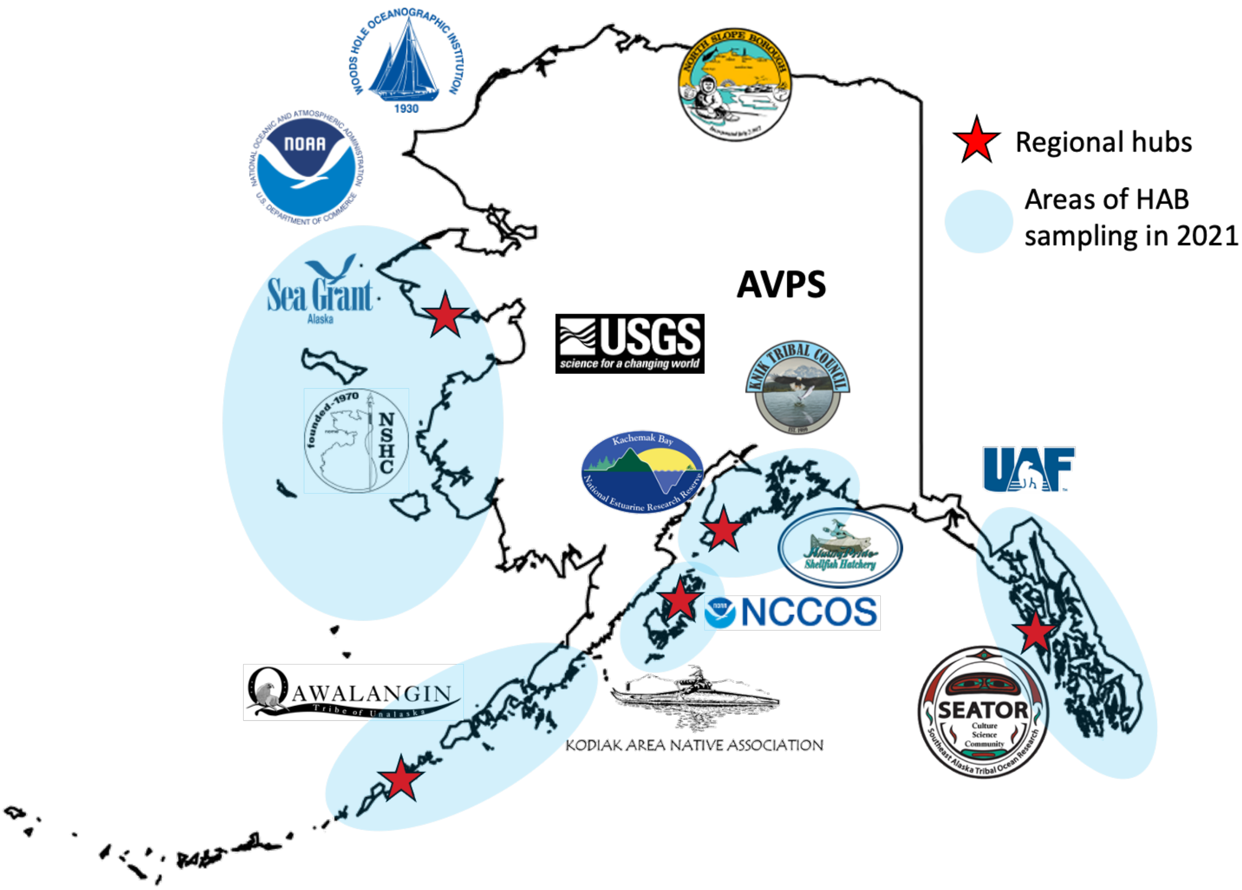

Figure 108: Map of HABs sampling areas and sampling partners in 2021.

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[16] `https://aoos.org/alaska-hab-network/`

Status and trends:
Alaska Region: Results from shellfish and phytoplankton monitoring showed a consistent presence of harmful algal blooms (HABs) throughout all regions of Alaska in 2021. Bivalve shellfish from areas that are well known for having PSP levels above the regulatory limit, including Southeast Alaska and Kodiak, continued to test above the regulatory limit. Shellfish in other areas, which have seen high levels only in recent years (e.g., the Aleutian Islands), continued to show high levels in 2021. Overall, 2021 seems to have been slightly less active for blooms and toxin levels than 2019 and 2020, but many areas continue to have HAB organisms in the water, and shellfish testing well above the regulatory limit, especially between March and September. Over the last few years, the dinoflagellate *Dinophysis* has become more common and abundant in water samples, and 2021 continued that trend.

Northern Bering Sea: Water samples were collected regularly in and near Nome, AK for microscopy to identify phytoplankton target species of *Alexandrium* spp., *Dinophysis*, and *Pseudo-nitzschia.* Identification is in the process of review through NOAA's NWFSC. Other samples of phytoplankton, cysts, clams, and worms to test for saxitoxin and domoic acid were collected at several locations in Diomede.

Sediment and water samples were collected during a Northern Bering Sea cruise for detection of *Alexandrium* spp. cysts and cells; water samples will also be analyzed for *Pseudo-nitzschia.* Shore-based water sampling kits were sent to the communities of Nome, Diomede, Savoonga, Gambell, Utqiaġvik, and Shishmaref. Weekly samples from each community have been preserved and will be analyzed using both microscopy and molecular methods for HAB species.

Through the ECOHAB project "Harmful algal bloom toxins in Arctic food webs", community samplers and researchers are collecting samples throughout the food web to test for HAB toxins. More information about this project can be found on p. 185.

Factors influencing observed trends: HABs are likely to increase in intensity and geographic distribution in Alaska waters with warming water temperatures. Observations in Southeast and Southcentral Alaska suggest *Alexandrium* spp. blooms occur at temperatures above 10°C and salinities above 20 (Vandersea et al., 2018; Tobin et al., 2019; Harley et al., 2020).

Implications: HABs pose a risk to human health when present in wildlife species that people consume, including shellfish, birds, and marine mammals. Research across the state is attempting to better understand the presence and circulation of HABs in the food web. HAB toxins have been detected in stranded and harvested marine mammals from all regions of Alaska in past years (Lefebvre et al., 2016).

ECOHAB: Harmful Algal Bloom (HAB) Toxins in Arctic Food Webs

Contributed by Kathi Lefebvre[1], Don Anderson[2], Gay Sheffield[3]
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Last updated: September 2021

Description of indicator: There is clear evidence that multiple harmful algal bloom (HAB) toxins are present in Arctic and Subarctic food webs (Figure 109). Two of the most common toxin types include domoic acid (DA; produced by *Pseudo-nitzschia* species) and Paralytic Shellfish Toxins (PSTs; produced by *Alexandrium* species). The risks of these toxins include human illness and death associated with seafood consumption as well as health impacts to marine wildlife at multiple trophic levels. Many commercially valuable shellfish and finfish are impacted by these toxins, as well as marine mammals, invertebrates, seabirds, and filter-feeding fishes that are harvested for subsistence purposes and consumed by Alaska's coastal communities.

Figure 109: Algal toxins detected in stranded and harvested marine mammals suggest widespread prevalence of HABs throughout the food web in all regions of Alaska (Lefebvre et al., 2016).

Status and trends: As the climate has warmed over the past few decades, the Pacific sector of the Arctic Ocean has warmed with dramatic consequences. The quality, quantity, and duration of sea ice has decreased markedly due to earlier melting and a delayed freeze-up (Frey et al., 2014). The input of Pacific water northwards through the Bering Strait has increased, warmed, and freshened (Woodgate et al., 2012). Warmer air temperatures have led to larger negative air-sea heat fluxes in summer (ocean warming), peaking earlier in the season (Pickart et al., 2013). Summertime northeasterly winds have also increased, leading to more upwelling-favorable conditions along the western Alaskan coast (Pickart et al., 2011). Combined, these physical changes have made conditions more favorable for HAB species, particularly the dinoflagellate *Alexandrium catenella* and diatoms in the genus *Pseudo-nitzschia* (Anderson et al., 2012). Recent studies reveal increasing toxin prevalence in food webs (Figure 110) and the potential for increased cyst germination in certain cyst-dense areas, such as the seafloor in the northeastern Chukchi Sea, which are directly linked to warmer ocean bottom temperatures (Anderson et al., 2021). A potential increase in cyst germination will result in a corresponding increase in HAB events and HAB toxin exposure risks to the Arctic marine ecosystem, including people, marine mammals, seabirds, fish, and other marine wildlife.

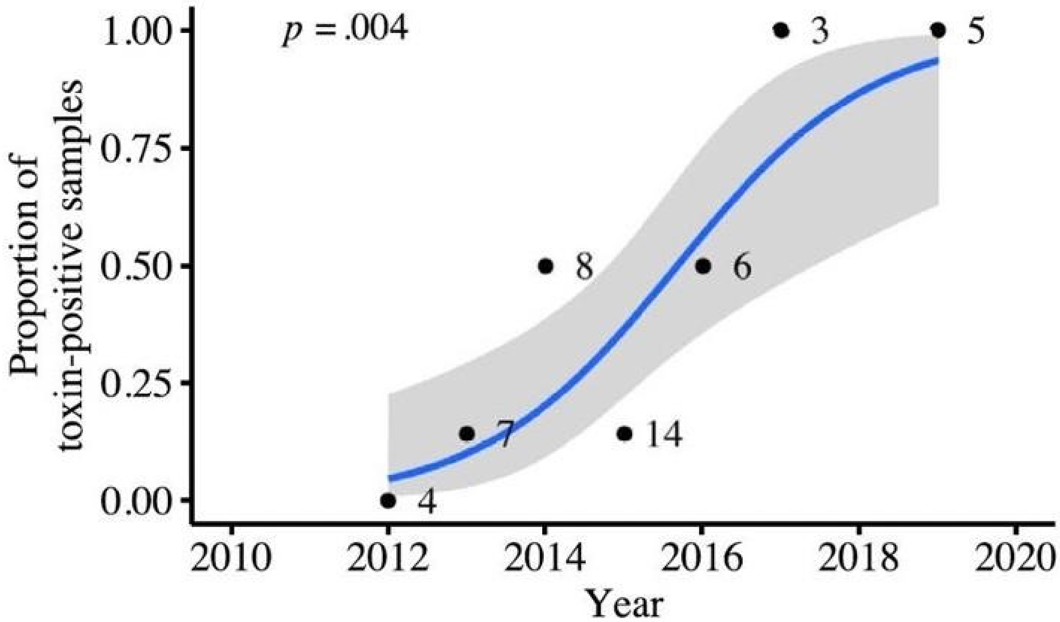


Figure 110: Increasing prevalence of the HAB toxin, domoic acid, in subsistence harvested bearded seals (*Erignathus barbatus*) in the Bering Sea, Alaska (Hendrix et al., 2021). Numbers represent the number of animals sampled each year.

Factors influencing observed trends: Increasing HAB toxin prevalence is linked to warming ocean temperatures throughout the water column (both surface and bottom) and increased sunlight associated with the loss of sea ice cover.

Implications: The impacts of increased biotoxin exposure include increased risks to ecosystem, wildlife, and public health in Northern Arctic regions. Impacts also include food security concerns to Arctic coastal peoples as well as conservation concerns for many species of marine resources, including several marine mammals currently listed under the Endangered Species Act (ESA). The increasing trend for HAB events highlights the lack of: 1) monitoring efforts for HAB toxin levels, 2) testing of non-commercial harvests (i.e., subsistence harvest) essential in remote off-road locations throughout the Arctic, and 3) transboundary communications with the Russian federation that not only has management authority of the same stocks of marine resources as NOAA but also have coastal peoples that utilize the same marine resources for consumption throughout the northern Bering and Chukchi Seas. Increases in HAB toxin presence in Arctic waters may impact commercially important fish species and should be considered in management decisions. Although there are currently no U.S. commercial fisheries in the Chukchi or Beaufort Seas, some commercially important fish species cross into these regions from the Bering Sea. For example, Russia began commercial fishing for pollock in the Chukchi Sea in 2020.

Fishing and Human Dimensions Indicators

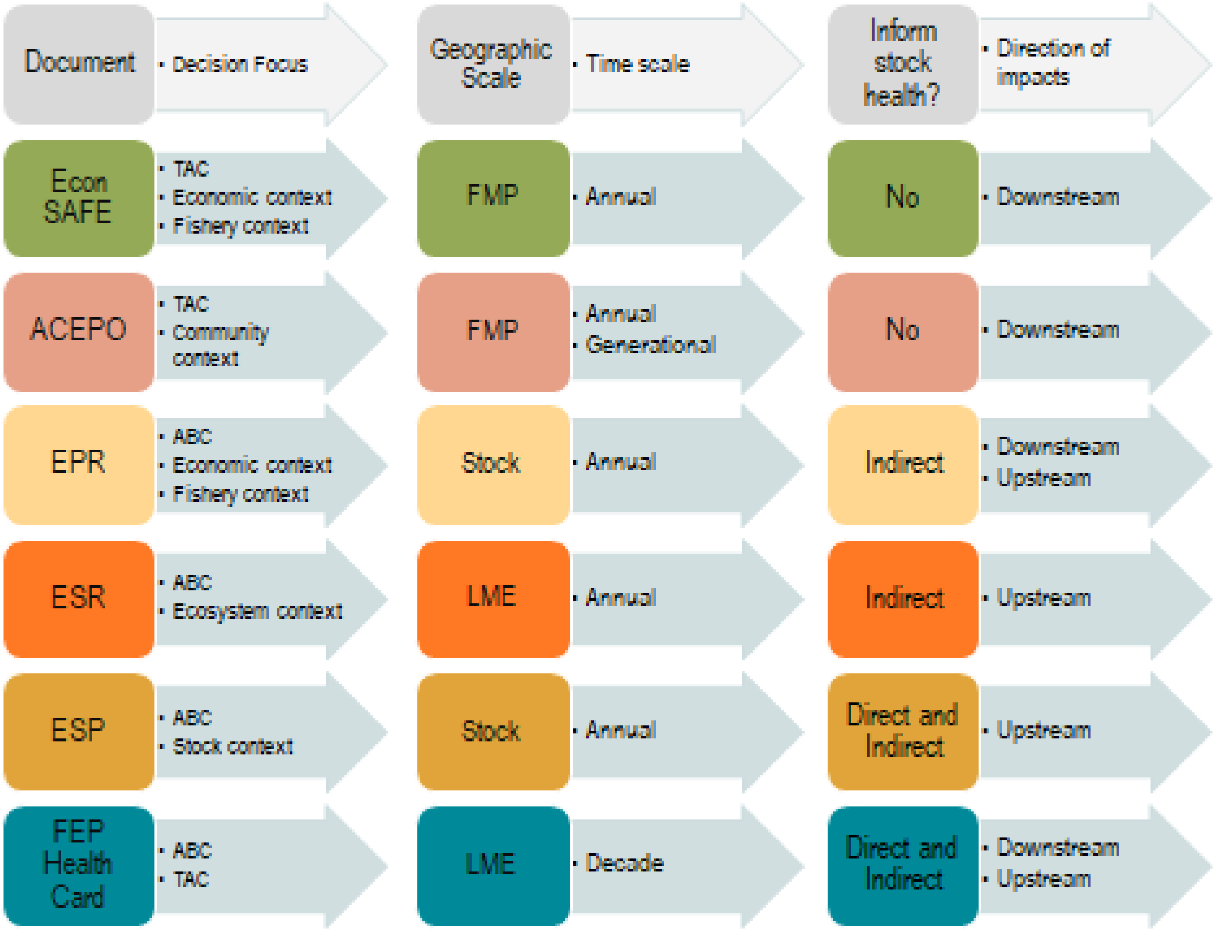
Indicators presented in this section are intended to provide a summary of the status of several ecosystem-scale indicators related to fishing and human economic and social well-being. These indicators are organized around objective categories derived from U.S. legislation and current management practices (see Table 1 for a full list of objective categories and resulting indicators):

- Maintaining diversity
- Maintaining and restoring fish habitats
- Sustainability (for consumptive and non-consumptive uses)
- Seafood production
- Profits
- Recreation
- Employment
- Socio-cultural dimensions

The indicators presented are meant to represent trends in different aspects of the general management objective, but some indicators are better proxies than others. For example, seafood production is a fairly good proxy for the production of seafood to regional, national, and international markets but ex-vessel and wholesale value are imperfect proxies for harvesting and processing sector profits. This suite of indicators will continue to be revised and updated to provide a more holistic representation of human/environment interactions and dependencies.

The Ecosystem Status Report (ESR) team places high value on including human dimensions information in our analysis of the status of the ecosystem to inform the North Pacific Fisheries Management Council's harvest specification process. This year, AFSC is reexamining what economic and social science information is most useful to the Council in the context of these ESRs and other Council documents. As a result, we have only updated some previous contributions in this section for 2021. Following the NPFMC's Science and Statistical Committee's October 2021 meeting discussion, the ESRs will be part of a holistic review of how economic and social science information is communicated and applied to the Council's harvest specification process.

NOAA's Alaska Fisheries Science Center's Economic and Social Science Research department has stated the following — *Previous human dimensions indicators (landings by functional group, fishery value and unit value (price) by functional group, trends in groundfish discards, trends in unemployment, and trends in human population) are being cut back for 2021 to better align the focus of the ESR specifically on informing next year's Allowable Biological Catch (ABC) determination. Going forward, we intend to focus on human dimensions contributions to the ESR which can provide near-term information on the health of a particular stock or region, primarily those currently considered fishing performance metrics (those effects that are upstream from fishing). Many of the removed indicators that speak to general ecosystem health (landings, volume, and unit value by functional group) appear to be more appropriate for the other products such as the Eastern Bering Sea FEP's* *upcoming Fisheries Ecosystem Health Card. This then properly aligns the human dimensions contributions across Council productions and allows the focus of the Ecosystem and Socioeconomic Profiles (ESPs) to be solely on single species stock health related ecosystem, economic, and social indicators. However, downstream impacts of the fishery on human well-being is outside the scope of the focus of the ESR and is treated more comprehensively in the Groundfish Economic SAFE, Crab Economic SAFE, and the Annual Community Engagement and Participation Overview (ACEPO). Figure 111 shows the AFSC's conceptualization of where human dimensions information is included in various NPFMC documents, including the Economic Performance Reports (EPRs) which are included within the stock assessment (or as an appendix), as well as the ESR and ESPs, and the upcoming FEP health card. Additional information on human dimensions indicators can be found at the following website:* `https://www.fisheries.noaa.gov/national/socioeconomics/social-indicators-coastal-communities`.



Document	Decision Focus	Geographic Scale	Time scale	Inform stock health?	Direction of impacts
Econ SAFE	TAC Economic context Fishery context	FMP	Annual	No	Downstream
ACEPO	TAC Community context	FMP	Annual Generational	No	Downstream
EPR	ABC Economic context Fishery context	Stock	Annual	Indirect	Downstream Upstream
ESR	ABC Ecosystem context	LME	Annual	Indirect	Upstream
ESP	ABC Stock context	Stock	Annual	Direct and Indirect	Upstream
FEP Health Card	ABC TAC	LME	Decade	Direct and Indirect	Downstream Upstream

Figure 111: NOAA Alaska Fisheries Science Center's human dimensions indicators mapping

Maintaining Diversity: Discards and Non-Target Catch

Time Trends in Groundfish Discards

Contributed by Jean Lee
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Alaska Fisheries Information Network, Pacific States Marine Fisheries Commission
Contact: jean.lee@noaa.gov
Last updated: September 2021

Description of indicator: Estimates of groundfish discards for 1993–2002 are sourced from NMFS Alaska Region's blend data, while estimates for 2003 and later come from the Alaska Region's Catch Accounting System. These sources, which are based on observer data in combination with industry landing and production reports, provide the best available estimates of groundfish discards in the North Pacific. Discard rates as shown in Figure 112 below are calculated as the weight of groundfish discards divided by the total (i.e., retained and discarded) catch weight for the relevant area-gear-target sector. Where rates are described below for species or species groups, they represent the total discarded weight of the species/species group divided by the total catch weight of the species/species group for the relevant area-gear-target sector. *These estimates include only catch of FMP-managed groundfish species within the FMP groundfish fisheries.* Discards of groundfish in the halibut fishery and discards of forage fish and species managed under prohibited species catch limits, such as halibut, are not included.

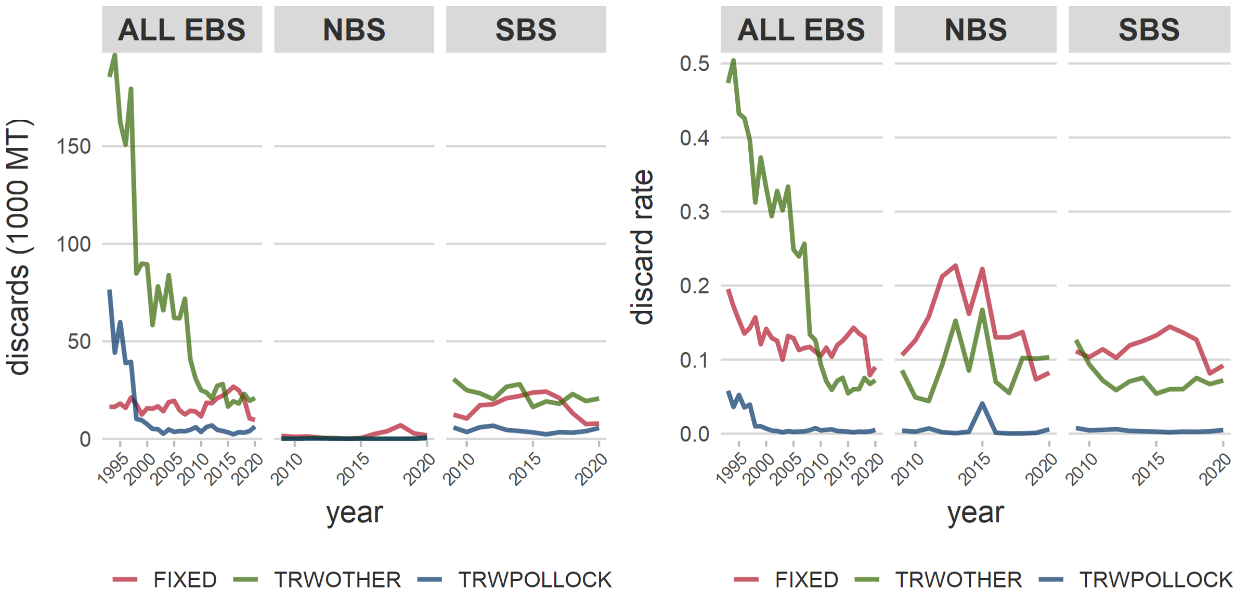

Figure 112: Total biomass and percent of total catch biomass of FMP groundfish discarded in the fixed gear (FIXED), pollock trawl (TRWPOLLOCK), and non-pollock trawl sectors (TRWOTHER) for the eastern Bering Sea (ALL EBS) region, 1993–2020; and for northern (NBS) and southern (SBS) subregions, 2009–2020. Discard rates are calculated as total discard weight of FMP groundfish divided by total retained and discarded weight of FMP groundfish for the sector (includes only catch counted against federal TACs).

Status and trends: Since 1993, discard rates of groundfish in federally-managed Alaskan groundfish fisheries have generally declined in the trawl pollock and non-pollock trawl fisheries in the eastern Bering Sea (EBS) (Figure 112). Annual discard rates in the EBS pollock trawl sector declined from 20% to about 1% in 1999 and have since remained below this level. Rates in the non-pollock trawl sector have declined from a high of 50% in 1994 and have remained at 8% or lower since 2011. Discard rates and volumes in the fixed gear (hook-and-line and pot) sector trended upward from 2010 to 2016, reaching the highest annual discard biomass (26.7K metric tons) over the entire time series before declining from 2017 to 2020. Fixed gear discards in the northern Bering Sea trended upward from 2016 to 2018 as some vessels targeting Pacific cod moved their fishing activity northward, but these increases were offset by declines in discard biomass in the southern subregion. Through week 33 of 2021, discard biomass for both trawl sectors is trending higher relative to the 2016–2020 period, while fixed gear discards are trending lower to date (Figure 113).

Factors influencing observed trends: Fishery discards may occur for economic or regulatory reasons. Economic discards include discarding of lower value and unmarketable fish, while regulatory discards are those required by regulation (e.g., upon reaching an allowable catch limit for a species). Minimizing discards is recognized as an ecological, economic, and moral imperative in various multilateral initiatives and in National Standard 9 of the Magnuson-Stevens Fishery Conservation and Management Act (Alverson et al., 1994; FAO, 1995; Karp et al., 2011). In the North Pacific groundfish fisheries, mechanisms to reduce discards include:

- Limited access privilege programs (LAPPs), which allocate catch quotas and may reduce economic discards by slowing down the pace of fishing
- In-season closure of fisheries once target or bycatch species quotas are attained
- Minimum retention and utilization standards for certain fisheries
- Maximum retainable amounts (MRAs), which allow for limited retention of species harvested incidentally in directed fisheries.

In the eastern Bering Sea, management and conservation measures aimed at reducing bycatch have contributed to an overall decline in groundfish discards since the early 1990s (NPFMC, 2016, 2017). Pollock roe stripping, wherein harvesters discard all but the highest value pollock product, was prohibited in 1991 (56 Federal Register 492). Throughout the 1990s, declines in total catch and discard of non-pollock groundfish in the pollock fishery coincided with the phasing out of bottom trawl gear in favor of pelagic gear, which allows for cleaner pollock catches (Graham et al., 2007). Full retention requirements for pollock and Pacific cod were implemented in 1998 for federally-permitted vessels fishing for groundfish (62 Federal Register 63880). Between 1997 and 1998 annual discard rates for cod fell from 13% to 1% in the non-pollock trawl sector and from 50% to 3% in the trawl pollock sector; pollock discards also declined significantly across both trawl gear sectors. In the trawl pollock fishery, discards of pollock have remained at nominal levels since passage of the American Fisheries Act, which established a sector-based LAPP and implemented more comprehensive observer requirements for the fishery in 2000.

Low retention rates in the non-AFA trawl catcher processor (head and gut) fleet prompted Amendments 79 and 80 to the BSAI Groundfish FMP in 2008 (NPFMC, 2016). Amendment 79 established a Groundfish Retention Standard (GRS) Program with minimum retention and utilization requirements for vessels at least 125 feet LOA; industry-internal monitoring of retention rates has since

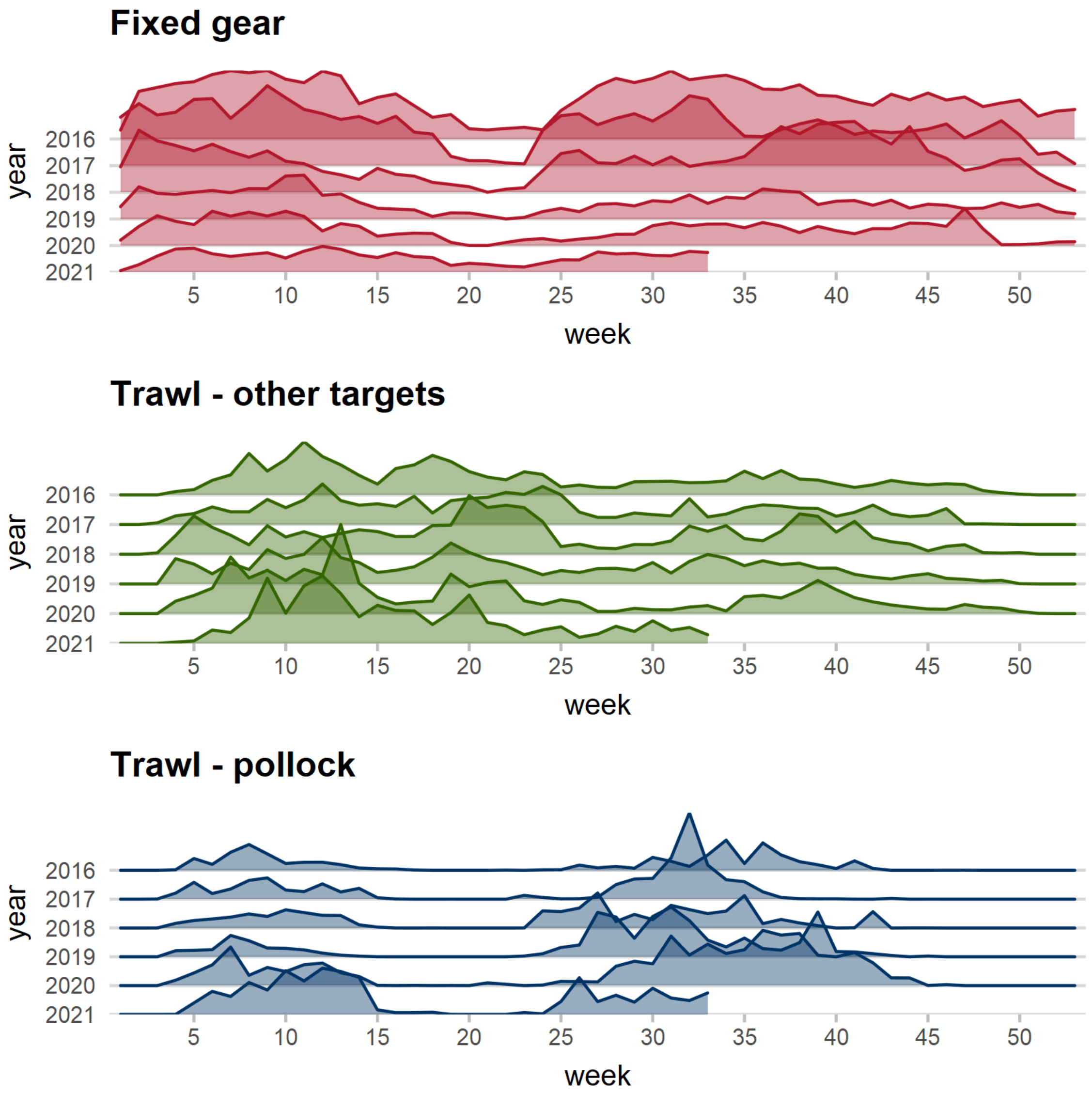

Figure 113: Total biomass of FMP groundfish discarded in the eastern Bering Sea region by sector and week, 2016–2021 (data for 2021 is shown through week 33). Plotted heights are not comparable across sectors.

replaced the program. Amendment 80 expanded the GRS program to all vessels in the fleet and established a cooperative-based LAPP with fixed allocations of certain non-pollock groundfish species. In combination with the GRS program, these allocations are intended to remove the economic incentive to discard less valuable species caught incidentally in the multi-species fishery. In 2013, NMFS revised MRAs for groundfish caught in the BSAI Arrowtooth flounder fishery, including an increase from 0 to 20 percent for pollock, cod, and flatfish (78 Federal Register 29248). Groundfish discard rates in the trawl flatfish fishery fell from 23% to 12% between 2007 and 2008 and have continued on a gradual decline since then.

Since 2003 across all Bering Sea sectors combined, discard rates for species groups historically managed together as the "other groundfish" assemblage (skate, sculpin, shark, squid, and octopus) have ranged from 65% to 80%, with skates representing the majority of discards by weight. In the fixed gear sector other groundfish typically account for at least 70% of total groundfish discards annually. Fluctuations in discard volumes and rates for these species may be driven by changes in market conditions and in fishing behavior within the directed fisheries in which these species are incidentally caught. For example, low octopus catch from 2007–2010 may be attributable to lower processor demand for food-grade octopus and decreases in cod pot-fishing effort stemming from declines in cod prices (Conners et al., 2016).

Implications: Fishery bycatch adds to the total human impact on biomass without providing a benefit to the Nation and as such is perceived as "contrary to responsible stewardship and sustainable utilization of marine resources" (Kelleher, 2005). Bycatch may constrain the utilization of target species and increases the uncertainty around total fishing-related mortality, making it more difficult to assess stocks, define overfishing levels, and monitor fisheries for overfishing (Alverson et al., 1994; Clucas, 1997; Karp et al., 2011). Although ecosystem effects of discards are not fully understood, discards of whole fish and offal have the potential to alter energy flow within ecosystems and have been observed to result in changes to habitat (e.g., oxygen depletion in the benthic environment) and community structure (e.g., increases in scavenger populations) (Queirolo et al., 1995; Alverson et al., 1994; Catchpole et al., 2006; Zador and Fitzgerald, 2008). Monitoring discards and discard rates provides a means of assessing the efficacy of measures intended to reduce discards and increase groundfish retention and utilization.

Time Trends in Non-Target Species Catch

Contributed by George A. Whitehouse[1] and Sarah Gaichas[2]
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Last updated: July 2021

Description of indicator: We monitor the catch of non-target species in groundfish fisheries in the Eastern Bering Sea (EBS). In previous years we included the catch of "other" species, "non-specified" species, and forage fish in this contribution. However, stock assessments have now been developed or are under development for all groups in the "other species" category (sculpins, unidentified sharks, salmon sharks, dogfish, sleeper sharks, skates, octopus, squid), some of the species in the "non-specified" group (giant grenadier, other grenadiers), and forage fish (e.g., capelin, eulachon, Pacific sand lance, etc.), therefore we no longer include trends for these species/groups here[17]. Invertebrate species associated with habitat areas of particular concern, previously known as HAPC biota (seapens/whips, sponges, anemones, corals, and tunicates) are now referred to as structural epifauna. Starting with the 2013 Ecosystem Status Report, the three categories of non-target species we continue to track here are:

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[17] See AFSC stock assessment website at `https://www.fisheries.noaa.gov/alaska/population-assessments/north-pacific-groundfish-stock-assessments-and-fishery-evaluation`

1. Scyphozoan jellyfish
2. Structural epifauna (seapens/whips, sponges, anemones, corals, tunicates)
3. Assorted invertebrates (bivalves, brittle stars, hermit crabs, miscellaneous crabs, sea stars, marine worms, snails, sea urchins, sand dollars, sea cucumbers, and other miscellaneous invertebrates).

Total catch of non-target species is estimated from observer species composition samples taken at sea during fishing operations, scaled up to reflect the total catch by both observed and unobserved hauls and vessels operating in all FMP areas. Catch since 2003 has been estimated using the Alaska Region's Catch Accounting System (Cahalan et al., 2014). This sampling and estimation process does result in uncertainty in catches, which is greater when observer coverage is lower and for species encountered rarely in the catch.

For this contribution the catch of non-target species/groups from the Bering Sea includes the reporting areas 508, 509, 512, 513, 514, 516, 517, 521, 523, 524, and 530 (https://www.fisheries.noaa.gov/alaska/sustainable-fisheries/alaska-fisheries-figures-maps-boundaries-regulatory-areas-and-zones).

Status and trends: The catch of jellyfish decreased from 2019 to 2020 and is the second lowest since 2011 (Figure 114). Highs in the catch of jellyfish occurred in 2011 and 2014, and were each followed by a sharp decrease in catch the following year. The catch of jellyfish in 2014 was more than double the catch in 2015 and was more than five times the catch in 2016, which is the lowest over the time period examined. Jellyfish are primarily caught in the pollock fishery.

The catch of structural epifauna was relatively steady from 2011 to 2018 but decreased in 2019 and again in 2020, to its lowest over the time period examined (Figure 114). Benthic urochordate caught in non-pelagic trawls were the dominant component of the structural epifauna catch in 2012 and 2015–2020. In 2013 and 2014, anemones caught in the Pacific cod fishery were the dominant part of the structural epifauna catch. Sponge were the dominant component of the structural epifauna catch in 2011 and were primarily caught in non-pelagic trawls.

Sea stars comprise more than 85% of the assorted invertebrate catch in all years (2011–2020) and are primarily caught in flatfish fisheries (Figure 114). The catch of assorted invertebrates generally trended upward from 2011–2015, then declined from 2015 to 2020.

Factors influencing observed trends: The catch of non-target species may change if fisheries change, if ecosystems change, or both. Because non-target species catch is unregulated and unintended, if there have been no large-scale changes in fishery management in a particular ecosystem, then large-scale signals in the non-target catch may indicate ecosystem changes. Catch trends may be driven by changes in biomass or changes in distribution (overlap with the fishery) or both. Fluctuations in the abundance of jellyfish in the EBS are influenced by a suite of biophysical factors affecting the survival, reproduction, and growth of jellyfish including temperature, sea ice phenology, wind-mixing, ocean currents, and prey abundance (Brodeur et al., 2008). The lack of a clear trend in the catch of scyphozoan jellyfish may reflect interannual variation in jellyfish biomass or changes in the overlap with fisheries.

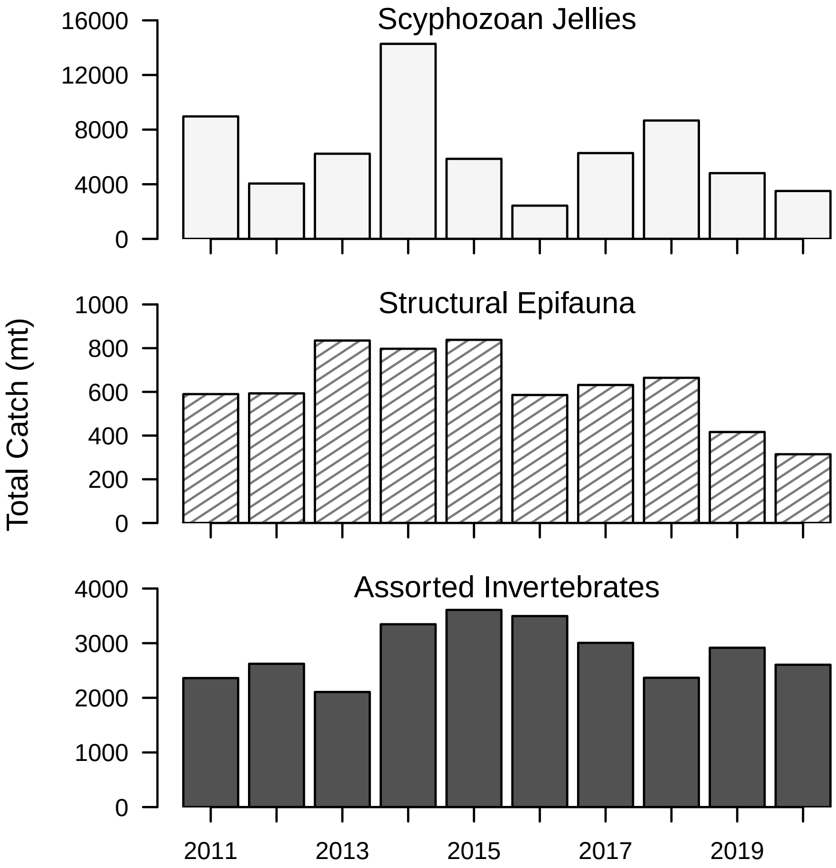

Figure 114: Total catch of non-target species (tons) in EBS groundfish fisheries (2011–2020). **Please note the different y-axis scales** between the species groups.

Implications: The catch of structural epifauna species and assorted invertebrates is very low compared with the catch of target species. Structural epifauna species may have become less available to the EBS fisheries (or the fisheries avoided them more effectively) since 2005. Abundant jellyfish may have a negative impact on fishes as they compete with planktivorous fishes for prey resources (Purcell and Arai, 2001), and additionally, jellyfish may prey upon the early life history stages (eggs and larvae) of fishes (Purcell and Arai, 2001; Robinson et al., 2014).

Seabird Bycatch Estimates for Groundfish Fisheries in the Eastern Bering Sea, 2011–2020

Contributed by Joseph Krieger and Anne Marie Eich
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Last updated: August 2021

Description of indicator: This report provides estimates of the number of seabirds caught as bycatch in commercial groundfish fisheries operating in federal waters of the U.S. Exclusive Economic Zone of the eastern Bering Sea for the years 2011 through 2020. Estimates of seabird bycatch from earlier years using different methods are not included here. Fishing gear types represented are demersal longline, pot, pelagic trawl, and non-pelagic trawl. These numbers do not apply to gillnet, seine, or troll fisheries. Data collection on the Pacific halibut longline fishery began in 2013 with the restructured North Pacific Observer Program.

Estimates are based on two sources of information: (1) data provided by NMFS-certified fishery observers deployed to vessels and floating or shoreside processing plants (AFSC, 2011), and (2) industry reports of catch and production. Observer deployment plans are reviewed and updated annually in the Annual Deployment Plan[18]. The NMFS Alaska Regional Office Catch Accounting System (CAS) produces the estimates (Cahalan et al., 2010, 2014). The main purpose of the CAS is to provide near real-time delivery of accurate groundfish and prohibited species catch and bycatch information for inseason management decisions. CAS also estimates non-target species (such as invertebrates) and seabird bycatch in the groundfish fisheries. The CAS produces estimates based on these two current data sets, which may have changed over time.

Estimates of seabird bycatch from the eastern Bering Sea include the reporting areas 508, 509, 512, 513, 514, 516, 517, 521, and 524[19].

Status and trends: The numbers of seabirds estimated to be caught incidentally in the eastern Bering Sea fisheries in 2020 (2,975 birds) decreased from 2019 (6,185 birds) by 52%, and was below the 2011–2019 average of 5,067 birds by 41% (Table 4, Figure 115). Northern fulmars, shearwaters, and gulls were the most common species or species groups caught incidentally in the eastern Bering Sea fisheries in 2020 that could be identified. In 2020, the number of northern fulmars and shearwaters decreased by 22% and 90%, respectively, compared to 2019, and were below the 2011–2019 average of 3,090 and 1,014 birds by 32% and 68%, respectively. In 2020, the number of gulls increased by 12% compared to 2019 but was below the 2011–2019 average of 659 birds by 74%. While no black-footed albatross were reported as taken in the EBS, two short-tailed albatross were reported taken in demersal longline fisheries (as discussed below). The number of Laysan albatross decreased by 38% compared to 2019 and was below the 2011–2019 average of 35 birds by 77% (Figure 116).

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[18] The 2021 plan is available at: `https://www.fisheries.noaa.gov/resource/document/2021-annual-deployment-plan-observers-and-electronic-monitoring-groundfish-and`

[19] `https://www.fisheries.noaa.gov/alaska/commercial-fishing/alaska-fisheries-figures-maps-boundaries-regulatory-areas-and-zones`

Table 4: **Estimated** seabird bycatch in eastern Bering Sea groundfish fisheries for all gear types, 2011 through 2020. Note that these numbers represent extrapolations from observed bycatch, not direct observations. See text for estimation methods.

Species Group	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Unidentified Albatross	0	0	0	12	0	0	0	0	0	0
Short-tailed Albatross	0	0	0	11	0	0	0	0	0	11
Laysan Albatross	28	37	9	13	13	12	25	166	13	8
Black-footed Albatross	1	0	0	6	0	0	0	0	0	0
Northern Fulmar	5,287	2,778	2,733	677	2,334	5,046	3,477	2,808	2,670	2,086
Shearwaters	157	477	196	116	358	3,161	979	545	3,133	327
Gull	1,565	810	451	576	927	575	372	504	155	173
Kittiwake	6	5	3	4	12	5	22	37	18	24
Murre	14	6	3	47	0	52	10	0	0	6
Puffin	0	0	0	0	0	10	0	0	0	0
Auklets	0	7	4	67	18	1	25	0	0	0
Other Alcid	0	0	0	0	0	0	0	6	6	0
Cormorant	0	0	0	0	3	0	0	0	0	0
Other Bird	0	0	0	0	0	0	63	0	0	7
Unidentified	355	300	268	73	144	282	250	77	190	333
Grand Total	7,413	4,420	3,667	1,602	3,809	9,144	5,223	4,143	6,185	2,975

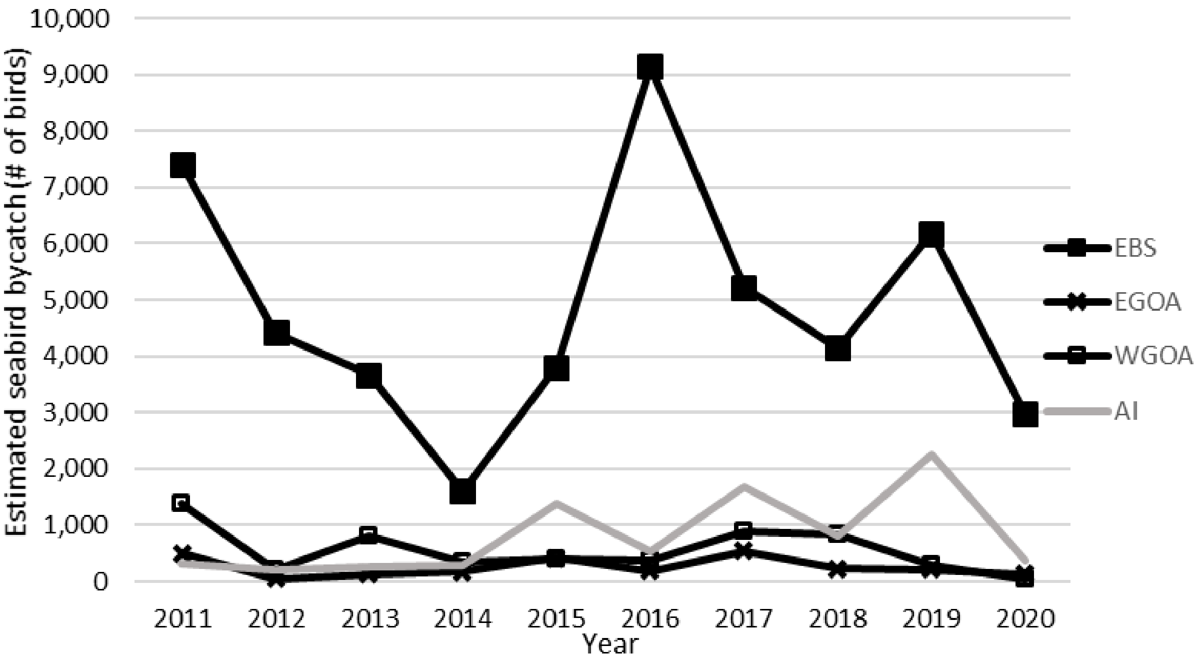

Figure 115: Total estimated seabird bycatch in eastern Bering Sea (EBS), Eastern Gulf of Alaska (EGOA), Western Gulf of Alaska (WGOA), and Aleutian Islands (AI) groundfish fisheries, all gear types combined, 2011–2020.

BSAI Pacific cod fisheries using demersal longline are responsible for the majority of seabird bycatch in the EBS – the average annual seabird bycatch for 2011 through 2019 was 4,741 birds per year (Table 13 in Krieger and Eich (2021)). In 2020, the estimated seabird bycatch was below the 2011–2019 average by 48% (2,487 birds; Table 13 in Krieger and Eich (2020)). Figure 117 shows the spatial distribution of observed seabird bycatch from 2015–2020 from the Pacific cod hook and line fisheries overlaid onto heat maps depicting fishing effort for the fishery.

Focusing solely on the bycatch of albatross (unidentified, short-tailed, Laysan, and black-footed) in the EBS, an average of 114 albatross were taken per year from 2011 through 2020 (Krieger and Eich, 2021). Two takes of short-tailed albatross were observed in the groundfish fisheries in 2020[20]. Both takes occurred in the EBS and from vessels fishing in the BSAI demersal longline fishery. The incidental take statement in the 2015 biological opinion on the groundfish fisheries, which was the current biological opinion when the takes occurred, anticipated the take of no more than six short-tailed albatross in a 2-year period (either by demersal longline or trawl; USFWS (2015)). This was the first observed take of short-tailed albatross in the groundfish fisheries (either by demersal longline, trawl, or pot) since December 2014.

Aside from the endangered short-tailed albatross, two species of eider are also listed under the U.S. Endangered Species Act. These are the threatened spectacled eider (*Somateria fischeri*) and the threatened Alaska-breeding population of Steller's eider (*Polysticta stelleri*). Two other populations of Steller's eider occur in waters off Alaska but only the Alaska-breeding population is listed under the U.S. Endangered Species Act. Prior to 2019, there had been no reported takes of either the

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[20] `https://www.fisheries.noaa.gov/bulletin/ib-20-76-noaa-fisheries-reports-take-short-tailed-albatross-bsai;https://www.fisheries.noaa.gov/bulletin/ib-20-80-noaa-fisheries-reports-take-second-short-tailed-albatross-bsai`

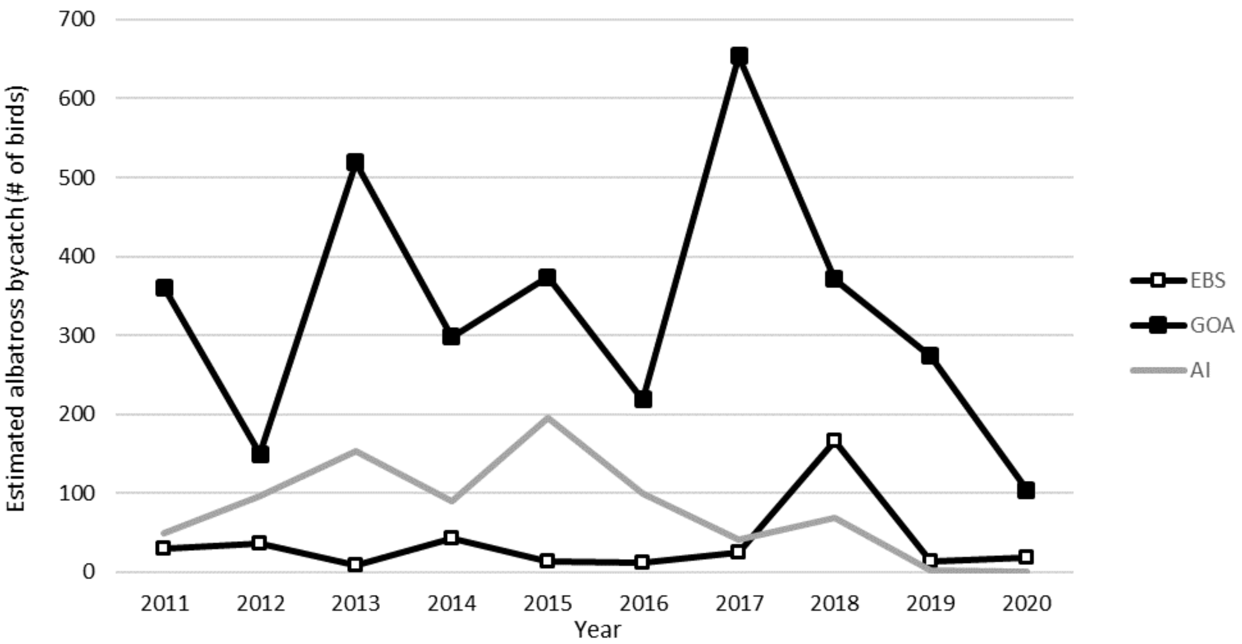

Figure 116: Total estimated albatross bycatch in eastern Bering Sea (EBS), Gulf of Alaska (GOA), and Aleutian Islands (AI) groundfish fisheries, all gear types combined, 2011–2020.

spectacled eider or the Alaska-breeding population of Steller's eider by vessels operating in federal fisheries off Alaska. However, in October of 2019, twenty-two spectacled eider fatally collided with a demersal longline vessel in the EBS (NMFS did not receive a report on this take until 2020)[21]. Then in March of 2020, a Steller's eider collided with another demersal longline vessel in the EBS[22]. These vessels were not fishing at the time of the bird strike mortality events. Since these birds were not taken by fishing gear, they are not included in the bycatch estimates provided in this report.

Because of the take of threatened spectacled and Steller's eider, NMFS reinitiated formal consultation under section 7 of the ESA with USFWS to ensure that the BSAI and GOA groundfish fisheries are not likely to jeopardize the continued existence of either the spectacled eider or Steller's eider or adversely modify their designated critical habitat. In March of 2021, the USFWS finalized a new Biological Opinion (USFWS, 2021) which supersedes the 2015 Biological Opinion.

Factors influencing observed trends: There are many factors that may influence annual variation in bycatch rates, including seabird distribution, population trends, prey supply, and fisheries activities. Further, standard observer sampling methods on trawl vessels do not account for additional mortalities from net entanglements, cable strikes, and other sources. Thus, the trawl estimates may be downward biased.

While a reduction in seabird bycatch in the Federal fisheries off Alaska is positive, several events occurred during the 2020 fishing seasons which may partially explain this reduction. As with many other things in 2020, the COVID-19 pandemic disrupted normal fishing operations throughout

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[21] `https://www.fisheries.noaa.gov/bulletin/ib-20-26-nmfs-reports-vessel-strike-mortality-event-22-spectacled-eiders-bering-sea`

[22] `https://www.fisheries.noaa.gov/bulletin/ib-20-32-nmfs-reports-vessel-strike-mortality-alaska-breeding-population-stellers`

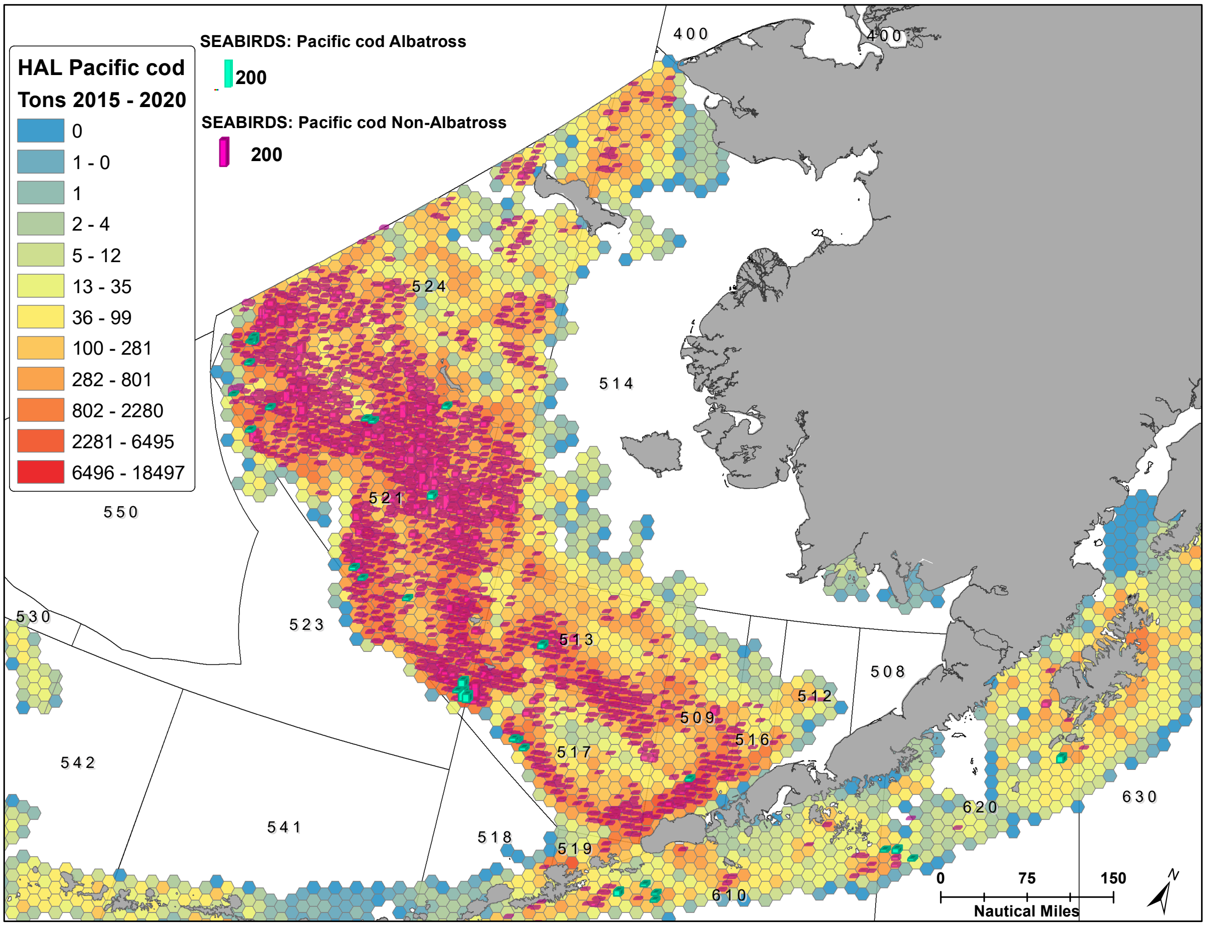

Figure 117: Spatial distribution of observed seabird bycatch from 2015–2020 from the Pacific cod (P. Cod) hook and line fisheries. Colored vertical bars indicate the sum of incidental takes at a location grouped within 1/10 of a degree of latitude and longitude. Incidental takes are separated between takes of albatross and takes of non-albatross seabirds. Figure includes locations of incidental takes of seabirds overlaid on to a heatmap depicting fishing effort. Note the difference of scale of observed takes of seabirds.

Federal fisheries. In Alaska, such disruptions included lost fishing days due to closures and stand-downs (primarily at the beginning of the pandemic) and reduced market prices for fish as restaurants and other buyers were not operating at normal levels and thus were not purchasing as much fish product. Less fishing effort would reduce the opportunities for interactions with seabirds and result in less seabird bycatch. Aside from disruptions associated with the COVID-19 pandemic, there was also a major shift in gear usage in the sablefish IFQ fishery that could partially explain the relatively low seabird bycatch estimates in 2020, however more so in the GOA than EBS. Many vessels in this fishery shifted from using hook-and-line gear to using pot gear. This was primarily done in an attempt to avoid whale depredation on sablefish catch. Take of seabirds by pot gear is relatively rare compared to take of seabirds by hook-and-line gear. If the sablefish IFQ fishery continues to increase its use of pot gear over hook-and-line gear, we would expect to see reduced take of seabirds in this fishery.

Dietrich and Fitzgerald (2010) found in an analysis of 35,270 longline sets from 2004 to 2007 that the most predominant species, northern fulmar, only occurred in 2.5% of all sets. Albatross, a focal species for conservation efforts, occurred in less than 0.1% of sets. Thus, while annual seabird bycatch estimates number in the 1,000's, given the vast size of the fishery, actual takes of seabird remains relatively uncommon (Krieger and Eich, 2021).

Implications: Estimated seabird bycatch in the Federal fisheries off of Alaska in 2020 decreased dramatically from 2019, and was among the lowest estimate in the 10 year time series. While several unique situations presented themselves in 2020 that may have affected seabird bycatch, they themselves likely do not fully explain the reason for the observed trend.

The first reported interaction between a fishing vessel from the BSAI groundfish fishery with threatened spectacled eider may be a direct result of ecological change in the EBS. Recent changes in ocean temperatures in the BSAI and the resulting ecological response of commercially valuable fish species, mainly Pacific cod, has led to an increase in the amount of fishing vessel traffic in areas near spectacled eider designated critical habitat. NMFS has observed a corresponding northward shift in fishing vessel activity and an increased harvest of Pacific cod, primarily in the northern areas of regulatory zones 514 and 524 from 2016 through 2020. In the analysis completed for the 2021 seabird Biological Opinion (USFWS, 2021), the authors note that compared to the number of fishing vessels present in the northern areas of the Bering Sea in 2015 (the baseline for that analysis), 2016 through 2019 show a substantial increase in the number of vessels, especially north of 61°N (as described in Section 7.9.2). How this fleet response to new ecological conditions will affect other species of seabirds remains to be seen.

However, it can be difficult to determine how seabird bycatch estimates and trends in some fisheries are linked to changes in ecosystem components because seabird mitigation gear is used in the longline fleet. There does appear to be a link between poor ocean conditions and the peak bycatch years, on a species-group basis. Fishermen have noted in some years that the birds appear starved and attack baited longline gear more aggressively. This probably indicates changes in food availability rather than distinct changes in how well the fleet employs mitigation gear. A focused investigation of this aspect of seabird bycatch is needed and could inform management of poor ocean conditions if seabird bycatch rates (reported in real time) were substantially higher than normal.

Maintaining and Restoring Fish Habitats

Area Disturbed by Trawl Fishing Gear in the Eastern Bering Sea

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Last updated: September 2021

Description of indicator: Fishing gear can impact habitat used by a fish species for the processes of spawning, breeding, feeding, or growth to maturity. This indicator uses output from the Fishing Effects (FE) model to estimate the area of geological and biological features disturbed over the Bering Sea domain, utilizing spatially-explicit VMS data summarized to 25km^2 grid cells in fishable depths (<1000m). The time series for this indicator is available since 2003, when widespread VMS data became available. In 2021, methods developed by the Alaska Regional Office of NMFS were used to incorporate unobserved fishing events over the entire time series (2003–2021) into FE analysis. Unobserved fishing events typically account for 7-12% of total effort in the VMS data set.

Status and trends: The percent of area disturbed due to commercial fishing interactions (pelagic and non-pelagic trawl, longline, and pot) decreased from about 10% prior to 2008 to approximately 8% currently.

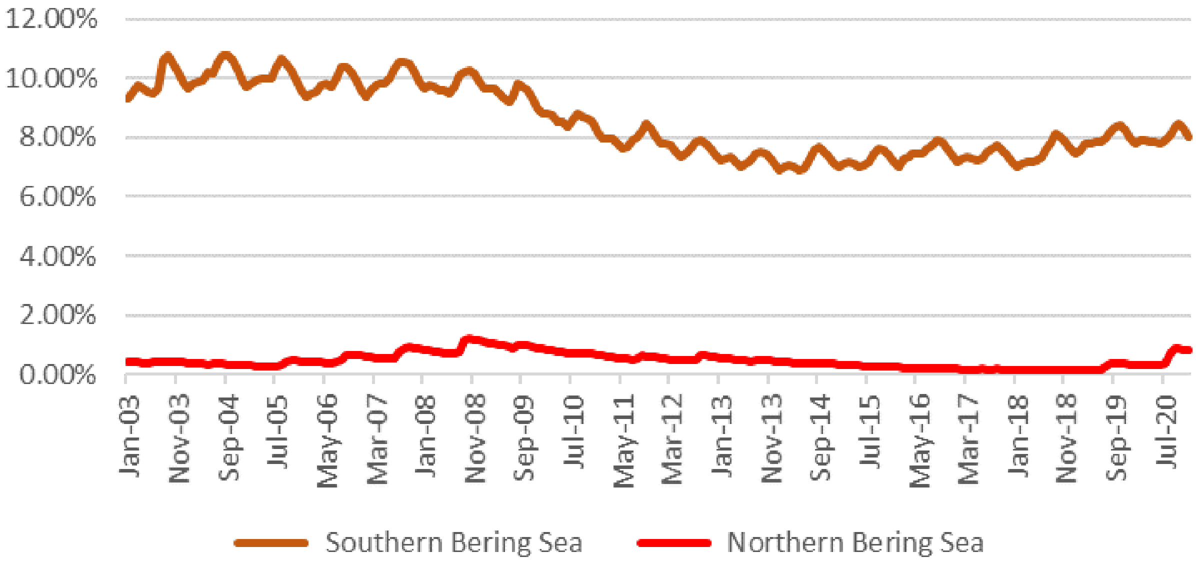

Figure 118: Percent area disturbed by commercial fishing gear, all gear types combined, from 2003 through 2020.

Factors influencing observed trends: Trends in seafloor area disturbed can be affected by numerous variables, such as fish abundance and distribution, management actions (e.g., closed areas), changes in the structure of the fisheries due to rationalization, improved technology (e.g., increased ability to find fish, acoustics to fish near the bottom without contact), markets for fish products, and changes in vessel horsepower and fishing gear. Intensive fishing in an area can result in a change in species diversity by attracting opportunistic fish species which feed on animals that have been disturbed by fishing activity, or by reducing the suitability of habitat used by some species. It is possible that increased effort in fisheries that interact with both living and non-living bottom substrates could result in increased habitat loss/degradation due to fishing gear effects. The footprint of habitat damage varies with gear (type, weight, towing speed, depth of penetration), the physical and biological characteristics of the areas fished, recovery rates of living substrates in the areas fished, and management or economic changes that result in spatial redistribution of fishing effort.

Between 2003 and 2008, variability in area disturbed was driven largely by the seasonality of fishing in the Bering Sea, and this pattern continues in 2020 but to a lesser degree. In 2008, Amendment 80 was implemented, which allocated BSAI Yellowfin sole, Flathead sole, Rock sole, Atka mackerel, and Aleutian Islands Pacific ocean perch to the head and gut trawl catcher processor sector, and allowed qualified vessels to form cooperatives. The formation of cooperatives reduced overall effort in the fleet while maintaining catch levels. In 2010, trawl sweep gear modifications were implemented on non-pelagic trawls in the Bering Sea, resulting in less gear contacting the seafloor and less habitat impact.

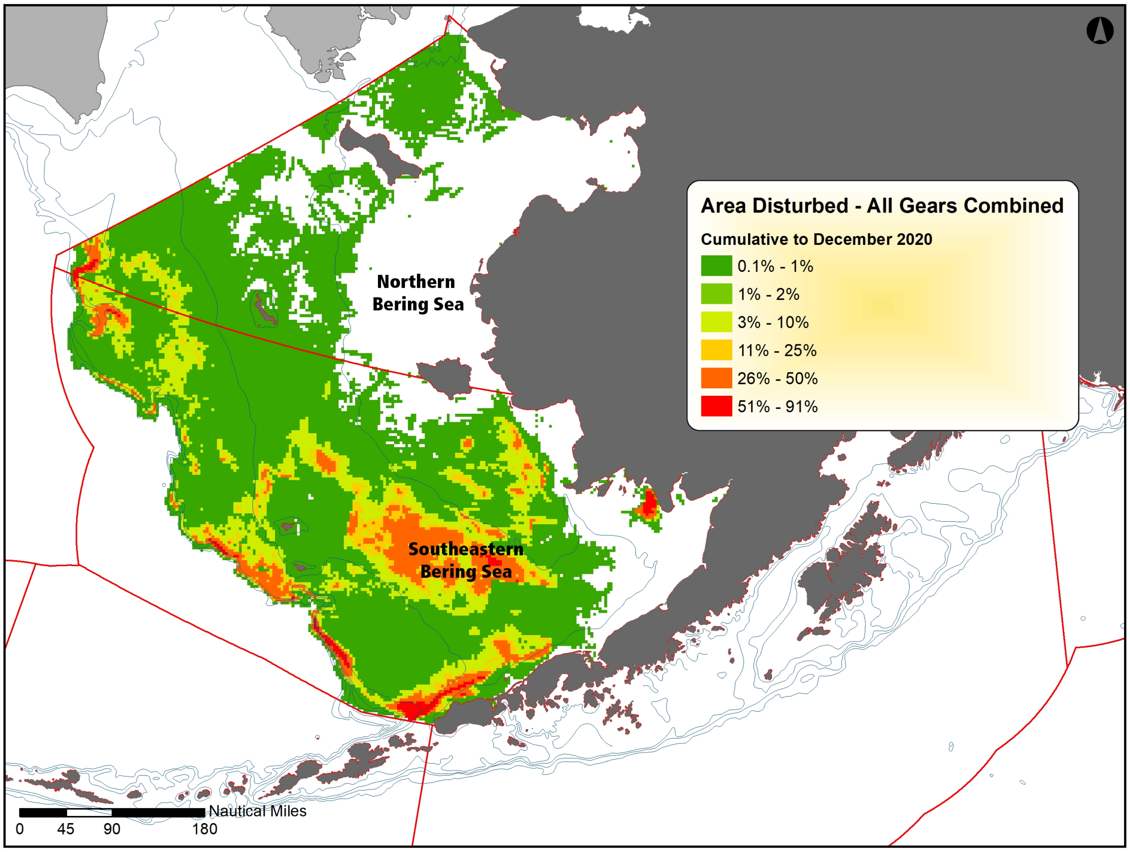

Figure 119: Map of percentage area disturbed per grid cell for all gear types. Effects are cumulative and consider impacts and recovery of features from 2003 to 2020.

Implications: The effects of changes in fishing effort on habitat are difficult to assess, although our ability to quantify those effects has increased greatly with the development of the Fishing Effects model as a part of the 2017 EFH 5-year Review[23]. The 2005 EFH FEIS and 2010 EFH 5-year Review concluded that commercial fisheries can have long term effects on habitat; however, those impacts were determined to be minimal and not detrimental to fish populations or their habitats. These previous EFH analyses indicated the need for an improved fishing effects assessment methodology. With the development and implementation of the FE model, many of the shortcomings of previous fishing effects methods were addressed. Vessel Monitoring System data provides a much more detailed treatment of fishing intensity, allowing better assessments of the effects of overlapping effort and distribution of effort between and within grid cells. The development of literature-derived fishing effects database has increased our ability to estimate gear-specific susceptibility and recovery parameters. The distribution of habitat types, derived from increased sediment data availability, has improved. The combination of these parameters has greatly enhanced our ability to estimate fishing impacts.

New methods and criteria were developed to evaluate whether the effects of fishing on EFH are more than minimal and not temporary on managed fish stocks in Alaska. These criteria were developed and reviewed by the Council and its advisory committees in 2016, and stock assessment authors in 2017. In April 2017, the Council concurred with the Plan Team consensus that the effects of fishing on EFH do not currently meet the threshold of more than minimal and not temporary, and mitigation action is not needed at this time.

Although the impacts of fishing across the domain are very low, it is possible that localized impacts may be occurring. The issue of local impacts is an area of active research.

Areas Closed to Bottom Trawling in the BSAI and GOA

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Description of indicator: Many trawl closures have been implemented to protect benthic habitat or reduce bycatch of prohibited species (i.e., salmon, crab, herring, and halibut) (Figure 120, Table 5). Some of the trawl closures are in effect year-round while others are seasonal. In general, year-round trawl closures have been implemented to protect vulnerable benthic habitat or vulnerable species life stages. Seasonal closures are used to reduce bycatch by closing areas where and when bycatch rates had historically been high.

Status and trends: Additional measures to protect the declining western stocks of the Steller sea lion began in 1991 with some simple restrictions based on rookery and haulout locations; in 2000 and 2001 more specific fishery restrictions were implemented. In 2001, over 90,000 nm^2 of the Exclusive Economic Zone (EEZ) of Alaska was closed to trawling year-round. Additionally, 40,000 nm^2 were closed on a seasonal basis. State waters (0-3 nmi) are also closed to bottom trawling in many areas. A motion passed the North Pacific Management Council in February 2009 which

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[23] `ftp://ftp.library.noaa.gov/noaa_documents.lib/NMFS/TM_NMFS_AFKR/TM_NMFS_FAKR_15.pdf`

closed all waters north of the Bering Strait to commercial fishing as part of the development of an Arctic Fishery management plan. This additional closure added 148,300 nm^2 to the area closed year-round to bottom trawling.

Implications: With the Arctic FMP closure included, almost 65% of the U.S. EEZ of Alaska is closed to bottom trawling. For additional background on fishery closures in the U.S. EEZ off Alaska, see Witherell and Woodby (2005).

Steller Sea Lion closure maps are available on NOAA Fisheries[24].

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[24] `https://www.fisheries.noaa.gov/alaska/sustainable-fisheries/alaska-fisheries-figures-maps-boundaries-regulatory-areas-and-zones`

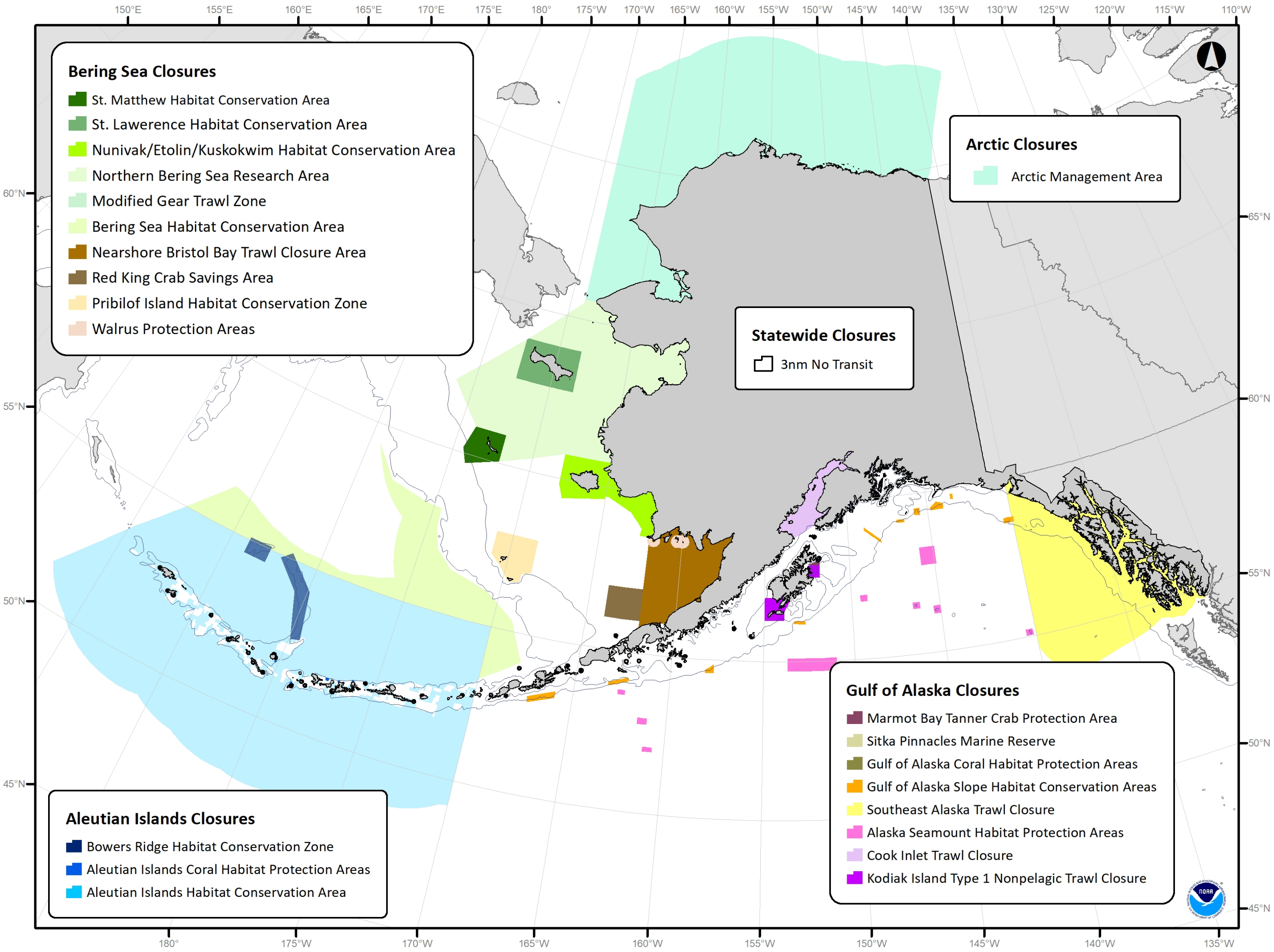

Figure 120: Year-round groundfish closures in the U.S. Exclusive Economic Zone (EEZ) off Alaska, excluding most SSL closures.

Table 5: Time series of groundfish trawl closure areas in the BSAI and GOA, 1995-2020. LLP = License Limitation Program; HCA = Habitat Conservation Area; HCZ = Habitat Conservation Zone.

Area	Year	Location	Season	Area size	Notes
BSAI	1995	Area 512	Year-round	8,000 nm^2	Closure in place since 1987
		Area 516	3/15-6/15	4,000 nm^2	Closure in place since 1987
		Chum Salmon Savings Area	8/1-8/31	5,000 nm^2	Re-closed at 42,000 chum salmon
		Chinook Salmon Savings Area	Trigger	9,000 nm^2	Closed at 48,000 Chinook salmon
		Herring Savings Area	Trigger	30,000 nm^2	Trigger closure
		Zone 1	Trigger	30,000 nm^2	Trigger closure
		Zone 2	Trigger	50,000 nm^2	Trigger closure
		Pribilofs HCA	Year-round	7,000 nm^2	
		Red King Crab Savings Area	Year-round	4,000 nm^2	Pelagic trawling allowed
		Walrus Islands	5/1-9/30	900 nm^2	12 mile no-fishing zones
		SSL Rookeries	Seasonal ext.	5,100 nm^2	20 mile extensions at 8 rookeries
	1996	Nearshore Bristol Bay Trawl Closure	Year-round	19,000 nm^2	Expanded area 512 closure
		C. opilio bycatch limitation zone	Trigger	90,000 nm^2	Trigger closure
	2000	Steller Sea Lion protections			
		Pollock haulout trawl exclusion zones for EBS, AI * areas include GOA	* No trawl all year	11,900 nm^2	
			No trawl (Jan–Jun)*	14,800 nm^2	
			No Trawl Atka Mackerel restrictions	29,000 nm^2	
	2006	Essential Fish Habitat			
		AI Habitat Conservation Area	No bottom trawl all year	279,114 nm^2	
		AI Coral Habitat Protection Areas	No bottom contact gear all year	110 nm^2	
		Bowers Ridge Habitat Conservation Zone	No mobile bottom tending fishing gear	5,286 nm^2	
	2008	Northern Bering Sea Research Area	No bottom trawl all year	66,000 nm^2	
		Bering Sea HCA	No bottom trawl all year	47,100 nm^2	
		St. Matthews HCA	No bottom trawl all year	4,000 nm^2	
		St. Lawrence HCA	No bottom trawl all year	7,000 nm^2	
		Nunivak/Kuskokwim Closure Area	No bottom trawl all year	9,700 nm^2	
Arctic	2009	Arctic Closure Area	No Commercial Fishing	148,393 nm^2	
GOA	1995	Kodiak King Crab Protection Zone Type 1	Year-round	1,000 nm^2	Red king crab closures, 1987
		Kodiak King Crab Protection Zone Type 2	2/15-6/15	500 nm^2	Red king crab closures, 1987
		SSL Rookeries	Year-round	3,000 nm^2	10 mile no-trawl zones
	1998	Southeast Trawl Closure	Year-round	52,600 nm^2	Adopted as part of the LLP
		Sitka Pinnacles Marine reserve	Year-round	3.1 nm^2	
	2000	Pollock haulout trawl exclusion zones for GOA* areas include EBS, AI	No trawl all year	11,900 nm^2*	
			No trawl (Jan–Jun)	14,800 nm^2	
	2006	Essential Fish Habitat			
		GOA Slope Habitat Conservation Area	No bottom trawl all year	2,100 nm^2	
		GOA Coral Habitat Protection Measures	No bottom tending gear all year	13.5 nm^2	
		Alaska Seamount Habitat Protection Measures	No bottom tending gear all year	5,329 nm^2	
	2010	Marmot Bay Tanner Crab Protection Area	No bottom trawl all year	112 nm^2	

Sustainability (for consumptive and non-consumptive uses)

Fish Stock Sustainability Index – Bering Sea and Aleutian Islands

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Last updated: July 2021

Description of indicator: The Fish Stock Sustainability Index (FSSI) is a performance measure for the sustainability of fish stocks selected for their importance to commercial and recreational fisheries[25]. The FSSI will increase as overfishing is ended and stocks rebuild to the level that provides maximum sustainable yield. The FSSI is calculated by awarding points for each fish stock based on the following rules:

1. Stock has known status determinations:
   (a) overfishing level is defined = 0.5
   (b) overfished biomass level is defined = 0.5
2. Fishing mortality rate is below the "overfishing" level defined for the stock = 1.0
3. Biomass is above the "overfished" level defined for the stock = 1.0
4. Biomass is at or above 80% of the biomass that produces maximum sustainable yield (B_{MSY}) = 1.0 (this point is in addition to the point awarded for being above the "overfished" level)

The maximum score for each stock is 4.

In the Alaska Region, there are 35 FSSI stocks and an overall FSSI of 140 would be achieved if every stock scored the maximum value, 4. Over time, the number of stocks included in the FSSI has changed as stocks have been added and removed from Fishery Management Plans (FMPs). To keep FSSI scores for Alaska comparable across years we report the FSSI as a percentage of the maximum possible score (i.e., 100%).

The list of stocks included in the FSSI was revised in 2020 to focus on stocks of heightened commercial and recreational importance[26]. In the BSAI, the Pribilof Islands blue king crab, Saint Matthew Island blue king crab, Pribilof Islands red king crab, and the black-spotted/rougheye rockfish stocks were removed from the FSSI and added to the group of non-FSSI stocks. The BSAI stock of Kamchatka flounder, the AI Pacific cod stock, and the Bogoslof stock of walleye pollock were added to the BSAI FSSI. These changes resulted in a net reduction from 22 to 21 FSSI stocks in the BSAI. With few exceptions, groundfish species (or species complex) in the BSAI are managed as single stocks and not separately for the Bering Sea and Aleutian Islands. As such, the FSSI scores are reported for the BSAI as a whole.

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[25] `https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`

[26] `https://www.fisheries.noaa.gov/national/population-assessments/status-us-fisheries#fish-stock-sustainability-index`

Table 6: Summary of status for the 21 FSSI stocks in the BSAI, updated through June 2021.

BSAI FSSI (21 stocks)	Yes	No	*Unknown*	*Undefined*	N/A
Overfishing	0	21	0	0	0
Overfished	0	19	2	0	0
Approaching Overfished Condition	0	19	2	0	0

Additionally, there are 28 non-FSSI stocks in Alaska, three ecosystem component species complexes, and Pacific halibut which are managed under an international agreement. Two of the non-FSSI crab stocks are overfished but are not subject to overfishing. The Pribilof Islands blue king crab stock is in year seven of a rebuilding plan, and the Saint Matthews Island blue king crab stock is in year one of a 26-year rebuilding plan. None of the other non-FSSI stocks are known to be subject to overfishing, are overfished, or are approaching an overfished condition. For more information on non-FSSI stocks see the Status of U.S. Fisheries webpage (`https://www.fisheries.noaa.gov/national/population-assessments/status-us-fisheries`).

Status and trends: The overall Alaska FSSI generally trended upwards from 80% in 2006 to a high of 94% in 2018 (Figure 121). The FSSI decreased in 2019 and 2020 to 88.9% but increased in 2021 to 89.6%.

As of June 30, 2021, no BSAI groundfish stock or stock complex is subject to overfishing, is known to be overfished, or known to be approaching an overfished condition (Table 6). The BSAI groundfish FSSI score is 59 out of a maximum possible 64. The AI Pacific cod stock and the walleye pollock Bogoslof stock both have FSSI scores of 1.5 due to not having known overfished status or known biomass relative to their overfished levels or to B_{MSY}. All other BSAI groundfish FSSI stocks received the maximum possible score of four points.

The BSAI king and tanner crab FSSI is 19 out of a possible 20. One point was deducted for the Bristol Bay red king crab stock's biomass decreasing to below the B/B_{MSY} threshold.

The overall BSAI FSSI score is 78 out of a maximum possible score of 84 (Table 7) and has generally trended upward from 74% in 2006 to 93% in 2021 (Figure 122).

Factors influencing observed trends: The overall trend in Alaska FSSI has been positive over the duration examined here (2006–2021). The one point increase in the overall score from 2020 to 2021 was due to an increase in the biomass of sablefish above 80% of B_{MSY}. One point was lost for the Bristol Bay red king crab stock biomass dropping to below 80% B_{MSY}. However, one point was gained for the biomass of the Norton Sound red king crab stock increasing to above 80% of B_{MSY}.

Implications: The majority of Alaska groundfish and crab fisheries appear to be sustainably managed. None of the FSSI stocks in the BSAI are subject to overfishing or known to be overfished.

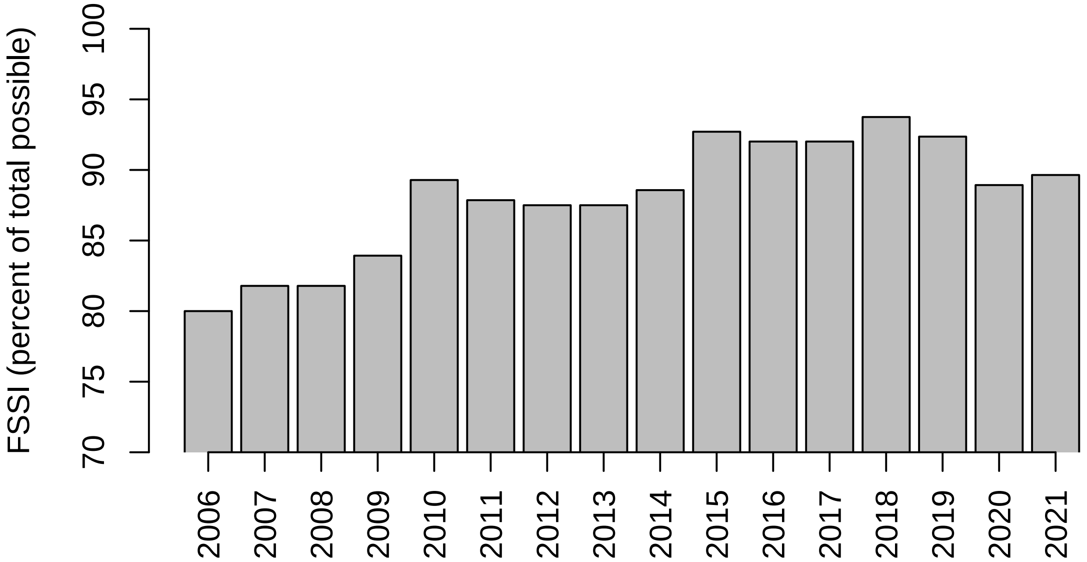

Figure 121: The trend in overall Alaska FSSI from 2006 through 2021 as a percentage of the maximum possible FSSI. The maximum possible FSSI is 140 from 2006 to 2014, 144 from 2015 to 2019, and 140 in 2020 and 2021. All scores are reported through the second quarter (June) of each year, and are retrieved from the Status of U.S. Fisheries website: `https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`.

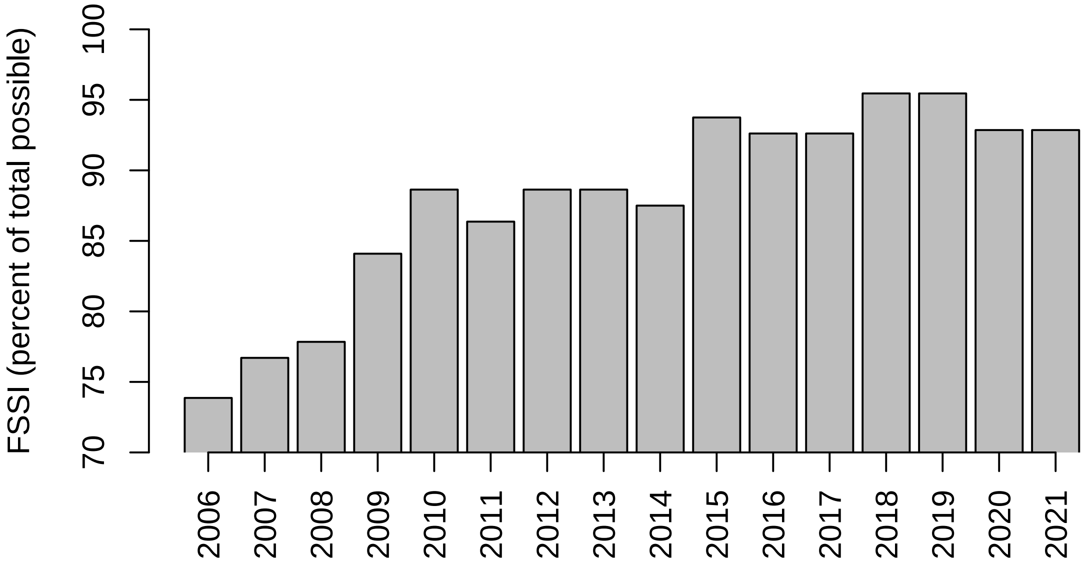

Figure 122: The trend in BSAI FSSI from 2006 through 2021 as a percentage of the maximum possible FSSI. All scores are reported through the second quarter (June) of each year, and are retrieved from the Status of U.S. Fisheries website: `https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`.

Table 7: BSAI FSSI stocks under NPFMC jurisdiction updated through June 2021 adapted from the NOAA Fishery Stock Status Updates webpage: `https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`. *See FSSI and Non-FSSI Stock Status Table on the Fishery Stock Status Updates webpage for definition of stocks and stock complexes.

Stock	Overfishing	Overfished	Approaching	Action	Progress	B/B_{MSY}	FSSI Score
Golden king crab - Aleutian Islands*	No	No	No	N/A	N/A	1.55/1.11	4
Red king crab - Bristol Bay	No	No	No	N/A	N/A	0.76	3
Red king crab - Norton Sound	No	No	No	N/A	N/A	0.80	4
Snow crab - Bering Sea	No	No	No	N/A	N/A	1.33	4
Southern Tanner crab - Bering Sea	No	No	No	N/A	N/A	0.96	4
BSAI Alaska plaice	No	No	No	N/A	N/A	1.84	4
BSAI Atka mackerel	No	No	No	N/A	N/A	1.24	4
BSAI Arrowtooth Flounder	No	No	No	N/A	N/A	2.35	4
BSAI Kamchatka flounder	No	No	No	N/A	N/A	1.4	4
BSAI Flathead Sole Complex*	No	No	No	N/A	N/A	2.08	4
BSAI Rock Sole Complex*	No	No	No	N/A	N/A	2.47	4
BSAI Skate Complex*	No	No	No	N/A	N/A	1.7	4
BSAI Greenland halibut	No	No	No	N/A	N/A	1.59	4
BSAI Northern rockfish	No	No	No	N/A	N/A	1.89	4
BS Pacific cod	No	No	No	N/A	N/A	1.32	4
AI Pacific cod	No	Unknown	Unknown	N/A	N/A	not estimated	1.5
BSAI Pacific Ocean perch	No	No	No	N/A	N/A	1.81	4
Walleye pollock - Aleutian Islands	No	No	No	N/A	N/A	1.26	4
Walleye pollock - Bogoslof	No	Unknown	Unknown	N/A	N/A	not estimated	1.5
Walleye pollock - Eastern Bering Sea	No	No	No	N/A	N/A	1.56	4
BSAI Yellowfin sole	No	No	No	N/A	N/A	1.86	4

Total Annual Surplus Production of Groundfish and Crab

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Last updated: August 2021

Description of indicator: Total annual surplus production (ASP) of 17 groundfish and crab stocks on the eastern Bering Sea (EBS) shelf from 1979–2017 was estimated by summing annual production across major commercial stocks for which assessment data were available over this time period from NOAA Fisheries (2021) (Table 8). Annual surplus production in year t can be estimated as the change in total adult biomass across species from year $t(\mathrm{B}_t)$ to year t+1 (B_{t+1}) plus total catches in year $t(\mathrm{C}_t)$:

$$ASP_t = \Delta B_t + C_t = B_{t+1} - B_t + C_t$$

All estimates of B and C are based on the most recent stock assessments. An index of total exploitation rate within each region was obtained by dividing the total catch across the major commercial species by the estimated combined biomass at the beginning of the year:

$$u_t = \mathrm{C}_t \ / \ \mathrm{B}_t$$

Table 8: Species included in computing annual surplus production in the BSAI management area. Data retrieved from NOAA Fisheries on September 24, 2020 (`www.st.nmfs.noaa.gov/stocksmart`).

Stock (BSAI unless otherwise indicated)
EBS walleye pollock (*Gadus chalcogrammus*)
AI walleye pollock (*Gadus chalcogrammus*)
EBS Pacific cod (*Gadus macrocephalus*)
Yellowfin sole (*Limanda aspera*)
Arrowtooth flounder (*Atheresthes stomias*)
Greenland turbot (*Reinhardtius hippoglossoides*)
Flathead sole (*Hippoglossoides elassodon*)
Northern rock sole (*Lepidopsetta polyxystra*)
Alaska plaice (*Pleuronectes quadrituberculatus*)
Pacific Ocean Perch (*Sebastes alutus*)
Northern rockfish (*Sebastes polyspinus*)
Rougheye/Blackspotted rockfish (*Sebastes aleutianus*, *S. melanostictus*)
Atka mackerel (*Pleurogrammus monopterygius*)
Bristol Bay, Pribilof Islands, and Norton Sound Red King crab (*Paralithodes platypus*)
Pribilof Islands Blue King Crab (*Paralithodes camtschaticus*)

Status and trends: The resulting indices suggest high variability in production in the eastern Bering Sea with multi-year periods of below- and above-average surplus production. ASP was lowest in the late 1980s, mid-1990s, from 2004–2007, and in 2017. Total exploitation rates (catch/mature biomass) for the combined species ranged from 9.5–24.7% (Figure 123). Overall exploitation rates were highest following periods of low surplus production in the late 1980s and mid-2000s. Trends in annual surplus production in the eastern Bering Sea are largely driven by variability in Walleye pollock (Figure 124). Therefore, ASP for the Bering Sea was also computed after excluding Walleye pollock (Figure 125). The results suggest variable aggregate surplus production of all non-pollock species ranging from a high of more than 800,000 tons in 1980, due to strong recruitment of a number of species, to a low of less than 300,000 t in the late 2000s. Annual non-pollock surplus production has decreased on average over the full time period, although the trend was not significant (p=0.20) and showed large periodic fluctuations. Besides Walleye pollock, stocks that contribute most to mean surplus production, and to its variability (not shown), include Pacific cod and Yellowfin sole, with neither species dominating the trends in Figure 125.

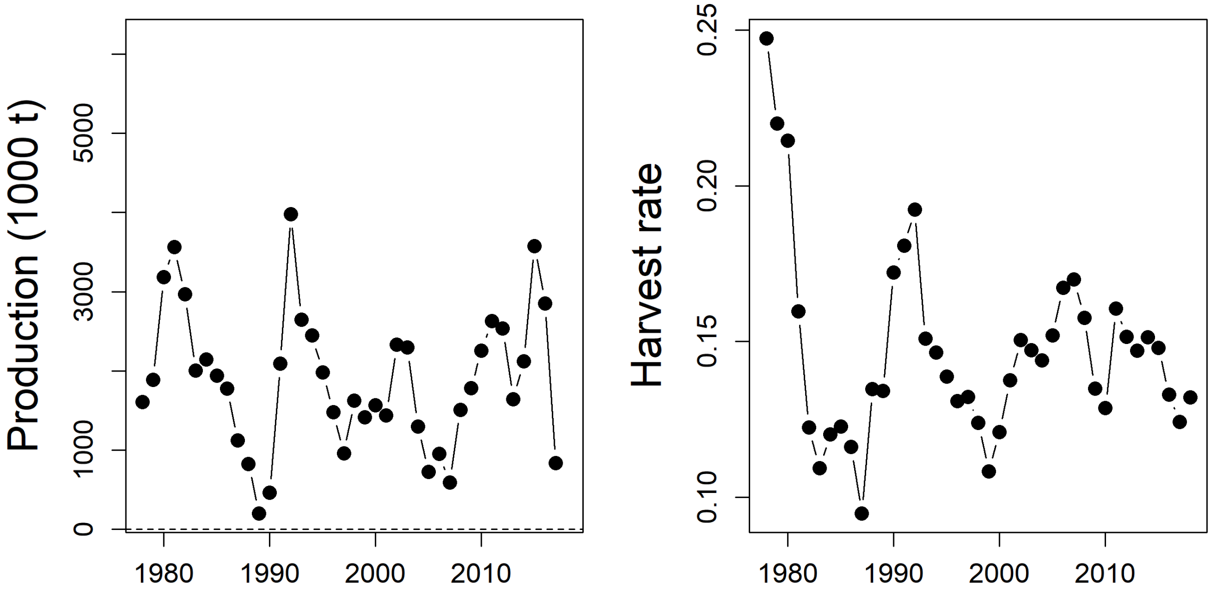

Figure 123: Total annual surplus production (change in biomass plus catch) across all major groundfish and crab stocks in the Bering Sea/Aleutian Islands (left) and total harvest rate (total catch/beginning-of-year biomass, each summed across the major stocks in Table 8).

Factors influencing observed trends: Annual Surplus Production is an estimate of the sum of new growth and recruitment minus deaths from natural mortality (i.e., mortality from all non-fishery sources) during a given year. It is highest during periods of increasing total biomass and lowest during periods of decreasing biomass (e.g., 2004–2007). In the absence of a long-term trend in total biomass, ASP is equal to the long-term average catch. Theory suggests that surplus production of a population will decrease as biomass increases much above B_{MSY}, which is the case for many species in the BSAI management area. Exploitation rates are primarily determined by management and reflect a relatively precautionary management regime with rates that have averaged about 15% of adult (mature) biomass for the species in Table 8 combined.

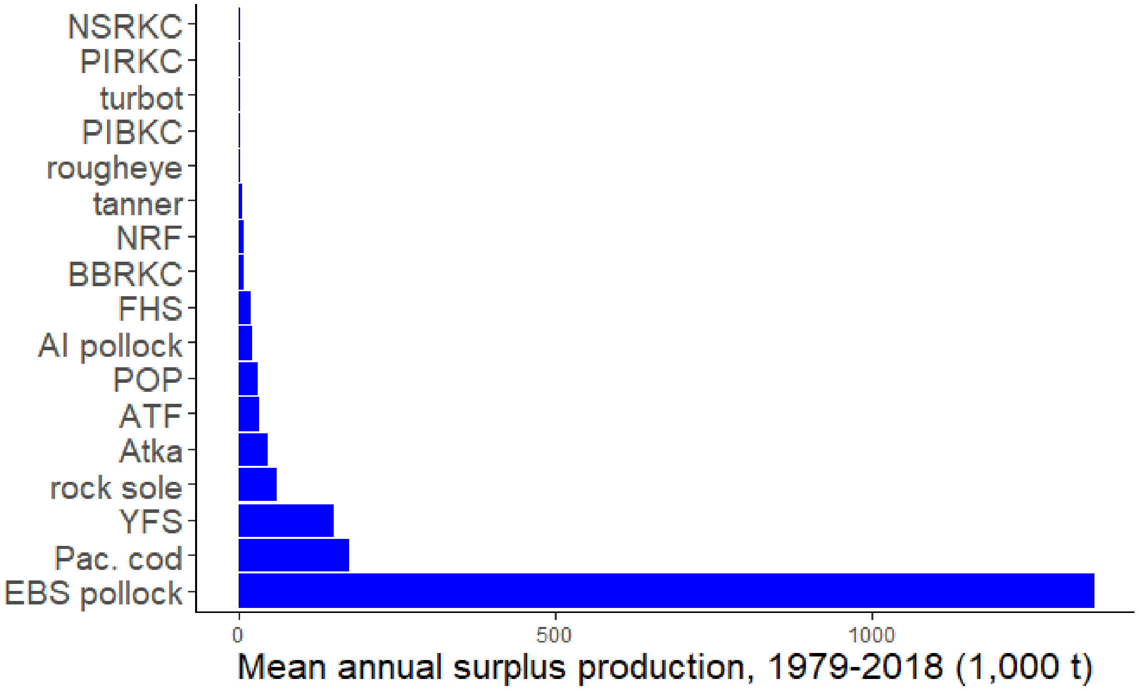

Figure 124: Contributions of each stock to mean annual surplus production.

Implications: Under certain assumptions, aggregate surplus production can provide an estimate of the long-term maximum sustainable yield of these groundfish complexes (Mueter and Megrey (2006), Figure 126). Although there is relatively little contrast in total biomass over time, it appears that biomass was generally above the level that would be expected to yield maximum surplus production under a Graham-Schaefer model fit to aggregate ASP (Figure 126). The estimated maximum sustainable yield for the complex encompassing the 17 stocks in Table 8 was close to 2.0 million tons.

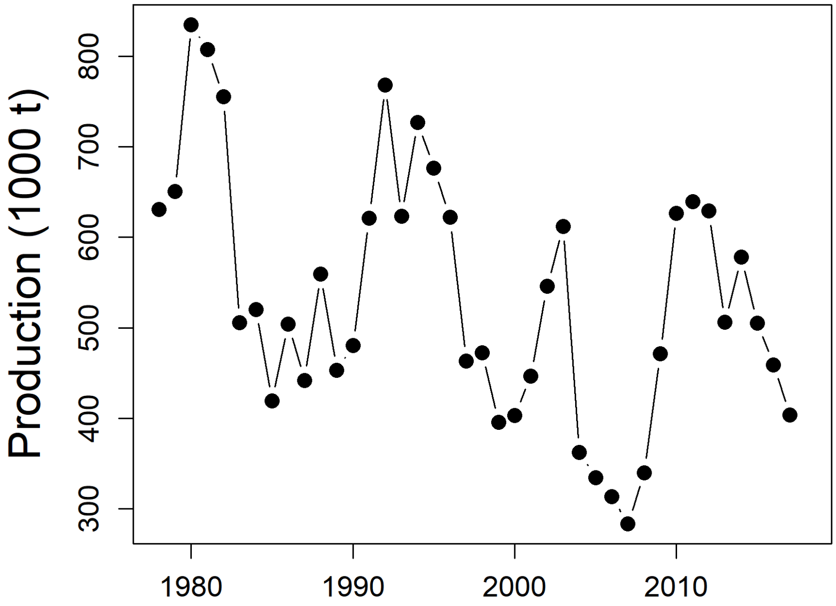

Figure 125: Total annual surplus production (change in biomass plus catch) in the Bering Sea across the major commercial stocks in Table 8, excluding Walleye pollock.

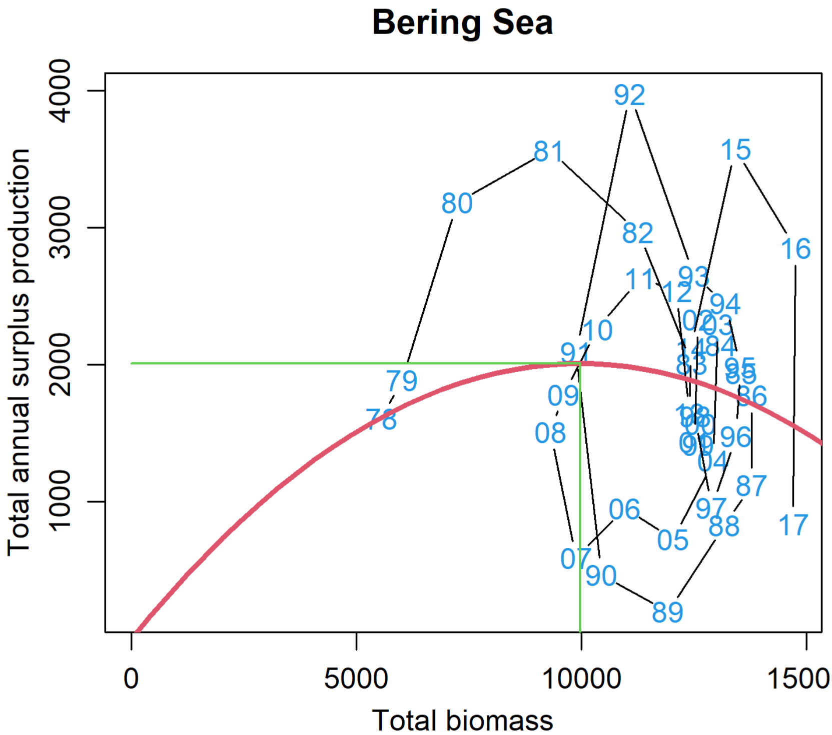

Figure 126: Estimated annual aggregated surplus production against total biomass of major commercial species with fitted Graham-Schaefer curve. Units on both axes are in 1000 t.

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Appendix

History of the ESRs

Since 1995, staff at the Alaska Fisheries Science Center have prepared a separate Ecosystem Status (formerly Considerations) Report within the annual Stock Assessment and Fishery Evaluation (SAFE) report. Each new Ecosystem Status Report provides updates and new information to supplement the original report. The original 1995 report presented a compendium of general information on the Gulf of Alaska, Bering Sea, and Aleutian Island ecosystems as well as a general discussion of ecosystem-based management. The 1996 edition provided additional information on biological features of the North Pacific, and highlighted the effects of bycatch and discards on the ecosystem. The 1997 edition provided a review of ecosystem-based management literature and ongoing ecosystem research, and provided supplemental information on seabirds and marine mammals. The 1998 edition provided information on the precautionary approach, essential fish habitat, effects of fishing gear on habitat, El Niño, local knowledge, and other ecosystem information. The 1999 edition again gave updates on new trends in ecosystem-based management, essential fish habitat, research on effects of fishing gear on seafloor habitat, marine protected areas, seabirds and marine mammals, oceanographic changes in 1997/98, and local knowledge.

In 1999, a proposal came forward to enhance the Ecosystem Status Report by including more information on indicators of ecosystem status and trends and more ecosystem-based management performance measures. The purpose of this enhancement was to accomplish several goals:

1. Track ecosystem-based management efforts and their efficacy
2. Track changes in the ecosystem that are not easily incorporated into single-species assessments
3. Bring results from ecosystem research efforts to the attention of stock assessment scientists and fishery managers
4. Provide a stronger link between ecosystem research and fishery management
5. Provide an assessment of the past, present, and future role of climate and humans in influencing ecosystem status and trends

Each year since 1999, the Ecosystem Status Reports have included some new contributions and will continue to evolve as new information becomes available. Evaluation of the meaning of observed changes should be in the context of how each indicator relates to a particular ecosystem component.

For example, particular oceanographic conditions, such as bottom temperature increases, might be favorable to some species but not for others. Evaluations should follow an analysis framework such as that provided in the draft Programmatic Groundfish Fishery Environmental Impact Statement that links indicators to particular effects on ecosystem components.

In 2002, stock assessment scientists began using indicators contained in this report to systematically assess ecosystem factors such as climate, predators, prey, and habitat that might affect a particular stock. Information regarding a particular fishery's catch, bycatch, and temporal/spatial distribution can be used to assess possible impacts of that fishery on the ecosystem. Indicators of concern can be highlighted within each assessment and can be used by the Groundfish Plan Teams and the Council to justify modification of allowable biological catch (ABC) recommendations or time/space allocations of catch.

We initiated a regional approach to the ESR in 2010 and presented a new ecosystem assessment for the eastern Bering Sea. In 2011, we followed the same approach and presented a new assessment for the Aleutian Islands based on a similar format to that of the eastern Bering Sea. In 2012, we provided a preliminary ecosystem assessment on the Arctic. Our intent was to provide an overview of general Arctic ecosystem information that may form the basis for more comprehensive future Arctic ecosystem assessments. In 2015, we presented a new Gulf of Alaska report card and assessment, which was further divided into Western and Eastern Gulf of Alaska report cards beginning in 2016. This was also the year that the previous Alaska-wide ESR was split into four separate report, one for the Gulf of Alaska, Aleutian Islands, eastern Bering Sea, and the Arctic[27].

The eastern Bering Sea and Aleutian Islands ecosystem assessments were based on additional refinements contributed by Ecosystem Synthesis Teams. For these assessments, the teams focused on a subset of broad, community-level indicators to determine the current state and likely future trends of ecosystem productivity in the EBS and ecosystem variability in the Aleutian Islands. The teams also selected indicators that reflect trends in non-fishery apex predators and maintaining a sustainable species mix in the harvest as well as changes to catch diversity and variability. Indicators for the Gulf of Alaska report card and assessment were also selected by a team of experts, via an online survey first, then refined in an in-person workshop.

Originally, contributors to the Ecosystem Status Reports were asked to provide a description of their contributed indicator, summarize the historical trends and current status of the indicator, and identify potential factors causing those trends. Beginning in 2009, contributors were also asked to describe why the indicator is important to groundfish fishery management and implications of indicator trends. In particular, contributors were asked to briefly address implications or impacts of the observed trends on the ecosystem or ecosystem components, what the trends mean and why are they important, and how the information can be used to inform groundfish management decisions. Answers to these types of questions will help provide a “heads-up” for developing management responses and research priorities. In 2018, a risk table framework was developed for individual stock assessments as a means of documenting concerns external to the stock assessment model, but relevant to setting the Acceptable Biological Catch (ABC) value. These concerns could be categorized as those reflecting the assessment model, the population dynamics of the stock, and environmental and ecosystem concerns—including those based on information from Ecosystem Status Reports. In the past, concerns used to justify an ABC below the maximum calculated by the assessment model were documented in an ad hoc manner in the stock assessment report

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[27] The Arctic report is under development

or in the minutes of the groundfish Plan Teams or Scientific and Statistical Committee reviews. With the risk table, formal consideration of concerns—including ecosystem—are documented and ranked, and the stock assessment author presents a recommendation for the maximum ABC or a value lower. Five risk tables were completed in 2018 as a test case. After review, the Council requested risk tables to be included in all stock assessments in 2019.

In Briefs were started in 2018 for the Eastern Bering Sea, 2019 for the Gulf of Alaska, and 2020 for the Aleutian Islands. These more public-friendly succinct versions of the full ESRs are now planned to be produced in tandem with the ESRs.

In 2019, risk tables were completed for all full assessments. Ecosystem scientists collaborated with stock assessment scientists to use the Ecosystem Status Reports to help inform the ecosystem concerns in the risk tables.

Ecosystem and Socioeconomic Profiles (ESPs) were initiated in 2017 (Sablefish) and ESR editors began working closely with ESP teams in 2019 (starting with GOA walleye pollock). These complimentary annual status reports inform groundfish management and alignment in research that feeds these reports increases efficiency and collaboration between ecosystem and stock assessment scientists.

This report represents much of the first three steps in Alaska's IEA: defining ecosystem goals, developing indicators, and assessing the ecosystems (Figure 127). The primary stakeholders in this case are the North Pacific Fishery Management Council. Research and development of risk analyses and management strategies is ongoing and will be referenced or included as possible.

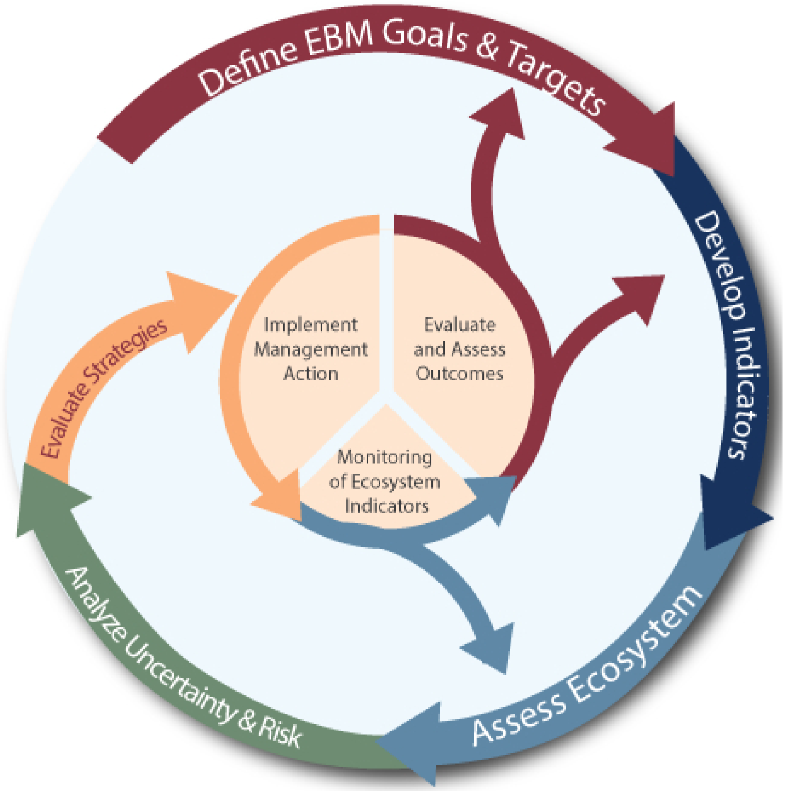

Figure 127: The IEA (integrated ecosystem assessment) process.

It was requested that contributors to the Ecosystem Status Reports provide actual time series data or make them available electronically. The Ecosystem Status Reports and data for many of the time series presented within are available online at: `http://access.afsc.noaa.gov/reem/ecoweb/`. These reports and data are also available through the NOAA-wide IEA website at: `https://www.integratedecosystemassessment.noaa.gov/regions/alaska`.

Past reports and all groundfish stock assessments are available at: `https://www.fisheries.noaa.gov/alaska/population-assessments/north-pacific-groundfish-stock-assessment-and-fishery-evaluation.`

If you wish to obtain a copy of an Ecosystem Considerations Report version prior to 2000, please contact the Council office (907) 271-2809.

Responses to SSC comments from October and December 2020 and October 2021

October 2020: C-1/C-2 Ecosystem Status Report Preview

The SSC received a preview of the Ecosystem Status Reports (ESR) on the Gulf of Alaska (GOA) by Bridgett Ferriss (NOAA-AFSC), the Aleutian Islands (AI) by Yvonne Ortiz (NOAA-AFSC), and the eastern Bering Sea (EBS) by Elizabeth Siddon (NOAA-AFSC). There was no public testimony. The SSC greatly appreciates the clear and informative presentations, which were all the more impressive given the restrictions on data gathering and in-person meetings due to the COVID-19 pandemic.

One issue, common to all three areas, was the lack of surveys and a significant loss in related environmental data. *This issue was least acute in the GOA, as 2020 was a year in which bottom trawl surveys were not scheduled to occur. The problem was most acute in the AI region, as there has not been a bottom trawl survey in three years. Missing too were the zooplankton surveys in the GOA and the EBS. In some cases, these losses were in part mitigated by data from partner organizations, but in others, there was no way to make up for the missing data.*

A second issue common to two of the three areas was the continued presence of elevated SSTs. *These concerns were moderate in the SE Bering Sea, especially in autumn 2019 and summer 2020, and most severe in summer 2020 in the GOA, where temperatures periodically exceeded the Hobday heatwave threshold. There were no data on sub-surface temperatures in the AI or the EBS, but ROMS model estimates were presented. In the GOA, sub-surface temperatures were sufficiently elevated to raise concerns about their effects on larval and juvenile fish.*

Southeastern Bering Sea Report

There was almost no collection of fishery-independent data on either commercially important fish stocks, or environmental data that might have been used to indicate probable year-class strength, or fish distribution. Remote-sensing data on sea-ice cover was available and, for 2020, it appears that ice cover was about average in aerial extent, though perhaps thinner than usual for an average year, and with an early retreat in mid-March. It is unclear how well this thin ice and early retreat will support the 2020 year-classes of pollock and Pacific cod. Reduced levels of chlorophyll-a concentrations (an estimate of phytoplankton biomass), typical of the last five years, may affect fish recruitment, though the connections are not well established. ***The SSC suggested that the authors examine indices of region-wide chlorophyll-a rather than focusing solely on the middle shelf.*** *The unexplained mortality event (UME) of grey whale die-offs continued in 2020. The SSC raised questions as to whether the beaching of grey whales was confined to the Bering Sea.* ***There were apparently beachings of these whales quite far south along the west coast of the United States, and the SSC requested that more information on this topic be provided in the December ESR.*** *If starvation is found to be the most likely cause, it may indicate that the whales have reached or exceeded the carrying capacity of their foraging grounds under current environmental conditions in the northern Bering and Chukchi seas.*

In the full 2020 Ecosystem Status Report, and in the December 2020 presentation to the SSC, a complete suite of chlorophyll-a information was provided. This included time series of chlorophyll-a biomass for 8 regions over the southeastern and northern shelf and time series of bloom timing for 3 regions over the southeastern shelf (bloom timing cannot be determined in the northern portion of the shelf due to sea ice coverage in early spring).

We were unable to acquire additional information on specific causes of gray whale mortalities connected to the UME. When possible, trained and authorized members of the NMFS Alaska Marine Mammal Stranding Network respond and collect life history data and samples as part of a partial or full necropsy; those efforts have been greatly curtailed during the on-going COVID-19 pandemic.

Considerable time was devoted to new modeling of ocean acidification and the spatial distribution of aragonite concentrations over the eastern Bering Sea shelf. From 15 July through August 2020, waters over the outer shelf were likely corrosive. ***The SSC requested that there be an effort to model aragonite concentrations at those times of year and locations where commercially important species of crabs would be most vulnerable and to compare these estimates to threshold levels for deleterious effects for Bristol Bay Red King crab, northern rock sole, and pteropods.***

In the full 2020 Ecosystem Status Report, a "Noteworthy" contribution on Ocean Acidification information available from the ROMS model was presented. The contribution highlighted the type of information that is available to researchers and stock assessment authors and can be tailored, both spatially and temporally, to stock-specific vulnerabilities or known thresholds.

In addition to the "In Brief" handouts developed by ESR authors for public outreach, the ESR authors have been preparing other public outreach materials. Story Maps were developed for the 2019 ESRs and will be produced for the 2020 ESRs, and educational outreach videos based on the ESRs are planned for 2020 to enable additional public engagement. The SSC was pleased to hear how the outreach efforts are being expanded and looks forward to hearing updates on their progress. ***The SSC also recommends that the ESR authors pursue the systematic and consistent incorporation of local knowledge (LK) and traditional knowledge (TK) as relevant to ecosystem status updates and reports.*** *This would be beneficial in the short-term for the identification of potential ecosystem "red flags" especially in a time when researchers do not have timely access to the typical full suite of survey data and over the long-term as the Council moves toward a greater focus on ecosystem-based management. The SSC recognizes that the systematic, methodologically sound, and culturally appropriate collection of all forms of LK and TK is beyond the purview of ESR authors, but sees the benefits of ESR use of these types of data as one more reason for moving forward in building relationships and exploring partnerships with the fishing industry, coastal communities, and regional entities, including tribal entities, in a coordinated manner with ESP authors, SAFE authors, and the Bering Sea LK/TK/Subsistence Task Force, among others.*

The ESR editors agree wholeheartedly in continuing to explore partnerships with the fishing industry, coastal communities, and regional entities, including tribal entities. Such partners have pertinent and relevant knowledge to inform the ESRs, both to help identify "red flags" and provide perspective and context to ecosystem trends. We continue to explore and invite partners to contribute to the ESRs while also awaiting advice on the systematic and consistent incorporation of local knowledge (LK) and traditional knowledge (TK) through the Bering Sea LK/TK/Subsistence Task Force.

The authors questioned the SSC as to whether the SSC would like to continue the practice of having brief ecosystem status updates at the October Council meeting. ***The SSC expressed appreciation for these valuable reports and requested that they be continued annually****, even if there is no pending crisis.*

The ESR authors will continue to provide brief ecosystem status updates at October Council meetings.

December 2020: C-3 BSAI and C-4 GOA Ecosystem Status Reports
The SSC received a review of the marine ecosystems of the Bering Sea (BS) from Elizabeth Siddon (NOAA-AFSC), the Aleutian Islands (AI) from Ivonne Ortiz (University of Washington), and the Gulf of Alaska (GOA) from Bridget Ferris (NOAA-AFSC). There were no public comments.

This year, as in the past, the Ecosystem Status Reports (ESRs) are insightful, well-written, and well-edited. They represent an enormous amount of work accomplished under very tight time constraints. All three chapters were helpful in providing a context within which to assess the stocks of commercially harvested fish in the federal waters of Alaska. As usual, the editors and authors have been responsive to the comments and suggestions provided by the SSC in 2019. The process this year, from the gathering of data to the analysis and presentation of the ESRs, has been affected by the necessary reduction in close personal interactions, whether they be in the laboratory or on a ship. The resulting deficit of new information on the status of the marine ecosystems that the Council manages was apparent to the SSC as it conducted its review of the ESRs for 2020. ***The SSC appreciates the extraordinary efforts made to provide quality ESRs under such difficult circumstances.***

The SSC noted that information from the EBS/AI ESRs were incorporated into the risk tables for 21 BSAI stock assessments (16 recommended ecosystem risk level of 1 and 5 recommended ecosystem risk level of >1). The GOA ESR information was incorporated into the risk tables for 8 stock assessments (7 recommended ecosystem risk level of 1, and sablefish (statewide) was the only assessment with an ecosystem risk level of 2).

Issues of Concern: Southeastern Bering Sea
There were four issues of concern in the EBS that the SSC wished to highlight for the Council:

- *There was an unusually high Prohibited Species Catch (PSC) of herring in the 2020 A season directed pollock fishery. The 2020 PSC of herring exceeded the 2020 herring PSC limit and the Summer Herring Savings Areas (HSA) 1 and Winter HSA were therefore closed. The SSC appreciated the efforts by the pollock fleet to provide information as to why this PSC overage occurred. The pollock fishermen suggested that the increased PSC was not due to a change in spatial or temporal overlap between pollock and herring, but due to an increased abundance of herring. The authors of the report in the ESR provided suggestions for research that could help explain why this high PSC occurred and how to avoid repeating similar high PSC in the future. They suggest a re-evaluation of herring spawning migration by stock, and a re-evaluation of HSAs with respect to their effectiveness for protecting herring. It could also be valuable to retain PSC herring for genetic analysis of the stock of origin.* ***The SSC recommends that efforts be made to address these issues quickly and agrees that the areas of research identified could inform the hypotheses surrounding the increase in herring PSC and the degree of concern about this PSC, depending on the stock of origin.***

- *Starting in late July 2020 and continuing through at least October, communities in the Bering Strait region, and eventually along the Chukchi Sea coast began reporting increased amounts of marine debris, which was predominantly foreign in manufacture, with Russian and Korean characters being readily identifiable. This debris has a potential for disrupting local fishing* *efforts and increasing the potential for ingestion of plastics by marine life (both initially, or in the future, as items degrade).* ***The SSC suggests that the Council may want to collaborate with U.S. and international agencies to determine the origin of the debris, and work toward eliminating future debris discharges.***

- *A new indicator of ocean acidification based on aragonite saturation states suggests that seasonal bottom water corrosive conditions peaked in 2013. Modeled output from a ROMS hindcast for summer 2020 indicated a more strongly corrosive outer shelf domain compared to the 2003–2019 average. The authors concluded that these corrosive conditions likely resulted from bacterial respiration of organic carbon produced by phytoplankton that had sunk below the mixed layer. Increased corrosivity of bottom waters is of concern, particularly for crab stocks. There seems to be little that the Council can do to ameliorate this problem.*
- *Starting in January 2019, and persisting into 2020, elevated numbers of North Pacific gray whales (*Eschrichtius robustus*) died along the west coast of North America, resulting in the declaration of an Unusual Mortality Event (UME). These deaths apparently occurred on the return migration of the whales to Alaska from their breeding grounds along the coast of Baja California, Mexico; reports suggest that they may have died of starvation. Gray whales feed in the northern Bering and Chukchi seas and are benthic feeders (e.g., amphipods, crab larvae). The 2019 mortality events may reflect 2018 feeding conditions in the Bering Sea, conditions experienced during migrations to the south, or a lack of available prey to complete the return migration to the Bering Sea in 2019 (Siddon 2019). The 2019 gray whale UME may also reflect a population approaching carrying capacity. Moore et al. 2001 first suggested that gray whales might be reaching the carrying capacity of their NBS and Chukchi Sea foraging grounds. At that time, there were an estimated 26,635 gray whales. The estimated population as of 2019 was 27,000*[28]*. The carrying capacity, as estimated in 2002, was between 19,830 and 28,470 individuals (Wade et al. 2002). Thus, the deaths of emaciated individuals in 2019, might have been expected. There is little the Council can do to address these mortalities. A survey of the amphipod beds in the NBS and the southern Chukchi Sea could provide information on the condition of food resources compared to what was there in the 1970s and 1980s.*

Ecosystem Trends: Southeastern Bering Sea

Indicators for the prey field (zooplankton and forage fish), seabirds, marine mammals, and holistic ecosystem indicators were missing for 2020 due to the COVID-19 pandemic. Data loss was partially mitigated by participation of citizen scientists, communities, and tribal governments who contributed observations and data. For example, when USFWS seabird monitoring was canceled, coastal community members, tribal governments, and state/university partners provided information on seabird dynamics, which were then synthesized with help from the USFWS. ***The SSC commends and greatly appreciates these efforts and supports development of similar activities that incorporate local and traditional knowledge (LK/TK) and collaborations where possible.***

The ESR editors are equally appreciative to the efforts of partners who have, and continue to, provide local and traditional knowledge (LK/TK) that better our understanding of ecosystem dynamics in the region.

The ESR editors and contributors continue to make strides at improving collaborations with many LK and TK holders. However, at this time, systematic incorporation of LK and TK into the ESR

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[28] `https://www.wbur.org/hereandnow/2019/05/27/gray-whales-wash-up-record-levels`

is outside the scope of these individual contributions and specifically the tasking and objectives of the LKTKS Task Force, and additional efforts focused on incorporating LK and TK into the ESR will be done in coordination with the LKTKS Task Force.

The combined climate section and the combined seabird section were both excellent and much easier to digest. ***The SSC greatly appreciates these efforts to streamline the ESR without losing important information.***

In this year's 2021 Ecosystem Status Report for the Eastern Bering Sea, we again present synthesized sections for (1) Physical Environment Information and (2) Integrated Seabird Information. We hope these sections continue to enhance the utility of the ESRs and the uptake of ecosystem information into the management process.

The use of data on seabirds, salmon and ice conditions to infer zooplankton abundance showed the power of annually gathering multiple, interrelated indices on ecosystem conditions.

We agree that by sampling and understanding the ecosystem holistically, we are better able to infer changes in conditions.

The 2019–2020 daily mean sea ice extent was within one standard deviation of the long-term mean. Sea ice cover exceeded the median extent in February and March of 2020, but had reduced thickness and retreated quickly. The cold pool extent and temperatures (as output from the ROMS hindcast model) were average. ***The SSC suggests that the use of the ROMS model for predicting specific indices in 2020, such as the extent of the cold pool or measures of mean bottom temperatures, continue to be validated with appropriate comparisons of hindcasts with data available from the bottom trawl surveys.***

In this year's 2021 Ecosystem Status Report for the Eastern Bering Sea we include a "Noteworthy" contribution focused on ROMS bottom temperature output, including information and references on model skill and validation.

Both the northern Bering Sea (NBS) and the southeastern Bering Sea (SEBS) have been in a persistent stanza of warm surface waters that has been greater in magnitude and duration than that of the early 2000s. A new metric of sea surface temperature (SST) that indicates when a marine heatwave (MHW) has occurred shows that the threshold for defining a MHW has been persistently exceeded in both the SEBS and NBS for much of the last five years. To date, this warming has not resulted in a major die off of a commercially important species in the EBS. However, there have been considerable re-distributions of stocks in the SEBS and NBS. Projections are for delayed sea ice formation, and moderately warm conditions over the shelf in 2021. ***The SSC urges the Council to seek comprehensive annual surveys of the NBS and collaborations with Russia to ascertain the implications of changing climate on the distribution and health of commercially important stocks.***

Information on primary production indicates that the spring bloom was early in 2020 in the SEBS, and that chlorophyll-a biomass was below average in 2020 in the NBS.

The use of the remotely controlled an Unmanned Surface Vehicle (USV) was superb and provided essential data on pollock distribution and abundance. The SSC suggests that these data be also used to extract information on the distribution and abundance of euphausiids, if possible.

Estimates for euphausiids from the 2020 Saildrone mission are being developed and AFSC staff hope they will be available in 2022. The acoustic equipment on the Saildrone was different from standard ship-based acoustic equipment and therefore further analysis is needed to ensure data are accurate and comparable.

Editorial Comments: all regions
1) ***SSC appreciates the efforts made to standardize and stabilize the formats and methods applied to the ESRs.*** *The ESRs for the EBS and GOA are already well aligned, and it would be good to put the AI ESR into a similar format, where possible. Standardized methodologies across ESRs would not have to be re-reviewed annually and changes to methods could be introduced in such a way that they could be quickly identified as new and then be evaluated. The SSC also continues to encourage the editors of the ESRs to work to reduce redundancy.*

The format of the AI ESR has been updated this year to be more cohesive across all ESRs. Some formatting differences between ESRs will remain as we try to portray the information in a way that highlights particular features of an ecosystem (e.g., regional report cards in the AI). With regards to standardized methodologies, contributors follow the same guidelines for all ESRs. However, sometimes using the same methodology is not possible or suitable, even when using the same kind of data. To help track changes in the ESR, any contribution that is either new or has updated methodology is marked by a dagger in the table of contents; updated contributions (new information, same methodology) are marked with an asterisk. Lastly, in an effort to reduce redundancy, we are removing the executive summary in the front matter of the ESR. Instead, we will focus on the ecosystem assessment and include links to the contributions as they are mentioned. The report card will continue to be included.

2) It would be useful to determine which of the sections of the ESRs are of greatest use to the intended audience.

The ecosystem information in this report is integrated into the annual harvest recommendations through inclusion in stock assessment-specific risk tables, presentations to the Groundfish and Crab plan teams in annual September and November meetings, presentations to the Council in their annual October and December meetings, and submission of the final report to the Council in December. However, the SSC is the primary audience for this report, as the final ABCs are determined by the SSC, based on "biological and environmental scientific information through the stock assessment and Tier process".

The Ecosystem Assessment section of the ESRs are likely to be of greatest use to the SSC in this regard. The assessments are based on a synthesis of myriad data in the reports, but are not necessarily reflective of all the information available. Instead, the authors strive to pull together the 'story' for the ecosystem in the current and previous year based on apparent connections and mechanisms supported by recent trends. Some indicators may be more influential than others in any particular year due to changing environmental conditions or food web interactions. These are highlighted in the Ecosystem Assessment, as well as common trends that may inform unobserved parts of the ecosystem.

Within each standard contribution, the last section is intended to highlight any implications of the indicator trends that could be informative for fisheries managers.

3) ***The SSC recommends that the ESR authors pursue the systematic and consistent incorporation of LK and TK as relevant to ESR.*** *As noted before, we recognize that the systematic, methodologically sound, and culturally appropriate collection of all forms of LK and*

TK is beyond the purview of the ESR authors, but see the benefits of the ESRs incorporating these types of data when available. As demonstrated in the EBS ESR, in light of recent disruptions to surveys due to the pandemic, established protocols for incorporation of LK and TK can be useful for avoiding data gaps.

The Ecosystem Status Report (ESR) team agrees wholeheartedly in continuing to explore partnerships with the fishing industry, coastal communities, and regional entities, including tribal entities. Such partners have pertinent and relevant knowledge to inform the ESRs, both to help identify "red flags" and provide perspective and context to ecosystem trends. We continue to explore and invite partners to contribute to the ESRs while also awaiting advice on the systematic and consistent incorporation of local knowledge (LK) and traditional knowledge (TK) through the Bering Sea LK/TK/Subsistence Task Force.

NOAA's Alaska Fisheries Science Center's Economic and Social Science Research department has stated the following–The social science contributors to the ESR agree that it is important to include LK and TK in the ESRs when this information is available, but caution against its inclusion when there are recognized limitations in the methodological approaches (at present they are neither systematic nor consistent) as well as their limits on representativeness across regions, species, and communities. We recommend continuing additional efforts focused on incorporating LK and TK into the ESR to be done in coordination with the LKTKS Task Force.

4) In addition to the ESR Chapters, the SSC is pleased to see the continued development of the "In Brief" for the EBS and GOA, the addition of a new "In Brief" for the Aleutian Islands, and updated storymaps. We also look forward to seeing the new videos being developed. These resources are essential for efficiently and clearly communicating the main ecosystem patterns to stakeholders and the public, and the ***SSC supports their continued development****.*

In 2020 we produced "In Brief" 4 page summaries for the EBS, GOA, and AI. We also produced an outreach video for the first time, summarizing the GOA 2020 ESR. In 2021 we plan to produce "In Briefs" for the EBS, GOA, and AI and a second outreach video summarizing the ESR products and process.

We have been examining the effort and resources required to produce these various outreach products ("In Brief", storymap, video) with the AFSC communications team and have settled on a strategy that includes the annual production of "In Briefs", intermittent production of storymaps focused on specific ecosystem stories, and no additional videos at this time.

5) The SSC suggests that the use of terms like "normal" is somewhat problematic given that what is "normal" seems to be changing rapidly. Some extremes are becoming normal. Regarding climate issues in particular, and perhaps for other areas in general, it might be better to use "average" and to indicate the years for which the average is calculated. It could also be appropriate to give departures from "average" in terms of standard deviations.

The ESR team agrees with the SSC and is working with our contributors to shift away from the term "normal" and to the term "average", with specified years and standard deviations, where appropriate. In certain contributions that are qualitative or a synthesis of multiple datasets and observations, we are exploring the appropriate terminology that describes the concept of average conditions without using the quantitative term. This is an evolving conversation that reaches beyond the ESRs, particularly in the context of social science and local and traditional knowledge.

6) The MHW index provides a relative value for each season in each year in comparison to a long-term mean. However, it is likely the absolute value that drives ecosystem responses to heat waves via metabolic rates. In this regard, it would be useful if the authors can provide an index that captures the relative metabolic stress.

Metabolic stress, especially when talking about "absolute" temperature values, is highly dependent on species. Bioenergetics indices, incorporating temperature-specific respiration, foraging rates, and varying prey quality, are being or have been incorporated into several stock-specific ESPs as requested by each stock's ESP development team. However, on an ecosystem scale, it would be difficult to develop an absolute stress measure that is meaningful across a wide range of species; rather, a relative index provides a view of how unusual current conditions are compared to past observation, thus indicating greater potential for broad species shifts that may include less stress for warmer-water preferring species alongside decreases in colder-water species. As ESPs expand to include more per-species bioenergetics rates, we are considering future reporting of a "meta-index" to indicate which/how many stocks are experiencing metabolic stress in any given year.

Additionally, the MHW does not seem to be reflected in the stability index. Is this because the index is averaged over 10 years? If so, this index may not be very sensitive to major perturbations of the ecosystem.

The lead contributor has provided a response to this comment: There is a certain amount of inertia built into these indicators. While they are responsive to and reflect change, they are not designed to show immediate and highly sensitive responses to small amounts of change, or change that is acutely felt by a single species. These community level indicators are intended to show when there is community-wide systemic change occurring, that integrate across species-specific responses. The changes in community indicator values during the heatwave may not have been as pronounced as one might have expected, perhaps due to variation in the magnitude and timing of the species-specific responses. While they may all ultimately end up having a similar trajectory in response to the heatwave (e.g., what may be happening with mean length and mean lifespan), it takes some time for the entire community to integrate those environmental changes. In summary, the inertia in these community indicators is intentional and they are designed to indicate systemic community-wide change.

Detailed response reflecting the 2014–2016 marine heatwave: The 10-year average dampens the effect of the survey index dip in 2017 (not 2016). While the survey biomass index dropped in 2017, the drop in the 10-year mean of the survey index was not remarkable. However, this indicator integrates information on both the mean and the variation in the index. In 2017, the survey biomass index was the second lowest over the time series (1999 was the lowest), the 10-year mean was the lowest over the time series, and the SD was the highest over the time-series. What is important to note about the indicator in 2017 is that the 10 [survey] year window included the two lowest survey index values (1999 and 2017) and the four highest index values, over the survey index time series. This led to the high standard deviation in 2017 and thus the low indicator value.

7) How meaningful is the index of mean lifespan of the community if so many species, and especially long-lived species such as rockfish, are excluded?

The lead contributor has provided a response to this comment: The mean lifespan indicator is specific to the portion of the groundfish community that is consistently sampled by the bottom-trawl survey gear. Rockfish are long-lived and would have an impact on the indicator value, particularly if they have high biomass in the survey area. Rockfish have previously been excluded from the bottom-trawl survey index, and thus the mean lifespan indicator, because the bottom-trawl surveys may not adequately sample the habitat or depths where rockfish are frequently found in order to represent their trends in abundance. The eastern Bering Sea shelf bottom-trawl survey is limited to depths less than 200 m and rockfish are routinely caught at only a small number of the standard stations, and in some years, some rockfish species are entirely absent from the survey catch.

Furthermore, the topography of the eastern Bering Sea, with a very large shelf area compared to slope, means that the rockfish contribution would have a minimal effect on the lifespan indicator, even when weighted by age. Therefore, we continue to exclude rockfish from the eastern Bering Sea shelf survey index and related indicators, while noting the need to develop indicators specifically targeted towards the eastern Bering Sea slope region using slope survey data. The Gulf of Alaska bottom-trawl survey samples to much greater depths than in the eastern Bering Sea as part of the standard survey design, the slope represents a larger proportion of the overall Gulf of Alaska survey area, and rockfish species are consistently encountered across all years in the time series. We have reviewed the catch of rockfish in the GOA bottom-trawl survey time series and the relevant stock assessment documents and now include several rockfish species in the Gulf of Alaska bottom-trawl survey index and related indicators.

8) The absolute takes of seabirds in some years, and for some species, are of conservation concern. While a standardized index, such as birds caught per line or net set may be useful for some management purposes, the number of dead birds are more useful from a conservation and ecosystem perspective.

The lead contributor has provided a response to this comment: In general, yes, providing only extrapolated numbers does generate a biased downward depiction of the take of seabirds. For example, the sablefish IFQ fishery has about 15% observer coverage. If we only provided observed takes of seabirds we would theoretically underestimate the seabird bycatch by 85%. We provide observed takes of ESA-listed seabirds (short-tailed albatross, Steller's eider, and spectacled eider), but I think it is less useful for something like northern fulmars whose populations number in the hundreds of thousands. In addition, we provide extrapolated and not extrapolated takes to the SSC when we present our annual bycatch report.

9) There have been suggestions that fluctuations in seabird bycatch possibly reflect prey availability; however, patterns differ among species or species groups. This may be an interesting area to investigate as the time series get longer and the methods of bycatch reduction stabilize. It may also be possible to relate seabird bycatch to die-off events, which also likely reflect a lack of available prey.

We agree with the SSC. We are hoping to include diet data of seabird bycatch in future ESRs to inform seabird bycatch trends and potentially prey availability. Currently, these food habits data exist but are in the process of being centralized into a searchable AFSC database. At that point, they will be available for further analyses to better understand these relationships of interest. We look forward to discussing these data in future ESRs.

10) In the description of fishing and human dimension indicators, it would seem useful to separate landings and price. Ex-vessel value may be what is of concern to economists or the industry, but when the two are multiplied together, the underlying driver behind the final number – whether the amount of fish has gone up or if the price has gone up – is unknown.

The AFSC Economic and Social Science Research Director has provided a response to this comment: The authors are unsure exactly to which area this comment applies. There are ESR contributions both for landings and value by functional group, as well as unit value (price) to make the distinction as suggested by the SSC.

11) Regarding the human dimension indicator of population and population change by community, the SSC recommends that the analysts consider flagging those communities that are currently directly engaged in the harvesting and/or processing sectors of federally managed fisheries.

The AFSC Economic and Social Science Research Director has provided a response to this comment: The social and economic conditions surrounding community participation in federal managed groundfish and crab species are more appropriately covered in the Annual Community Engagement and Participation Overview (ACEPO), which is its primary focus.

12) The addition of new data on HABs is excellent. Should there also be an effort to report on other pollutants and heavy metals?

Unfortunately, there are no yearly or periodic surveys for pollutants and heavy metals. We have included mercury in the food webs in the Aleutian Islands as a Noteworthy contribution as that is an ongoing project and also because levels of concern have been identified for mercury in several species. Threshold levels are not available for a lot of other pollutants (e.g., PCBs) but we will try to incorporate them as Noteworthy contributions as they become available.

13) ***The SSC reiterates that authors who wish to include figures make certain that these figures are readable when reduced to page or half-page size.*** *This has been an issue of concern for a number of years. Perhaps the editors can scan contributions from authors when they are first submitted and return them to the authors if the included figures are unreadable. Fonts within figures are a particular problem; and figures that show long-term trends might benefit from zooming in on more recent years to show current trends.*

The ESR authors continue to work with contributors to improve the readability and utility of submitted figures.

October 2021: D3 October Preview of Ecosystem Status Reports

The SSC received presentations by Elizabeth Siddon (NOAA-AFSC), Bridget Ferriss (NOAA-AFSC), and Ivonne Ortiz (UW-CICOES) on the Ecosystem Status Reports (ESR) for the EBS, the GOA, and the AI. Overall, data loss due to COVID in 2021 was limited in the GOA and AI, and moderate in the EBS with most loss due to survey cancellations, survey reductions (smaller footprints), and lab/data processing delays. Though preliminary, the presentations were informative and highlighted the great strides that the authors and editors of the ESRs have made in producing documents that are insightful and of benefit to the management of Federal fisheries off Alaska. The SSC appreciates the consistent high quality of the ESR presentations and looks forward to seeing the final products in December. Public testimony was provided by Chris Tran (Aleut Corporation of St. Paul).

The NPI was strongly positive in winter 2020–2021, the AO was negative in winter and positive in spring and summer 2021, while the PDO was negative. Water temperatures were warmer than average offshore and cooler inshore.

Eastern Bering Sea

In 2021, there was a decoupling of the winds in the NBS (strong winds from the north) and the southeastern Bering Sea (moderate to strong winds from the south). As a result, there was widespread and thick sea ice in the northern Bering, and reduced sea-ice extent and thickness in the southeast. Over the southeastern shelf, the advancement of sea ice stalled at the end of January, resulting in a relatively small cold pool, similar in size to those occurring in the warm years of the early 2000s. In 2021, air temperatures, as measured at St. Paul Island, were again quite warm, continuing the period of temperatures above the 100-year mean observed since 2012. This period of above average air temperatures is also reflected in total annual cumulative SSTs being high since 2012, particularly in the southeastern Bering Sea. The winter SSTs in 2021 were slightly below the long-term mean in the north, and somewhat above the long-term mean in the southeastern Bering Sea. Summer SSTs were above average throughout the eastern Bering Sea, though less warm than in 2019. The inner shelf south of St. Matthew Island was closer to the long-term mean than were the middle or outer shelf regions. There was no indication of a marine heatwave in the NBS, but in the southeastern Bering Sea, temperatures briefly achieved heatwave status.

Red Flags

The presentation noted several red flags related to population declines or die-offs occurring in the EBS. In 2021, there was a 25% decline in BBRKC mature female biomass and a sharp, 69% decrease in legal male snow crab in the survey. There were also seabird die-offs in the NBS and the AYK Chinook and chum salmon returns were low. There is apparently no "smoking gun" as to the causes of the precipitous declines in snow crab and sustained period of low production of BBRKC, but several hypotheses related to changing ocean environmental conditions will be explored and presented by the ESR authors at the December Council meeting including: cumulative impacts of thermal exposure and metabolic demands, changes in stratification and vertical distribution of prey resources, and prey switching and lack of functional redundancy. ***The SSC looks forward to the synthesis of more indicators in the full ESR in December and emphasizes the need for mechanistic studies, especially as they relate to the benthos in the EBS, to understand the impacts of climate change****.*

Please see the Ecosystem Assessment (p. 8) for the full synthesis and discussion of ecosystem indicators and status of 2021.

Description of the Report Card Indicators

1. The North Pacific Index (NPI) winter average (Nov-Mar): The NPI index (Trenberth and Hurrell, 1994) was selected as the single most appropriate index for characterizing the climate forcing of the Bering Sea. The NPI is a measure of the strength of the Aleutian Low, specifically the area-weighted sea level pressure (SLP) for the region of 30°N to 65°N, 160°E to 140°W. Above (below) average winter (November–March) NPI values imply a weak (strong) Aleutian Low and generally calmer (stormier) conditions.

The advantage of the NPI include its systematic relationship to the primary causes of climate variability in the Northern Hemisphere, especially the El Niño-Southern Oscillation (ENSO) phenomenon, and to a lesser extent the Arctic Oscillation (AO). It may also respond to North Pacific SST and high-latitude snow and ice cover anomalies, but it is difficult to separate cause and effect.

The NPI also has some drawbacks: (1) it is relevant mostly to the atmospheric forcing in winter, (2) it relates mainly to the strength of the Aleutian Low rather than its position, which has also been shown to be important to the seasonal weather of the Bering Sea (Rodionov et al., 2007), and (3) it is more appropriate for the North Pacific basin as a whole than for a specific region (i.e., Bering Sea shelf).

Implications: For the Bering Sea, the strength of the Aleutian Low relates to wintertime temperatures, with a deeper low (negative SLP anomalies) associated with a greater preponderance of maritime air masses and hence warmer conditions.

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2. Bering Sea ice extent: The Bering Sea ice year is defined as 1 August–31 July. Bering Sea ice extent data are from the National Snow and Ice Center's Sea Ice Index, version 3 (Fetterer et al., 2017), and use the Sea Ice Index definition of the Bering Sea, effectively south of the line from Cape Prince of Wales to East Cape, Russia (i.e., this index includes ice extent in both the western and eastern Bering Sea). The daily mean annual ice extent integrates the full ice season into a single value. *Implications:* Seasonal sea ice coverage impacts, for example, the extent of the cold pool, bloom strength and timing, and bottom-up productivity.

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3. Cold pool extent: Area of the cold pool in the eastern Bering Sea (EBS) shelf bottom trawl survey area (including strata 82 and 90) from 1982–2021. The cold pool is defined as the area of the southeastern Bering Sea continental shelf with bottom temperature <2°C, in square kilometers (km^2). *Implications:* The cold pool has a strong influence on the thermal stratification and influences the spatial structure of the demersal community (Spencer, 2008; Kotwicki and Lauth, 2013; Thorson et al., 2020), trophic structure of the eastern Bering Sea food web (Mueter and Litzow, 2008; Spencer et al., 2016), and demographic processes of fish populations (Grüss et al., 2021).

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4. Aggregate forage fish: This index aggregates survey biomass estimates for key forage fish species in the eastern Bering Sea. The constituents are members of the "forage fish" group included as Ecosystem Components in the BSAI Fishery Management Plan: eulachon, Pacific capelin, sand lance species, rainbow smelt, Pacific sandfish, and a group of minor smelt species. This aggregate does not include important forage species such as age-0 Walleye pollock or Pacific herring. The biomass estimates are from the eastern Bering Sea shelf bottom trawl survey including the northwestern survey strata 82 and 90. Because this survey is not optimized for small pelagic fishes, the data should be viewed with caution. *Implications:* Forage fish fill an important trophic niche in the food web of the eastern Bering Sea. When this index is higher, there is more food available to upper trophic predators (including fish, seabirds, and mammals), and vice versa.

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5., 6., 7., 8. Description of the Fish and Invertebrate Biomass Indices: We present four guilds to indicate the status and trends for fish and invertebrates in the eastern Bering Sea: motile epifauna, benthic foragers, pelagic foragers, and apex predators. Each is described in detail below. The full guild analysis involved aggregating all eastern Bering Sea species included in a food web model (Aydin and Mueter, 2007) into 18 guilds by trophic role, habitat, and physiological status (Table 9). For the four guilds included here, time trends of biomass are presented for 1982–2021. Foraging guild biomass is based on catch data from the NMFS-AFSC annual summer bottom trawl survey of the EBS shelf (<200 m), modified by an Ecopath-estimated catchability coefficient that takes into account the minimum biomass required to support predator consumption (see Appendix 1 in (Boldt, 2007) for complete details). This survey index is specific to the standard bottom trawl survey area in the southeastern Bering Sea (does not include strata 82 and 90) and does not include the northern Bering Sea. New this year, foraging guild biomass is weighted by strata area (km^2) which has resulted in a minor shift in the biomass values from reporting in previous years but the trends and patterns remain the same. Also, we no longer include species that lack time series and were previously represented by a constant biomass equal to the mid-1990s mass balance level estimated in (Aydin and Mueter, 2007).

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5. Motile epifauna (fish and benthic invertebrates): This guild includes both commercial and non-commercial crabs, sea stars, snails, octopuses, other mobile benthic invertebrates, and eelpouts. There are ten commercial crab stocks in the current Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs; we include seven on the eastern Bering Sea shelf: two red king crab *Paralithodes camtschaticus* (Bristol Bay, Pribilof Islands), two blue king crab *P. platypus* (Pribilof District and St. Matthew Island), one golden king crab *Lithodes aequispinus* (Pribilof Islands), and two Tanner crab stocks (southern Tanner crab *Chionoecetes bairdi* and snow crab *C. opilio*). The three dominant species comprising the eelpout group are marbled eelpout (*Lycodes raridens*), wattled eelpout (*L. palearis*), and shortfin eelpout (*L. brevipes*). The composition of seastars in shelf trawl catches is dominated by the purple-orange seastar (*Asterias amurensis*), which is found primarily in the inner/middle shelf regions, and the common mud star (*Ctenodiscus crispatus*), which is primarily an inhabitant of the outer shelf. *Implications:* Trends in

Table 9: Composition of foraging guilds in the eastern Bering Sea.

Motile Epifauna	**Benthic Foragers**	**Pelagic Foragers**	**Apex Predators**
Eelpouts	Yellowfin sole	W. pollock	P. cod
Octopuses	Flathead sole	P. herring	Arrowtooth
Tanner crab	N. rock sole	Atka mackerel	Kamchatka fl.
King crab	Alaska plaice	Misc. fish shallow	Greenland turbot
Snow crab	Dover sole	Salmon returning	P. halibut
Sea stars	Rex sole	Capelin	Alaska skate
Brittle stars	Misc. flatfish	Eulachon	Other skates
Other echinoderms	Greenlings	Sandlance	Sablefish
Snails	Other sculpins	Other pelagic smelts	Large sculpins
Hermit crabs		Other managed forage	
Misc. crabs		Scyphozoid jellies	

the biomass of motile epifauna indicate benthic productivity and/or predation pressure, although individual species and/or taxa may reflect shorter or longer time scales of integrated impacts of bottom-up or top-down control.

6. Benthic foragers (fish only): The species which comprise the benthic foragers group are the Bering Sea shelf flatfish species, greenlings, and small sculpins. *Implications:* Trends in the biomass of benthic foragers indirectly indicate availability of infauna (i.e., prey of these species).

7. Pelagic foragers (fish and Scyphozoid jellies only): This guild includes adult and juvenile Walleye pollock (*Gadus chalcogrammus*), other forage fish such as Pacific herring (*Clupea pallasi*), Capelin (*Mallotus villosus*), Eulachon (*Thaleichthys pacificus*), and Sandlance, salmon, Atka mackerel (*Pleurogrammus monopterygius*), and Scyphozoid jellies. *Implications:* Trends in the biomass of pelagic foragers largely track Walleye pollock which is an important component of the Bering Sea ecosystem, both as forage and as a predator.

8. Apex predators (shelf fish only): This guild includes Pacific cod (*Gadus macrocephalus*), Arrowtooth flounder, Kamchatka flounder (*Atheresthes evermanni*), Pacific halibut (*Hippoglossus stenolepis*), Greenland turbot (*Reinhardtius hippoglossoides*), Sablefish (*Anoplopoma fimbria*), Alaska skate, and large sculpins. *Implications:* Trends in the biomass of apex predators indicate relative predation pressure on zooplankton and juvenile fishes within the ecosystem.

9. Habitat impacted by trawls: Fishing gear can affect habitat used by a fish species for the processes of spawning, breeding, feeding, or growth to maturity. This indicator uses output from the Fishing Effects (FE) model to estimate the habitat reduction of geological and biological features over the Bering Sea domain, utilizing spatially-explicit VMS data. The indicator reflects an estimate of time that gear is in contact with the substrate; disturbance is assumed cumulative over the year, therefore the December value of each year is plotted. Further detail on this index is reported on p. 202. *Implications:* An estimate of the area of seafloor disturbed by trawl gear provides an indication of habitat disturbance.

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Methods Description for the Report Card Indicators

For each plot, the mean (green dashed line) and ±1 standard deviation (SD; green solid lines) are shown as calculated for the entire time series. Time periods for which the time series was outside of this ±1 SD range are shown in yellow (for high values) and blue (for low values).

The shaded green window shows the most recent 5 years prior to the date of the current report. The symbols on the right side of the graph are all calculated from data inside this 5-year moving window (maximum of 5 data points). The first symbol represents the "2016–2020 Mean" as follows: '+ or -' if the recent mean is outside of the ±1 SD long-term range, '.' if the recent mean is within this long-term range, or 'x' if there are fewer than 2 data points in the moving window. The symbol choice does not take into account statistical significance of the difference between the recent mean and long-term range. The second symbol represents the "2016–2020 Trend" as follows: if the magnitude of the linear slope of the recent trend is greater than 1 SD/time window (a linear trend of >1 SD in 5 years), then a directional arrow is shown in the direction of the trend (up or down), if the change is <1 SD in 5 years, then a double horizontal arrow is shown, or 'x' if there are fewer than 3 data points in the moving window. Again, the statistical significance of the recent trend is not taken into account in the plotting.

The intention of the figure is to flag ecosystem features and the magnitude of fluctuations within a generalized "fisheries management" time frame (i.e., trends that, if continued linearly, would go from the mean to ±1 SD from the mean within 5 years or less) for further consideration, rather than serving as a full statistical analysis of recent patterns.