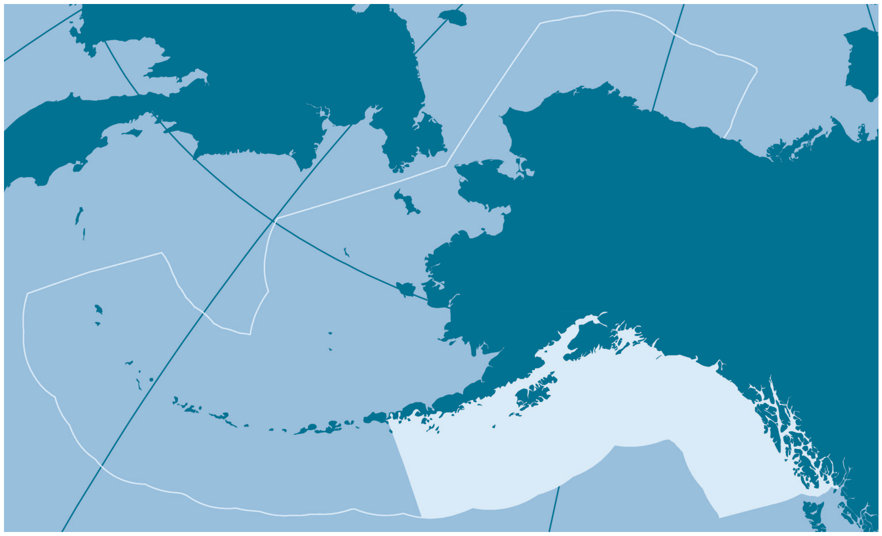
Ecosystem Status Report 2021
Gulf of Alaska



Edited by:
Bridget Ferriss and Stephani Zador
Resource Ecology and Fisheries Management, Alaska Fisheries Science Center, NOAA

With contributions from:
Grant Adams, Robyn Angliss, Mayumi Arimitsu, Kelia Axler, Kerim Aydin, Brenda Ballachey, Steve Barbeaux, Sonia Batten, Barb Bodenstein, James Bodkin, Nick Bond, Eric Bortz, Matt W. Callahan, Rob Campbell, Doug Causey, Jack Chen, Wei Cheng, Heather Coletti, Dan Cooper, Jessica Crance, Deana Crouser, Daniel Cushing, Seth Danielson, Thomas Dean, Alison Deary, Jane Dolliver, Martin Dorn, Sherri Dressel, Brie Drummond, Darcy Dugan, Anne Marie Eich, Daniel Esler, Grace Ellwanger, Thomas Farrugia, Emily Fergusson, Benjamin Fissel, Christine Gabriele, Sarah Gaichas, Jeanette Gann, Kim Goetz, Andrew Gray, Colleen Harpold, Courtney Hart, Scott Hatch, Stormy Haught, Kyle Hebert, Steve Heinl, Dom Hondolero, Kris Holderied, Anne Hollowed, Kirstin Holsman, Russell Hopcroft, Jim Ianelli, Katrin Iken, Annette Jarosz, Tim Jones, Robb Kaler, Steve Kibler, David Kimmel, Alexander Kitaysky, Kim Kloecker, Brenda Konar, Joseph Krieger, Ned Laman, Geoffrey M. Lang, Kari Lanphier, Jean Lee, Mandy Lindeberg, Alexander Kitaysky, Caitlin Marsteller, Rosie Masui, Caitlin McKinstry, Daniel Monson, John Moran, Franz Mueter, Jamal Moss, James Murphy, Jens Nielsen, Janet Neilson, Cecilia O'Leary, John Olson, Olav Ormseth, Clare Ostle, Wayne Palsson, W. Scott Pegau, John Piatt, Andrew Piston, Chandra Poe, Justin T. Priest, André Punt, Matthew Redlinger, Heather Renner, Brian Robinson, Lauren Rogers, Sean Rohan, Natalie Rouse, Gregory T. Ruggerone, Joshua Russell, Kate Savage, Sarah Schoen, Leon D. Shaul, Valerie Shearn-Bochsler, Kate Sheehan, Kevin Siwicke, Matthew Smith, Ingrid Spies, Ian Stewart, Janice Straley, William Stockhausen, Wesley Strasburger, Robert Suryan, Fred Tremblay, John Trochta, Caroline Van Hemert, Scott Vulstek, Muyin Wang, Jordan Watson, Ben Weitzman, Shannon Whelan, George A. Whitehouse, Alexis Will, Matthew Wilson, Carrie Worton, Bruce Wright, Ellen Yasumiishi, Stephani Zador, and Alex Zerbini

Reviewed by:
The Gulf of Alaska Groundfish Plan Team
November 19, 2021
North Pacific Fishery Management Council
1007 West Third, Suite 400, Anchorage, AK 99501

Support for the assembly and editing of this document was provided jointly by NOAA Fisheries and the NOAA Integrated Ecosystem Assessment (IEA) program. This document is NOAA IEA program contribution #2021_7.

The recommended citation for this document is as follows:
Ferriss, B.E. and Zador, S. 2021. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska 99501.

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.253).

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

Western Gulf of Alaska 2021 Report Card

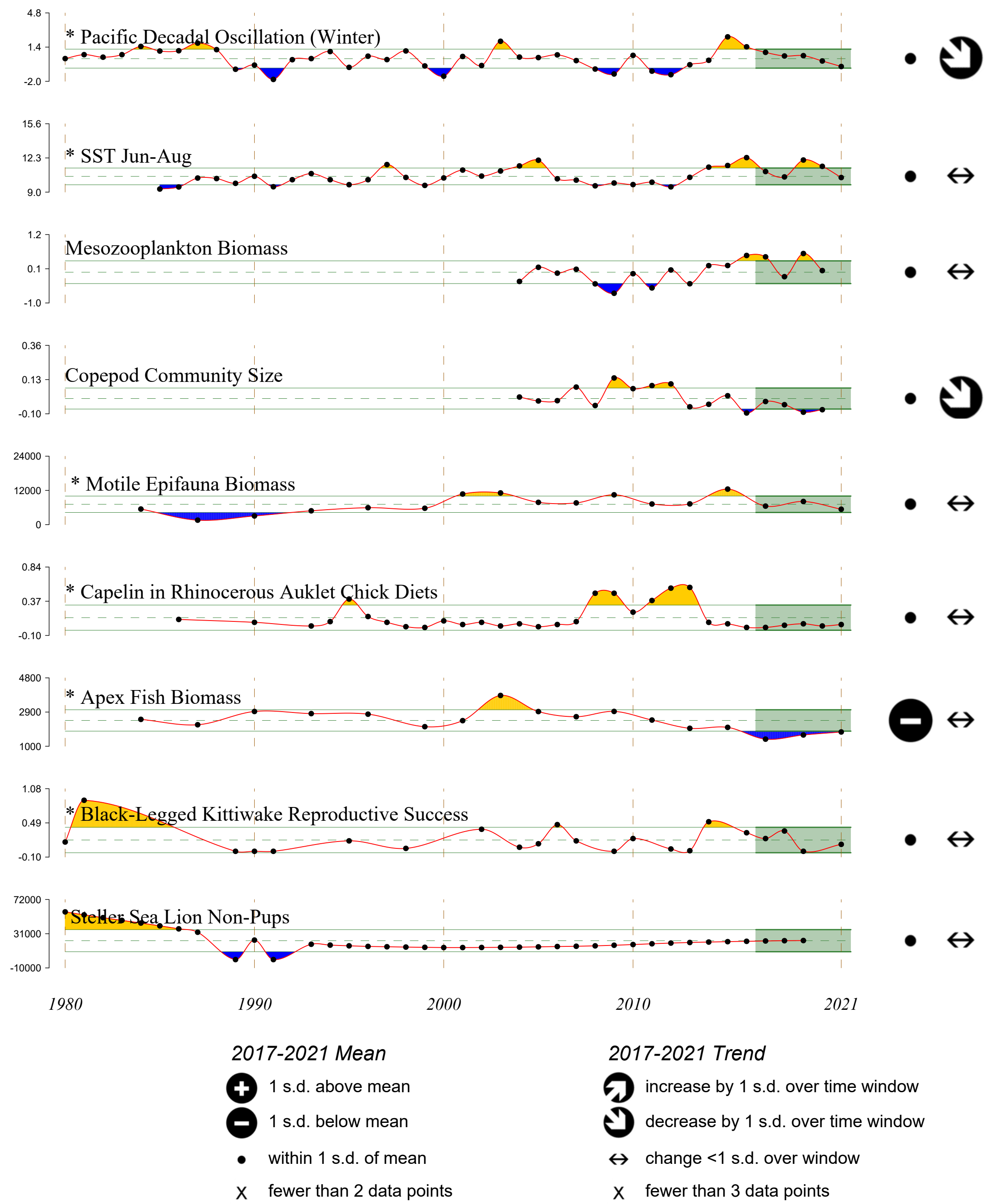


Figure 1: Western Gulf of Alaska report card indicators. See bullets below and the full report for descriptions. * indicates time series updated with 2021 data

Eastern Gulf of Alaska 2021 Report Card

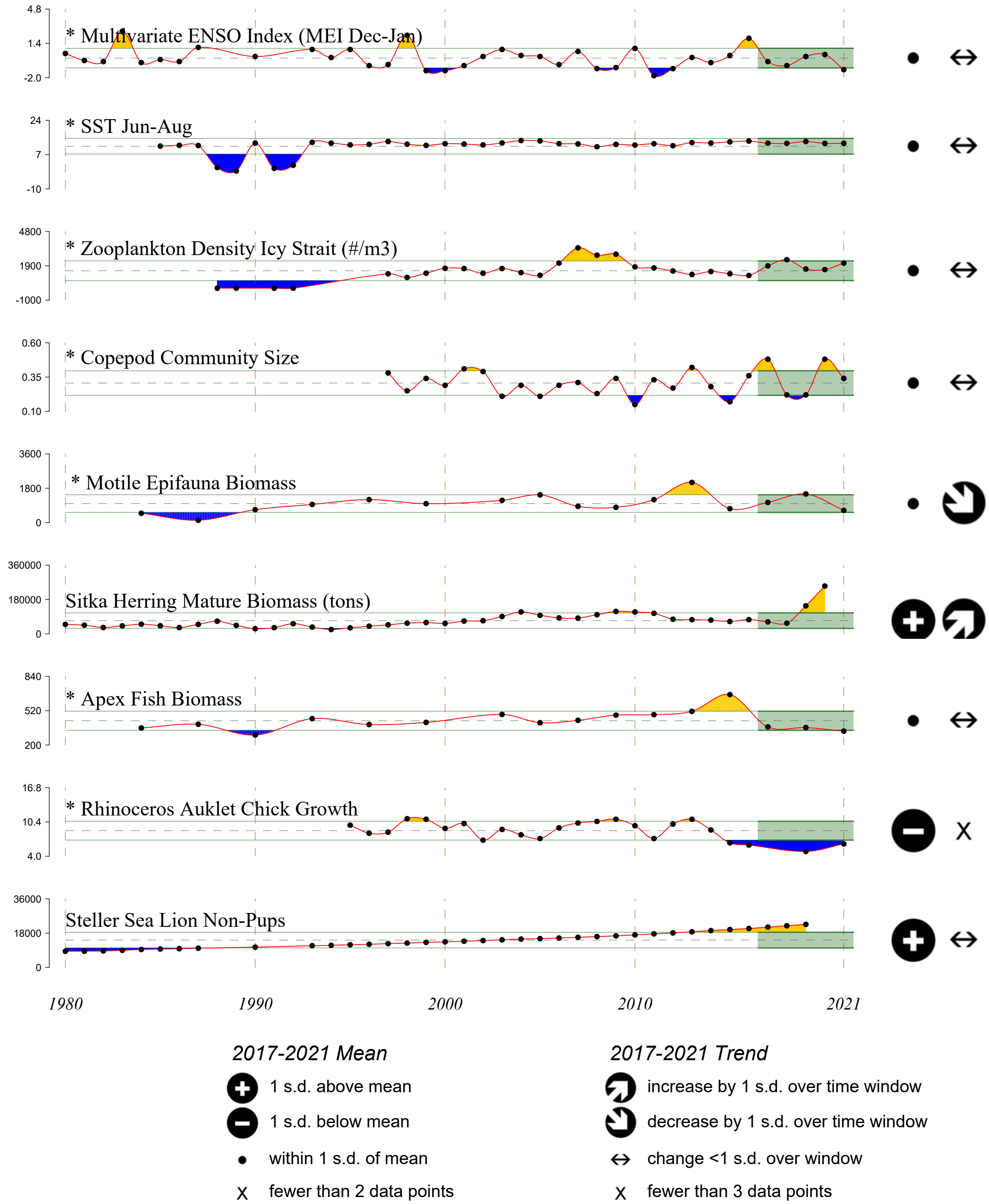


Figure 2: Eastern Gulf of Alaska report card indicators. See bullets below and the full report for descriptions. * indicates time series updated with 2021 data

Western Gulf of Alaska 2021 Report Card

For more information on individual Report Card indicators, please see "Report Card indicator Description and Methods" in the Appendix of this Report (p.264).

- The **Winter average PDO index (Dec.-Feb.)** continued its **negative trend** in 2021, reflecting cooling sea surface temperatures in the GOA.
- **Summer (June-August) 2021 sea surface temperatures** in the western GOA were generally lower than 2020, returning to **within 1SD of the long-term mean**, although spring surface temperatures were elevated.
- **Mesozooplankton biomass** (sampled April-Sept) decreased in 2020 to **within 1SD of the long-term mean**, measured by the continuous plankton recorder, indicating **average foraging conditions for planktivorous predators**. These data are not yet available for 2021.
- **Copepod community size slightly increased in 2020** (sampled April-Sept), to **within 1SD of the long-term mean**, but remains low, indicating there were slightly more large species available (often considered of higher nutritional quality). These data are not yet available for 2021.
- **Motile epifauna biomass**, observed during 2021 AFSC bottom trawl survey (May-Aug), **decreased from 2019 to 2021 but remains within 1SD of the long-term mean**. The biomass of this guild is dominated by octopuses, hermit crabs, and brittle stars. Hermit crabs, brittle stars, and octopus are below their long-term means while other echinoderms are above their long term mean.
- Trends in **capelin**, as sampled by rhinoceros auklets at Middleton Island (April-Aug.), **continue to be minimal in seabird chick diets in recent years, including 2021** but still remain **within 1SD of the long-term mean**. They were abundant from 2008 to 2013, during a period of cooler ocean temperatures.
- **Fish apex predator biomass**, observed during 2021 AFSC bottom trawl survey (May-Aug), increased from 2019 to 2021 to within **just above 1SD below the long-term mean**. The primary species driving these trends include **Pacific cod biomass, continuing to stay above their low in 2017** but remain below their long term mean, **Arrowtooth flounder, which has trended upward** since their low in 2017 but also remain below their long-term mean, and **sablefish which are well above their long-term mean**.
- **Black-legged kittiwakes reproductive success in 2021** (June-July) increased from 2020 and remain **within 1SD of the long-term mean** at the Semidi Islands potentially indicating moderate prey availability for these surface-feeding seabirds.
- Modelled estimates of **western Gulf of Alaska Steller sea lion non-pup counts continued a slightly increasing trend from previous years, remaining within 1SD of the long-term mean** in 2019, however realized counts for non-pups (not shown here) show the lowest values in this area since 2011. These data have not been updated since 2019.

Eastern Gulf of Alaska 2021 Report Card

- **La Niña conditions** prevailed in winter 2020/2021 (Multivariate ENSO Index: Dec./Jan.). La Niña conditions are predicted for winter 2021/2022.
- **Summer (June-Aug.) 2021 sea surface temperatures** in the eastern GOA remain **within 1SD of the long-term mean**.
- Total **zooplankton density in in SEAK inside waterst (May-Aug) increased** from 2020 but remains **within 1SD of the long-term mean**. This suggests **improved foraging conditions for planktivorous fish, seabirds, and mammals**.
- The **overall copepod community size** (ratio of large calanoid copepods to total calanoid copepods) **decreased to within 1SD of the long-term mean** in 2021 (May-Aug) due to decreased densities of large copepods (although still above average) and increased densities of small copepods.
- **Motile epifauna biomass**, observed during 2021 AFSC bottom trawl survey (May-Aug), decreased from 2019 to 2021 but remains **within 1SD of the long-term mean**. Hermit crabs, brittle stars, and other echinoderms are all below their long-term means. Eelpouts have also decreased from 2019 to 2021 but remain above their long term mean.
- **Estimated total mature herring biomass (age 3+) of Sitka herring in spring 2020 continued to increase** to the largest value in the time series (since 1980), remaining **greater than1SD above the long-term mean**. The two populations with ocean influence (Sitka Sound and Craig) were elevated while populations in SEAK inner waters and Prince William Sound increased but remained low. These data are not yet available for 2021.
- **Fish apex predator biomass**, observed during 2021 AFSC bottom trawl survey (May-Aug), trended downward from a high in 2015 to their **second lowest value over the time series in 2021**, but remainnig just within 1SD of the long-term mean. The decrease over this time period has largely been driven by arrowtooth flounder which are at their lowest value over the time series, more than one standard deviation below their long term mean. Pacific halibut, sablefish, and Pacific cod, have all increased from 2019 and are above their long term means.
- **Growth rates of piscivorous rhinoceros auklet chicks remain 1SD below the long-term mean in 2021** (June-July), a pattern since 2015, suggesting that the adults were unable to find sufficient prey to support optimal chick growth.
- Modelled estimates of eastern Gulf of Alaska **Steller sea lion non-pups counts continue an increasing trend above 1SD of the long-term mean through 2019**. However, counts suggest that non-pup have been lower than predicted in 2019 and 2017. These data have not been updated since 2019.

Ecosystem Assessment

Bridget Ferriss, Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: bridget.ferriss@noaa.gov
Last updated: November 2021

This assessment reflects the recognition that the western and eastern GOA ecosystems (divided at 147°W) have substantial differences. The GOA is characterized by topographical complexity, including islands, deep sea mounts, a continental shelf interrupted by large gullies, and varied and massive coastline features such as the Cook Inlet, Prince William Sound, Copper River, and Cross Sound, which bring both freshwater and nutrients into the GOA. The topographical complexity leads to ecological complexity, such that species richness and diversity differ from the western to eastern GOA. Thus, local effects of ecosystem drivers may swamp basin-wide signals. With this in mind, we present report cards and assessments of current ecosystem state for the western and eastern GOA ecoregions separately to highlight inherent differences.

The Gulf of Alaska: Multi-Year Trends

There have been large fluctuations in the GOA groundfish community biomass at a species and functional group level, since the 2014–2016 marine heatwave, with increases in certain species (e.g., sablefish, Pacific Ocean perch, herring) and decreases in others (e.g., capelin, Pacific cod, arrowtooth flounder). Seabirds (e.g., common murres) and marine mammals (e.g., Prince William Sound humpback whales) have also undergone large changes in abundance. The GOA is still in transition from this period, in terms of shifts in species-specific biomass. The Pacific Decadal Oscillation has become negative (p.31) and ocean temperatures had a second consecutive year of temperatures closer to long-term averages (p.39), which are more characteristic of pre-heatwave environmental conditions. However, despite these environmental shifts, we have not observed a complete return to the pre-heatwave biological community. Potential explanations of this continued transitional status are briefly described below. If 2022 continues to experience cooler ocean temperatures, as predicted (p.36), it will be interesting to see if the biological community continues to recover or if alternate biomass trends and food web dynamics persist.

1. *Cumulative effects of and variable recovery times* to the 2014–2016 and 2019 marine heat wave years (Suryan et al., 2021; Arimitsu et al., 2021). Some species continue to have reduced populations since the heat wave periods, and have not responded to cooler waters and

periods of improved lower trophic productivity of 2017/2018 and 2020. Examples of these species include capelin, common murres, Prince William Sound humpback whales, groundfish condition (consistently below average for a subset of species), and abundance of some groundfish species (e.g., Pacific cod). Delayed species' effects and responses to the heatwaves may be due to life history (long-lived species will respond and recover more slowly, e.g., common murres), changes in age structure or population demographics (e.g., capelin), asynchronous recovery of the Gulf food web, or reduced system productivity (see #2 below). Changes in epifaunal habitat, such as a seven-year decline in sponges (as sampled by the AFSC bottom trawl survey, p.59 and fishery observer data, p.213), may also hinder the recovery of structure-oriented species (e.g., certain rockfish).

2. *Lower system productivity in the GOA.* The GOA may be experiencing continued, reduced productivity at the base of the food web, due to below-average chlorophyll-a in the eastern GOA since 2016 and three of the lowest levels in the western GOA in the past six years (p.63). In addition, the GOA has experienced a persistent shift in euphausiid species community composition and larger lipid-rich copepods have had reduced abundance (with exceptions in certain years) since the 2014–2016 marine heatwave (Arimitsu et al., 2021, p.70, Hopcroft pers. comm.). The body condition (weight at length) of a subset of groundfish species continues to be below average since 2015 (including southern rock sole, Pacific Ocean perch, age 2+ walleye pollock, southern rockfish, northern rockfish, dusky rockfish, and arrowtooth flounder) (p.130), and age-0 walleye pollock from around the Semidi Islands have had negative condition from 2015-2019 (2021 data are not available, p.88). Juvenile sablefish are shifting their distribution to deeper than traditional waters off the shelf, potentially in response to poor foraging conditions (Goethel et al., 2021). In addition, the total biomass of apex groundfish predators (Pacific cod, sablefish, Pacific halibut, arrowtooth founder) is still one standard deviation below the long-term mean (although the sablefish population has been increasing) (p.174). Certain seabirds (e.g., common murres) and humpback whales (Prince William Sound whales) also remain at reduced population sizes (p.206). There are numerous examples of other species that have recovered and/or exceeded pre-heatwave abundances (e.g., SEAK herring and sablefish), adding complexity to this theory.

3. *Pink salmon have high returns in 2021*, with potential for competition and predation impacts, within the past year (p.106). Pink salmon feed on zooplankton, squid, and small fish, which can lead to reduced abundance of large copepods (grazing pressure) and increased large diatoms (reduced grazing pressure from copepods) (Batten et al., 2018), reduced reproductive success of black-legged kittiwakes (Zador et al., 2013), changes in diet and reduced size of other salmon species (Tadokoro et al., 1996; Ruggerone et al., 2003), and reduced condition of short-tailed shearwaters (Toge et al., 2011). While trophic cascades in open ocean systems is debated, these trends were supported in 2021 with observations of increased diatom abundance (p.65), regions of reduced large copepods (around Kodiak Island, p.70, but not along the Seward Line, p.76), and reduced black-legged kittiwake reproductive success on Middleton Island and Semidi Islands, but not on the Barren Islands (p.152).

Interestingly, at a broad ecosystem level, the Gulf of Alaska groundfish community is relatively stable and resilient, although it has gone through an approximately seven year period of variability at the species level, with implications for key commercial fisheries and the human communities upon which they depend. In aggregate, the decreasing biomass trends in certain groundfish species have been offset by increasing biomass of others. Key metrics of stability in the groundfish community, including high total biomass (p.184), low average biomass variability over time (p.176), high species richness and diversity (p.186), and stable (eastern GOA) or slightly increasing (western GOA) mean length and lifespan of groundfish (p.178 and p.181), point to overall high stability and resilience in the GOA (represented by species regularly caught by the AFSC bottom trawl survey). These stability indicators show trends in ecosystem structure and function, related to total optimum yield, and longer-term ecosystem context.

The Status of the Gulf of Alaska 2021

Western Gulf of Alaska 2021

The western Gulf of Alaska had a second consecutive non-marine heatwave year, with temperatures at surface and depth generally hovering around long-term averages. An exception was warmer surface waters in the western GOA in the late winter/early spring (p.39). No above-average temperatures were observed at depth in 2021, indicating the residual subsurface warmer temperatures from previous marine heatwave years (as observed in 2020) have cooled (p.39). These average temperatures fit within the expected conditions associated with a negative Pacific Decadal Oscillation and La Niña winter conditions (p.31). Surface temperatures are predicted to continue cooling into 2022, consistent with a second La Niña winter (p.36). The 2020/2021 winter experienced northward transport (southerly winds) (p.53). Westerly winds in the spring and summer reduced the northward transport and created upwelling favorable conditions that contributed to the cooling ocean temperatures (p.32). Strong, persistent eddies were located along the shelf edge off Seward and Kodiak in the winter and spring, with higher than average winter eddy kinetic energy indicating greater transport of nutrients across the shelf (p.49). Spring winds in Shelikof Strait were downwelling-favorable northeasterly winds (conducive to enhanced retention of pollock larvae and juveniles) (p.56). The peak spring phytoplankton bloom was approximately average, with lower than average spring phytoplankton biomass (similar to 2016 and 2019) (p.63). A large, 3 week, phytoplankton bloom was observed in central GOA in April (Hopcroft pers. comm.), however the ecological response of this large bloom was not immediately apparent in the upper trophic levels.

Zooplankton had mixed trends across the western GOA. The zooplankton and larval groundfish community metrics around Kodiak Island were characterized by a warmer signature (lower abundance of large copepods, larval walleye pollock, Pacific cod, and northern rock sole) (p.70, p.85). Seabird reproductive success on Chowiet (south of Kodiak) was low to average for planktivorous seabirds (black legged kittiwakes, parakeet auklets) (p.152). Closer to the central GOA, the Seward Line survey observed average to above average spring abundance of large calanoid copepods in association with the large phytoplankton bloom (p.76). This productivity was not reflected in higher trophic levels as planktivorous seabirds had below average reproductive success in this region (East Amatuli fork-tailed storm petrels) (p.152). In the western GOA overall, adult pollock and Pacific Ocean perch (both planktivorous) continued to have lower than average condition (weight at length) reflecting food limitation (p.130).

Forage fish were potentially more available, although the community composition was supplemented by a more diverse suite of species. Of the more typical forage species, capelin (a colder-water associated forage fish) remains depleted since the 2014 marine heatwave, although some larger numbers were observed around the Shumagins and Barnabas Trough (p.99, p.94). Sand lance (warm-water associated) was locally abundant but patchy, and was present in Middleton Island seabird diets in moderate proportions (p.94). Age-1 pollock and cod were observed in relative high abundances. Less common species, such as nearshore greenlings are prominent in Middleton Island seabird diets (p.94). In general, piscivorous seabirds had average to above average reproductive success, indicating adequate forage availability and condition, and perhaps reflecting their ability to find alternative prey (Chowiet glaucous-winged gulls, common murres, tufted puffins) (p.152). Some piscivorous groundfish had improved condition (weight at length) relative to 2020, although most remained negative (p.130). While not considered forage fish, other prey species including Tanner crab and shrimp around Kodiak continue to increase (p.135, p.149). The reasons for increased abundance of shrimp around Kodiak are not known; however, contributing factors could include favorable environmental conditions and decreased predator abundance, including walleye pollock, Pacific cod, and Pacific halibut.

Adult salmon returns improved from the lows of 2020, largely driven by high pink salmon returns (p.106). High abundance of adult pink salmon reflects good marine survival in 2020, which was also a good survival year for larval cod and pollock.

HABs continued to be observed in 2021. The frequency and concentration of paralytic shellfish toxins in shellfish on Kodiak Island decreased in 2021 (from 2020 and 2019), resulting in fewer shellfish samples exceeding the regulatory limit for human consumption (p.189). Middleton Island (central GOA) experience a seabird die-off event, of which the primary suspect was botulinum toxin type C (p.24). While analysis is ongoing, this has not been linked to changes in prey availability, or algal toxins, however this may be an indicator of naturally occurring toxins expanding northward with warming oceans and changing weather patterns.

Eastern Gulf of Alaska 2021

The eastern GOA continued a second consecutive year of approximately average ocean temperatures, entering the fall of 2021 with average surface temperatures on the shelf and inside waters of Icy Strait, and slightly above average at $\sim$ 200 m depth on the shelf and upper slope (p.39).

Productivity at the lower trophic levels was at average to reduced levels in 2021, with potentially higher production in SEAK inside waters. At the base of the food chain, chlorophyll-a concentrations continued a six-year trend below average. However, the peak phytoplankton bloom timing was slightly early, which can be conducive to improved feeding conditions for larval fish, relative to a late bloom (p.63). Total zooplankton density in Icy Strait (inside waters) increased from 2020 to above average, driven by increases in euphausiids and small calanoid copepods, with a slight decline in large calanoid copepods (but still above average) (p.78). Contrary to the more productive inside waters, zooplankton indicators from the eastern GOA shelf (planktivorous seabird reproductive success on St. Lazaria Island, p.152) show average to below average zooplankton quantity and quality (p.152).

Despite the lower to moderate plankton productivity, forage fish were observed in higher abundance. Herring spawning stock biomass continues to increase after their strong 2016 year class (p.102), supporting upper trophic level species such as piscivorous groundfish, the increasing population of humpback whales in Glacier Bay (p.164), and fish-eating seabirds (average reproductive success, p.152). Juvenile salmon in Icy Strait were less available but higher quality prey, with below average abundance but generally above average energy density (p.109, p.113).

Adult salmon returns improved from the lows of 2020, largely driven by high pink salmon returns, p.106), including 10 th highest return to Auke Creek (p.116). Other salmon trends remain low, including sockeye which had the 10th lowest escapement of adults to Auke Creek (p.122). Chinook salmon populations still remain low.

HABs continued to be observed in 2021. The frequency and concentration of paralytic shellfish toxins in shellfish decreased in 2021 (from 2020 and 2019), resulting in fewer shellfish samples exceeding the regulatory limit for human consumption (p.189). The lower levels were likely due to cooler ocean conditions.

Prince William Sound 2021

Prince William Sound continues to show lagged effects of 2014–2016, and 2019 marine heatwaves. Ocean temperatures have returned to approximately average (often one year lagged from shelf conditions) (p.195). Herring stocks remain low but have followed the increasing trend observed in SE AK following the large 2016 year class (p.202). The humpback whale population also remains low following the warm periods, either explained by mortality or a change in distribution (p.206). Intertidal algae and invertebrate communities experienced a shift in community composition in 2016 that continues to persist. Primary producers (*Fucus*) and predators (sea stars) remain in relatively low abundance, whereas secondary consumers (mussels) remain positive or near the long-term mean (p.197).

Review of the Gulf of Alaska 2020 Ecosystem State

While COVID-19 caused disruptions to human communities, fisheries, and numerous research and monitoring programs, most data normally included in the GOA ESR were collected and analyzed in 2020 as expected. Notable exceptions include missing seabird reproductive success data, due to cancelled field camps by the Alaska Maritime National Wildlife Refuge (USFWS), and delayed lab analysis of zooplankton, larvae, and ichthyofauna samples.

The 2020 GOA marine environment was characterized by a partial return to long-term average conditions after the 2014-2016 and 2019 marine heatwave years, with some indicators showing continued residual and lagged responses in the system. The GOA ocean temperatures trended toward to long-term average conditions, ending the 2019 marine heatwave conditions. Sea surface temperatures returned to long-term mean levels for winter and spring (western and eastern GOA), followed by elevated temperatures in the summer and fall in the western GOA. The eastern GOA sea surface temperatures oscillated around the heatwave threshold throughout the summer and remained warm through the fall. Residual heat remains at depth, as seen along the Seward Line, which remains a concern for lagged ecological recovery from these heatwaves. Cooler or average temperatures indicated improved spawning conditions (relative to 2019) for late winter/early spring shelf spawners such as Pacific cod, walleye pollock, and northern rock sole. Results of these improved spawning condition were observed in 2021 survey results showing relatively abundant age-1 pollock and cod. Chlorophyll-a data indicated early peak phytoplankton bloom timing, and approximately average phytoplankton biomass in western and eastern GOA.

The North Pacific atmosphere-ocean climate system of 2020 included anomalously high sea level pressure (during winter 2019/2020), indicated by the strongly positive state of the Arctic Oscillation, resulting in westerly winds. These caused eastward and southward ocean surface transport, and upwelling conditions in the eastern GOA. Indicators of surface transport show upwelling inducing westerly winds in the winter, and south and eastward winter transport. High eddy kinetic energy in the central GOA transported phytoplankton and nutrients away from the coast, and spring wind trajectories were toward the southwest in Shelikof Strait (conducive to increased age-1 pollock abundance).

Forage conditions in the GOA improved relative to 2019, with average to increased zooplankton biomass (increased large copepods) and mixed forage fish trends (although very limited data). These trends suggest an improved prey base for planktivorous and piscivorous fish, seabirds, and marine mammals (with exceptions as described below). Zooplankton indicators suggest zooplankton prey were not limiting. Spring biomass estimates of large copepods and euphausiids were near the long-term average along the Seward Line (May 2020). Zooplankton density in SEAK inside waters (Icy Strait, summer) was near the long-term average, but had increased values of large copepods, decreased small copepods, and decreased euphausiids. A lack of additional zooplankton data makes these trends difficult to extrapolate across the western and eastern GOA, including offshore waters, due to an "off-year" of NOAA GOA surveys and COVID-related cancellations of planktivorous seabird surveys. Continuous Plankton Recorder data on transects across the central shelf show zooplankton biomass anomalies were higher than average, with more abundant smaller copepods and average diatom abundance, potentially reflecting the warmer surface temperatures. Herring (mature spawning, age 3+) continued to increase in biomass from the 2019 high levels in Sitka Sound and Craig (ocean influenced populations). Juvenile salmon abundances in SEAK inside waters (Icy Strait) remain below average but continue an increasing trend since a low in

2017. COVID-related cancellations of piscivorous seabird surveys resulted in a lack of additional forage fish data. Forage fish-eating seabirds (surface feeding and diving) at Middleton Island found sufficient prey to successfully rear chicks, although chick diets were diverse and included an unusual increased proportion of greenlings. These diets suggested that the more typical forage fish, such as capelin, were not abundant.

Groundfish biomass trends in 2020, an "off-year" for the GOA-wide bottom trawl surveys, are based on ADF&G surveys off Kodiak Island over Barnabus Gully and in two inshore bays. Catch rates were below the long-term mean for arrowtooth flounder, flathead sole, Pacific cod, Pacific halibut, skates, and walleye pollock. Catch rates were above the long-term mean for Tanner crab. Southwest wind trajectories in Shelikof Strait and an early spring phytoplankton bloom (similar to 2017 and 2018) predicted good age-1 walleye pollock in 2021, which was born out in 2021 surveys.

Paralytic shellfish toxins (saxitoxins) concentrations in phytoplankton and shellfish were lower in 2020, relative to 2019, possibly due to the rainy summer and cooler temperatures in 2020. Saxitoxin concentrations in Kachemak Bay and Kodiak Island were generally below regulatory limits, while some samples exceeded this threshold in southeast Alaska

Salmon commercial harvest was low across most of GOA, and lowest in SEAK since 1976, resulting in numerous request for the State to declare salmon fishery disasters. The low returns in SEAK were primarily driven by low chum and sockeye. Low adult returns are tied to juvenile mortality in 2017 (and years since then for certain life histories) but the mechanism driving that trend (e.g., environment, predation) is still uncertain. Juvenile salmon energy density in Icy Strait (SEAK) was at or above average (decreasing for pink and sockeye and increasing for chum and coho, relative to 2019), indications of potentially improved future adult returns (although not a direct relationship).

Seabirds and marine mammals had mixed trends in 2020, with continued effects of the marine heatwave years. Humpback whales counts in Prince William Sound remained lower in 2020 than pre-2014 heatwave levels. Humpback whale productivity and juvenile survival in Glacier Bay and Icy Strait returned to more typical, pre-2014 heatwave levels, reflecting good feeding conditions (for females) from 2018–2020. This could include the increased herring abundance described above. Overall, the status of seabirds was fair to good in the western GOA in 2020. Colony attendance remains low in some populations compared to historic levels, however, when birds did arrive to breed, reproductive success was fair to good for both surface, fish-eating birds and diving, fish-eating birds. Seabird bycatch in 2020 declined from 2019 by 50% in the GOA, led by declines in catches of black-footed albatross and gulls (the lowest western GOA seabird bycatch in 10 years). This decline reflects COVID-related reductions in fishing effort and shifts in sablefish fishery gear from hook-and-line to pots.

The marine heatwave years (2014–2016, 2019) continue to have cumulative and lagged effects throughout the system. Residual heat at depth was observed along the Seward Line ($\sim$ 150m) with potential implications for early survival of groundfish that use these habitats for spawning (e.g., Pacific cod). There were mixed trends in forage fish abundance (although limited data), with continued decreased abundance of capelin, a key prey species. Some groundfish (e.g., Pacific cod), seabird (e.g., common murres), and whales (Prince William Sound humpback whales) are still lower abundance than pre-heatwave levels.

Contents

* indicates contribution updated with 2021 data
† indicates new contribution

List of Tables

List of Figures

Ecosystem Indicators

Noteworthy

We include information here that is relevant to ecosystem considerations of fisheries managers, but does not fit our typical indicator format. Information included here is often new or a one-time event.

Seabird Mortality Event: Middleton Island July 2021

In mid-July 2021, a large number of sick and dying seabirds were observed on Middleton Island, south of Prince William Sound (PWS) in the Gulf of Alaska. During the 10-day period, 250 Black-legged Kittiwakes *Rissa tridactyla*, 70 Glaucous-winged Gulls *Larus glaucescens* and 2 Herring Gulls *Larus argentatus* were found dead, and 220 kittiwakes and 19 Glaucous-winged Gulls were observed sick. Kittiwakes and Glaucous-winged Gulls are among six seabird species monitored by the Institute for Seabird Research and Conservation on Middleton Island. Affected birds exhibited neurological signs and abnormal behavior. At first, sick birds lost their ability to fly, then gradually lost their ability to move, and all died within ~ 5 days of the first signs of sickness. This mortality event was detected and monitored by seabird researchers already on Middleton Island conducting ecology and disease studies, and large numbers of carcasses, blood, feces, and food samples were collected from all monitored seabird species. A coordinated response to determine the cause of this die-off was launched by scientists at the Institute for Seabird Research and Conservation, the University of Alaska Fairbanks, the University of Alaska Anchorage, McGill University (Quebec, Canada), Frostburg State University, the U.S. Fish and Wildlife Service, and the U.S. Geological Survey Alaska Science Center and National Wildlife Health Center. The University of Alaska INBRE program provided funding for the collection, shipment, and initial molecular analyses of bird samples and carcasses, which allowed us to advance the investigation of potential causes of the die-off. The National Oceanographic and Atmospheric Administration (NOAA) Alaska Sea Grant provided additional funding to assist with transportation of personnel to participate in sample processing and training.

The cause of death was not immediately clear. Many sick and deceased birds were emaciated or in poor condition, but tested negative for highly pathogenic avian influenza, and the biotoxins saxitoxin (STX) and domoic acid (Table 1). Blue mussels, plankton, and forage fish samples from recent kittiwake foraging locations near the outer islands of PWS (Figures 3 and 4) also tested negative for STX, as did blue mussels and feces from both presumably healthy and sick kittiwakes collected at Middleton during the die-off (Table 1). Next generation sequencing (metagenomics) analysis of RNA samples collected from sick and dead kittiwakes indicated the presence of *Clostridia* spp. in all birds, and significant reads in cloacal swabs classifiable as *C. botulinum* (n=2/12 birds, 17% prevalence; Table 2). *Clostridia* are a group of bacterial species that can produce botulinum neurotoxins, which can cause botulism. Further analysis of blood from two deceased kittiwakes revealed a positive bioassay test for (avian) botulinum toxin type C in one bird and a suspected positive result for the other; both birds tested negative for botulinum toxin type E, the botulinum toxin type that has been found to cause botulism in humans in the Arctic. Researchers plan to conduct additional tests to determine whether botulinum toxin type C was the culprit of the die-off and to investigate sources of this neurotoxin. This appears to be the first verified case of botulinum toxin type C in Alaska. Botulism can cause large die-offs of waterbirds, but botulinum toxin type C has not been associated with disease in humans.

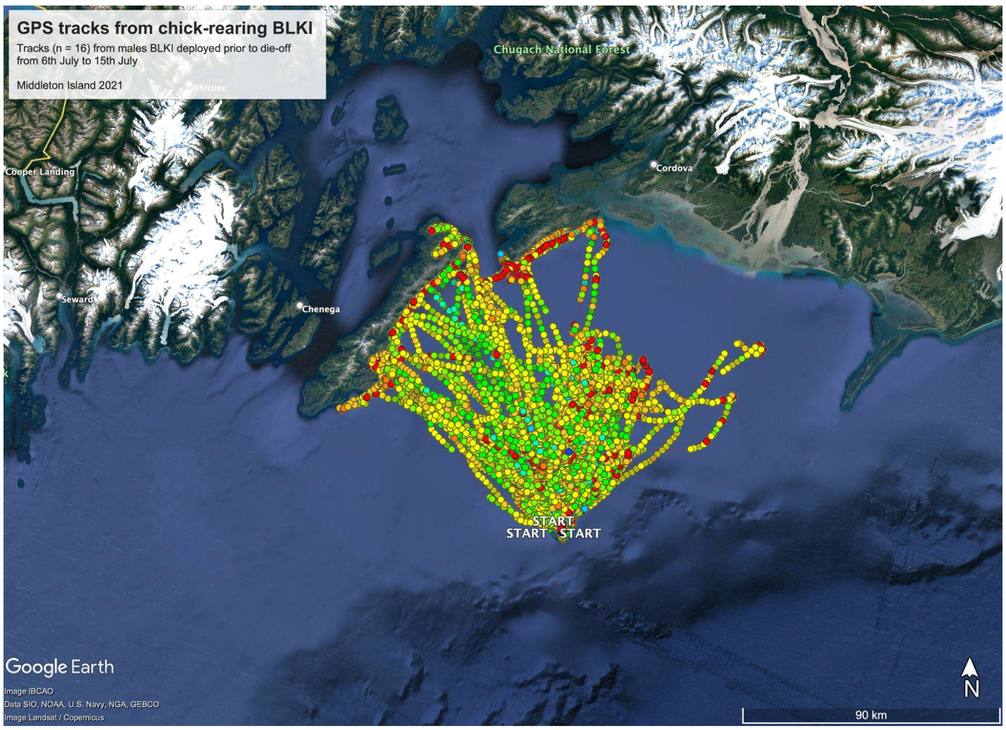


Figure 3: GPS foraging tracks (n=16) of male, chick-rearing Black-legged Kittiwakes originating from Middleton Island from July 6-July 15, 2021 (prior to the seabird mortality event). Colors represent each bird's speed, with lowest value (red, 0 km h^{-1}) representing no movement and assumed foraging. Data provided by the Institute for Seabird Research and Conservation.

Table 1: Number of individuals that tested negative for highly pathogenic avian influenza (HPAI), and below detection for the biotoxins saxitoxin (STX) and domoic acid (DA).[1]Pooled sample.

Species	HPAI	STX	DA
Black-legged Kittiwake	37	31	4
Glaucous-winged Gull	7	2	–
Herring Gull	2	–	–
Blue mussels[1]	–	8	–
Pacific herring	–	3	–
Plankton[1]	–	1	–

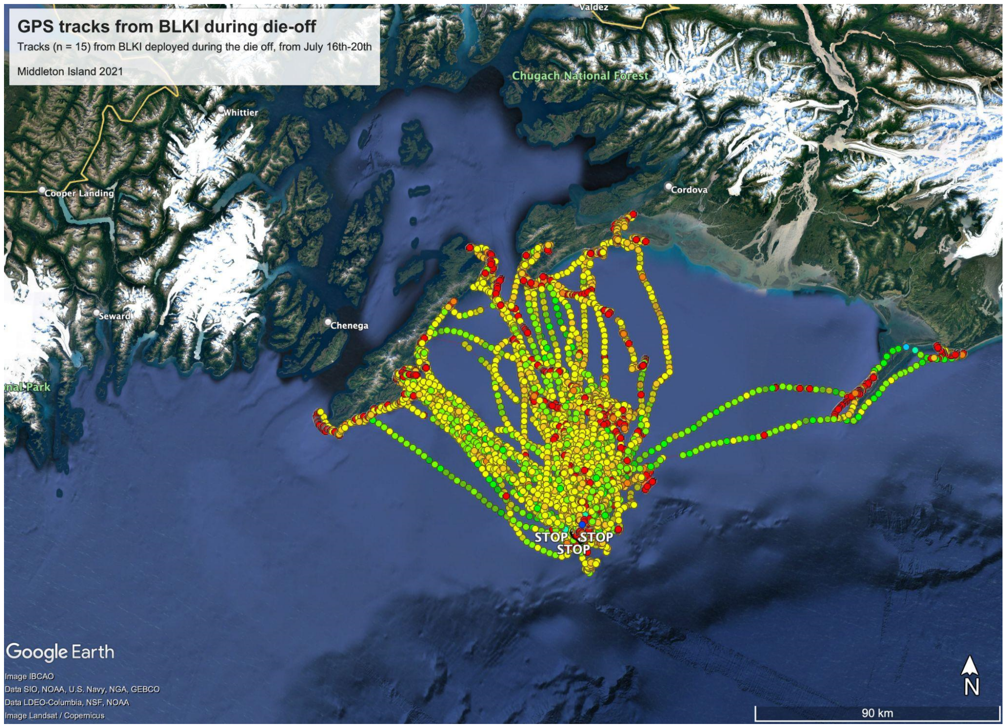


Figure 4: GPS foraging tracks of chick-rearing Black-legged Kittiwakes (n=15) originating from Middleton Island from July 16-July 20, 2021 (during the seabird mortality event). Colors represent each bird's speed, with lowest value (red, 0 km h^{-1}) representing no movement and assumed foraging. Data provided by the Institute for Seabird Research and Conservation.

Table 2: Metagenomics classification of *Clostridia* spp. reads from RNA-seq on cloacal swabs from black-legged Kittiwakes from Middleton Island, Alaska, including *C. botulinum* (n=2 of 12, 17% prevalence).

Bacterial read classification	CL2	CL6
Clostridium perfringens	1129	780
Clostridium septicum	275	341
Clostridium argentinense	150	197
Clostridium fermenticellae	64	94
Clostridium botulinum	63	75
Clostridium isatidis	54	51
Total *Clostridia* spp. reads	1735	1538
Interpretation	Positive	Positive

The ecological implications of this seabird mortality event are still being explored. Seabird die-offs in Alaska have increased in magnitude, duration, and frequency since 2015. Most seabird die-offs have been attributed to starvation from a presumed lack of available food, however, this die-off appears likely to have been caused by a disease. The potential origin of the botulinum toxin remains unknown, but fresh or brackish water pools that contain dipteran populations (that can be part of the maggot-cycle) on Middleton Island in which kittiwakes often bathe are potential sources. Diet and reproductive data of kittiwakes collected during the time of the die-off on Middleton Island do not show indication of poor foraging conditions that might have contributed to changes in foraging behavior (i.e., feeding in the brackish pools of Middleton Island). The diet composition and GPS tracking data indicate the kittiwakes were feeding more nearshore, closer to PWS, continuing a trend observed since the 2014–2016 marine heatwave (Figures 3 and 4) (see Seabird Synthesis in Report, p.94). While extended foraging trips, and reduced capelin in kittiwake diets may contribute to a level of foraging stress, as shown in supplemental feeding experiments, other 2021 indicators, such as reproductive success and timing were close to the $\sim$ 40 year average (see Seabird Synthesis in Report, p.152). If the cause of this event is determined to be botulism, this event and subsequent mortality could be a harbinger of more such events as the distribution of naturally occurring toxins expands northward alongside warming oceans and changing weather patterns.

Contributed by Sarah Schoen[1], Fred Tremblay[2,3], Barb Bodenstein[4], Eric Bortz[5], Doug Causey[5], Jack Chen[6,7], Scott Hatch[2], Robb Kaler[8], Alexander Kitaysky[6], John Piatt[1], Matthew Redlinger[5], Valerie Shearn-Bochsler[4], Kate Sheehan[9], Matthew Smith[1], Caroline Van Hemert[1], Shannon Whelan[2], and Alexis Will[6]
[1] U.S. Geological Survey Alaska Science Center, Anchorage, AK
[2] Institute for Seabird Research and Conservation, Anchorage, AK
[3] McGill University, Montreal, QC
[4] U.S. Geological Survey National Wildlife Health Center, Madison, WI
[5] University of Alaska Anchorage, Anchorage, AK
[6] University of Alaska Fairbanks, Fairbanks, AK
[7] Alaska State Virology Laboratory, Fairbanks, AK
[8] U.S. Fish and Wildlife Service, Anchorage, AK
[9] Frostburg State University, Frostburg, MD

North Pacific Right Whale Sightings

Four unique North Pacific right whales (*Eubalaena japonica*), two during each of two sightings, were sighted during a large whale survey (PacMAPPS) near Kodiak Island (see Crance in this Report, p.168). This endangered population is estimated to consist of approximately 30 whales and this is more sightings of these North Pacific right whales than occurred on any other cetacean survey in the GOA. Two whales were sighted in Barnabas Trough (sighted 21 Aug), and two whales were sighted near Trinity Islands (sighted 24 Aug). Of the four animals, two were confirmed new and added to the catalog. One animal (a male from the Trinity Islands sighting) was first sighted in 2006 in Barnabas Trough, and this is the first re-sighting of that animal, only about 100 nm from his first sighting location. One animal (from the Barnabas sighting) was first sighted near Haida Gwaii in June of this year by DFO Canada. This is the first time we've matched an animal from Haida Gwaii to any other location.

Sightings of right whales in the GOA are even more rare than Bering Sea sightings. It is unknown whether the Bering and the GOA right whales might be two separate subpopulations or part of the same population. We have yet to match a whale from the Bering Sea to the GOA. Both right whale sightings occurred along Albatross Bank, an area known for being highly productive and having high concentrations of zooplankton. This area was identified as a Biologically Important Area for feeding for North Pacific right whales in 2015 (Ferguson et al., 2018). There was feces in the water and behavior associated with feeding (e.g., expelling water from the mouth) during both sightings, providing further evidence that this area is important habitat for right whales. It is difficult to interpret the identification of two new whales in terms of population status or trends, since re-sightings (and sightings in general) are so infrequent. Dedicated marine mammal visual surveys are crucial and provide much better information on cetacean distribution, density, and abundance than just opportunistic observations. Two of the right whales would not have been sighted without the 25x big-eye binoculars used during these surveys - they were too far from the trackline to have been seen with handheld 7x50 binoculars.

Contributed by Jessica Crance, Kim Goetz, and Robyn Angliss
Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: jessica.crance@noaa.gov

Ecosystem Status Indicators

Physical Environment

Physical Environment Summary

Climate: 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°N and 50°N and lower than normal SLP from eastern Siberia into the southern Chukchi Sea (see Bond in this Report, p.32). 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 (see Bond in this Report, p.30). 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 (see Bond in this Report, p.36).

Ocean Temperature: Much of 2021 has been cooler than the previous few years, with temperatures in both the western and eastern GOA often hovering close to the long-term average (see Watson and Callahan in this Report, p.39). Despite this generally cooler pattern, the year started out relatively warm in the western GOA before trending more towards typical temperatures. The eastern GOA still has higher than average temperatures at depth ($\sim$ 200m), although still lower than in the previous few years). Subregional surface temperatures in the (Kodiak and Shelikof Strait, Seward Line) were cooler than average, whereas in the eastern GOA (Icy Strait) temperatures oscillated around the long-term mean (see Ocean Temperature Synthesis in this Report, p.39). Prince William Sound surface temperatures, known to lag the GOA shelf by $\sim$ one year, have cooled to long-term mean after warmer temperatures continued into 2020 (see Campbell and McKinstry in this Report, p.195). La Niña conditions are predicted for winter 2021–2022 (following a La Niña winter in 2020/2021), along with moderate to slightly cooler sea surface temperatures in the northern GOA (National Multi-model Ensemble Model).

Ocean Transport: The 2020/2021 winter experienced northward transport (southerly winds) (see Stockhausen in this Report, p.53). Westerly winds in the spring and summer reduced the northward transport and created upwelling favorable conditions. Strong, persistent eddies were located along the shelf edge off Seward and Kodiak in the winter and spring, with higher than average winter eddy kinetic energy indicating greater transport of nutrients across the shelf (see Cheng in this Report, p.49). Spring winds in Shelikof Strait were downwelling-favorable northeasterly winds (conducive to enhanced retention of pollock larvae and juveniles) (see Wilson in this Report, p.56).

Climate: North Pacific Overview

Contributed by Nick Bond (UW/JISAO), NOAA/PMEL, Building 3, 7600 Sand Point Way NE, Seattle, WA 98115-6349
Contact: nicholas.bond@noaa.gov

Last updated: September 2021

Regional Highlights of Gulf of Alaska and Neighboring Regions:

Aleutian Islands. The winter of 2020–2021 was stormy for the Aleutian Islands with the mean wind anomalies associated with suppressed northward 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.

Gulf of Alaska. The coastal GOA experienced a relatively wet winter in 2020–21, with the coldest air temperatures occurring in February and March 2021. The weather was considerably drier in late spring and summer relative to seasonal norms. This period also included westerly wind anomalies, which are upwelling favorable in the coastal zone. One consequence was a pocket of cold sea surface temperature anomalies of minor magnitude in the northern GOA in the summer 2021 as opposed to the generally warm temperatures that were present across virtually the entire North Pacific Ocean north of 30°N. The Alaskan Peninsula had positive SST anomalies were present in this region during the latter portion of 2020, especially on the Bering Sea side to the north.The weather early during the winter of 2020–21 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.

British Columbia Coast. This region had upper ocean temperatures on the order of 0.5 to 1°C above normal during the fall of 2020. Due to an overall weather pattern that brought about anomalous upwelling in the coastal zone, temperatures moderated over the winter 2020/2021 and spring 2021, resulting in near normal SSTs over the shelf during the summer of 2021. An extreme heat wave in late June 2021 was associated with record-setting air temperatures in the Pacific Northwest including British Columbia. One of the notable consequences of this event was a mass die-off of nearshore shellfish such as barnacles, clams and mussels in locations where low tides occurred in the afternoon during the hottest time of day. The heatwave also resulted in sharp rises in stream temperatures and enhanced upper elevation snow and glacial melt; conceivably it will end up having lasting impacts on the coastal marine ecosystem.

Climate Indices

Contributed by Nick Bond (UW/JISAO), NOAA/PMEL, Building 3, 7600 Sand Point Way NE, Seattle, WA 98115-6349
Contact: nicholas.bond@noaa.gov
Last updated: September 2021

Description of indices: Climate indices provide a means of characterizing the state of the North Pacific atmosphere-ocean system. The focus here is on five commonly used indices: the NINO3.4 index for the state of the El Niño/Southern Oscillation (ENSO) phenomenon, Pacific Decadal Index (PDO), 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 5.

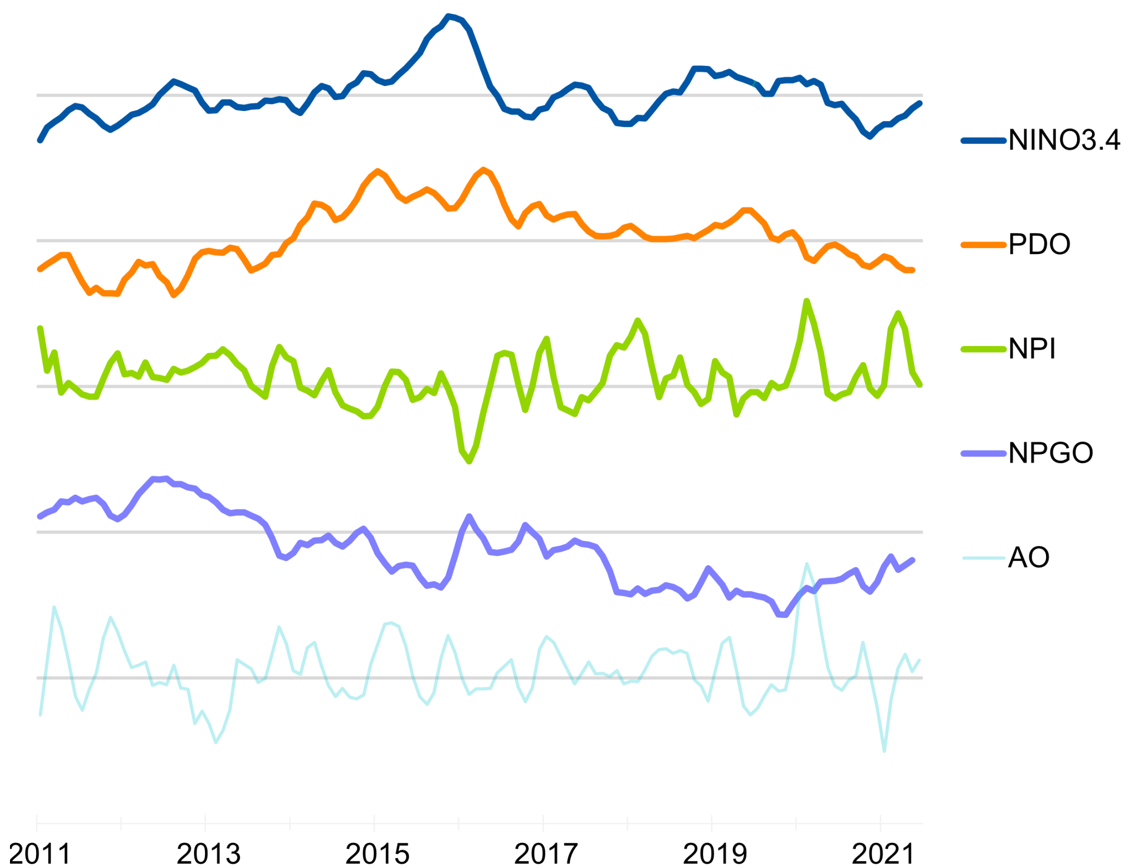


Figure 5: Time series of the NINO3.4 (blue), PDO (orange), NPI (green), NPGO (purple), and AO (turquoise) indices for 2011–2021. Bold lines (all but AO) are the most relevant of these indices for the GOA. Each time series represents monthly values that are normalized using a climatology based on the 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 Earth Systems Laboratory at `http://www.esrl.noaa.gov/psd/data/climateindices/`.

Status and trends: The NINO3.4 index was negative from spring 2020 through early summer 2021. This index bottomed out with a value of -1.42 in November 2020, implying that the equatorial Pacific was in a moderately strong La Niña state. Slow warming followed with near-neutral conditions developing by late spring/early summer 2021. Relatively cool water remains at depth in the tropical Pacific with more likely than not a weak to moderate La Niña forming by late fall 2021.

The PDO (the leading mode of North Pacific SST variability) continued its mostly negative trend following a strongly positive state during the major Northeast Pacific marine heat wave of (MHW) of 2014-16. The PDO reached a value of about -1 during the spring of 2021 and remained near that value through the following summer. The moderately negative state of the PDO during spring and summer 2021 can be largely attributed to relatively cool temperatures in the eastern subtropics and warm temperatures in the western mid-latitudes of the North Pacific; a negligible contribution was represented by the SST anomalies in the Alaskan waters portion of the PDO spatial pattern.

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 2020-21 before returning to an average of near neutral 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 NPGO has been mostly negative since 2014; this sign of the NPGO is generally accompanied by warmer than normal upper ocean temperatures south of Alaska between 35 and 50°N and is associated with high SLP over the GOA and low SLP in the vicinity and northeast of the Hawaiian Islands. The NPGO underwent a decrease in intensity from about -2 in early 2020 to -1 in early 2021.

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 2020-21, followed by mostly positive values in spring and summer 2021 with considerable month-to-month variability.

Sea Surface Temperature and Sea Level Pressure Anomalies (North Pacific)

Contributed by Nick Bond (UW/JISAO), NOAA/PMEL, Building 3, 7600 Sand Point Way NE, Seattle, WA 98115-6349
Contact: nicholas.bond@noaa.gov

Last updated: September 2021

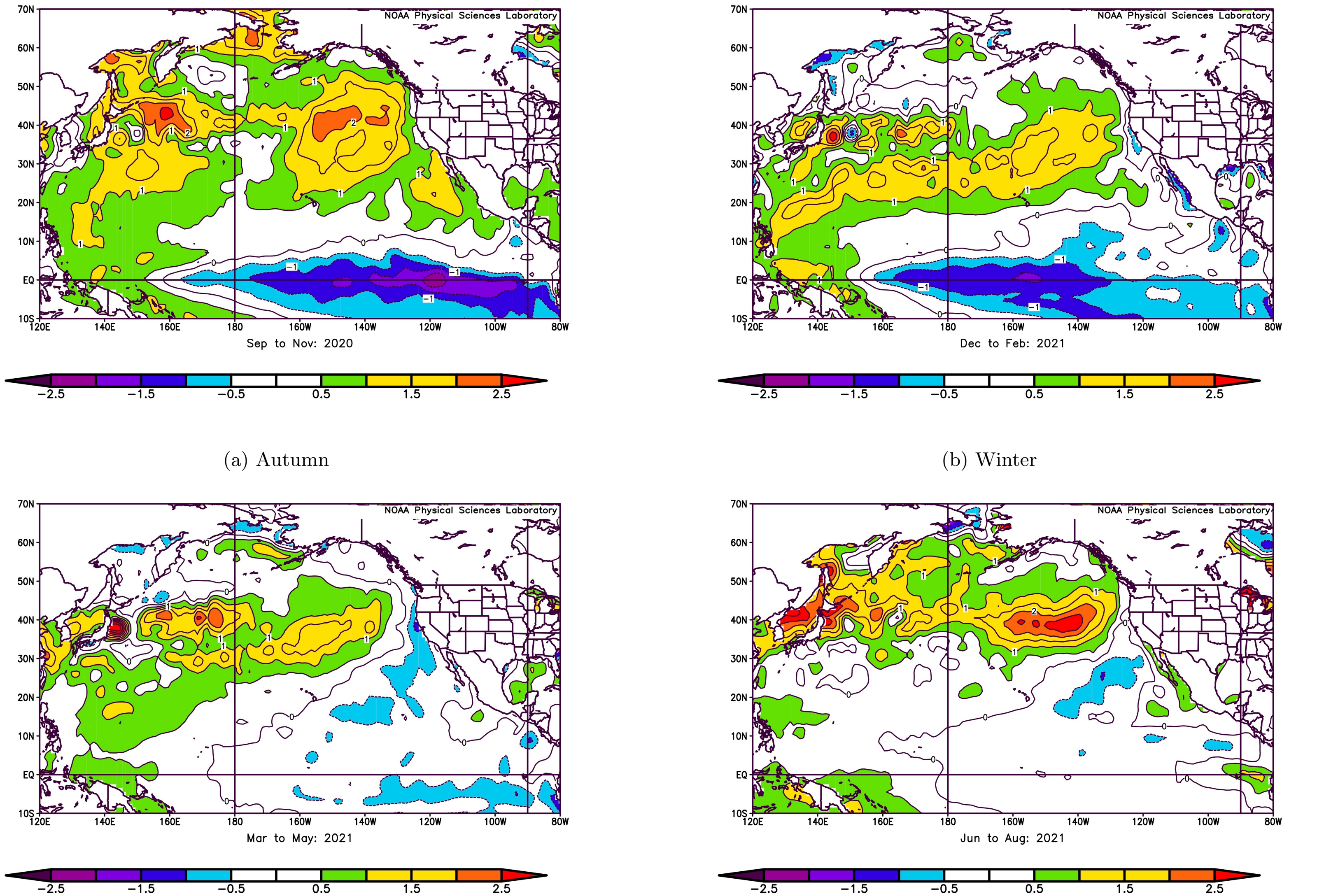
Description of indices: The state of the North Pacific climate from autumn 2020 through summer 2021 is summarized in terms of seasonal mean sea level pressure (SLP) and sea surface temperature (SST) anomaly maps. The SLP and SST anomalies are relative to mean conditions over the period of 1981–2010. The SLP data are from the NCEP/NCAR Reanalysis project; the SST data are from NOAA's Optimum Interpolation Sea Surface Temperature (OISST) analysis. Both data sets are made available by NOAA's Physical Sciences Laboratory (PSL) at https://www.psl.noaa.gov/cgi-bin/data/composites/printpage.pl.

Status and trends: The autumn of 2020 (Figure 6a) 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°W 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 autumn 2020 SLP pattern (Sep-Nov) 2020 (Figure 7a) included positive anomalies south of the Aleutians extending through the Gulf of Alaska (GOA), 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 and the GOA.

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 6b shows that the region of relative warmth was confined largely to a basin-wide band between 15°N 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 winter featured strongly negative SLP anomalies in the southwestern Bering Sea with relatively low pressure extending across Alaska into northwestern Canada, and positive SLP anomalies in the eastern part of the mid-latitude North Pacific, with a center located near 35°N, 140°W (Figure 7b). The consequence was enhanced westerlies stretching from the Aleutians to the GOA. The high pressure off the coast of the lower 48 states was associated with a dearth of landfalling storms into California.

The spring (Mar–May) of 2021 (Figure 6c) had a large-scale SST anomaly pattern in the North Pacific similar to that of the previous winter. There were increases in the magnitude of the warm anomalies in the western North Pacific from Japan to the dateline, and to a lesser extent for the southeastern Bering Sea. A minor cold SST anomaly emerged in the GOA between the Kenai Peninsula and Kodiak Island. The tropical Pacific returned to near-neutral ENSO conditions, with slightly cool SSTs east of the dateline. The positive SLP anomalies in the NE Pacific during the previous season persisted through the spring (Figure 7c), 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.

During the summer (Jun–Aug) of 2021, 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 (Figure 6d). Positive anomalies of about 1°C were present in the western Aleutian Islands. There were minor warm SST anomalies on the southeastern Bering Sea shelf; temperatures in the northern GOA were near normal. The tropical Pacific was in a near-neutral state. The distribution of SLP anomalies across the North Pacific during this period is shown in (Figure 7d). As is often the case during this time of year, the seasonal mean anomalies were generally of moderate amplitude. Lower than normal SLP over Alaska and northwestern Canada with relatively high SLP south of 50°N led to anticyclonic wind anomalies for the northern and eastern GOA. The negative SLP anomalies over the northern Bering Sea extending across the Chukchi Sea to north of Alaska implies enhanced storm activity for those regions.



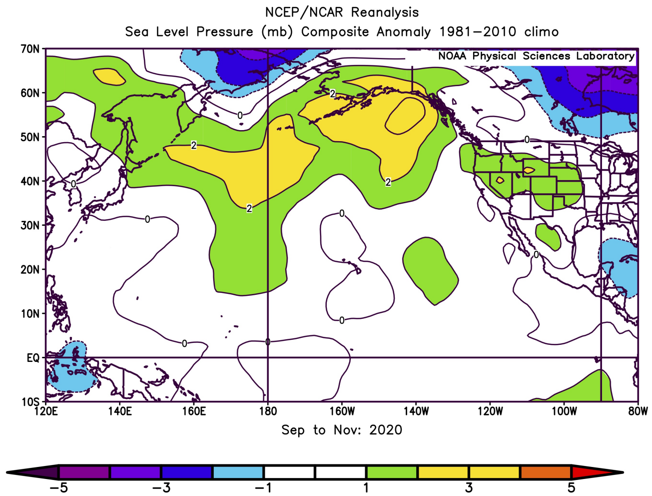
(a) Autumn

(b) Winter

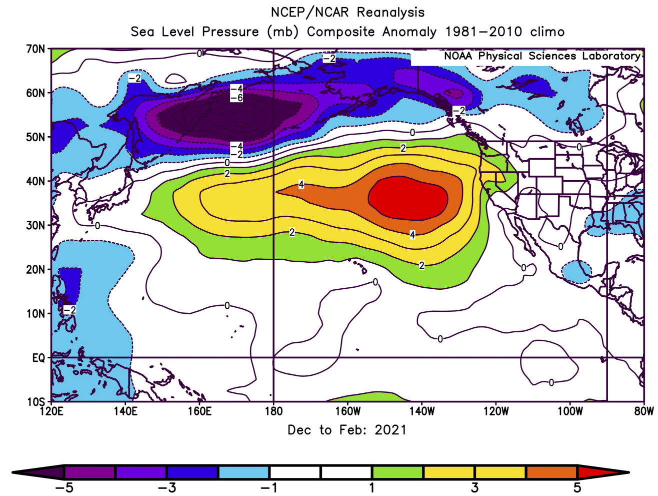
(c) Spring

(d) Summer

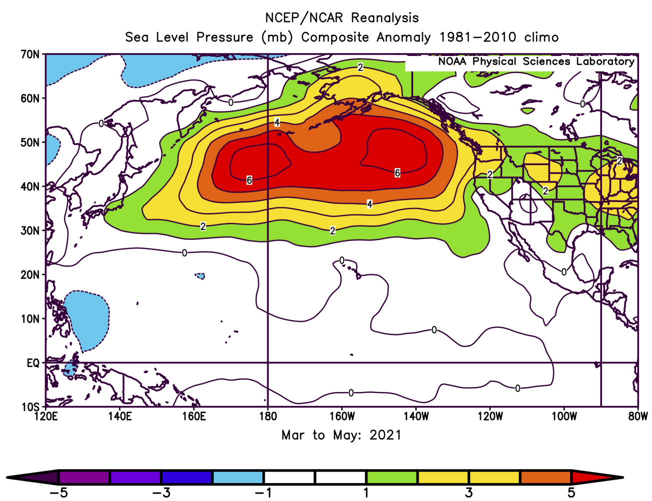
Figure 6: SST anomalies for autumn (September–November 2020), winter (December 2020–February 2010), spring (March–May 2021), and summer (June–August 2021).



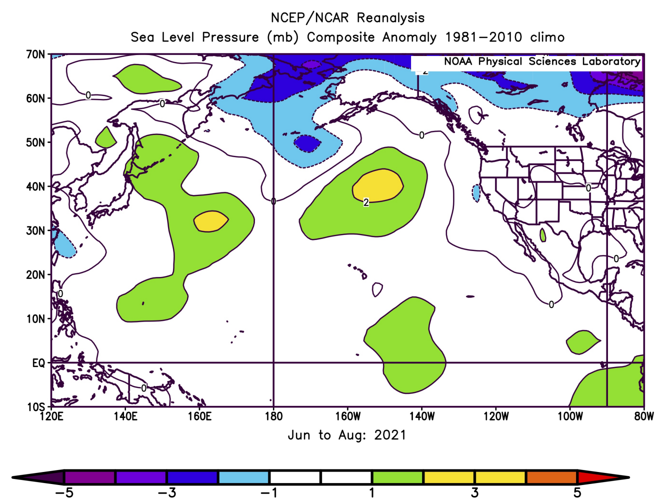
(a) Autumn



(b) Winter



(c) Spring



(d) Summer

Figure 7: Sea level pressure anomalies for autumn (September–November 2020), winter (December 2020–February 2010), spring (March–May 2021), and summer (June–August 2021).

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

Contributed by Nick Bond (UW/JISAO), NOAA/PMEL, Building 3, 7600 Sand Point Way NE, Seattle, WA 98115-6349
Contact: nicholas.bond@noaa.gov

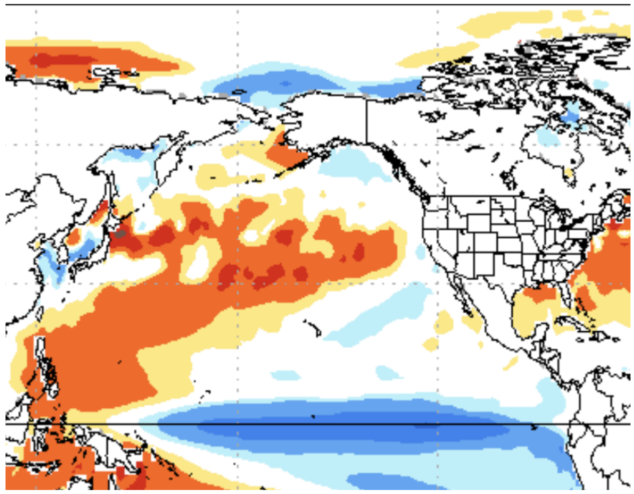
Last updated: September 2021

Description of indicator: Seasonal projections of SST from the National Multi-Model Ensemble (NMME) are shown in Figure 8. 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/`.

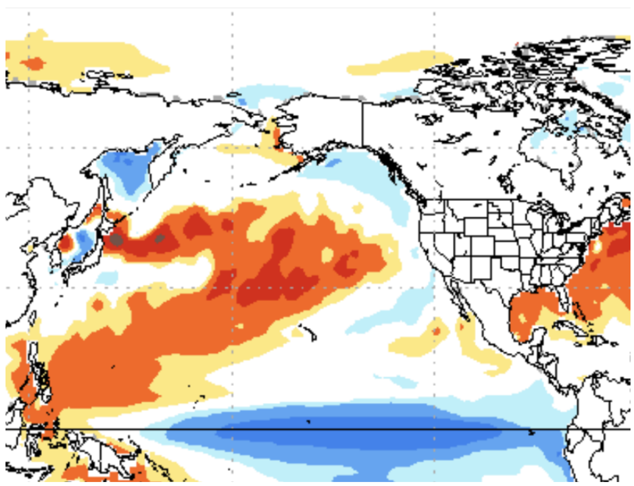
Status and trends: The projections from a year ago are first reviewed briefly. In general, the model forecasts from September 2020 for the following fall and winter indicated a continuation of positive SST anomalies across the North Pacific south of 50°N and in the northern Bering Sea. For the spring 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-average 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 of December 2020 through February 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, i.e., the predictions for Feb-Apr 2021.

These 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 8a). 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 here 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 8b) as compared with climatological norms.

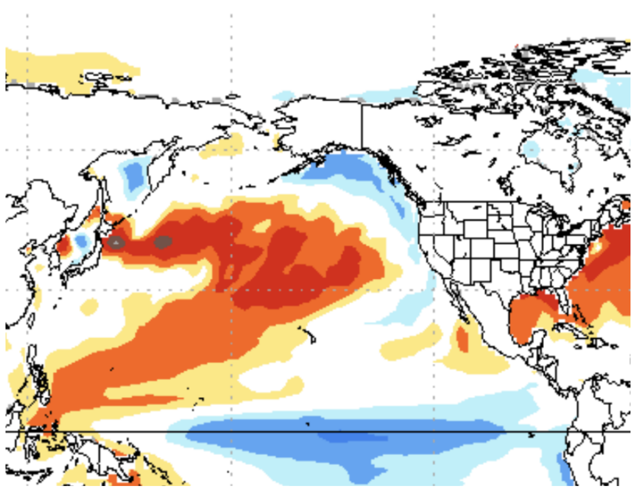
Implications: These changes are consistent with what has occurred in past La Niña winters; the models as a group are predicting tropical Pacific temperatures commensurate with a moderate La Niña. The distribution of SST anomalies predicted for February through April of 2022 (Figure 8c) shows that the 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-average 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 eastern Bering Sea. Most but not all of the models suggest conditions that would result in ice extending south of 60^{o}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

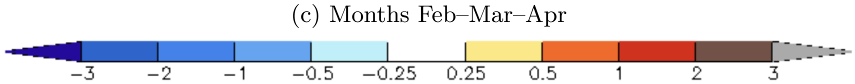


Figure 8: Predicted SST anomalies from the NMME model for Oct–Nov–Dec (1-month lead), Dec–Jan–Feb (3-month lead), and Feb–Mar–Apr (5-month lead) for the 2021–2022 season.

Ocean Temperature: Gulf of Alaska Synthesis

Satellite Data: Jordan T. Watson, Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA; Contact: jordan.watson@noaa.gov
Seward Line Survey: Seth L. Danielson and Russell R Hopcroft, University of Alaska, Fairbanks; Contact: sldanielson@alaska.edu, rrhopcroft@alaska.edu
AFSC Southeast Coastal Monitoring Survey: Emily Fergusson, Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA ; Contact: emily.fergusson@noaa.gov
Bottom Trawl Survey: Ned Laman, Groundfish Assessment Program, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA; Contact: ned.laman@noaa.gov
AFSC Longline Survey: Kevin Siwicke, Marine Ecology and Stock. Assessment Program, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA; Contact: kevin.sewicki@noaa.gov
AFSC EcoFOCI Spring Larval Survey: Lauren Rogers, EcoFOCI, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA; Contact: lauren.rogers@noaa.gov
Reanalysis Data: Muyin Wang: Pacific Marine Environmental Lab, NOAA; Contact: muyin.wang@noaa.gov
Last updated: October 2021

Description of indicator: Ocean temperature can vary sub-regionally, due to differences in circulation, freshwater runoff, wind-driven mixing, and other oceanographic drivers (Bograd2005). Local temperatures can influence survival or condition of critical life history periods of certain species, such as salmon in the inside waters of southeast Alaska. Sea surface temperature is a foundational characteristic of the marine environment and temperature dynamics impact many biological processes. Changes in temperatures can influence physiological processes of fish (e.g., metabolic rates and growth rates), fish distribution (Yang et al., 2019), trophic interactions, availability of spawning sites (Laurel and Rogers, 2020), and energetic value of prey. Extended periods of increased SST can lead to marine heat waves (Bond et al., 2015; Hobday et al., 2016).

In recent years, warm water events have become so frequent in the world's oceans that a new method for describing them has been formalized. We consider marine heatwaves (MHWs) to occur when SST exceeds a particular threshold for five or more days. That threshold is the 90^{th} percentile of temperatures for a particular day of the year based on a 30-year baseline (Hobday et al., 2016). The intensity of a MHW can be further characterized by examining the difference between the 90^{th} percentile threshold for a given day and the baseline temperature for that day. If the threshold is exceeded, the event is considered *moderate*, *strong* (2 times the difference between then threshold and normal), *severe* (3 times the difference between the threshold and normal), or *extreme* ($\leq$ 4 times the difference) (Hobday et al., 2018).This section presents a collection of empirically collected temperature measurements from 2021 spring and summer surveys.

In this section we describe trends in ocean temperature at surface and at depth throughout the GOA. We first show satellite data and reanalysis monthly data for 2021 ocean temperatures at surface and at depth, averaged across the western GOA and eastern GOA shelf. This is followed by a description of trends observed across multiple GOA sub-regional surveys conducted in the spring and summer of 2021. We then show observations related to marine heatwave conditions. Detailed methods are listed at the end of the contribution.

Status and trends: Much of 2021 has been cooler than the previous few years, with temperatures in both the western and eastern GOA hovering close to the long-term mean. Despite this generally cooler pattern, the year started out relatively warm in the western GOA before trending more towards the long-term mean (Figure 9). Reanalysis data show approximately average temperatures at ∼ 100m and cooler than average temperatures at ∼ 200m (Figure 10). Subregional surface temperatures in the western GOA (Kodiak and Shelikof Strait, Seward Line) are cooler than average and the eastern GOA (Icy Strait) show temperatures oscillating around the long-term mean.

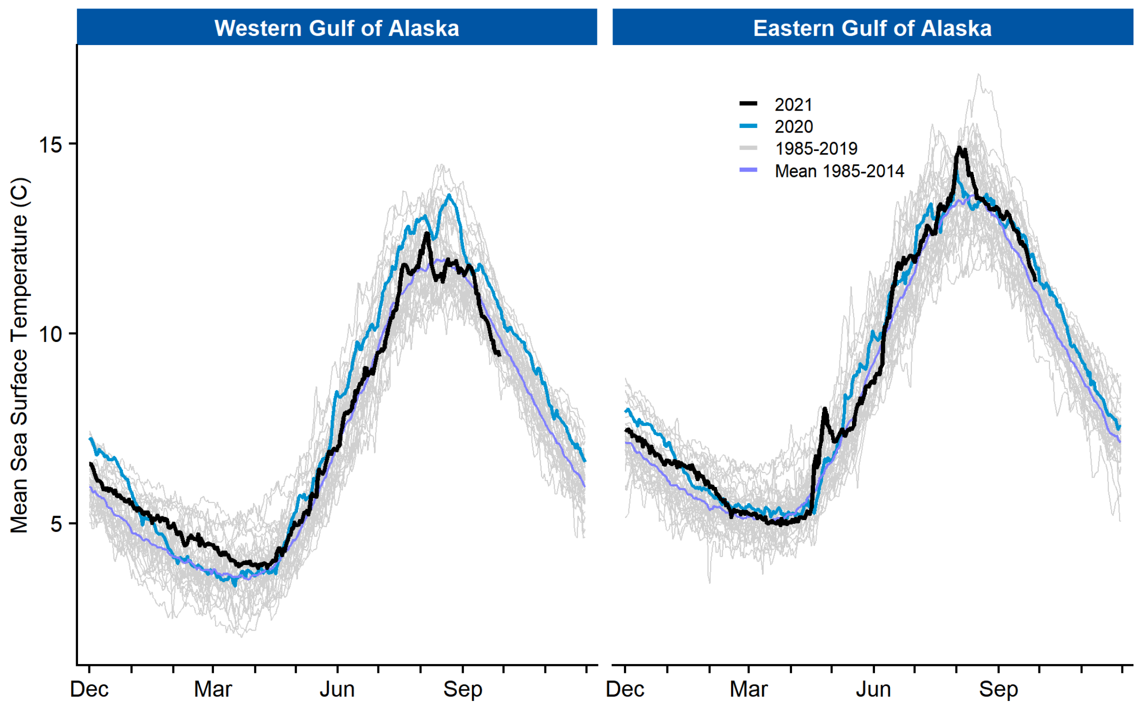


Figure 9: Daily sea surface temperatures (SST) for the western GOA and eastern GOA. Lines illustrate the daily SST for 2021 through Oct. 4 (black), the daily SST for 2020 (blue), the 30-year (1985–2014) mean SST for each day (purple), and daily SST for each year of the time series (1985-2019; gray). Survey details are in the "Methods" section at the end of this contribution.

Spring western GOA: May 2021 surface temperatures in the western GOA were cooler than in 2020 and approximately 0.5°C below the survey-specific long-term means (EcoFOCI: 5.7°C, Seward Line Survey: 5.9°C) (Figure 11). Temperatures were slightly warmer in Shelikof Strait and on the shelf between Kodiak and Chirikof Island, and cooler towards the southwest of Kodiak. May 2021 was about 0.5°C below the long-term mean of the past 24 years (5.7°C). The Seward Line (5.9°C) was cooler than average.

Summer western GOA: The 2021 summer surface waters in the western GOA were cooler than 2020 (Seward Line) and 2019 (Bottom Trawl Survey), and were cooler (10.5°C and 8.8°C, respectively) than the survey-specific long-term means (Figure 12). At ∼ 200 m depth Seward Line (5.4°C) and Bottom Trawl temperatures (5.3°C) cooled from previous surveys (2020 and 2019 respectively) to the approximate long-term mean, while the Longline Survey temperatures (5.2°C) remained above

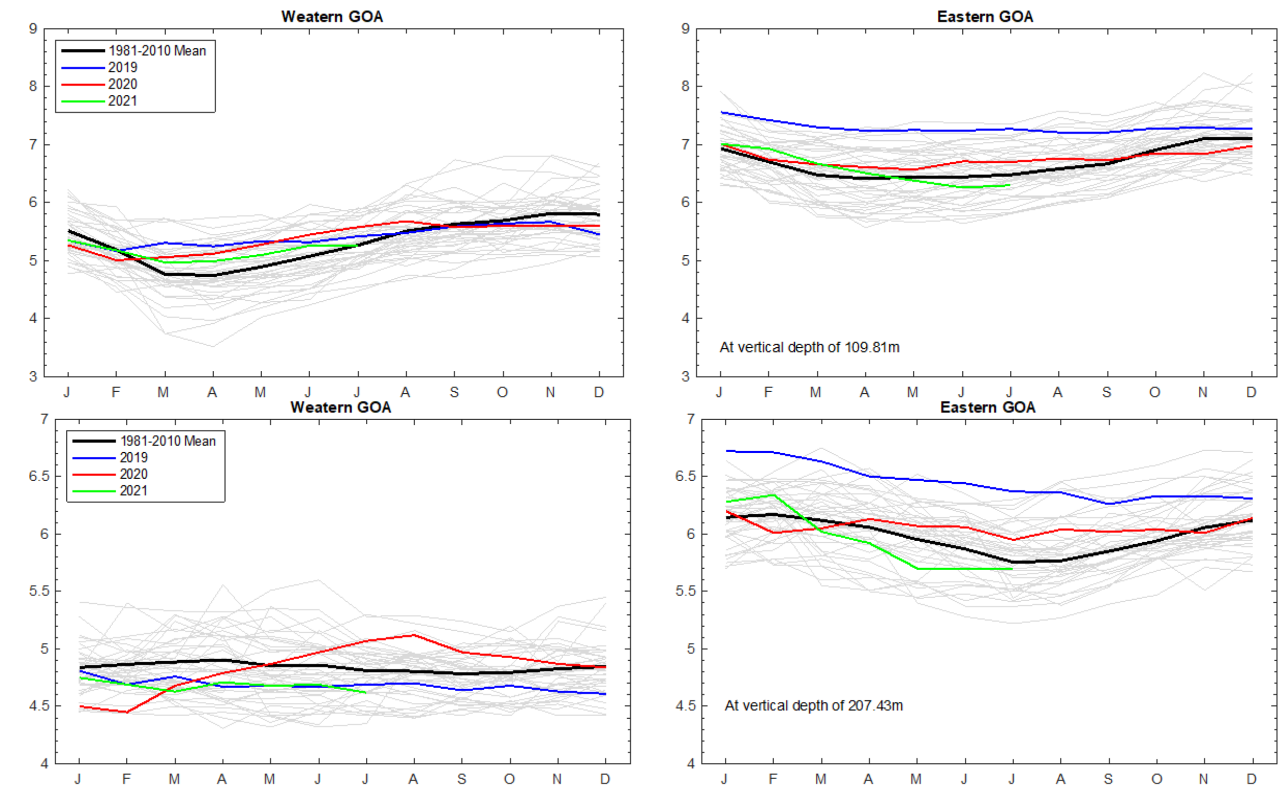


Figure 10: Seasonal cycle of ocean temperature at the depth of 110m (top), and 207m (bottom). Each layer represents an average of 10m–30m in depth. Climatology (black) is computed as the average of 1981–2010. Thin grey lines are for each individual year. Three recent years are highlighted: 2019 (blue), 2020 (red), and 2021 (green, up to July 2021 only).

the long-term mean.

Summer eastern GOA: The 2021 summer surface waters over the eastern GOA shelf were cooler than 2019 (Bottom Trawl Survey: 13.4°C) cooling to approximately the long-term mean (Figure 12). The inside surface waters in SEAK (Icy Strait) remained just below the long-term mean, at 8.9°C, for a second year. At ∼ 200 m depth, temperatures were cooler than in the previous surveys (Longline Survey (5.5°C) and Bottom Trawl Survey (5.9°C) but still slightly warmer than survey-specific long-term means.

Marine Heat Waves: The western GOA has remained below marine heatwave status throughout 2021 so far, while the eastern GOA had several brief and moderate events (Figures 13 and 14). This year (2021) stands out from the previous half decade as having remarkably few days in marine heatwave status (Figure 14). An important ecological consideration with marine heatwaves is the extent of a particular area that experiences the warm conditions, and whether there may be thermal refugia for species within that domain. For the brief eastern GOA marine heatwave in April, ∼84% of the satellite pixels (5 km grid) analyzed experienced a marine heatwave that week, suggesting that most of the eastern GOA experienced such warming.

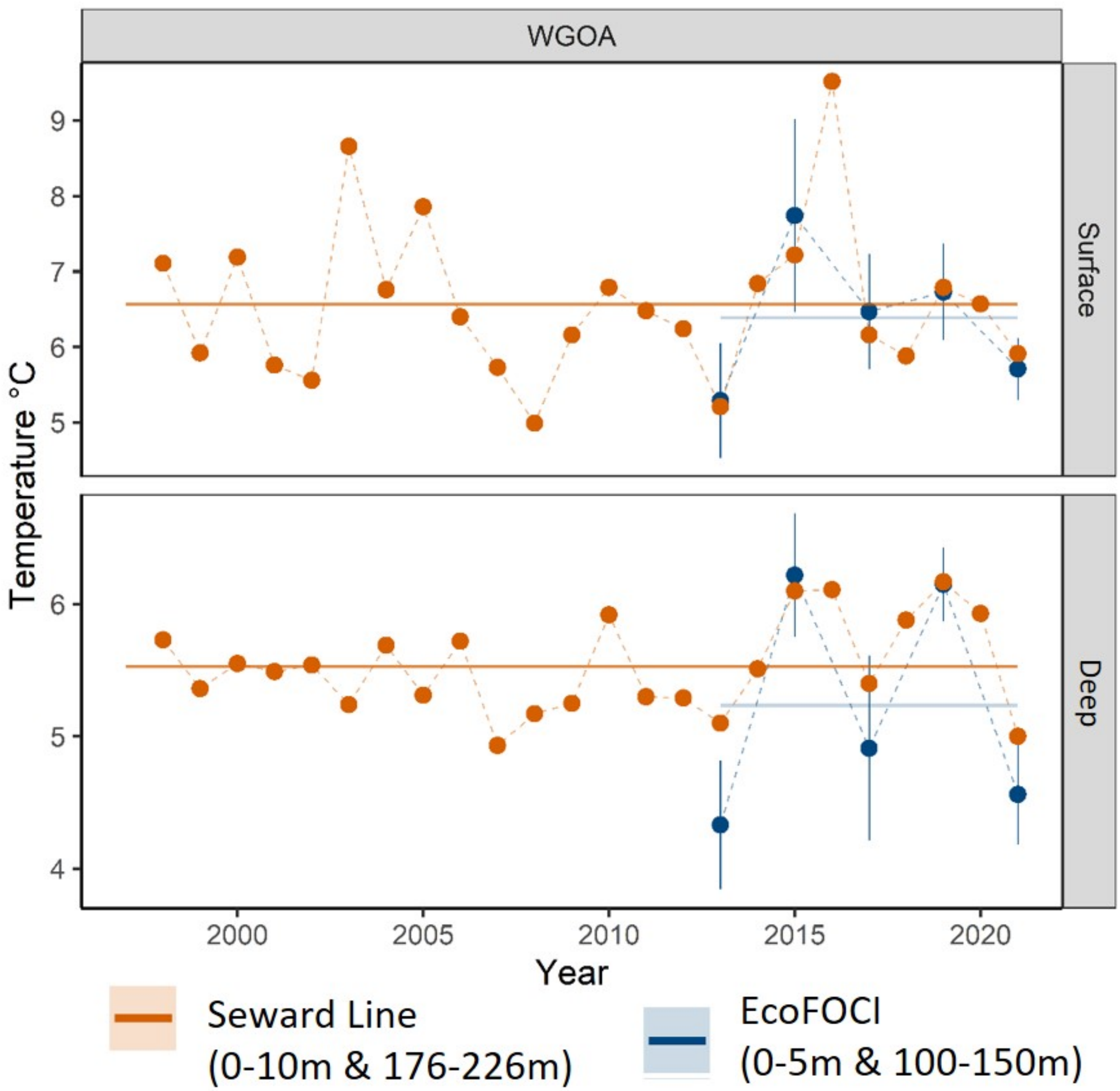


Figure 11: Observed temperatures at surface and depth from the AFSC EcoFOCI spring (May-June) larval survey and the Gulfwatch Alaska spring (May) Seward Line survey.

Factors influencing observed trends: Ocean temperatures in 2021 reflect a second consecutive year of no persistent marine heatwave conditions (e.g., 2014–2016 and 2019) (Bond et al., 2015; Hu et al., 2017; Barbeaux et al., 2020*b*) with temperatures at the surface and depth trending towards the long-term mean. Warm years are often associated with El Niño events (1998, 2003, and 2016) and marine heat waves. Cool conditions are related to complex winter balances between heat loss, coastal runoff and stratification (Janout et al., 2010). The 2021 cooling temperatures relate to upwelling conditions due to the westerly winds in winter/spring 2021 and a negative Pacific Decadal Oscillation. Predicted La Nina conditions in the winter of 2021/2022 may continue this cooling trend.

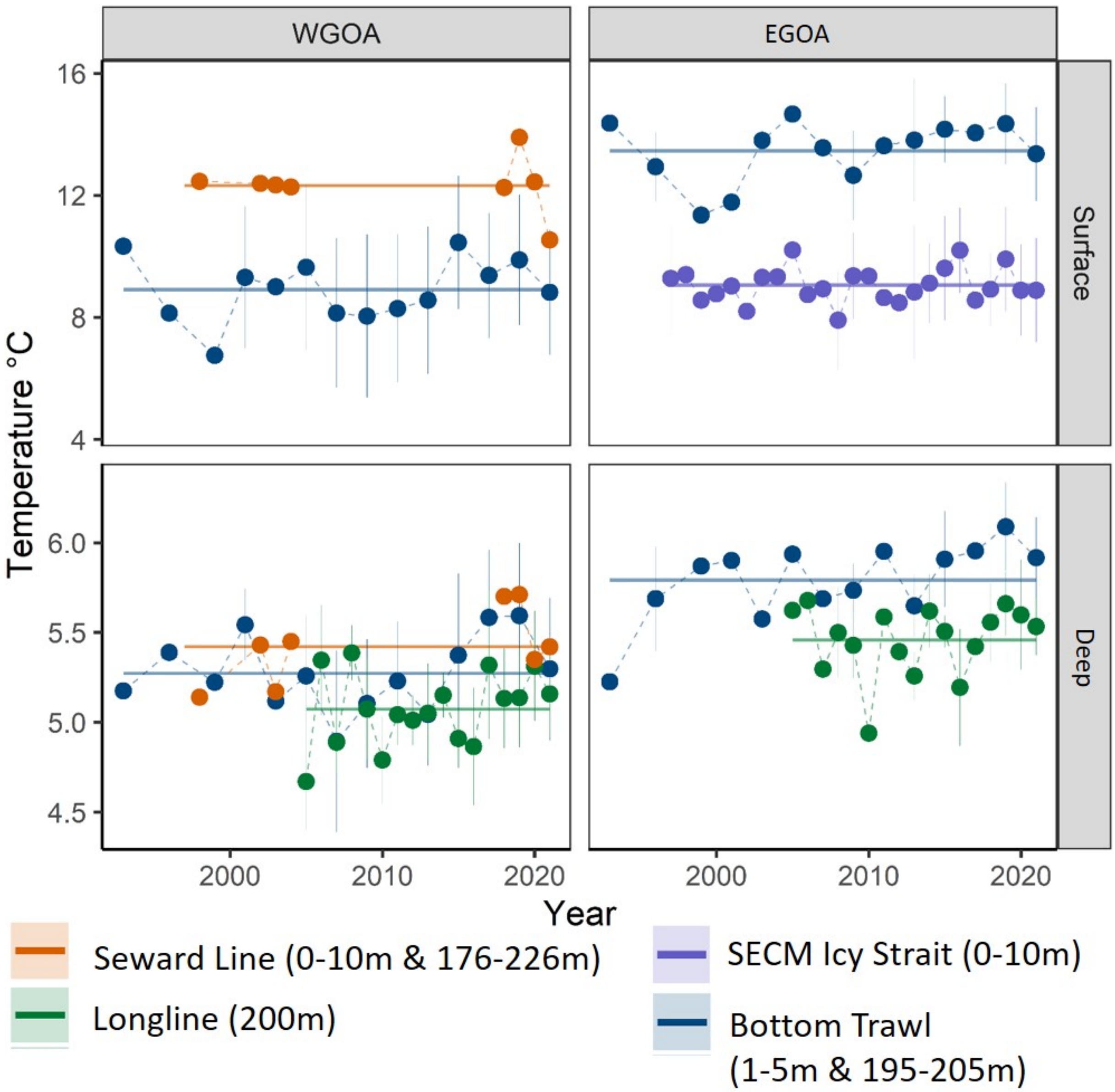


Figure 12: Observed temperatures at surface and depth from the AFSC Bottom Trawl Survey, AFSC Longline Survey, AFSC Southeast Alaska Coastal Monitoring (SECM Survey), and the Gulfwatch Alaska spring (May) Seward Line survey. Survey details are in the "Methods" section at the end of this contribution.

Many factors can influence sea surface temperatures and the formation of MHWs, including a suite of weather, climatic, and oceanographic factors (Holbrook et al., 2019). Meanwhile, defining or contextualizing heatwaves depends upon the selection of baseline years (1985–2014). As long-term climate change leads to warmer temperatures, the baseline will change as well, requiring consideration of how baseline selection affects our interpretation of deviations from normal and thus, events like MHWs (Jacox, 2019; Schlegel et al., 2019). The more warm years that are included in the baseline, the warmer that baseline will appear.

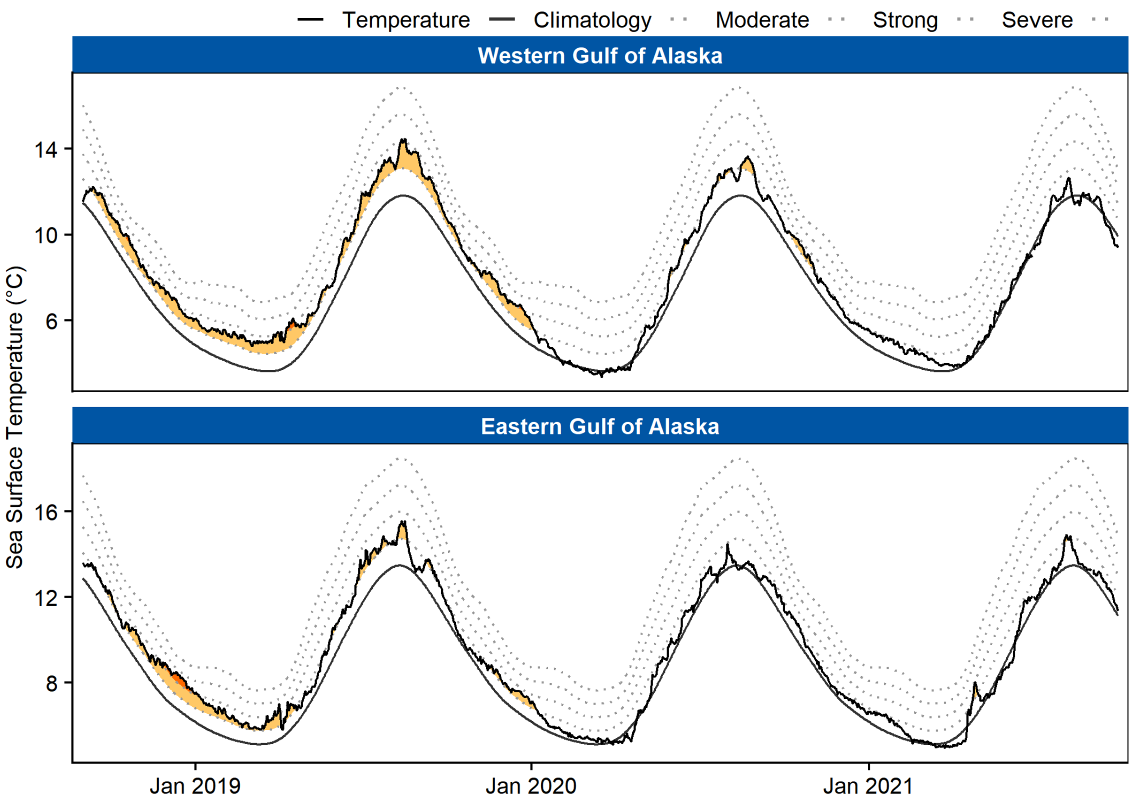


Figure 13: Marine heatwave (MHW) status from Dec. 2018 through Oct. 2021. Filled (yellow) areas depict MHW events. Black lines represent the 30-year baseline (smoothed line; 1985–2014.) and observed daily sea surface temperatures (jagged line). Faint grey dotted lines illustrate the MHW severity thresholds in increasing order (moderate and strong).

Icy Strait differs from the other shelf-oriented temperature datasets, reflecting conditions in the inside waters in SEAK. This region supports numerous forage species (e.g., herring, juvenile salmon), groundfish, salmon, marine mammals (e.g., humback whales) and seabirds. Icy Strait is a principal migration corridor for juvenile and returning salmon and temperature can influence the species composition of the zooplankton community affecting prey quality and availability (i.e., warmer temperatures can be associated with smaller zooplankton species with lower lipid densities).

Implications: Barbeaux et al. (2020*b*) provide tangible evidence for the potential implications of warming conditions on groundfish, in particular Pacific cod. Holsman et al. (2020) further emphasize the risk of warming conditions on gadid populations and highlight the value of an ecosystem-based management approach for buffering the impacts of projected temperature increases and more frequent marine heat waves. The conditions in 2021 have been persistently cooler and closer to the long-term mean than the previous few years. Moreover, the little heatwave activity that was experienced in the eastern GOA was ephemeral and relatively moderate compared to recent years. These temperatures provide average conditions (similar to 2020) for spawning, zooplankton quality and quantity, and fish metabolic demands (Yang et al., 2019; Barbeaux et al., 2020*b*).

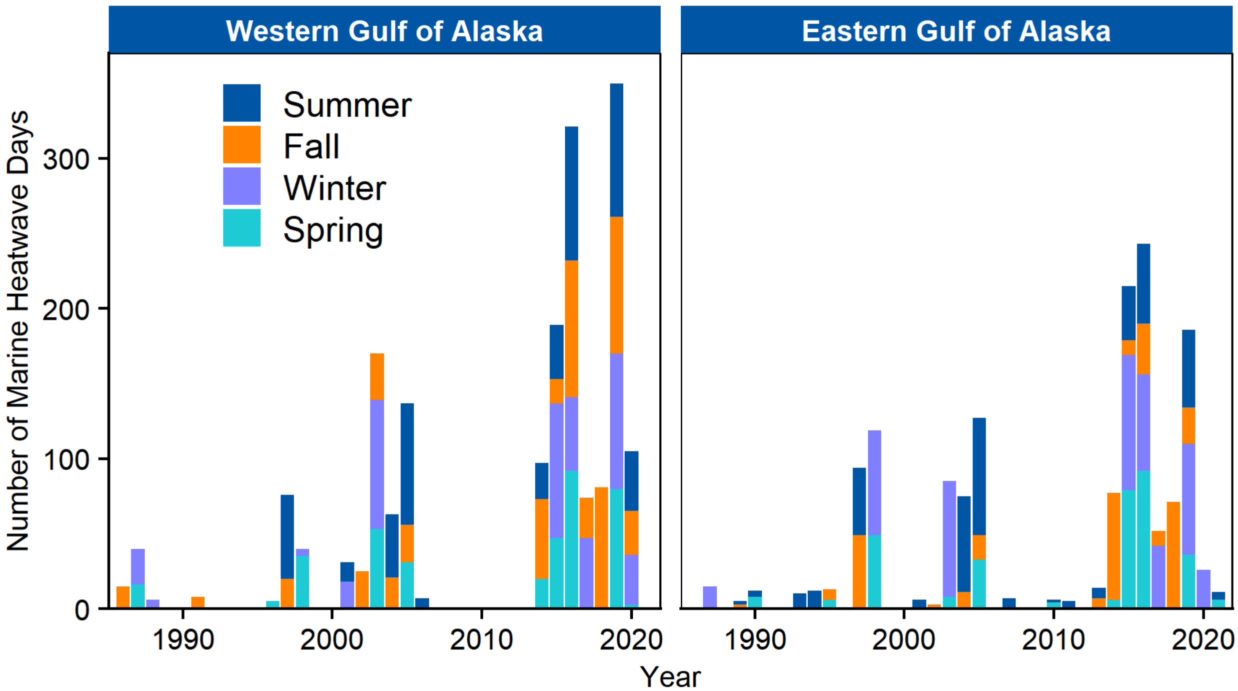


Figure 14: Number of days during which marine heatwave conditions persisted in a given year. Seasons are summer (Jun-Aug), fall (Sept-Nov), winter (Dec-Feb), spring (Mar-Jun). Years are shifted to include complete seasons so December of a calendar year is grouped with the following year to aggregate winter data (e.g., Dec. 2020 occurs with winter of 2021).

Methods:

AFSC EcoFOCI Spring Larval Survey: EcoFOCI conducts biennial surveys in spring (May-June) and summer (August- September) in the Western Gulf of Alaska, targeting early life stages of fishes and their prey. At each sampling station, a bongo net array is towed obliquely from surface to 100m (spring) or 200m (late summer), or to 10m off bottom in shallower waters. Attached to the wire above the bongo frame is a Seabird FastCAT profiler which measures temperature, salinity, and depth. Up casts were processed and used to generate maps and time-series of temperatures at the surface and at maximum tow depth using the custom R package FastrCAT (https://github.com/Copepoda/FastrCAT). Survey dates were 10–26 May 2021. The late summer EcoFOCI survey was cancelled in 2021, so no update of late summer data is provided.

AFSC Bottom Trawl Survey: Since 1993, water column temperatures have been routinely recorded during Alaska Fisheries Science Center (AFSC) Resource Assessment and Conservation Engineering Groundfish Assessment Program (RACE-GAP) GOA bottom trawl surveys using bathythermograph data loggers attached to the headrope of the bottom trawl net. In 2003, a SeaBird (SBE-39) microbathythermograph (Sea-Bird Electronics, Inc., Bellevue, WA) replaced the Brancker XL200 data logger (Richard Brancker Research, Ltd., Kanata, Ontario, Canada) which had been in use from 1993 to 2001 (Buckley et al., 2009). The analyses presented here combine these two types of bathythermic data; the downcast data from each RACE-GAP trawl haul were isolated and used to inform our models.

Spatial and temporal coverage of the GOA RACE-GAP summer bottom trawl surveys has varied from year to year. Starting dates have ranged from the middle of May to the first week in June, and survey end dates ranged from the third week in July to the first week in September. The number of vessels employed, the areal extent, and the maximum depth of the GOA survey have all varied among survey years (e.g., water temperatures were not collected from the eastern GOA in 1993 and 2001, stations in the deepest GOA stratum [700–1000 m] have been sampled in just 5 of the last 13 surveys). Since the GOA survey sweeps from west to east over the late spring and summer, the expectation is a trend toward warmer water temperatures collected late in the summer in southeast Alaska compared with those collected in the western GOA in late spring; this anticipated trend is expected to be particularly pronounced in the upper layers of the water column.

2021 temperatures were not standardized to account for the effect of collection date as in past years, but those methods will resume next year.

Gulfwatch Alaska Seward Line Survey: Since 1998, hydrographic transects have been completed in May (typically during the first 10 days of the month) along a sampling line that extends from the mouth of Resurrection Bay near Seward to the outer continental slope of the northern Gulf of Alaska. Data analyzed here is water column profile data that have been averaged over the top 100m of the water column to provide an index of upper water column heat content on the northern Gulf of Alaska shelf.

AFSC Southeast Coastal Monitoring Survey (Icy Strait): Temperature has been collected annually in Icy Strait during monthly (May to August) fisheries oceanography surveys conducted by the Southeast Coastal Monitoring (SECM) project of Auke Bay Laboratories, AFSC. The Icy Strait Temperature Index (ISTI, °C) is the average temperature of the upper 20 m integrated water column.

Satellite Data: Satellite SST data from the NOAA Coral Reef Watch Program were accessed via the

NOAA Coast Watch West Coast Node ERDDAP server (`https://coastwatch.pfeg.noaa.gov/erddap/griddap/NOAA_DHW.html`) for January 1985 - September 2021. A limitation of SST records derived from satellites has been data missing as a result of cloud cover. Using the NASA multi-scale ultra-high resolution (MUR) SST dataset however, a combination of collection modalities creates a gap-free blend of data. Daily SST data were averaged within the western (147°W– 163°W) and eastern (133°W–147°W) Gulf of Alaska (western GOA and eastern GOA, respectively) for depths from 10m – 200m (i.e., on the shelf). Detailed methods are online, including maps of the spatial strata and processing the data in R (`github.com/jordanwatson/EcosystemStatusReports/tree/master/SST`).

We use the earliest complete 30-year time series (1985–2014) as the baseline period for mean and standard deviation comparisons although the guidance on such choice varies across studies (Hobday et al., 2018; Schlegel et al., 2019). Three notable differences exist between the current marine heatwave indicators and those previously presented to the North Pacific Fishery Management Council (detailed in Barbeaux et al., 2020*b*). First, the current indicator uses a different NOAA SST dataset, with a slightly different time period (beginning mid-1985 instead of mid-1982) and spatial resolution (the current indicator has finer spatial resolution and thus, more data points within the same region). Given the shorter time series, the 30-year baseline period is necessarily different (1986–2015 instead of the previous 1983–2012). Finally, the previous indicator was bounded spatially to target management of Pacific cod in the GOA, whereas the current indicator is bounded spatially by the ESR regions for a broader comparison.

Reanalysis data: The data used here Met Office Hadley Centre "EN" series of data sets of global quality controlled ocean temperature (UK EN4.2.1), which include profiles and analyses with bias corrections applied (Good et al., 2013). The climatology is computed as the monthly means averaged over the 1981–2010 period. There are 327 valid grid points in the GOA domain for defining the bottom T (at z = 100–200 meters) for the region y = 52 - 61°N, x = 165w - 129°W, as shown above. These are the data points we used to compute the regional mean.

AFSC Summer Longline Survey: The Alaska Fisheries Science Center (AFSC) has been conducting a longline survey since 1987 to sample groundfish from the upper continental slope annually in the Gulf of Alaska (GOA), during odd years in the Bering Sea (BS), and during even years in the Aleutian Islands (AI). More details related to this survey can be found in Siwicke et al. (2021). The survey samples the GOA from west to east for the western portion of the region during the second half of June before transiting to Ketchikan and sampling from east to west and ending southwest of Kodiak Island in late August. Beginning in 2005, a temperature (depth) recorder (TDR) has been used for the purpose of measuring in-situ bottom temperature at each station. There are 71 stations sampled by the AFSC longline survey located within the GOA ESR region (41 in the western GOA and 30 in the eastern GOA), but sometimes units fail, so not all stations are successfully sampled every year.

The TDR used is an SBE 39 (Seabird Electronics) which is attached directly to the middle of the longline, with a second TDR being attached deeper starting in 2019. The TDR records water temperature and depth every 10 seconds, and the downcast is processed to 1-m increments via the double parabolic method used by the World Ocean Atlas 2018 (Reiniger and Ross, 1968; Locarnini et al., 2019). The mean of the temperature while the TDR is on the bottom is a point estimate of the bottom temperature while the longline is fishing (which is usually two to six hours), and the range of temperatures recorded can be useful in interpreting how much variation occurs at a station.

The mean temperature from 1-m increment depths over the 246–255 m depth range was selected as an index for subsurface temperature because this layer was shallow enough to be consistently sampled across space and time and also deep enough to be below thermoclines and mixed layer dynamics. The depth of the profile does not always reach $\sim$ 250 m depth, but sample sizes have improved since 2019 because the second TDR deployment could be used if the first was unsuccessful or too shallow. Temperatures were weighted relative to the area of the depth-stratified regions the survey stations were in, which are described in Echave et al. (2013).

Eddies in the Gulf of Alaska

Contributed by Wei Cheng, Pacific Marine Environmental Laboratory, NOAA, Seattle, WA, and University of Washington, CICOES, Seattle, WA
Contact: Wei.Cheng@noaa.gov
Last updated: September 2021

Description of indicator: Eddies in the northern Gulf of Alaska have been shown to influence distributions of nutrients (Ladd et al., 2009, 2005, 2007), including dissolved iron (Crusius et al., 2017; Ladd et al., 2009), phytoplankton (Brickley and Thomas, 2004), and ichthyoplankton (Atwood et al., 2010). In addition, the settlement success of arrowtooth flounder (Goldstein et al., 2020), the feeding environment for juvenile pink salmon (Siwicke et al., 2019), and the foraging patterns of fur seals (Ream et al., 2005) can be influenced by the presence of eddies. Eddies propagating along the slope in the northern and western Gulf of Alaska are generally formed in the eastern Gulf in autumn or early winter (Okkonen et al., 2001) and sometimes they are associated with gap winds from Cross Sound (Ladd and Cheng, 2016). Using altimetry data from 1993 to 2001, Okkonen et al. (2003) found that strong, persistent eddies occurred more often after 1997 than in the period from 1993 to 1997. Ladd (2007) extended that analysis to 2006 and found that, in the region near Kodiak Island (Figure 15; region c), eddy energy in the years 2002–2004 was the highest in the altimetry record. The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (`http://www.marine.copernicus.eu`).

Since 1992, a suite of satellite altimeters has been monitoring sea surface height. Eddy kinetic energy (EKE) can be calculated from gridded altimetry data (Ducet et al., 2000), giving a measure of the mesoscale energy in the system. A map of eddy kinetic energy in the Gulf of Alaska averaged over the altimetry record (updated from Ladd, 2007) shows four regions with local maxima (labeled a, b, c and d in Figure 15). The first two regions are associated with the formation of the Haida (a) and Sitka (b) eddies. Eddies that move along the shelf-break often feed into the third and fourth high EKE regions (c and d). By averaging EKE over the regions, we obtain an index of energy associated with eddies in these regions (Figure 16).

Analysis updates — The most recent data were downloaded on August 21, 2021 so our time series now covers 1/1/1993 to 8/21/2021, at daily temporal resolution and on a 0.25^o longitude x 0.25^o latitude grid. The original data set is global but we subset it to 150^{o}E - 125^{o}W and 40^{o}N - 72^{o}N during download. Data from 1993 to 2019 is the delayed/reprocessed product whereas those in 2020 and 2021 are from the "NRT" (near real time) products. The horizontal map shown below is averaged over all full years from 1993 to 2020, monthly climatology/mean seasonal cycle is updated using the full years from 1993–2020, and monthly anomalies are defined relative to this climatology.

Status and trends: The seasonal cycles of EKE in the eastern and central GOA regions (Figure 15, box a-c) have similar phasing (high in winter/spring and low in summer/fall), suggesting their formation mechanisms are inter-related. As noted, region (d) (western GOA) has an opposite seasonal cycle phase than the other regions (high EKE in the autumn and low EKE in the spring), suggesting separate forcing mechanisms in the western GOA. In year 2021 thus far, EKE amplitude in regions (a) and (b) (eastern GOA) are close to the climatology while those in regions (c) and (d) are higher than the climatology (Figure 16). In particular, EKE amplitude in (c) is the 4th highest since the start of the satellite data, being only lower than 2016, 2002 and 2004. Previous reserach

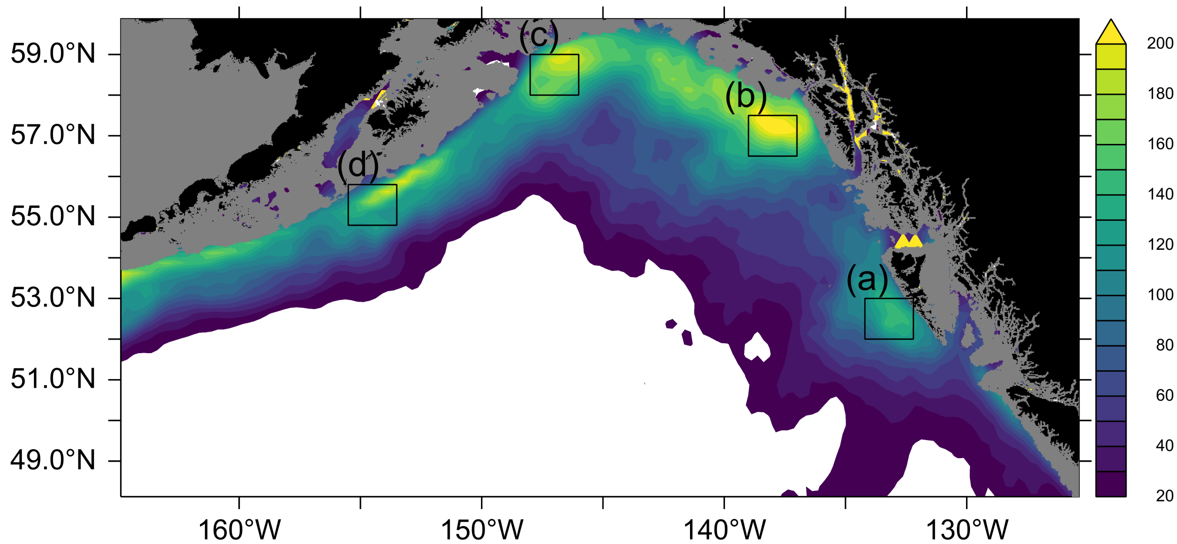


Figure 15: Eddy Kinetic Energy (cm^2 s^{-2}) averaged over January 1993–December 2020 calculated from satellite altimetry. Regions (a)-(d) denote regions over which EKE was averaged for Figure 16.

Ladd (2007) noted that high EKE in region (c) in 2002–2004 occurred when three large persistent eddies passed through the region; similarly, the highest EKE in region (c) in 2016 occurred when a strong persistent eddy remained in the region for multiple months.

The passage of eddies is seen in 2021 as well (Figure 17). In region (d), EKE in winter of 2020/2021 is similar in amplitude to winter of 2017/2018 but lower than in previous winter (2019/2020). Both regions dropped below average by summer 2021, however. An eddy passed through region (c) in March, April, and May (Figure 17c-e). Another eddy is situated almost stationary near region (d) January through May and strengthened over the same time period, it then moved southwestward in June, July and August. Eddies didn't pass through boxes (a) and (b), but they existed in slighly off-shore locations adjacent to these boxes.

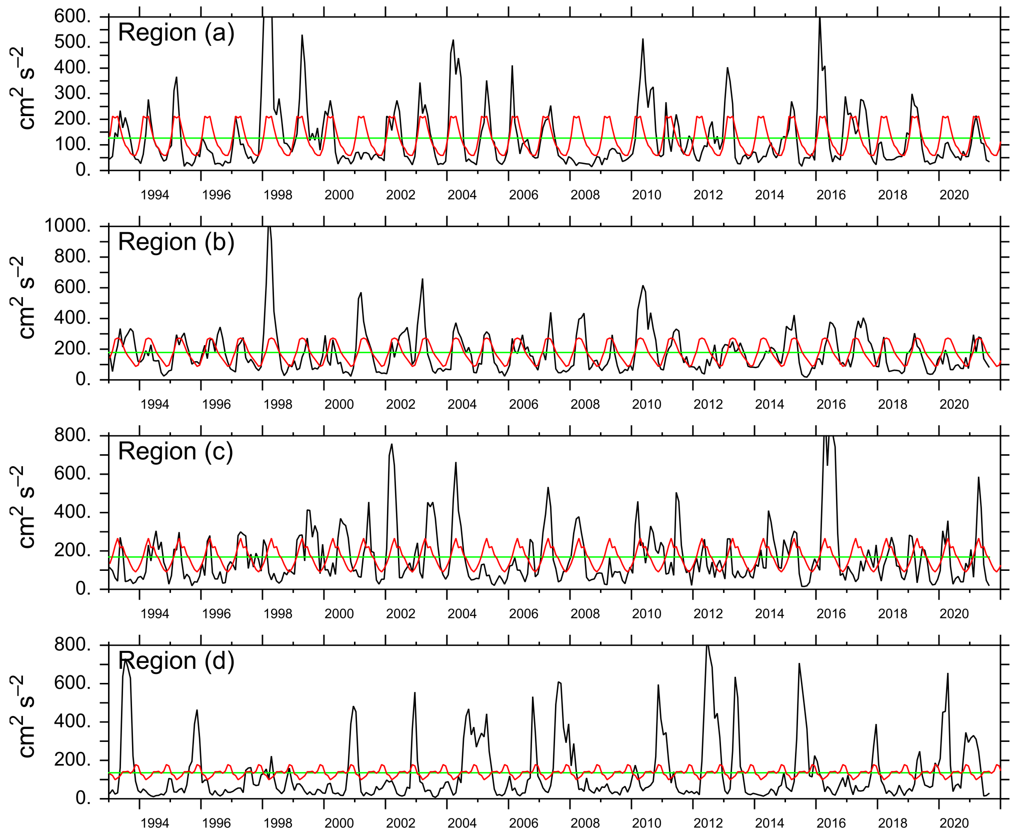
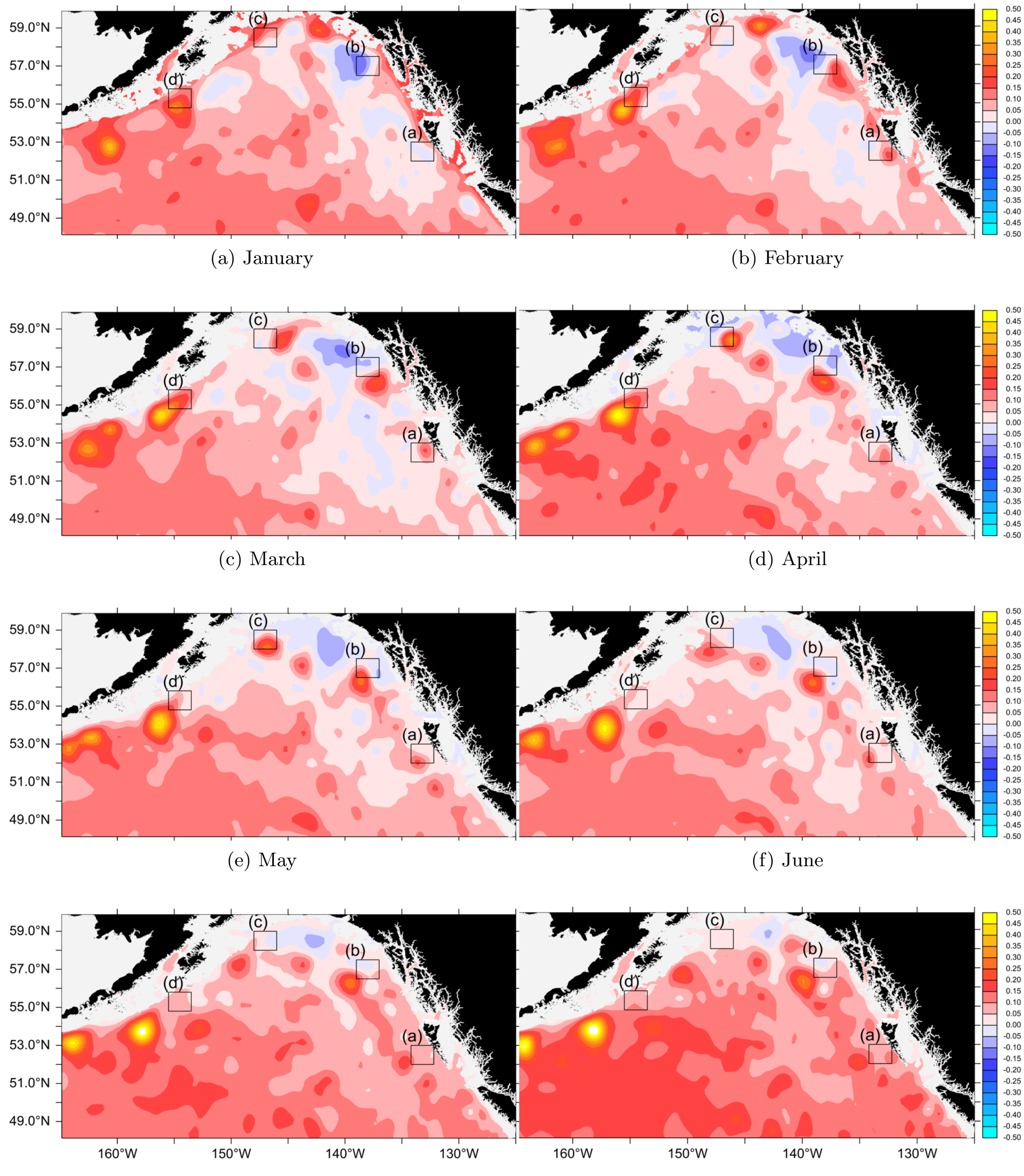


Figure 16: Eddy kinetic energy (cm^2 s^{-2}) averaged over regions shown in Figure 15. Black (line with highest variability): monthly EKE; Red: mean seasonal cycle; Green (straight line): mean over entire time series.



(a) January (b) February (c) March (d) April (e) May (f) June (g) July (h) Aug

Figure 17: Monthly sea surface height anomalies (unit: meter) in 2021. Panels from top to bottom correspond to January through August.

Factors influencing observed trends: In the eastern Gulf of Alaska, interannual changes in surface winds (related to the Pacific Decadal Oscillation, El Niño, and the strength of the Aleutian Low) modulate the development of eddies (Combes and Di Lorenzo, 2007; Di Lorenzo et al., 2013). Regional-scale gap-wind events may also play a role in eddy formation in the eastern GOA (Ladd and Cheng, 2016). In the western GOA, variability is related both to the propagation of eddies from their formation regions in the east and to intrinsic variability.

Implications: The eddy in Region (c) occurred in March-May, simultaneously with a large phytoplankton bloom in that region. It is difficult to directly connect the two phenomena, however cross shelf transport may have contributed to the bloom. Eddies sampled in 2002–2004 were found to contain different ichthyoplankton assemblages than surrounding slope and basin waters indicating that eddies along the slope may influence the distribution and survival of fish (Atwood et al., 2010). Carbon isotope values suggest that cross-shelf exchange due to eddies may be important to the marine survival rate of pink salmon (Kline, 2010).Eddies may result in enhanced settlement and recruitment for arrowtooth flounder (Goldstein et al., 2020) and marine survival rate of pink salmon (Kline, 2010)

Ocean Surface Currents—Papa Trajectory Index

Contributed by William T. Stockhausen, Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: william.stockhausen@noaa.gov
Last updated: August 2021

Description of indicator: The Papa Trajectory Index (PTI) provides an annual index of near-surface water movement variability, based on the trajectory of a simulated surface drifter released at Ocean Station Papa (50°N, 145°W; Figure 18). The simulation for each year is conducted using the "Ocean Surface CURrent Simulator" (OSCURS; `http://oceanview.pfeg.noaa.gov/oscurs`). Using daily gridded atmospheric pressure fields, OSCURS calculates the speed and direction of water movement at the ocean's surface at the location of a simulated surface drifter. It uses this information to update the position of the simulated drifter on a daily basis over a specified time period. For the index presented here, OSCURS was run for 90 days to simulate a surface drifter released at Ocean Station Papa on December 1 for each year from 1901 to 2020 (trajectory endpoints years 1902–2021).

Status and trends: The 2020/21 trajectory was primarily to the north, initially arcing slightly to the east in December (Figure 19). This year was most similar to those of 2011/12, 2013/14, and 2015/16.

The 2020/21 value in the PTI time series (Figure 19) represents a return to PTI values above the long-term mean, following 4 consecutive years of values below the mean. The PTI time series indicates high interannual variation in the north/south component of drifter trajectories, with an average between-year change of >4° and a maximum change of greater than 13° (between 1931–1932).

The change in the PTI between 2010/11 and 2011/12 was the largest since 1994, while the changes between 2011/12 and 2012/13, and between 2012/13 and 2013/14, represented reversals with

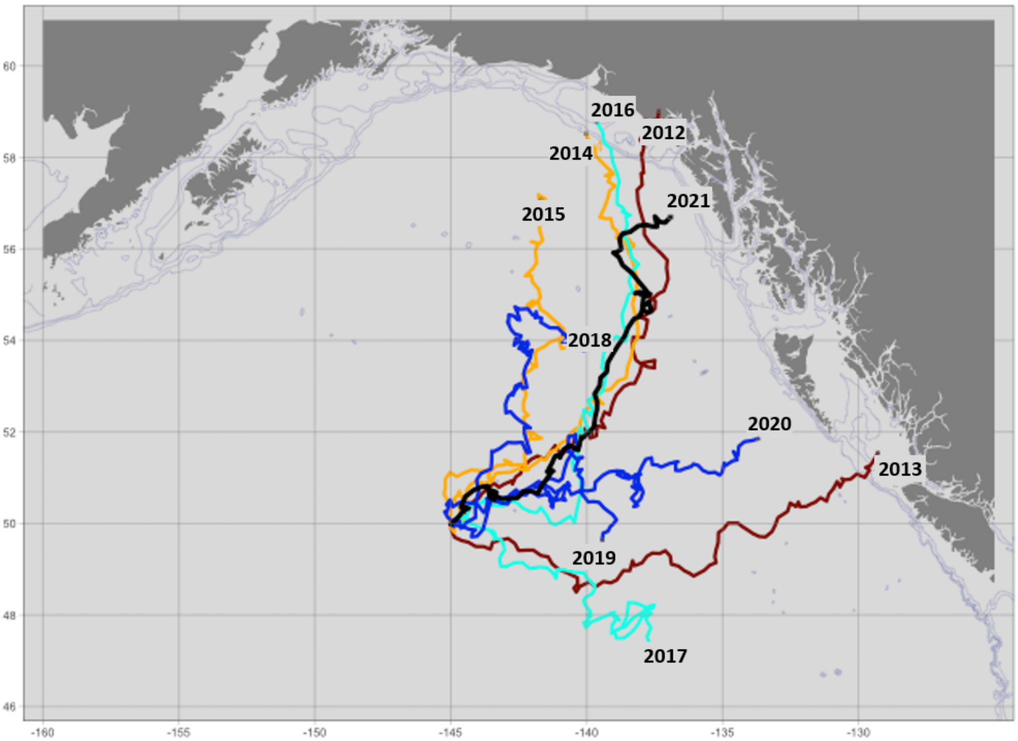


Figure 18: Simulated surface drifter trajectories for winters 2011–2021 (endpoint year). End points of 90-day trajectories for simulated surface drifters released on Dec. 1 of the previous year at Ocean Station Papa are labeled with the year of the endpoint (50°N, 145°W). Note the black line is 2020/2021, the northern pale blue line is 2015/2016, the northern brown line is 2011/2012, the orange lines are 2014/2015 and 2013/2014.

slightly less, but diminishing, magnitude. Such swings were not uncommon over the entire time series. The changes from 2013/14 to 2015/16 constituted a relatively rare event when the index changed very little over three successive years.

Over the past century, the filtered (5-year running average) PTI has undergone five complete oscillations with distinct crossings of the mean, although the durations of the oscillations are not identical: 26 years (1904–1930), 17 years (1930–1947), 17 years (1947–1964), 41 years (1964–2005), and 10 years (2005–2015) (Figure 19). The filtered index indicates that a shift occurred in the mid 2000s to predominantly southerly anomalous flow following a ∼25 year period of predominantly northerly anomalous flow. This was indicative of a return to conditions (at least in terms of surface drift) similar to those prior to the 1977 environmental regime shift, although this cycle ended rather quickly, as the filtered PTI crossed the mean in the opposite direction in 2011. A similar shift back to anomalous southerly flow appears to have occurred in 2016. Since 2005, the PTI appears to be fluctuating on a much shorter time scale (∼10 years per mean crossing) than previously.

Factors influencing observed trends: The 2020/21 trajectory was influenced in December by low sea level pressure (SLP) anomalies centered far to the west in the Aleutian Islands coupled with a weaker system of high pressure anomalies off California that formed a dipole oriented from the southeast (high pressure anomalies) to the northwest (low pressure anomalies), with the resulting winds contributing to the northeasterly progression of the drifter. By February, however, the SLP

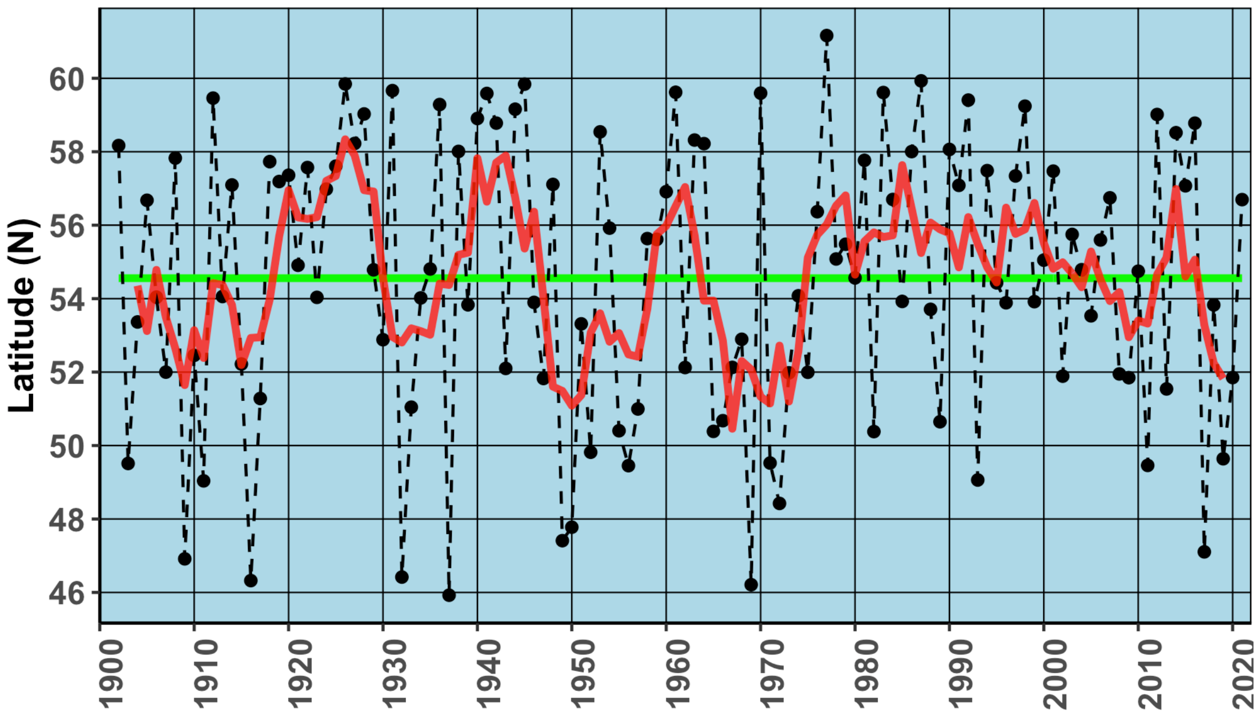


Figure 19: Annual, long-term mean (green line), and 5-year running mean (red line and squares) of the Papa Trajectory Index time series end-point latitudes (dotted black line and points) for 1902–2021 winters.

system had rotated somewhat counterclockwise so that it was oriented along a more east-west line. In addition, the high pressure anomalies had increased in the east while the low pressure anomalies had decreased in the west. The resulting shift in the winds stalled the drifter in its previously northerly direction and forced it more to the east. As a result, the ending latitude for the 2020/21 trajectory (and thus its PTI value) was $\sim 2^{o}$ more southerly than the 2011/12, 2013/14, and 2015/16 trajectories (the 2011/12 trajectory was notable because its ending latitude was the northernmost of all trajectories since 1994; Figure 19). The 2013/14 and 2015/16 trajectories coincided with the development and continuation of a marine heatwave along the eastern Pacific coast and the return of the Pacific Decadal Oscillation (PDO) to a warm, positive phase associated with winds from the south near the coast. The increased southerly winds contributed to well-above-average sea surface temperatures in the GOA in 2015/16. In contrast to 2013/14 and 2015/16, the PDO was negative during the winter of 2020/21.

Implications: The year-to-year variability in near-surface water movements in the North Pacific Ocean has been shown to have important effects on the survival of walleye pollock (*Gadus chalcogrammus*) by affecting its spatial overlap with predators (Wespestad et al., 2000), as well as to influence recruitment success of winter spawning flatfish in the eastern Bering Sea (EBS; Wilderbuer et al., 2002). Filtered PTI values greater than the long-term mean are indicative of increased transport and/or a northerly shift in the Alaska Current, which transports warm water northward along the west coast of Canada and southeast Alaska from the south and consequently plays a major role in the Gulf of Alaska's heat budget. Interdecadal changes in the PTI reflect changes in ocean climate that appear to have widespread impacts on biological variability at multiple trophic levels (King, 2005). There is strong evidence that the productivity and possibly the carrying capacity of the Alaska Gyre, and of the continental shelf, were enhanced during the "warm" regime that began in 1977. Zooplankton production was positively affected after the 1977 regime shift (Brodeur and Ware, 1992), as were recruitment and survival of salmon and demersal fish species. Recruitment of rockfish (Pacific ocean perch) and flatfish (arrowtooth flounder, halibut, and flathead sole) also increased. However, shrimp and forage fish such as capelin were negatively affected by the 1977 shift (Anderson, 2003). The reduced availability of forage fish may have contributed to the decline in marine mammal and seabird populations observed after the 1977 shift (Piatt and Anderson, 1996).

Spring Surface Wind in the Coastal Western Gulf of Alaska

Contributed by Matthew Wilson and Lauren Rogers, Resource Assessment and Conservation Engineering Division,Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: matt.wilson@noaa.gov
Last updated: August 2021

Description of indicator: Surface wind is fundamental to the oceanography, hydrography, biology and ecology of the Gulf of Alaska ecosystem. As a driver of coastal circulation, surface wind affects upwelling/downwelling, turbulent mixing (e.g., mixed layer depth), and transport of planktonic organisms including zooplankton and ichthyoplankton. Its relevance to regional groundfish production in the Gulf is illustrated by studies of wind-driven turbulent mixing on walleye pollock larvae (Porter et al., 2005) and of wind-driven transport on juveniles and recruitment (Wilson and Laman, 2021).

Two complementary datasets were used here to indicate springtime (April – May) surface wind in the coastal Gulf. We focus on spring to coincide with the seasonal occurrence of many groundfish larvae. The first dataset consists of high-resolution empirical measurements recorded by the National Data Buoy Center (NDBC) at site AMAA2. We chose AMAA2 as its location might be considered a gateway of sorts where winds determine whether coastal flow either funnels into and down Shelikof Strait along the Alaska Peninsula or is diverted southward around Kodiak Island as demonstrated by Ladd and Cheng (2016). This bifurcation is a prominent feature in the circulation dynamics of the western Gulf. Springtime measurements at AMAA2 are currently available for 15 years: 2004 to 2021, except 2007, 2008, and 2018. Measurements were recorded hourly during 2004 and at 30 min intervals during other years (see `https://www.ndbc.noaa.gov/` for data and additional methods detail). The second dataset consists of lower-resolution, model-based data from the National Centers for Environmental Prediction (NCEP) (Kalnay et al., 1996). The NCEP Reanalysis Derived data averaged by month and year from 1948–2021 were provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site (`https://www.esrl.noaa.gov/psd/cgi-bin/data/timeseries/timeseries1.pl`). We specified the geographic area to be 55 – 60°N latitude and 150 – 160°W longitude.

For both datasets, NDBC-AMAA2 and NCEP, wind was expressed as the components u (+u is wind blowing to the east, "westerly" wind) and v (+v is northward wind, "southerly" wind). Correlation of annual means (n=13) between the two datasets was r=0.64 for the u component, and r=0.75 for the v component. The NDBC-AMAA2 data are used to construct progressive wind diagrams; conceptually, these can be thought of as a progression through time of the hypothetical displacement from AMAA2 station during any given year (Wilson and Laman, 2021).

Status and trends: The progressive wind diagram, or hypothetical displacement, at NDBC-site AMAA2 was toward the southwest during spring 2021 (Figure 20). This was similar in direction to the trajectories for 2012, 2017, and 2020. In contrast, the trajectories for 2015 and 2016 were northwestward and westward, respectively, while the trajectory for 2013 was strongly southward.

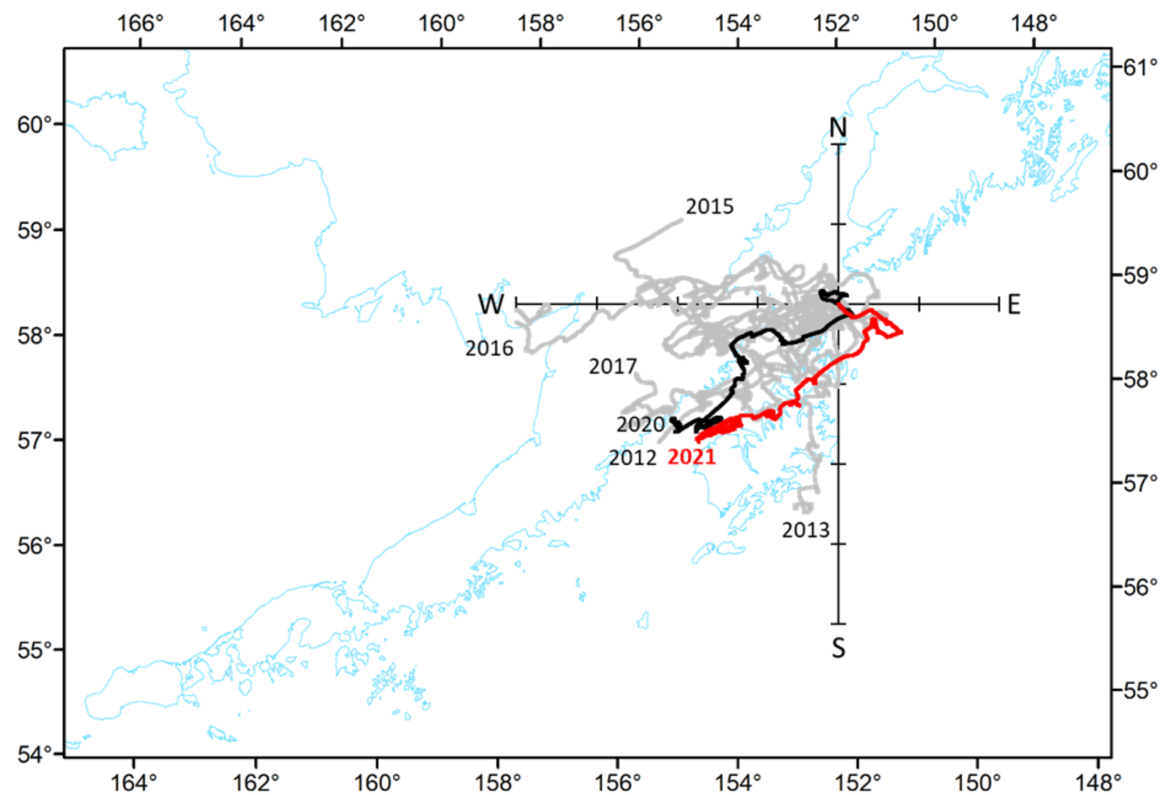


Figure 20: Progressive wind diagrams from NDBC-AMAA2 for spring (April–May) 2004–2021 (except 2007, 2008, and 2018). Select individual trajectory endpoints are labeled by year. The wind trajectories are superimposed on the Alaska coastline with the trajectory origin centered on the location of the AMAA2 site. Note, the scale of distance differs between the trajectories and the coastline. One tick mark ∼2700 nm.

The lower-resolution NCEP winds also indicated similarity in direction and magnitude during 2020 and 2021 with mean wind toward the southwest (Figure 21). This contrasts with the period 2015–2019 when means indicate a relatively strong northward component.

Factors influencing observed trends: In the Gulf, winds are dominated by cyclonic storm systems that exhibit pronounced seasonality (Stabeno et al., 2004). During spring, cyclonic winds begin to moderate and anticyclonic winds can drive intermittent upwelling. While the Aleutian

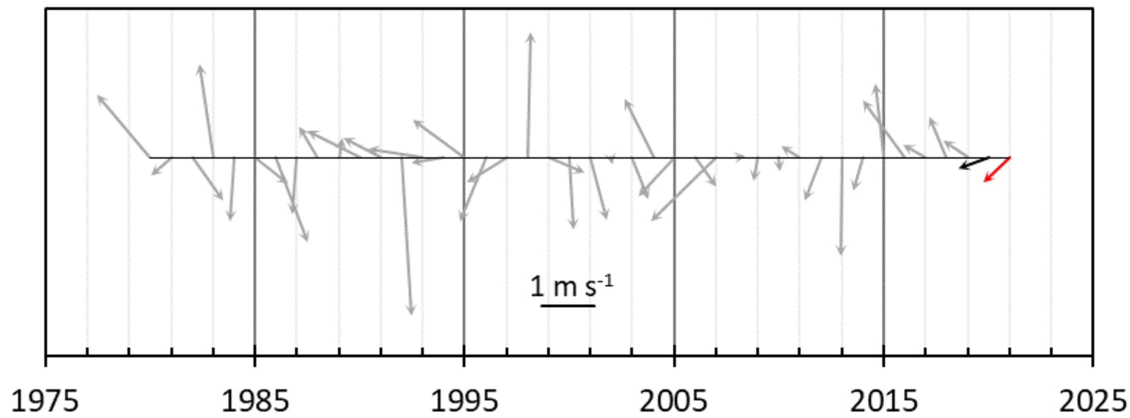


Figure 21: Mean wind from NCEP for spring (April – May) 1980–2019 (gray), 2020 (black), and 2021 (red). Each "stick" represents the magnitude (y-axis) and direction (e.g., northward is up, eastward is to the right) toward which the wind is blowing during each year

Low influences wintertime conditions and the El Nino-Southern Oscillation can affect conditions in the Gulf at multi-year intervals, factors influencing the coastal environment are complicated by numerous coastal mountains. Local terrain effects can lead to "gap" winds that profoundly affect oceanographic processes. For example, the strong northerly winds during 2013 were locally intensified at AMAA2 by orographic gaps in the Alaska Peninsula (Ladd and Cheng, 2016). We specifically chose the AMAA2 site to indicate winds at a point where they are likely to affect the bifurcation of coastal flow. Interestingly, the strong northerly wind in 2013 agreed between the two datasets; however, the disparity between the datasets in other years might reflect the difference in spatial representation and location.

Implications: Wind speed and direction greatly influences coastal circulation in the Gulf at multiple scales. At small scales, wind-driven turbulence has implications for vertical stratification of the water column, and the patchiness and vertical distribution of plankton, including fish larvae. At larger scales, wind can determine the occurrence of upwelling and downwelling with consequent effects on vertical circulation and transport. At large scales, wind-driven transport influences the life history strategy of organisms, and the variation in transport has long been hypothesized to affect the replenishment of adult fish and shellfish stocks by transporting larvae to favorable or unfavorable habitat. For walleye pollock, the period April-May is particularly important because that is when the eggs and larvae are in the water column and subject to wind-driven transport. In fact, when the AMAA2 wind trajectories for this period (Apr-May) are toward the southwest (down Shelikof Strait), estimates of age-1 abundance tend to increase presumably because downwelling-favorable northeasterly winds enhance retention of larvae (Stabeno et al., 1996, 2004) and juveniles in areas that favor survival (Wilson and Laman, 2021).

Habitat

Structural Epifauna—Gulf of Alaska

Contributed by Wayne Palsson, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: Wayne.Palsson@noaa.gov
Last updated: October 2021

Description of indicator: Structural epifauna groups considered to be Habitat Area of Particular Concern (HAPC) biota include sponges, corals (both hard and soft), and anemones. NOAA collects data on structural epifauna during the biennial bottom trawl surveys in the Gulf of Alaska conducted during the summer months. For each species group, the catches for each year were scaled to the largest catch over the time series (which was arbitrarily scaled to a value of 100). The standard error (±1) was weighted proportionally to the CPUE to get a relative standard error. The percentage of positive catches in the survey bottom trawl hauls was also calculated.

Additional GOA-wide indices for Structure Forming Invertebrates (SFI including Gorgonian Corals, Pennatulaceans (sea pens and sea whips), and Sponges) using the VAST spatio-temporal model. The models runs used the same parameters and options those developed for model-based indices from survey data used in key stock assessments for key GOA species (750 knots, depths to 700 m). These model runs differ slightly from those SFE VAST runs performed for previous HAPC biota reports.

Status and Trends A few general patterns are clearly discernible among the different structural epifauna (Figure 22). Sponges are caught in about 50% of bottom trawl survey hauls in all areas of the GOA when combined across areas. This percentage has been increasing in the Yakutat (to about 30% of hauls) and Southeastern (to about 60% of hauls) regions. However, the CPUE is generally highest in the Shumagin region and then lower to the east. Sponge CPUE has substantially declined in the Shumagin and Kodiak regions, while CPUE has remained fairly constant in the three other areas except for an increase in 2019 in Yakutat and a high observed value in the Southeastern area in 2017. Sea anemones occur in low abundance in the Southeastern GOA, while they are common (occur in ∼50% of tows) at a relatively constant abundance in the Shumagin, Chirikof and Kodiak regions. There was a decrease in anemones in 2019 and 2021 in the Shumagin region and they slightly declined in the Kodiak region in 2021. Gorgonian corals show an opposite pattern to sponges and anemones, as gorgonians are in highest abundance in the southeastern GOA, although they are relatively uncommon in catches for all areas. The peak abundance occurred in 1999 in the Southeastern region, catches have declined there during recent surveys, especially since 2019 and 2021. The sea pen and sea whip (pennatulaceans) time series is dominated by large CPUE's in 2005 and 2015 in the Chirikof region, but they occur uncommonly in bottom trawl tows (< 10% occurrence) in all areas. Soft coral CPUE has been uniformly low with the exception of a large catch in the Shumagin region during the 1984 survey. Hydrocorals (stony corals) catches are rare except for high values observed during the 1984 and 1990 in the Shumagin region and 2011 in the Kodiak region.

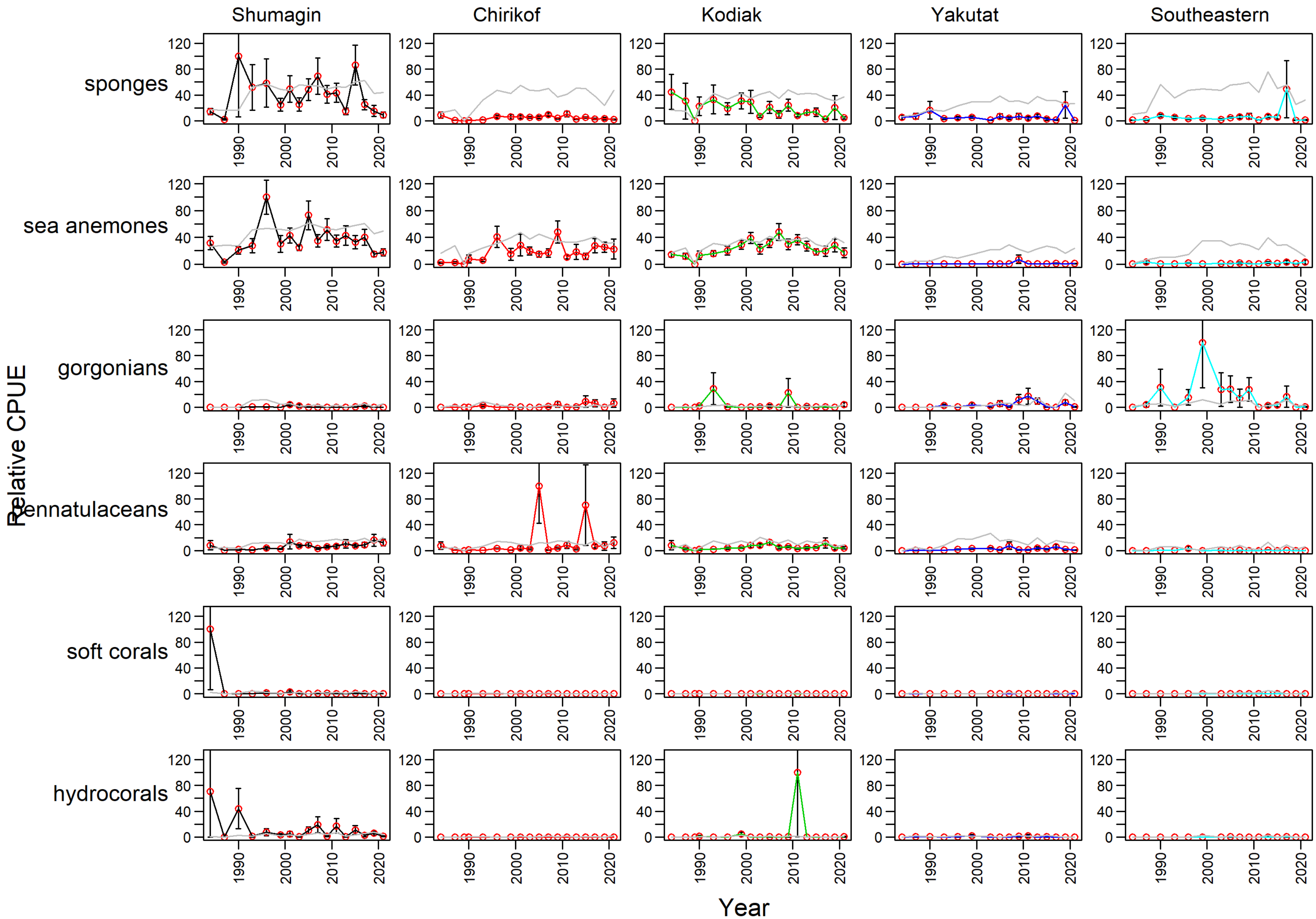


Figure 22: Mean CPUE of HAPC species groups by area from RACE bottom trawl surveys in the Gulf of Alaska from 1984 through 2021. Error bars represent standard errors. The gray lines represent the percentage of non-zero catches.

A VAST model was run for gorgonian corals, pennatulaceans, and sponges integrating and modeling trawls station densities across the Gulf of Alaska (Figure 23). The coral abundance index is variable over time but the trend suggest low abundances resulting from the two most recent surveys compared to most index values observed before 2017. The gulf-wide abundance of pennatulaceans shows an increasing trend from 1990 to 2005 and then a variable trend thereafter and a peak in 2017 followed by a decline in 2019. However, the 2021 index value increased from the 2019 value. The trend of sponges shows relative stability until 2015 followed by a continual decline in the GOA wide index through 2021 to a historic low value.

Factors influencing observed trends: The Gulf of Alaska Bottom Trawl Survey does not sample any of these fauna well, so some caution is recommended in interpreting these trends in CPUE and abundance indices.

Implications: Changes in structural epifauna CPUE may indicate changes in habitat, but at present no research has demonstrated definitive links. The decline of sponges in the Gulf of Alaska are alarming, especially in the western-most survey region. Sponges are slow growing ($\sim$ 2 cm yr^{-1} (Stone et al., 2011) and are not anticipated to quickly recover. Further studies are suggested to better understand the sponge decline and also the lower values of corals. These declines may be a lingering response to the recent marine heat waves.

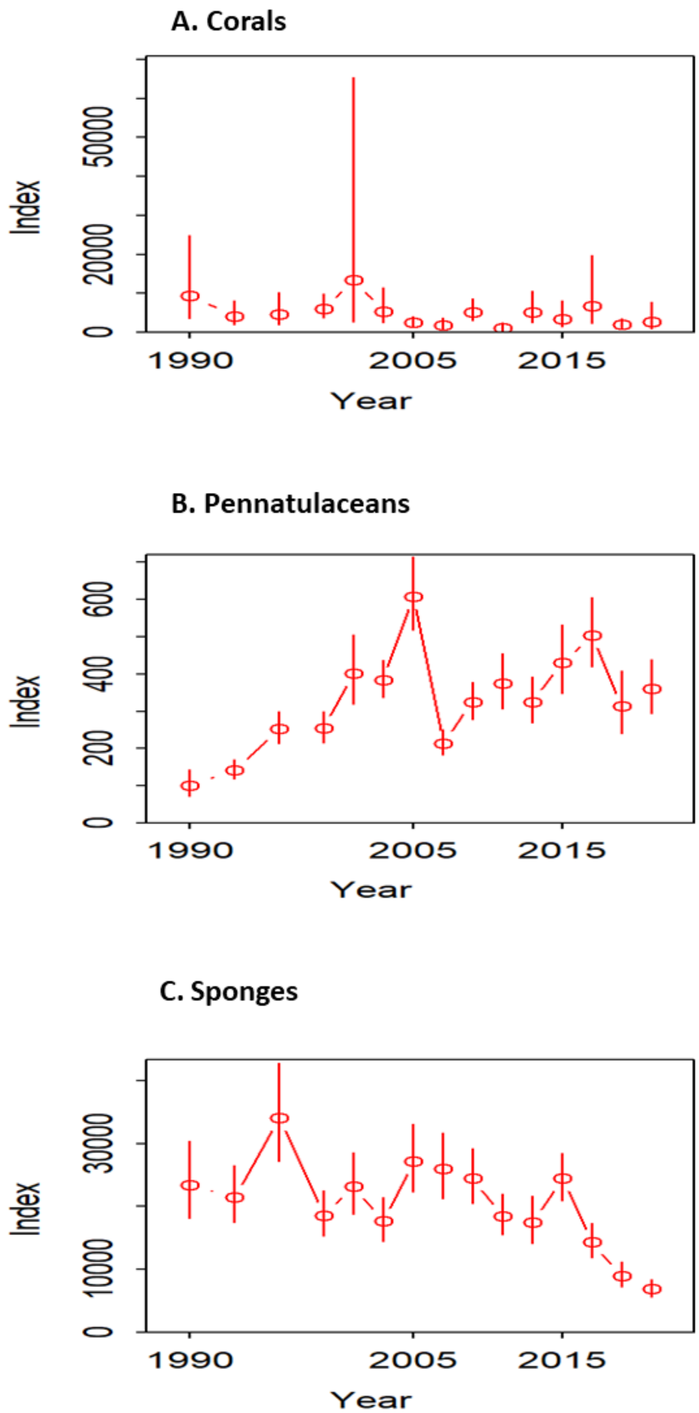


Figure 23: Time series of structure forming invertebrate biomass estimates for the Gulf of Alaska. Estimates (and standard deviations) were produced using a VAST model that included combined gorgonian coral groups, combined pennatulaceans and combined sponge groups.

Primary Production

Satellite-derived Chlorophyll-a Trends in the Gulf of Alaska

Contributed by Jordan T. Watson, Jens M. Nielsen, Matt W. Callahan, and Jeanette C. Gann, Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: jordan.watson@noaa.gov
Last updated: August 2021

Description of indicator: Phytoplankton provide the basal resources for secondary consumers like zooplankton and larval fish. During spring, a large bloom occurs once the upper surface of the water column stratifies, and light intensity becomes strong enough to support phytoplankton growth. This bloom takes advantage of higher nutrient stores remaining in surface waters after winter storms when phytoplankton activity is low. The spring bloom is critical for nourishing zooplankton, which in turn provide food for fish populations. The timing and magnitude of the bloom can play an important role on the success of cohorts each year.

The timing and magnitude of spring phytoplankton blooms vary annually, and satellite data provide a good opportunity to capture these large scale spatio-temporal dynamics and trends of phytoplankton. Several studies that include *in situ* data comparisons have shown that satellite chlorophyll data provide reasonable proxies for phytoplankton concentrations in surface waters (Batten et al., 2018; Waite and Mueter, 2013). We used 8 day composite chlorophyll-a data from the MODIS satellite `http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMBchla8day.html` for the eastern and western GOA to examine phytoplankton dynamics from 2003–2021. We calculated average concentrations from April–June to capture the spring bloom period. We summarized the magnitude of the annual spring event (Figure 24) as well as a chronology of phytoplankton concentrations throughout the season to better resolve annual phenologies. Furthermore, we focus on coastal areas (on the continental shelf) as these regions are the major feeding and spawning areas for fish. Data were further filtered to include only waters > 3 miles offshore, as chlorophyll estimates from nearshore areas can be highly uncertainty due to river outputs. After filtering, the spatial grids contained up to ∼4,000 and ∼11,000 records for the eastern and western GOA, respectively. These two regions have different oceanographic dynamics that can influence timing and magnitude of the bloom. While the mean chlorophyll-a concentrations are not statistically different over the time series, they do not always correspond on an annual basis.

Status and trends: A high degree of inter-annual variability was observed for average spring (April–June) chlorophyll-a values (Figure 24) and the timing of peak spring bloom (Figure 25) in both the western and the eastern GOA. In the western GOA, chlorophyll-a concentrations were particularly low in 2016, 2019, and 2021 (Figure 24), years that also appear to have had an average to late spring bloom peak (Figure 25). Meanwhile, 2021 was the 6^{th} consecutive year of spring chlorophyll concentrations below the time series average in the eastern GOA. The eastern GOA bloom timing during these recent low years has been average to early.

The timing of the 2021 spring bloom was about average in the western GOA and slightly early in the eastern GOA. The higher values in the western GOA coincided with a spring bloom peak around day 149 (the 2003–2020 mean occurred on day 136) (Figure 25) while the eastern GOA demonstrated a peak around day 117 (the 2003–2020 mean occurred on day 131).

The western and eastern GOA regions have different oceanographic dynamics that can influence timing and magnitude of the bloom. While the mean chlorophyll-a concentrations are not statistically different over the time series, they do not always correspond on an annual basis.

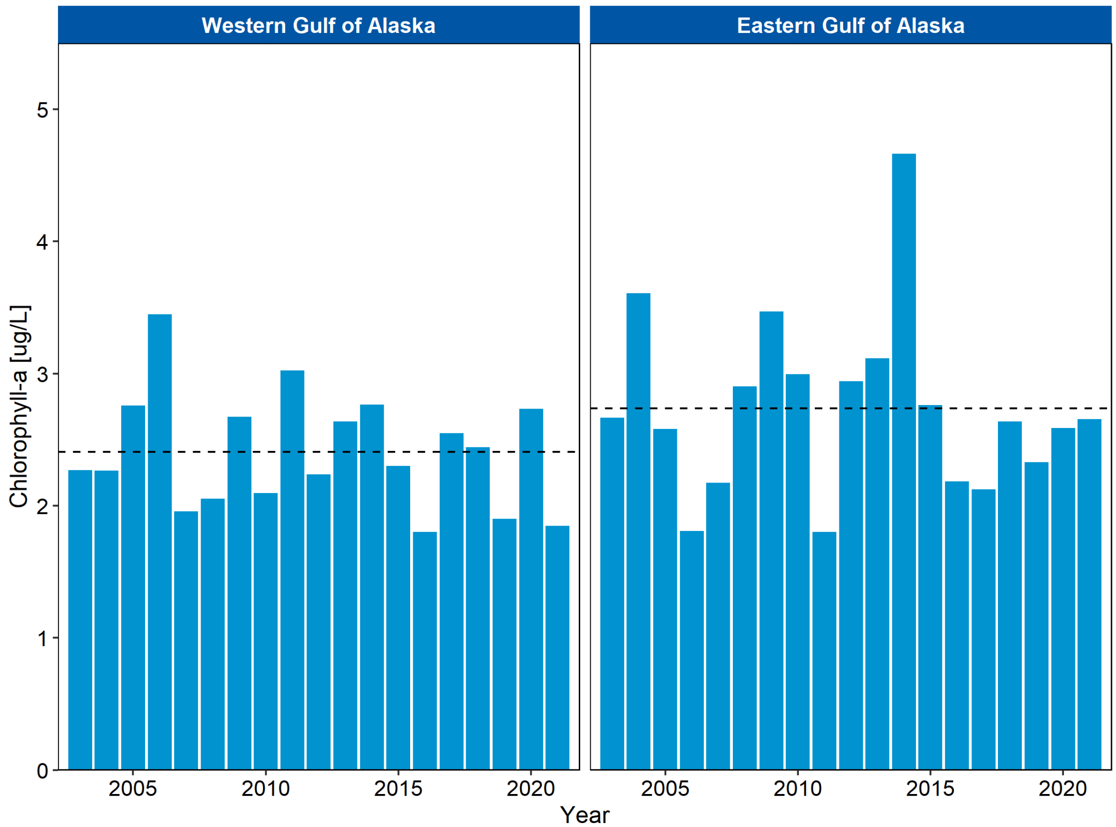


Figure 24: Average spring (April-June) chlorophyll-a concentrations based on MODIS satellite 8 day composites for the western and eastern GOA. The horizontal dashed line is the long-term mean (2003–2021).

Factors influencing observed trends: There were no significant relationships between average spring chlorophyll-a concentrations and sea surface temperatures (SST) in either the western or the eastern GOA at the spatial scales presented here. We only examined simple linear relationships here but it is likely that nonlinear relationships with temperature exist, and recent warm events may have exceeded certain threshold conditions that diminish the linear relationships observed here. Furthermore, temperatures alone are unlikely to drive phytoplankton concentrations. It is known that mesoscale eddies play a large role in the GOA and the patchy nature of phytoplankton 'hot spots' over the shelf. Researchers are further examining the impacts of winds and other potential oceanographic drivers (e.g., stratification, currents), which also play a role.

A persistent consideration with satellite-based chlorophyll data is the effect of cloud cover, which precludes quality data collection. On average, about 25% of data was missing during the spring periods examined for each year and further research is necessary to fully resolve the impacts of these missing data on inference.

Implications: Chlorophyll concentrations may be a proxy for food availability for zooplankton

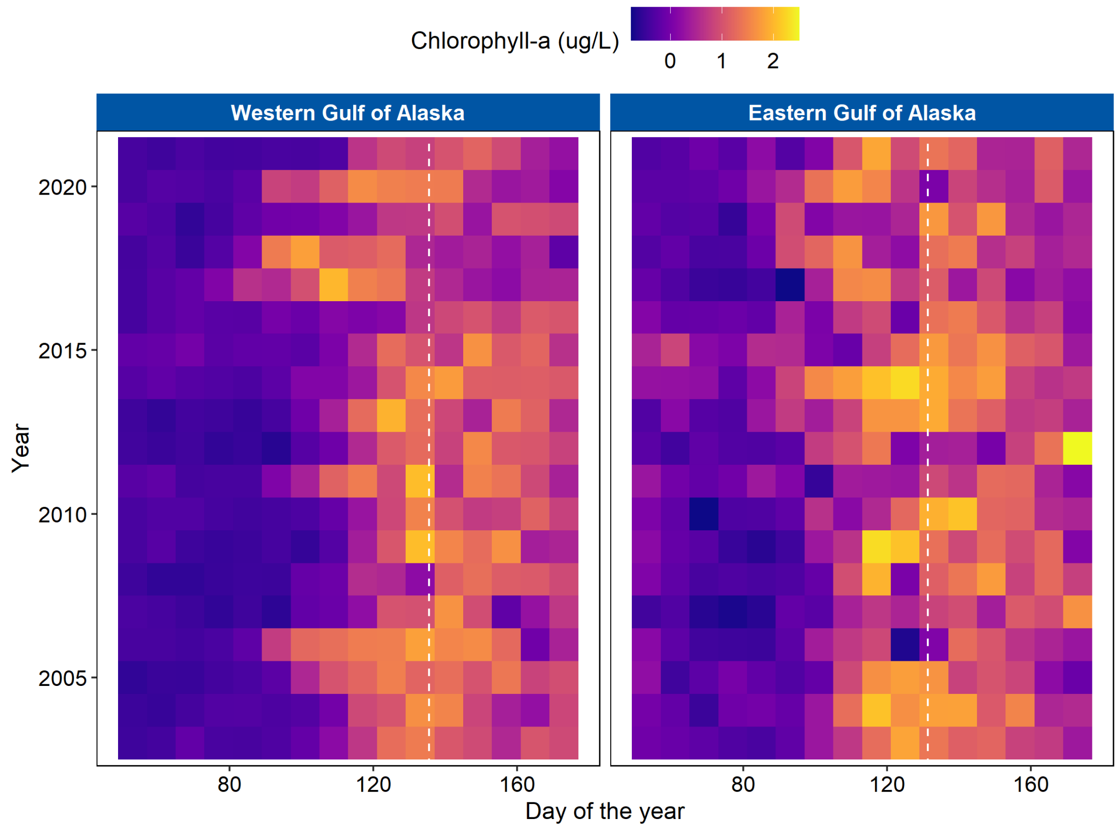


Figure 25: Average 8-day composite chlorophyll concentrations (log-transformed) for the western and eastern GOA. The brightest (yellow) color within each year will represent the peak bloom (less bright yellow reflect a lower peak). All years are on the same color scale. Vertical dashed lines illustrate the mean day of the year of spring bloom timing for the western (day 136; approximately May 16) and the eastern (day 131; approximately May 11) Gulf of Alaska. For reference, days of year 100 and 180 fall around April 9 and June 30, depending on leap years.

and is thus also relevant for many of the planktivores that rely on zooplankton. The chlorophyll-a indicator is relatively new and more work will be required to resolve any connections between groundfish recruitment and chlorophyll concentrations.

In the western GOA, 2021 suggests similar bloom patterns (Figure 25) to 2019 and 2016, which were both marine heatwave years with delayed bloom timing. This could be an important implication for groundfish populations if other similarities track across the season.

Seward Line May Phytoplankton Size Index

Contributed by Suzanne Strom, Shannon Point Marine Center, Western Washington University
Contact: stroms@wwu.edu
Last updated: October 2021

Description of indicator: Since 1998, hydrographic transects have been completed in May (typically during the first 10 days of the month) along a sampling line that extends from the mouth of Resurrection Bay near Seward to the outer continental slope of the northern Gulf of Alaska. Episodically beginning in 2001 and annually beginning in 2011, chlorophyll-a (chl-a) in two size fractions ($< 20\ \mu$m and $> 20\ \mu$m) as well as total chl-a have been measured at 6-7 depths (0 to 50 or 75 m) at stations spanning the continental shelf and offshore waters. Data provided here are an index of size composition of the phytoplankton comprising the shelf community. The index is computed from transect averages of depth-integrated shelf station values, for each early May cruise, of the fraction total chl-a found in the large ($> 20\ \mu$m) size fraction (i.e., chl-$a_{>20}$ / chl-a_{total}). High values of the size index correspond to diatom-dominated communities, while low values of the size index correspond to phytoplankton communities dominated by small flagellates and cyanobacteria. In addition, comparison with remote sensing-based estimates of spring bloom timing and magnitude show that the size index is a predictor of two important aspects of the spring bloom. 1) When the index is low (≤ 0.25, meaning that small cells strongly dominate), the spring bloom begins and peaks relatively late in the year. 2) When the index is $\geq$0.5, meaning that large cells comprise half or more of the total chl-a, the value of the index is strongly correlated with the cumulative magnitude of the spring bloom (April – June) as measured by remote sensing.

Status and trends: No long-term secular trend is evident in the phytoplankton size index, although there is a suggestion that variance has increased in recent years (Figure 26). The marine heatwave years of 2014–2016 show the lowest values in the time series, with the (lesser) heatwave year of 2019 also showing a low value. May 2021 had the highest size index observed to date (0.94), consistent with the intense diatom bloom that occurred in late April and early May. This indicates favorable feeding conditions for large zooplankton consumers and the higher trophic levels dependent upon them.

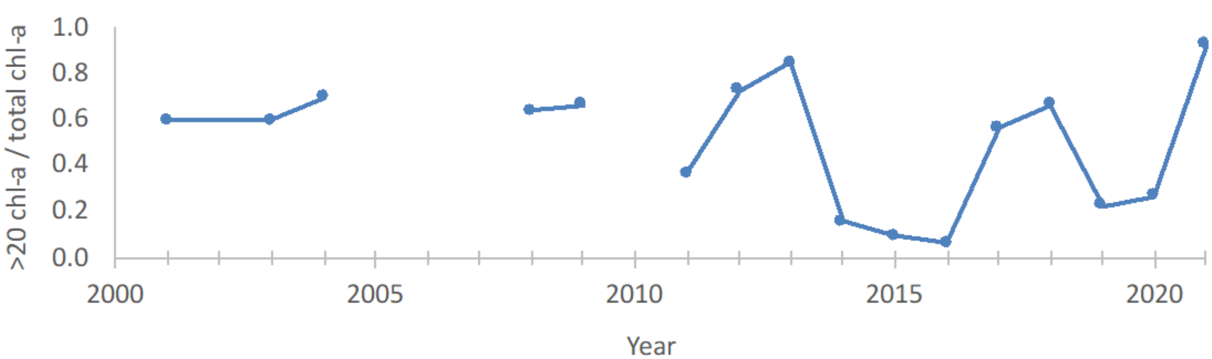


Figure 26: May 2001–2021 time series of phytoplankton size index (fraction of total chl-a present in cells $> 20\ \mu$m) for the Seward Line shelf stations.

Factors influencing observed trends: The mix of resource availability (light, micro- and macronutrients) and top-down controls leading to shifts in the spring size index is under active investigation. Spring water temperature per se probably has little direct influence, as the range observed is small relative to the physiological tolerance of these phytoplankton.

Implications: High values of the size index correspond to diatom-dominated communities, which are known to provide high amounts of lipid-rich prey for zooplankton (i.e., large copepod, euphausiid) consumers. Low values of the size index correspond to phytoplankton communities dominated by small flagellates and cyanobacteria, which are less available to large zooplankton and lead to less efficient transfer of primary production to higher trophic levels. A late spring bloom may lead to timing mismatches between the emergence/development of important zooplankton grazers and the availability of diatom prey, which would have negative effects on transfer of production to higher trophic levels. Conversely, a larger spring bloom introduces more primary production into the ecosystem in a form that can be efficiently transferred to higher trophic levels.

Zooplankton

Continuous Plankton Recorder Data from the Northeast Pacific, 2000–2020

Contributed by Clare Ostle[1] and Sonia Batten[2]
[1] CPR Survey, The Marine Biological Association, The Laboratory, Citadel Hill, Plymouth, Devon, PL1 2PB, UK
[2] PICES, 4737 Vista View Cr, Nanaimo, BC, V9V 1N8, Canada
Contact: claost@mba.ac.uk
Last updated: August 2021

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 (∼Apr–Sept) 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. In this Report we update three indices for three regions (Figure 27); 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), mesozooplankton biomass (estimated from taxon-specific weights and abundance data) and 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. Anomaly time series of each index have been calculated as follows: A monthly mean value for each region is first calculated (2002–2019 for the GOA). Each sampled month's mean is then compared to the long-term geometric mean of that month and an anomaly calculated (Log_{10}). The mean anomaly of all sampled months in each year is calculated to give an annual anomaly.

The indices are calculated separately for the oceanic eastern GOA, oceanic western GOA (divided at 147°W), and the Alaskan shelf southeast of Cook Inlet (Figure 27). Only the red points within the shaded boxes in Figure 27 are included in the calculations (for example the red points on the shelf outside the shaded box were considered too small a sample size to adequately represent conditions). The oceanic eastern GOA regions have better sampling resolution than the Alaskan shelf and oceanic western GOA region as both transects intersect here. This region has been sampled up to 8 times per year with some months sampled twice. The Alaskan shelf region is sampled 5–6 times per year by the north-south transect.

Status and trends: The diatom abundance anomaly for the shelf region was at an average level for 2019 and 2020, whereas it was positive in 2017 and 2018 (Figure 28). On the western side of the oceanic GOA the diatom abundance anomaly was negative for the last two years. On the eastern side of the oceanic Gulf of Alaska the diatom anomaly was negative in 2020. The copepod community size anomaly was strongly negative in both the Alaskan shelf and eastern GOA regions in the last 3–5 years, but it has oscillated in the western GOA from positive in 2019 to negative 2020. Zooplankton biomass anomalies were positive in both the shelf and eastern GOA regions in 2020, while the anomaly was negative in the western GOA.

Factors influencing observed trends: The Pacific Decadal Oscillation (PDO) monthly values

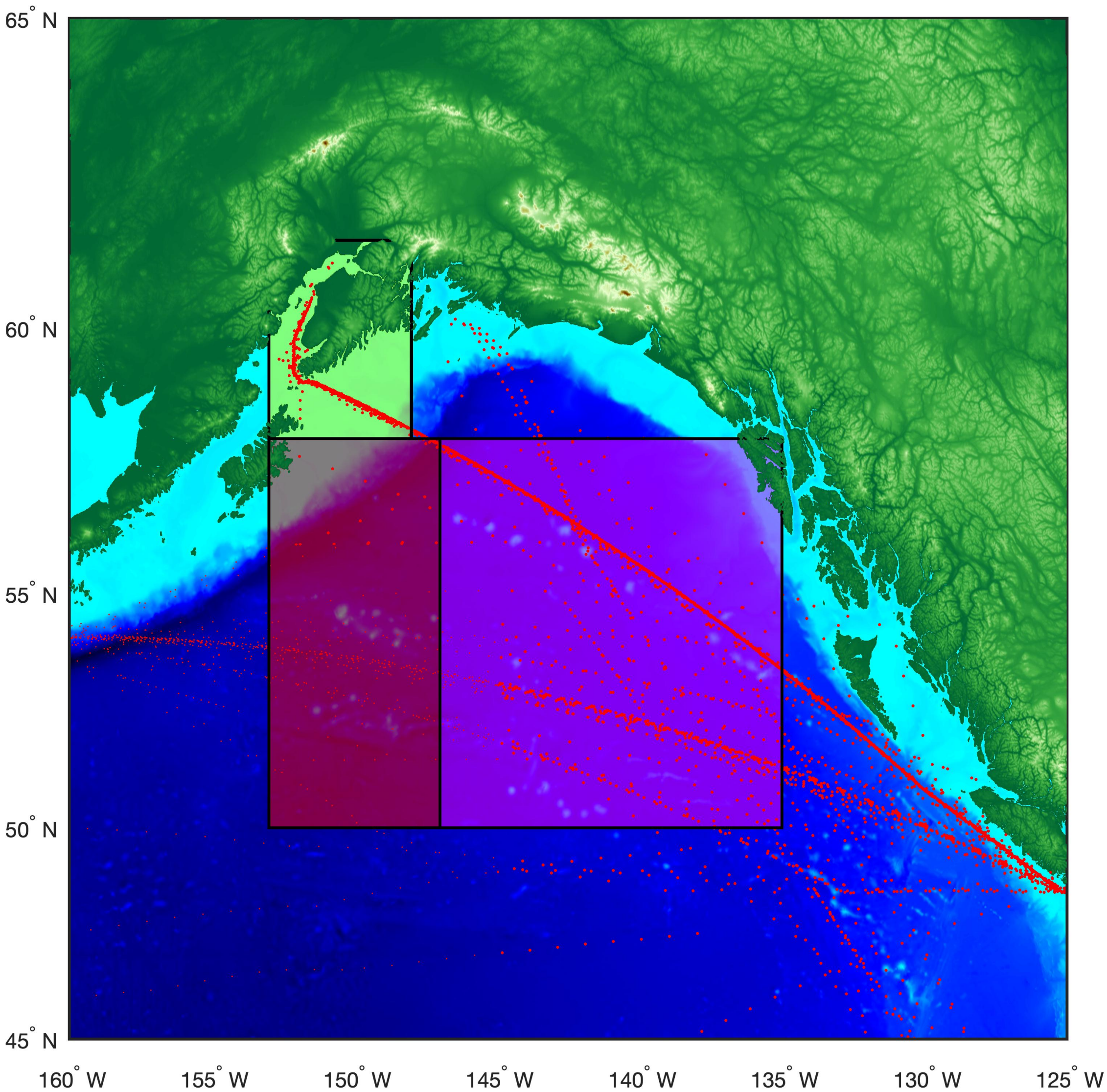


Figure 27: Location of the data used in this Report, highlighted as Alaskan shelf (yellow rectangle), eastern Gulf of Alaska (magenta rectangle), and western Gulf of Alaska (red rectangle). Red dots indicate actual sample positions (note that for the shelf region the multiple transects overlay each other almost entirely).

were often negative in 2017 causing a lower annual mean value compared to the years of 2014–2016 and 2018–2019, which experienced marine heat waves (Di Lorenzo and Mantua, 2016). 2020 was another warm year, though not as warm as 2019. In warm conditions smaller species tend to be more abundant and the copepod community size index was mostly negative throughout the marine heat wave periods of 2014–2016, and 2018–2020. The decline in zooplankton biomass seen in 2018 is reversed in 2019, particularly in the shelf region, which had their most positive anomaly of the time series in 2019. The large diatom abundance was close to the average of the sampling period in the shelf region in 2020, with the western and eastern GOA regions showing a lower than average diatom abundance. This decrease in diatom abundance could potentially be linked to the increase in temperatures or the slight increase in mesozooplankton abundance, increasing predation on diatoms in the area.

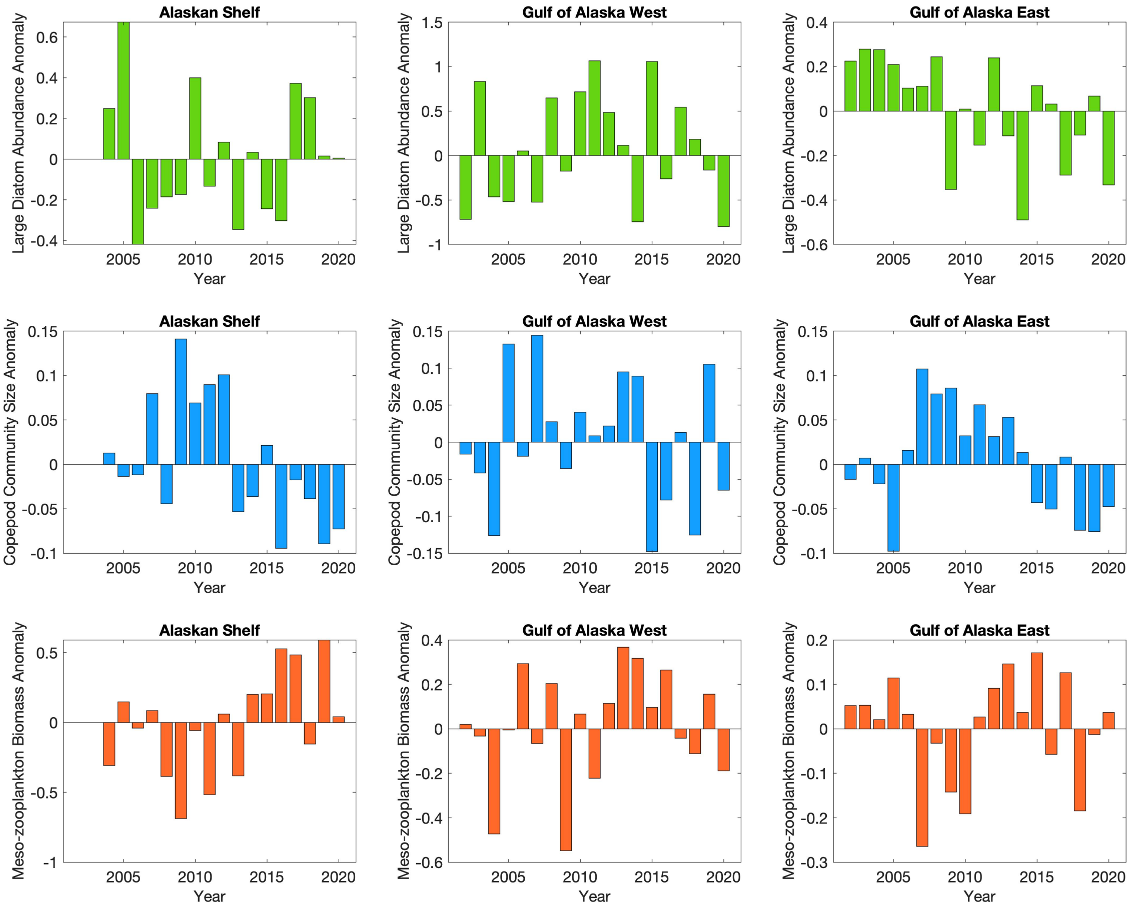


Figure 28: Annual anomalies of three indices of lower trophic levels (see text for description and derivation) for all three regions shown in Figure 27. Note that sampling of the shelf region did not begin until 2004.

Implications: Each of these variables is important to the way that ocean climate variability is passed though the phytoplankton to zooplankton and up to higher trophic levels. 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 organisms to their predators. Changes in abundance or biomass, together with size, influences availability of prey to predators. It is likely that the high temperatures have led to high mesozoopankton biomass and a decrease in diatom abundance due to increased predation, in both the shelf and western oceanic GOA regions.

Current and Historical Trends for Zooplankton in the Western Gulf of Alaska

Contributed by David Kimmel, Kelia Axler, Alison Deary, Colleen Harpold, Deana Crouser, Eco-FOCI Program, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: david.kimmel@noaa.gov
Last updated: August 2021

Description of indicator: In 2015, 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. Paired with this assessment are measurements of total lipid content from selected zooplankton categories within the same RZA sample. The method employed uses coarse categories and standard zooplankton sorting methods (Harris et al., 2000). The categories are small copepods ($<$ 2 mm; example species: *Acartia* spp., *Pseudocalanus* spp. and *Oithona* spp.), large copepods ($>$ 2 mm; example species: *Calanus marshallae* 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. In spring, there is a possibility that earlier stages of the large copepods may be counted as small copepods, as some life-history stages may be $<$ 2 mm (copepodite I to III stages of *Calanus*). A 2 ml Stempel pipet is used to estimate small copepods, as opposed to the larger 10 ml pipet used to subsample for large copepods. Therefore, we are much more likely to be counting smaller species such as *Oithona* spp. and *Pseudocalanus* spp. as opposed to members of the annual cohort of the large species, such as *Calanus* spp. Other, more rare 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 overall. 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 western Gulf of Alaska in spring. The mean abundance of each RZA category was plotted for the western Gulf of Alaska and represented primarily May and early June in spring. The summer/fall survey was not conducted in 2021 in the western Gulf of Alaska, and updates are not shown for fall time-series. In the spring, we expanded the spatial area beyond the traditional "Line 8" in the Shelikof Strait (an area approximately bounded by 57.46–57.73°N and 154.67–155.30°W) sampling to match the region where pollock larval rough counts are conducted southwest of Kodiak Island (Rogers and Dougherty, 2019, see Deary in this Report, Figure 36, p.83, for area description). 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 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*b*). This method was proven to be highly accurate for analyzing zooplankton lipids in a recent inter-laboratory cross validation study (Pinger In Prep.).

Status and trends: Large copepods were most abundant in Shelikof Strait and southwest of Kodiak Island (Figure 29). Small copepods were abundant throughout the sampling area and were most abundant in the same areas as the large copepods (Figure 29). Euphausiid abundances were low throughout the region (Figure 29). Large copepods showed variability over time during spring (Figure 30). Most notable was the rise in abundance of large copepods seen in spring from 2003-2006 and the decline in large copepods observed in 2015, 2019, and 2021. Small copepods showed very little variability over time during spring (Figure 30). Euphausiid abundances showed considerable variability over time and were low during 2003-2006 and during 2015, 2019, and 2021 (Figure 29). For percent lipid content, a total of 36 and 31 samples of large copepods and euphausiids, respectively, were analyzed. Large copepods were on average higher and more variable (mean = 6.5, SD = 4.1) in percent lipid than in euphausiids (mean = 1.4, SD = 0.9), with both taxa showing highest values nearshore and southwest of Kodiak Island (Figure 31).

Factors influencing observed trends: Large zooplankton abundances appear to respond to different environmental conditions most strongly in spring, notably temperature (Sousa et al., 2016; Kimmel and Duffy-Anderson, 2020). The survey occurred approximately two weeks earlier in the year in 2019 and 2021 relative to historical timing, thus we would have expected larger numbers of *Neocalanus* spp. We conclude that warmer temperatures likely accelerated the entry into diapause for the larger copepods *Neocalanus cristatus* and *N. plumchrus/flemingeri* lowering overall large copepods numbers. This was most pronounced during the recent marine heatwaves in 2015 and 2019, and 2021 had similar low abundance values. Spring 2021 was warmer than average (see Watson in this Report, p.39) and likely accelerated the exit of larger *Neocalanus* spp. from the western Gulf. During less extreme warm conditions as in 2003-2005, large copepod numbers increase and this is likely due to the increased abundances of Calanus marshallae (Kimmel and Duffy-Anderson, 2020) that are developing to later stages more quickly. Large copepod numbers have remained low in the summer recently as *C. marshallae* may either enter into diapause earlier due to more rapid development times or is subject to increased mortality. The exact mechanism is not known and increased temperatures may lead to a second cohort of *C. marshallae*, whose earlier stages would not be considered large copepods (Banas et al., 2016; Kimmel and Duffy-Anderson, 2020). Small copepod abundances appear to be less impacted by warming as opposed to the larger copepods and showed little variability in either spring or summer. This makes sense with respect to life history characteristics of small copepods, e.g., multiple generations per year, faster turnover times, and metabolic rates that scale less dramatically with temperature (Kiörboe and Sabatini, 1995). The large error bars occurring from 1999 to 2011 represent the fact that these samples only came from Line 8. The error for small copepods dramatically reduces when the sampling area increased in 2013 (Figure 30). The significant decline in euphausiid numbers during the spring (Figure 30) can be partially explained by the development of euphausiids resulting in larger sized individuals that can effectively avoid the 60 cm bongo net. This reflects the inability of the bongo nets to adequately capture older euphausiids. Furthermore, it should be noted that the RZA and processed estimates of abundances often differ (Figure 30). This is expected due to the patchy nature of euphausiid distribution and the difficulty in accurately estimating euphausiid abundances (Hunt et al., 2016). Overall, variability in lipids were high for both taxa, but there was a general trend of higher lipid content in nearshore waters, and more specifically a region just southwest of Kodiak Island (Figure 3). This may be a result of higher primary production in nearshore waters, and potential entrainment and concentration of lipid-rich phytoplankton in the lee side of Kodiak Island, as has been noted in the past (Napp et al., 1996). The larger lipid content in some copepods reflected large *Neocalanus spp.* that were accumulating lipid prior to overwintering, whereas *C. marshallae* copepods were generally lower in lipid.

Implications: Zooplankton are an important prey base for larval and juvenile fishes in spring and summer. Small copepod numbers remained high during spring and this indicates that there is likely a significant number of nauplii and smaller copepods available as prey for larval fishes. Note the small copepod proportion does not include nauplii (the primary prey for early larval fishes)

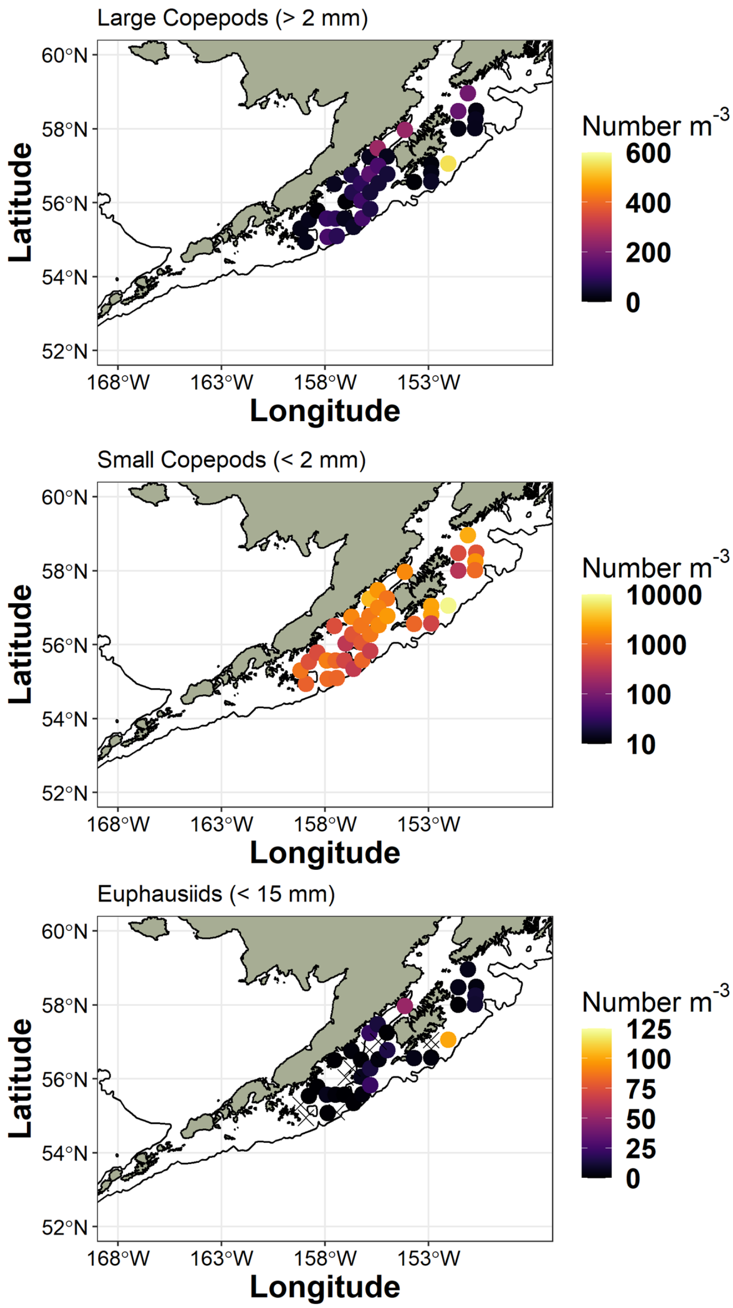


Figure 29: Maps show the spring abundance of large copepods, small copepods, and euphausiid larvae/juveniles estimated by the rapid zooplankton assessment. Note each map has a different abundance scale (No. m^{-3}). X indicates a sample with abundance of zero individuals m^{-3}.

and recent work has suggested a decline in nauplii did occur during the recent marine heatwave (Rogers et al., 2020). The lack of large copepods is less relevant in spring for larval fishes; however,

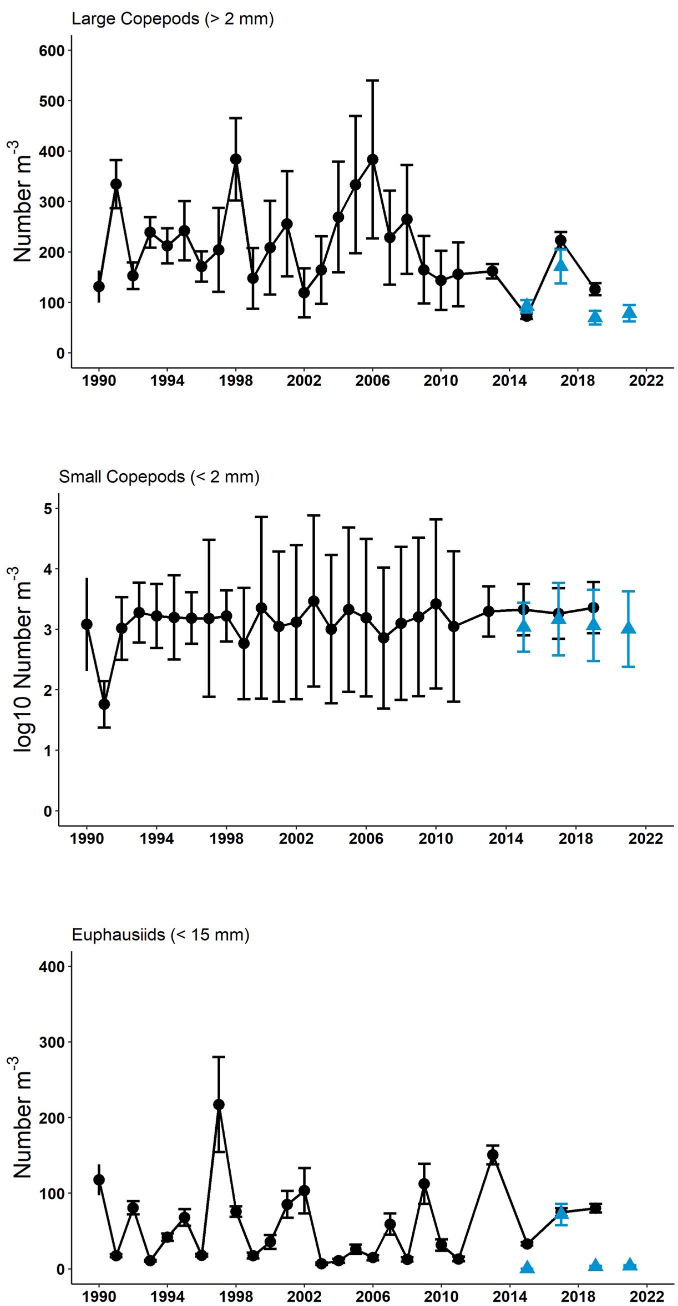


Figure 30: Mean abundance of large copepods (> 2 mm), small copepods (< 2 mm), and euphausiids (< 15 mm) in western Gulf of Alaska during spring (May–June). Black circles represent archived data, blue triangles represent RZA data. Note differences in scale.

it may indicate that the system timing for larger copepods is changing or may indicate shifts in overall productivity (Kimmel and Duffy-Anderson, 2020). The overall higher lipid content in large

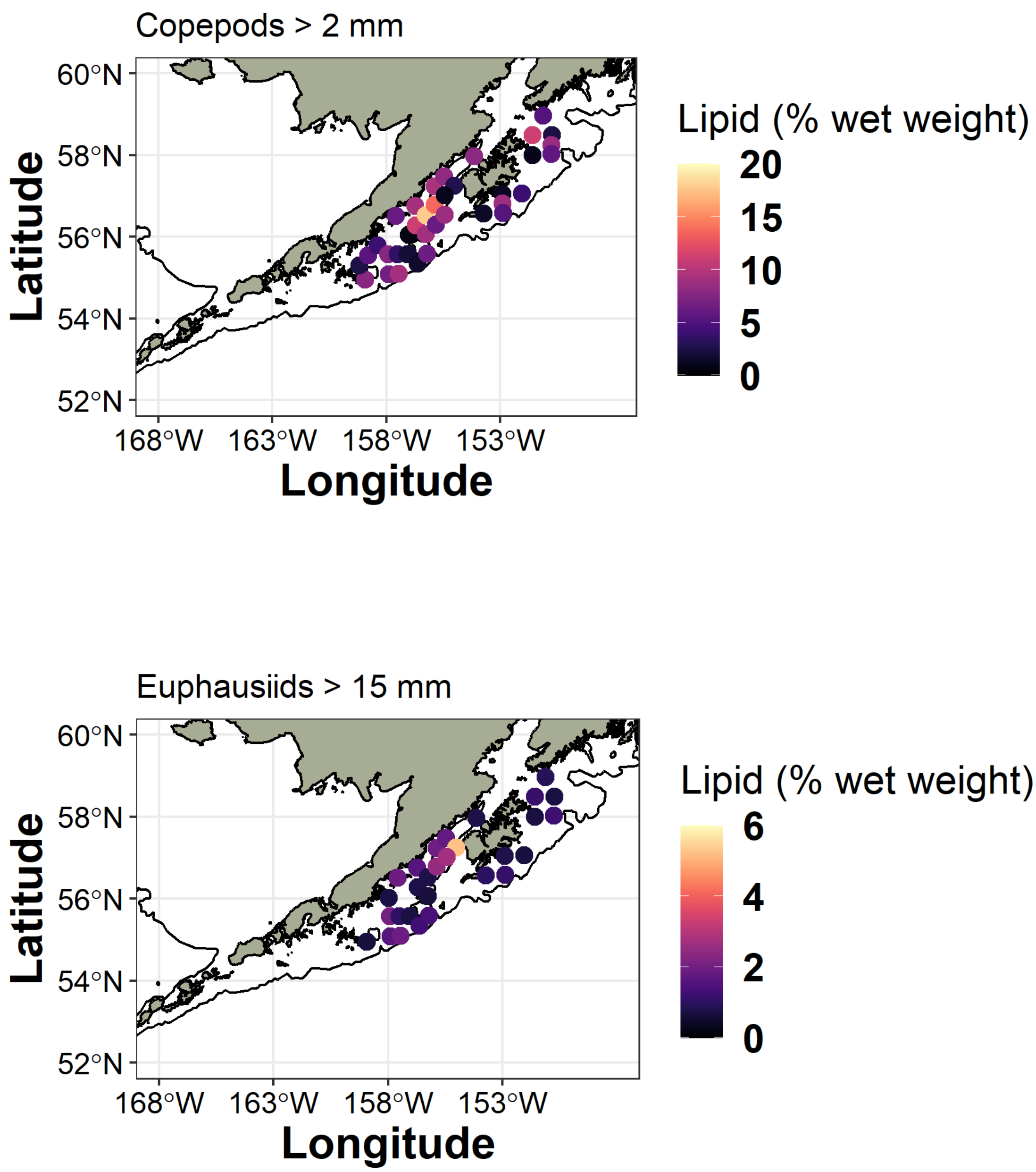


Figure 31: Lipid content (% wet weight) for large copepods (> 2mm) and euphausiids (> 15 mm) collected during the survey. All values shown here are non-zero.

copepods relative to euphausiids underscores their value as an energy source to higher trophic levels. The recent, low large copepod abundances in summer suggest the standing stock of *C. marshallae* is lower during warming events. A lack of large copepods leads to diet shifts where less energetically dense prey items are consumed (Lamb and Kimmel, 2021). Euphausiid numbers are variable in the spring, but low numbers have persisted in recent years. This suggests that warming results in reduced euphausiid abundances during spring.

Spring and Fall Large Copepod and Euphausiid Biomass: Seward Line

Contributed by Russell R Hopcroft, University of Alaska, Fairbanks
Contact: rrhopcroft@alaska.edu
Last updated: September 2021

Description of indicator: Transects have been completed south of Seward Alaska typically during the first 10 days of May and during mid-September for over two decades to determine species composition, abundance and biomass of the zooplankton community. Data are averaged over the top 100 m of the water column to provide estimates of wet-weight biomass of zooplankton summarized here for all calanoid copepods and euphausiids (a.k.a. krill) retained by a 0.5 mm mesh net. These categories represent key prey for a variety of fish, marine mammals and seabirds.

Status and trends: While May 2019 was at or slightly-below average, preliminary data for May 2020 and 2021 suggest average or slightly above average calanoid biomass (Figure 32). May 2020 euphausiid biomass appears to be average, while September 2020 was well below average. Data are not yet available for 2021 (Figure 33).

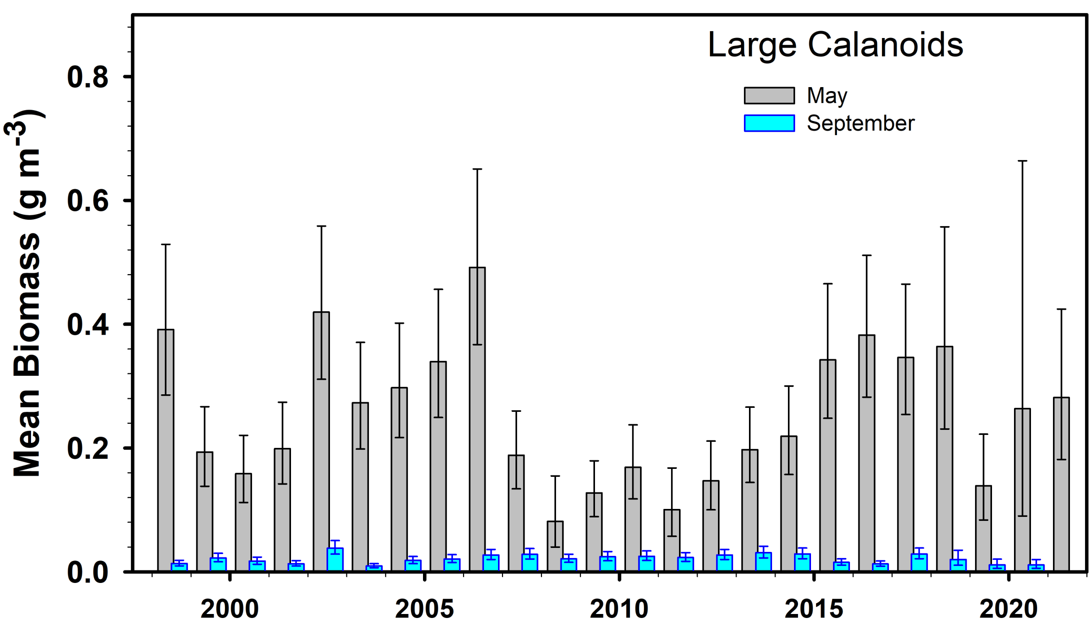


Figure 32: Biomass of calanoid copepods along the Seward Line sampled using a 0.5 mm mesh at night. Transect means and 95% confidence intervals are calculated on power-transformed data. Data for 2019–2021 are only available from a subset of stations and will change as more stations are completed.

Factors influencing observed trends: Temperatures during 2021 appear to have remained below average through the sampling year along the Seward Line, while 2020 temperatures were near the 24-year thermal mean (see Seward Line temperatures in this Report, p.39). Large copepod biomass during May often tends to track spring temperatures, not because there are more of them, but because they grow faster and therefore individuals are larger when waters are warmer. By September most large calanoids have descended into offshore waters and their biomass is greatly reduced.

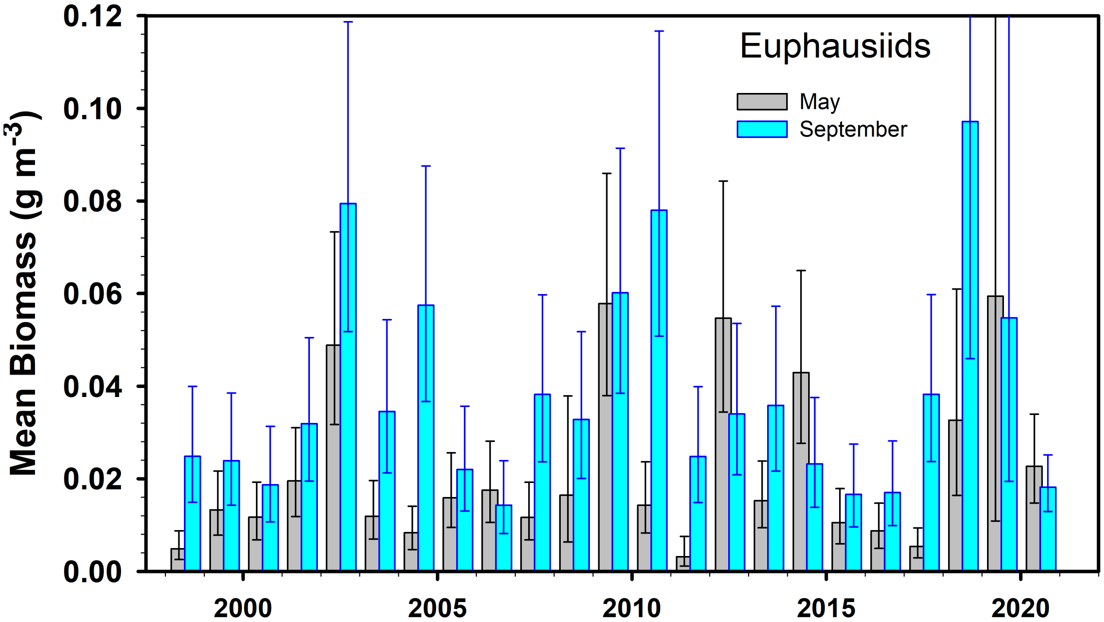


Figure 33: Biomass of euphausiids along the Seward Line sampled using a 0.5 mm mesh at night. Transect means and 95 confidence intervals are calculated on power-transformed data. Data for 2019-2021 is only available from a subset of stations and will change as more stations are completed.

In contrast, May euphausiid biomass appears to be negatively impacted by warm springs, with peaks in May often driven by high abundances of larval stages when conditions are favorable. Continued growth and recruitment often lead to higher biomass by September.

Implications: While high biomass of larger zooplankton does not guarantee success of species dependent upon them (due to a variety of other factors), low biomass does makes predator success challenging. Changes in the mixture (and energetic content) of species contributing to overall biomass may be of consequence to specific predators. With biomass of large copepods average during 2020 and 2021 relatively normal prey resources can be expected for copepod predators those years. The low biomass of euphausiids during fall 2020 suggests their predators may be somewhat food-limited compared to recent years.

Zooplankton Trends in Icy Strait, Southeast Alaska

Contributed by Emily Fergusson, Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: emily.fergusson@noaa.gov
Last updated: September 2021

Description of indicator: The Southeast Coastal Monitoring (SECM) project of Auke Bay Laboratories, AFSC, has been investigating how climate change may affect Southeast Alaska (SEAK) nearshore ecosystems in relation to juvenile salmon and associated biophysical factors since 1997 (Fergusson et al., 2013; Orsi et al., 2015). Zooplankton data have been collected annually in Icy Strait during monthly (May to July) fisheries oceanography surveys.

This Report presents 2021 annual values of zooplankton data in relation to the long-term trends in Icy Strait. Zooplankton density (number per m^3) was computed from 333-μm bongo net samples ($\leq$200 m depth) (Orsi et al., 2004; Park et al., 2004). Zooplankton density anomalies were computed as deviations from the long-term annual mean values for small copepods (species whose adults are $\leq$ 2.5mm), and large copepods (species whose adults are > 2.5 mm).

Status and trends: Densities of euphausiid larvae, small calanoid copepods, hyperiid amphipods, and gastropods increased from 2020 to 2021, and all were at or above the long-term mean. Large calanoid copepods decreased from 2020 densities but were still above average. The increase in zooplankton taxa densities may reflect a rebound in the zooplankton population as water temperatures return to average after the prolonged anomalously warm waters that resulted from the marine heat wave.

Zooplankton density trends over time represent prey availability to higher trophic levels and the zooplanktons response to climate and ocean conditions. Total zooplankton density ranged from 922 to 3,420 organisms per m^3 from 1997 to 2021. Recent trends in total zooplankton indicated increases in density of all zooplankton taxa with the exception of large calanoid copepods, which showed a slight decrease from 2021 but remained above the long-term mean. All other zooplankton taxa densities were at or above average in 2021, marking an increase from below average densities in 2020 (Figure 34). This increase in average densities indicates positive availability of selected prey utilized by larval and juvenile fish in Icy Strait.

Factors influencing observed trends: Subarctic zooplankton typically follow seasonal cycles of abundance, however, responses to climate change vary by species. Additionally, changes in density are influenced by seasonal timing cues, phenology, physiology, and environmental parameters including temperature, salinity, and phytoplankton bloom intensity (Mackas et al., 2012). These responses also depend on the monthly timing, magnitude, and duration of temperature anomalies in warm or cold years.

Implications: The above average densities for all zooplankton taxa in 2021 suggest beneficial feeding conditions for larval and juvenile fish such as larval herring, juvenile Pollock, and juvenile salmon that reside in Icy Strait and inland waters of SEAK. Favorable feeding conditions in terms of an abundance of prey and potentially high prey quality can directly and indirectly influence early-stage fish growth and recruitment.

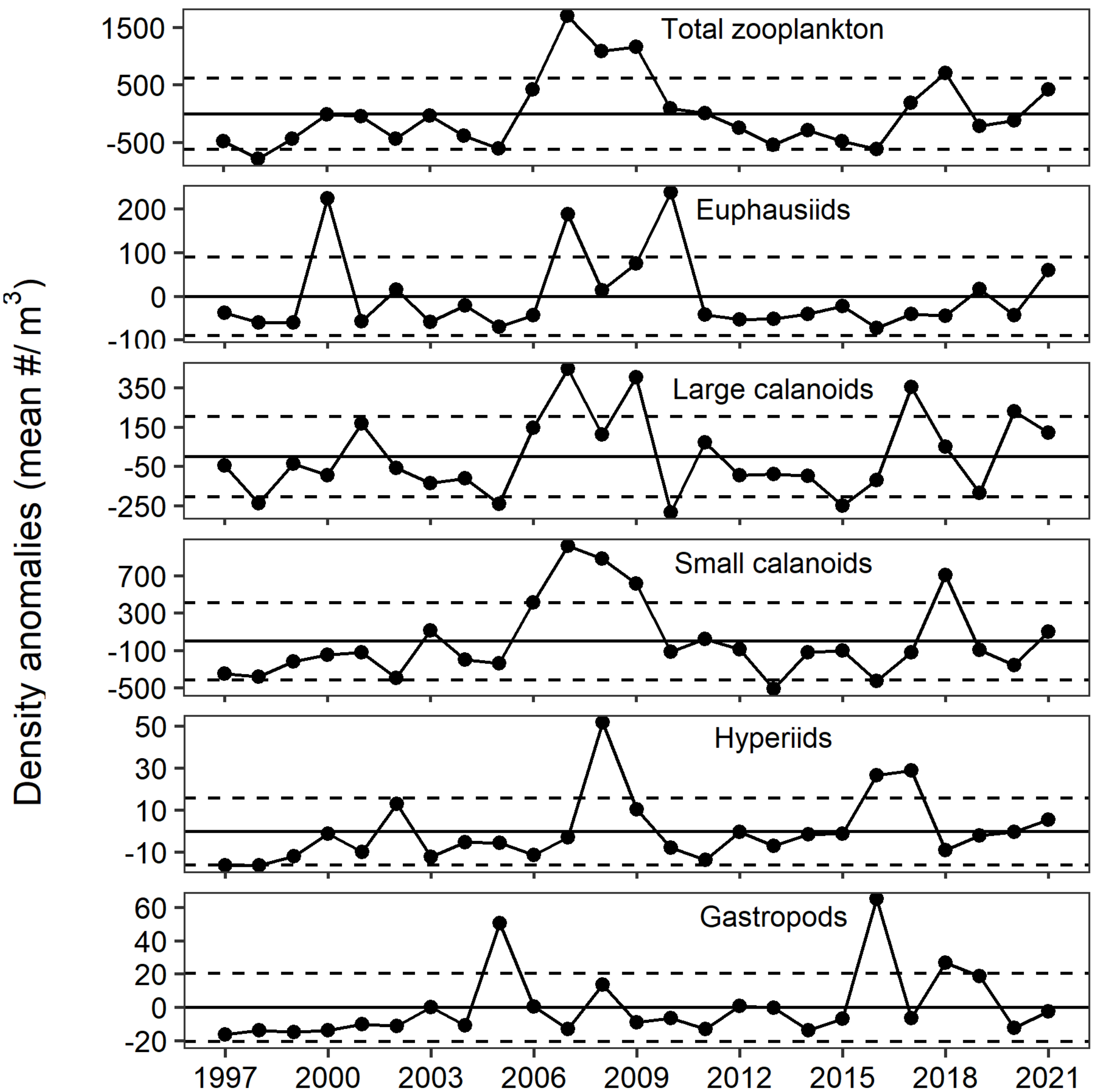


Figure 34: Average annual total zooplankton and taxa specific density anomalies for the northern region of SEAK (Icy Strait) from the Southeast Coastal Monitoring project time series, 1997–2021. One standard deviation above and below the mean is indicated by the dashed lines. Annual densities are composed of zooplankton samples collected monthly from May to July in Icy Strait. No samples were available for May 2007.

Jellyfish—Gulf of Alaska Bottom Trawl Survey

Contributed by Wayne Palsson, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: Wayne.Palsson@noaa.gov
Last updated: October 2021

Description of indicator: RACE bottom trawl surveys in the Gulf of Alaska (GOA) are designed primarily to assess populations of commercially important fish and invertebrates. However, many other species are identified, weighed and counted during the course of these surveys and these data may provide a measure of relative abundance for some of these species. Jellyfish are probably not sampled well by the gear due to their fragility and potential for catch in the mid-water during net deployment or retrieval. Therefore jellyfish are encountered in small numbers, which may or may not reflect their true abundance in the GOA. The fishing gear used aboard the Japanese vessels that participated in all GOA surveys prior to 1990 was very different from the gear used by all vessels since. This gear difference almost certainly affected the catch rates for jellyfish. For jellyfish, the catches for each year were scaled to the largest catch over the time series (which was arbitrarily scaled to a value of 100). The standard error (± 1) was weighted proportionally to the CPUE to get a relative standard error. The percentage of positive catches in the survey bottom trawl hauls was also calculated.

Status and trends: The 2021 catch per unit effort (CPUE) of jellyfish decreased from the high values observed in 2019 in all regions and are more comparable to the background CPUE observed since 1990 in most regions (Figure 35). There was a two to three fold increase in relative abundance in 2019 in each of the regions than during any previous survey and 2021 except in the Yakutat and Southeastern regions where CPUEs were closely matched with the second highest CPUEs in the time series. Despite the return of CPUEs to lower values, the frequency of occurrence in 2021 trawl catches remained high, at or near the near peak values observed in 2019. Jellyfish were most prevalent in the Chirikof, Kodiak, Yakutat, and Southeastern regions. Jellyfish in the Yakutat and Southeastern regions occurred at almost every survey station.

Factors influencing observed trends: Unknown

Implications: The 2021 GOA survey shows a subsidence of relative CPUE compared the high relative abundances observed in the GOA during 2019. The relatively high frequencies and CPUEs of jellyfish in the Yakutat and Southeastern regions suggest that the eastern GOA may have other oceanographic drivers than the western and central GOA. However, the higher occurrences in the eastern regions also may be related to survey timing because these regions are sampled almost two months after the western GOA.

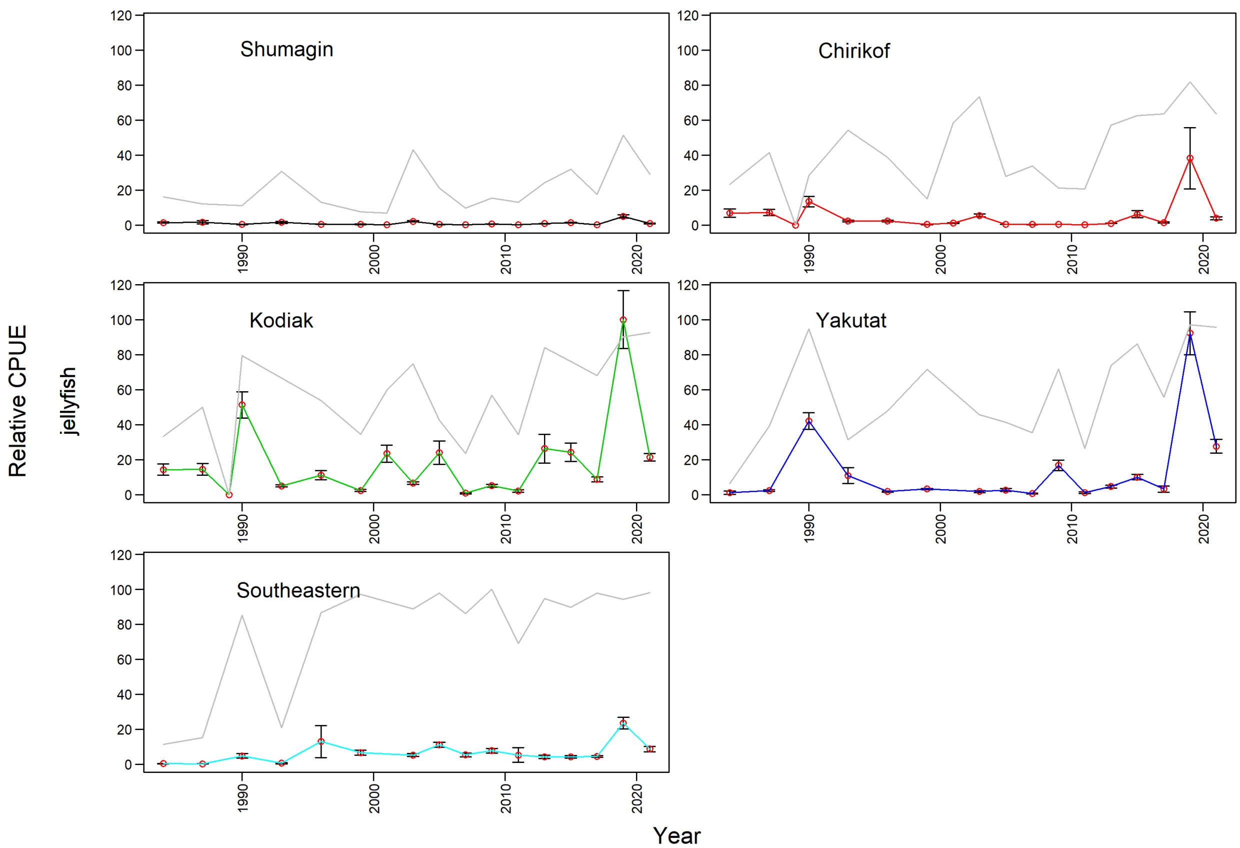


Figure 35: Relative mean CPUE of jellyfish species by area from RACE bottom trawl surveys in the Gulf of Alaska from 1984 through 2021. Error bars represent standard errors. The gray lines represent the percentage of non-zero catches.

Ichthyoplankton

Larval Fish Abundance in the Gulf of Alaska 1981–2021

Contributed by Alison Deary, Lauren Rogers, and Kelia Axler
EcoFOCI Program, Resource Assessment and Conservation Engineering, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: lauren.rogers@noaa.gov
Last updated: September 2021

Description of indicator: The Alaska Fisheries Science Center's (AFSC) Ecosystems and Fisheries Oceanography Coordinated Investigations Program (EcoFOCI) has been sampling ichthyoplankton in the Gulf of Alaska (GOA) from 1972 to the present, with annual sampling from 1981–2011 and biennial sampling during odd-numbered years thereafter. The primary sampling gear used is a 60-cm bongo sampler fitted with 333 or 505 μm mesh nets. Oblique tows are carried out mostly from 100 m depth to the surface or from 10 m off bottom in shallower water (Matarese et al., 2003, Ichthyoplankton Information System `https://apps-afsc.fisheries.noaa.gov/ichthyo/index.php`). Historical sampling has been most intense in the vicinity of Shelikof Strait and Sea Valley during mid-May through early June (Figure 36). However, in 2019 and 2021, sampling occurred several weeks earlier than the historical sampling starting in early May and concluding in late May. From this area and time, a subset of data has been developed into a time series of ichthyoplankton abundance (after Doyle et al., 2009) for the 12 most abundant larval taxa in the GOA, including commercially and ecologically important species (Figure 37). These time series are updated in even years, one year after collection, due to processing time required for quantitative data. On-board counts of a limited number of taxa give rapid estimates of relative abundance (Rapid Larval Assessment), which are presented in the year of collection. Due to the COVID–19 pandemic and the closure of the Western Regional Center, the 2019 ichthyoplankton data have not followed the same quality assurance steps established by EcoFOCI as the data prior to 2019 and are, therefore, preliminary. Quantitative data for 7 of 12 taxa are provided, with the remaining 5 pending laboratory verification. The 2019 data will be updated and are subject to change once full quality assurance steps can be completed.

Status and trends: Northern rock sole and southern rock sole had low abundances in 2021 similar to or marginally higher than what was observed in 2019 (Figure 37). These species were not common in the core survey area but were consistently captured along the southeastern margin of the core (Chirikof Island to Kodiak) as in prior years (Figure 38). Arrowtooth flounder increased in abundance from 2019, approaching the 40-year average for each time series. Arrowtooth flounder were consistently caught in the southwestern portion of the core survey area, as in prior years. Pacific cod and walleye pollock abundance remained low in 2021, similar to observations in 2015 and 2019. For both walleye pollock and Pacific cod, abundances were highest along the southeastern margin of the Kodiak Archipelago, outside the core area. Rockfish abundance remained elevated in 2021 relative to the first two decades of observations but declined from the high abundances of the most recent decade to the time series average. Unlike prior years, rockfish were not as common along the southwestern region of the core survey area, which parallels the shelf break. Pacific sand lance larvae declined in abundance from a peak in 2019, returning to the time series average, but were present at most stations sampled in 2021. For the remaining 5 indicator taxa (ronquils, starry flounder, northern lampfish, flathead sole, and Pacific halibut), we had neither Rapid Larval

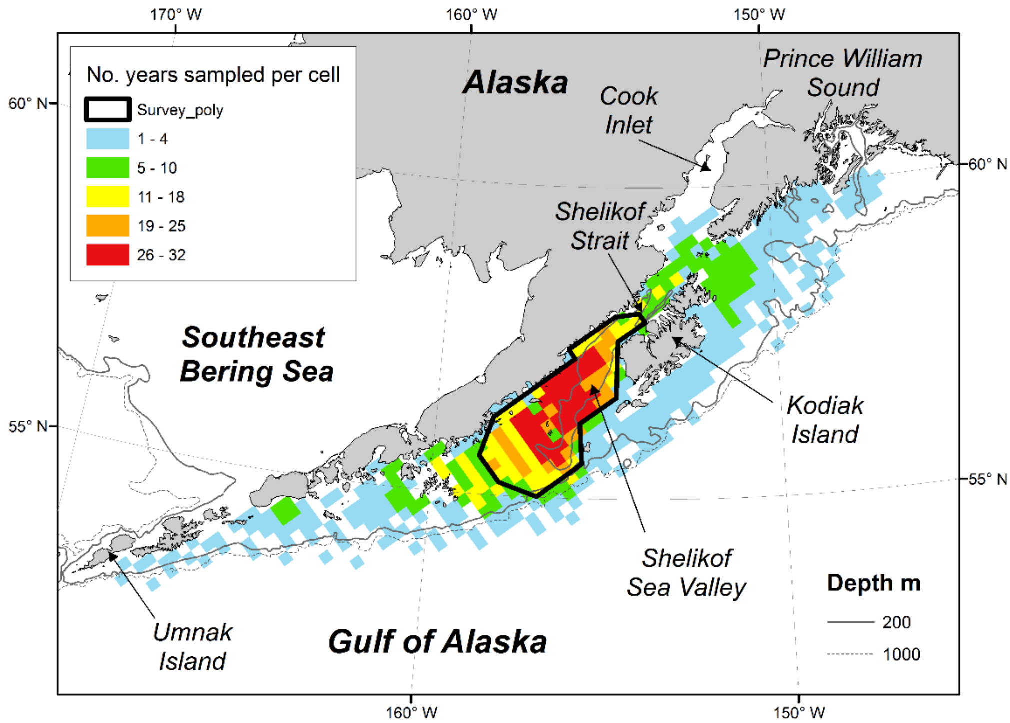


Figure 36: Distribution of historical ichthyoplankton sampling in the Gulf of Alaska by NOAA's Alaska Fisheries Science Center using a 60 cm frame bongo net. Sampling effort is illustrated by the number of years where sampling occurred in each 20 km^2 grid cell during late spring. A time series has been developed for the years 1981–2021 from collections in the polygonal area outlined in black where sampling has been most consistent during mid-May through early June. Note that this polygon was updated in 2018 to reflect sampling intensity through the most recent years.

Assessment nor quantitative data to assess abundance trends for 2021.

Factors influencing observed trends: Sea surface temperatures averaged across the western GOA shelf were warmer than the long-term mean during the winter of 2021 (see Satellite data in the Ocean Temperature Synthesis in this Report, p.39). In March, sea surface temperatures decreased to the time series average, which persisted through the survey in May. This was confirmed by in-situ temperature profiles (see EcoFOCI survey in Ocean Temperature Synthesis in this Report, p.39), with the 2021 temperatures at surface and at depth being similar to 2013 and the time series average. Survey timing may also impact the trends observed in 2021 since the survey occurred about two weeks earlier than the historical time series but was consistent in timing with the 2019 survey.

Previous work has explored trends in abundance of these species in relation to atmospheric and oceanographic conditions (Doyle et al., 2009; Doyle and Mier, 2012). Similarities in response to environmental forcing were apparent among species that display similarities in patterns of early life

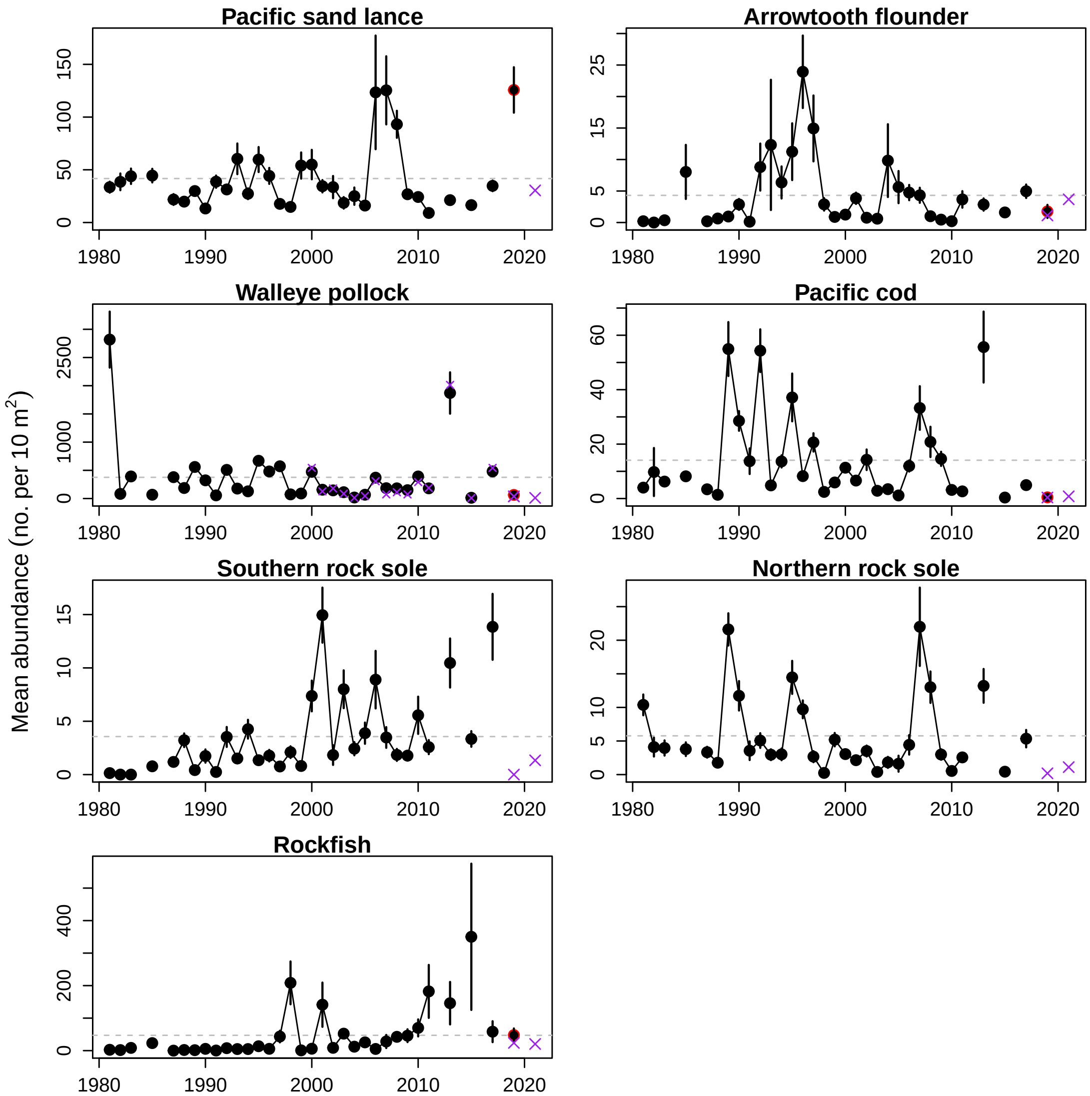


Figure 37: Interannual variation in late spring larval fish abundance in the Gulf of Alaska, 1981–2021. The larval abundance index is expressed as the mean abundance (no. 10 m^{-2}), and the long-term mean is indicated by the dashed line. Error bars show +/- 1 SE. No data are available for 1984, 1986, 2012, 2014, 2016, 2018 or 2020. Purple x's denote estimates from onboard Rapid Larval Assessments. Points with red outlines indicate preliminary quantitative data for 2019. Due to laboratory restrictions in 2020/2021, data were not available for select species.

history exposure to the environment (Doyle et al., 2009). For instance, years of high abundance for the late winter to early spring shelf spawners (Pacific cod, walleye pollock, and northern rock sole) were associated with cooler winters and enhanced alongshore winds during spring. With temperature conditions being consistent with a moderate climate year (baseline 1985-2014, see Watson in this Report, p.39), we expected to observe average abundances of Pacific cod and walleye pollock. However, abundances or these two species were especially low and the highest catches were outside of the core area, which is unusual. The predominant wind pattern during the spring 2021 survey was to the southwest, which is consistent with enhanced larval retention and increased age-1 abundance the following year (Wilson and Laman, 2021, and see Wilson and Rogers in this Report, p.56). Pacific sand lance recruitment and abundance are notably higher at warmer temperatures, which was not the case in 2021, likely contributing to the average abundance observed after a peak in 2019 corresponding to a warm year (Hedd et al., 2006; Sydeman et al., 2017).

Implications: Ichthyoplankton surveys can provide early-warning indicators for ecosystem conditions and recruitment patterns in marine fishes. In both 2015 and 2019, low abundances of walleye pollock and Pacific cod larvae were the first indicators of failed year-classes for those species. In 2021, the warming that had been persistent in the Gulf of Alaska eased, and 3 of the 7 indicator species were found to have abundances approaching average; however, walleye pollock, Pacific cod, northern rock sole, and southern rock sole had low abundances similar to 2019. With potential average year classes, it is difficult to forecast survival into later stages because many environmental factors can act over the first summer to impact year class strength, but low larval abundance is a more reliable indicator of poor year-class strength. The late-summer Young-of-Year survey was canceled in 2021, therefore, we lack the final assessment of abundance and condition prior to overwintering, especially for walleye pollock, Pacific cod, and forage fishes. If the prey field in the spring and summer is not bioenergetically rich enough for larvae and juveniles to provision for their first winter, then a year class can still fail to recruit (Lamb and Kimmel, 2021, see Kimmel in this Report, p.70).

Multispecies Larval Indicator for the Gulf of Alaska

Contributed by Jens M. Nielsen, Lauren A. Rogers, EcoFOCI Program, Resource Assessment and Conservation Engineering, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: lauren.rogers@noaa.gov
Last updated: October 2021

Description of indicator: Ichthyoplankton sampling in the Gulf of Alaska (GOA) has been conducted by the Alaska Fisheries Science Center (AFSC) Ecosystems and Fisheries Oceanography Coordinated Investigations Program (EcoFOCI) annually from 1981–2011 and biennially during odd-numbered years thereafter. The most consistent sampling has been conducted in the region of Shelikof Strait and Sea Valley from mid-May to early June providing consistent time series data (see Deary et al. in this Report, p.85). Here, a multispecies larval indicator is used to capture the annual dynamics of the most common ichthyoplankton fauna. Because early life stages of single species often exhibit high variability, a multispecies approach may be advantageous in capturing general dynamics of the larval community, and could provide an indicator and link to recruitment and ecosystems conditions. Ichthyoplankton were analyzed using Bayesian dynamic factor analysis which is a multivariate time series technique useful for estimating common trend(s) from multiple timeseries data (Ward et al., 2019). Loading estimates for each individual species time series denote if a species is positively or negatively correlated to a common trend. We developed a multispecies larval Dynamic Factor Analysis (DFA) based on 7 common and commercially important species: walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), northern rock sole (*Lepidopsetta polyxystra*), southern rock sole (*Lepidopsetta bilineata*), rockfishes (*Sebastes spp.*), arrowtooth flounder (*Atheresthes stomias*) and Pacific sandlance (*Ammodytes personatus*). We specified the DFA model to estimate one common trend. Starting in 2019, a Rapid Larval Assessment has been conducted for these 7 species, which provides immediate information on species abundances. Rough counts are subsequently replaced with the quantitative data once laboratory work is complete, about a year after sampling (see Deary et al. in this report, p.85, for details on 2019 and 2021 data sources and laboratory verification). Previous rough counts for walleye pollock align closely with the quantitative data suggesting that this method provides a valuable and rapid assessment of abundance levels.

Status and trends: The larval DFA showed that the estimated common trend was overall low and only slightly higher than the previous low estimates in 2015 and 2019 (Figure 39A). The analysis showed that *Gadus chalcogrammus*, *Gadus macrocephalus* and *Lepidopsetta polyxystra* co-vary over time and all loaded positively to the larval DFA, i.e., these species have higher abundance when the common trend is positive (Figure 39B). Contrarily, *Sebastes* spp loaded negatively to the trend (i.e., negative trend values indicative of higher abundance). *Lepidopsetta bilineata* and *Atheresthes stomias* were poorly explained by the model. *Ammodytes personatus* loaded weakly but positively to the common trend.

Factors influencing observed trends: The multispecies larval indicator supports the idea that ichthyoplankton respond rapidly to environmental changes. A negative value of the larval DFA, indicative of low abundance of *Gadus chalcogrammus*, *Gadus macrocephalus* and *Lepidopsetta polyxystra*, was again observed in 2021, similar to the years 1998, 2003-2005, and in particular 2015 and 2019, all warm years. This suggests that the ichthyoplankton in 2021 resembled past warm years, including the recent 2014-2016 marine heatwave that had major impacts on the GOA ecosystem (Nielsen et al., 2021). This pattern is also supported by a significant relationship between spring (Mar–Apr) temperatures and the larval DFA trend (data not shown). While temperatures in the western GOA in May 2021 were not unusually warm (see EcoFOCI survey in Ocean Temperature Synthesis in this Report, p.39), surface temperatures reflected heatwave conditions in the earlier spring months (see Watson in this Report, p.39), which may have affected earlier stages of the larvae collected.

Implications: Ichthyoplankton are good indicators of ecosystem dynamics (Boeing and Duffy-Anderson, 2008). The multispecies larval indicator developed here appears to capture well the dynamics of several of the most common ichthyoplankton species in the Gulf of Alaska. In addition, previous analyses have shown that the larval DFA based on the 7 species, aligns closely with a larval DFA using 20 of the most common species, suggesting that the Rapid Larval Assessment represents the general ichthyoplankton dynamics well. The low values of the common trend in 2019 and 2021 suggest that walleye pollock, Pacific cod and northern rock sole all experienced high mortality rates and thus suggests low recruitment potential. Recruitment trends of the 7 species considered here are likely to have impacts on commercial fisheries for these species, and may influence survival of higher trophic level predators, such as seabirds and mammals that forage on larger individuals of these species. Due to the biennial sampling our estimates do not inform about larval patterns in even numbered years, e.g., 2018 and 2020. Preliminary analyses also suggest that the multispecies larval indicator is correlated to spring temperatures and abundance of *Pseudocalanus spp.* (a smaller but abundant copepod and potential prey species), indicating that the larval DFA has value as an indicator of ecosystem dynamics in the Gulf of Alaska.

Forage Fish and Squid

Summary of Forage Conditions

Contributed by Olav Ormseth, Resource Ecology and Fisheries Management, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: olav.ormseth@noaa.gov
Last updated: November 2021

The abundance of forage fishes in the GOA is difficult to measure. There are no dedicated large-scale surveys for these species, and the existing surveys are limited in their ability to assess forage species due to issues such as gear selectivity and catchability. While the AFSC summer acoustic survey has shown promise for monitoring the abundance of capelin, the capacity of this survey for assessing non-pollock echosign is limited. The monitoring of seabird diets has provided some useful information on relative forage abundance, but those data are influenced by variation in spatial distribution, foraging behavior, and other factors.

Despite these difficulties, it is possible to use multiple indicators to discern some broad trends in forage availability in the GOA. Survey-based indices (see McGowan in this Report, p.99) and seabird diets at Middleton Island (see Hatch in this Report, p.94) indicate that the GOA capelin population increased in the years prior to the 2014-2016 marine heat wave, declined dramatically during the heat wave, and have yet to make a substantial recovery. Similarly, the AFSC bottom trawl survey suggests that eulachon biomass dropped following those warm years (Ormseth, pers. comm.). Data for Pacific herring are regionally variable: spawning populations of herring in Southeast Alaska and PWS increased substantially during 2020-2021 (see Hebert in this Report, p.102 and Pegau in this Report p.202), driven by the large 2016 year class. Herring are abundant in some seabird diets, but shelf-wide bottom trawl survey biomass estimates dropped in 2021 (Ormseth, pers.comm.). The strong recruitment of age-1 pollock in 2021 has led to an increased model estimate of biomass of pollock being consumed by predators, including arrowtooth flounder (see Adams in this Report, p.142).

It appears that forage availability in the GOA is recovering after the marine heat wave, but as might be expected from this complex ecosystem patterns vary considerably among species and species groups. The capacity for predators to switch prey depending on availability is not well understood, but the seabird diets at Middleton Island suggest that some species groups that are not typically considered to be forage species (e.g., juvenile greenlings, Hatch p.94) may be especially important when other species are low in abundance. Piscivorous surface-feeding and diving seabirds generally had average to above average reproductive success, implying adequate forage fish were available (see Seabird Synthesis in this Report, p.152). The body condition(weight at length) of certain piscivorous groundfish species generally continued a below-average trend since 2015, implying less than adequate forage availability, although some showed signs of improvement in 2021 see O'Leary in this Report, p.130).

Body Condition of age-0 pollock in the Western Gulf of Alaska

Contributed by Lauren Rogers, Matthew Wilson, Dan Cooper, EcoFOCI Program, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: lauren.rogers@noaa.gov
Last updated: August 2021

Description of indicator: Body condition of fishes is an integrated indicator, reflecting conditions for growth, such as prey availability and temperature, as well as stock resilience, as fish in better condition (i.e., with greater energetic reserves) can survive longer under poor prey conditions. This may be particularly true for juvenile pollock as they transition into their first winter; when food becomes scarce, sufficient energy stores may be critical for overwinter survival (Sogard and Olla, 2000; Duffy-Anderson et al., 2016; Lamb and Kimmel, 2021).

The AFSC EcoFOCI juvenile groundfish survey is a midwater trawl survey that has sampled age-0 walleye pollock throughout the Western Gulf of Alaska in late summer (August–September) since 2000 (Figure 40). Individual age-0 pollock were frozen at sea and later measured for length and weight in the laboratory. Body condition was measured as residuals from a regression of log(weight) on log(length), with positive residuals indicating "fatter" fish having larger body mass per unit length. Because body condition can vary with season (Buchheister et al., 2006), and survey timing varied by up to a month between years, we included an additional term in the regression model to account for the day of year fish were collected. In 2011, the survey occurred in October, a month later than other years, and data from that year have been excluded. Only a subset of fish from each station were measured, thus residuals were weighted by station CPUE when constructing an annual average. Fish collected in the consistently sampled Semidi bank region (Figure 40) were used to construct the index. Laboratory access was limited in 2020 due to COVID-19, which delayed reporting of 2019 results until this year.

Status and trends: Average body condition of age-0 pollock in 2019 was the lowest observed in the time series. Condition was also low in the two previous years sampled (2015 and 2017) as well as 2005 (Figure 41). Higher than average body condition was observed in 2001, 2003, 2007 and 2009. In 2019, a spatial pattern was evident, with higher age-0 body condition observed in fish collected in Shelikof Strait and near Kodiak relative to the Semidi area where the index was calculated (Figure 40).

Factors influencing observed trends: Body condition of age-0 pollock is likely influenced by temperature, which increases metabolic demands, and prey quality and quantity, which determine their ability to meet those demands. In 2015, during the North Pacific marine heatwave, temperatures were warm and prey quality and quantity were reduced (Rogers et al., 2010), resulting in poor body condition. This pattern was simultaneously observed for other forage fishes such as Pacific sand lance (Von Biela et al. 2019). Warm temperatures were also observed in 2005. In 2017, body condition was somewhat higher than in 2015, but still low, matching observations for older stages of groundfishes in the GOA (Boldt et al., 2017). Krill, an important prey for age-0 pollock which has been associated with improved body condition (Wilson et al., 2013), were relatively scarce in 2017 (Rogers and Mier, 2017). In 2019, warm conditions returned to the GOA, including at depth, which likely contributed to low condition at end of summer for age-0 pollock. Historically, higher body condition in the Kodiak-Shelikof vicinity, relative to the Semidi area, has been associated with enrichment of krill in the prey field and cooler water (Wilson et al., 2013).

Implications: Juvenile pollock rapidly increase their energy storage in late summer, presumably to increase their survival chances during winter, when prey are scarce (Siddon et al., 2013). In the Bering Sea, low energy storage prior to the first winter has been associated with poor year-class strength for juvenile pollock. Whether this relationship holds for the Gulf of Alaska is yet to be seen, but poor body condition in 2015, 2017, and 2019 reflects suboptimal ecosystem conditions for pollock growth both during and after the recent marine heat waves, which may have had adverse effects on overwinter survival. Poor condition of age-0 pollock also results in reduced quality of these fish as prey for seabirds and other piscivorous predators. The geographic pattern in body condition, Kodiak-Shelikof versus Semidi, is consistent with habitat-related spatial structure within the population that likely is important in buffering against widespread losses (Wilson et al., 2018).

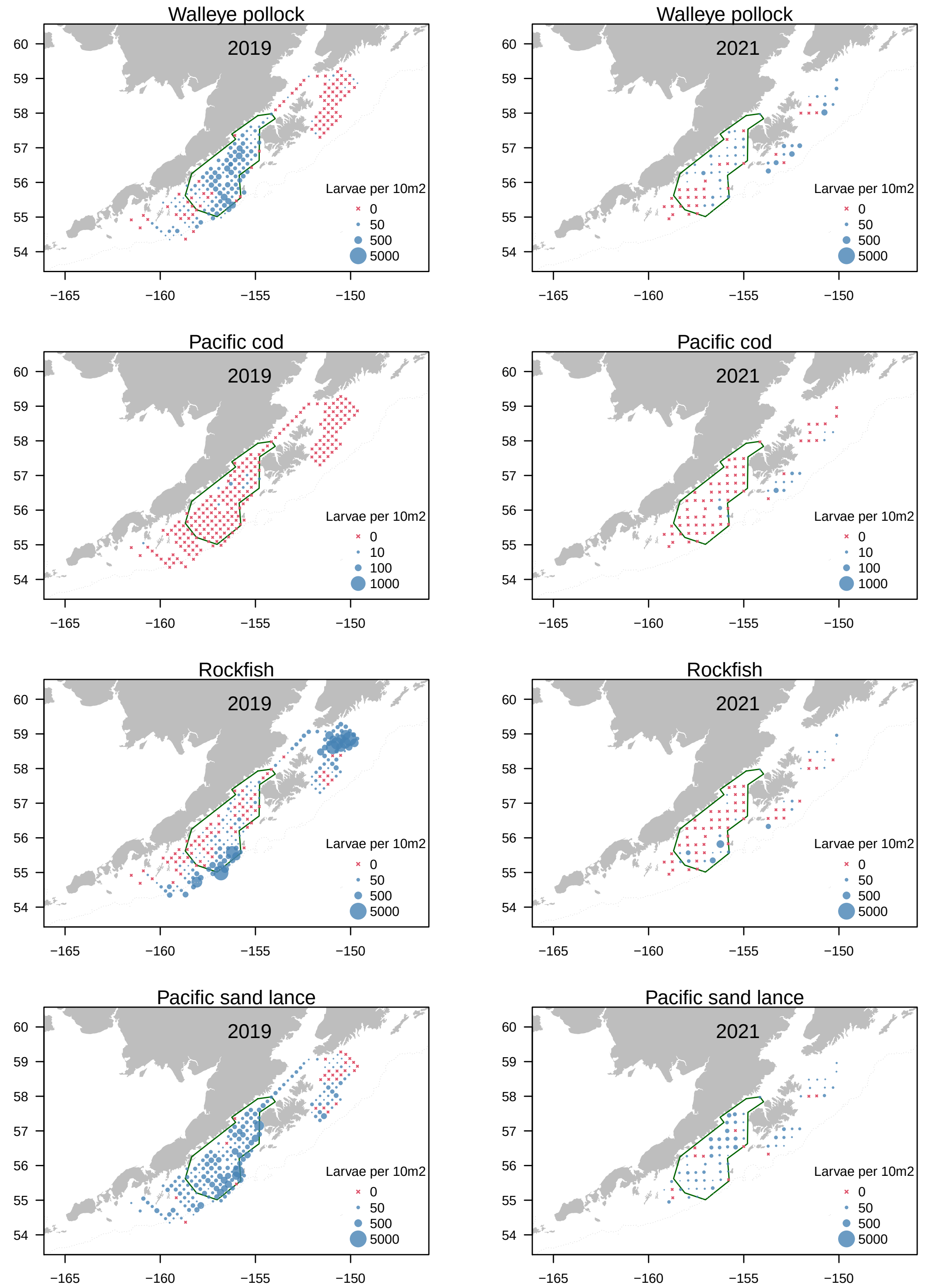


Figure 38: Abundance of larval walleye pollock and larvae of other fish on the EcoFOCI spring larval survey for 2019 and 2021. The at-sea rough counts were used to generate the distribution for 2021 whereas quantitative laboratory data are shown for 2019. Note that 2019 shows preliminary quantitative data.

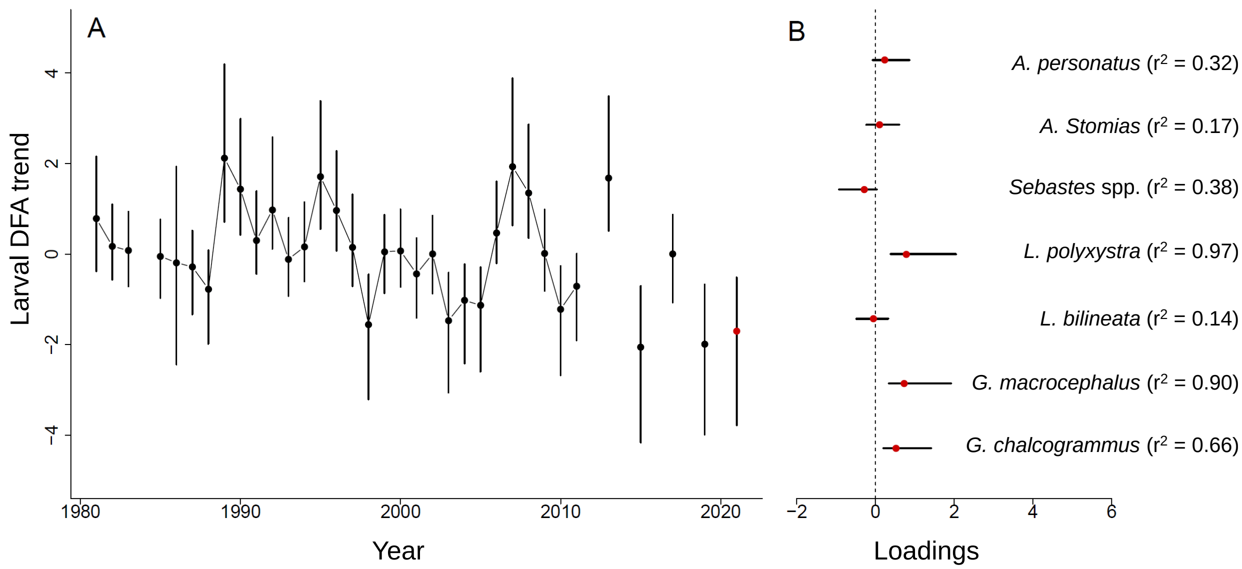


Figure 39: A) Time trend of the multispecies larval DFA trend, with the 2021 value based on the Rapid Larval Assessment in red. B) Loading of the 7 larval fish taxa on the time trend shown in A.

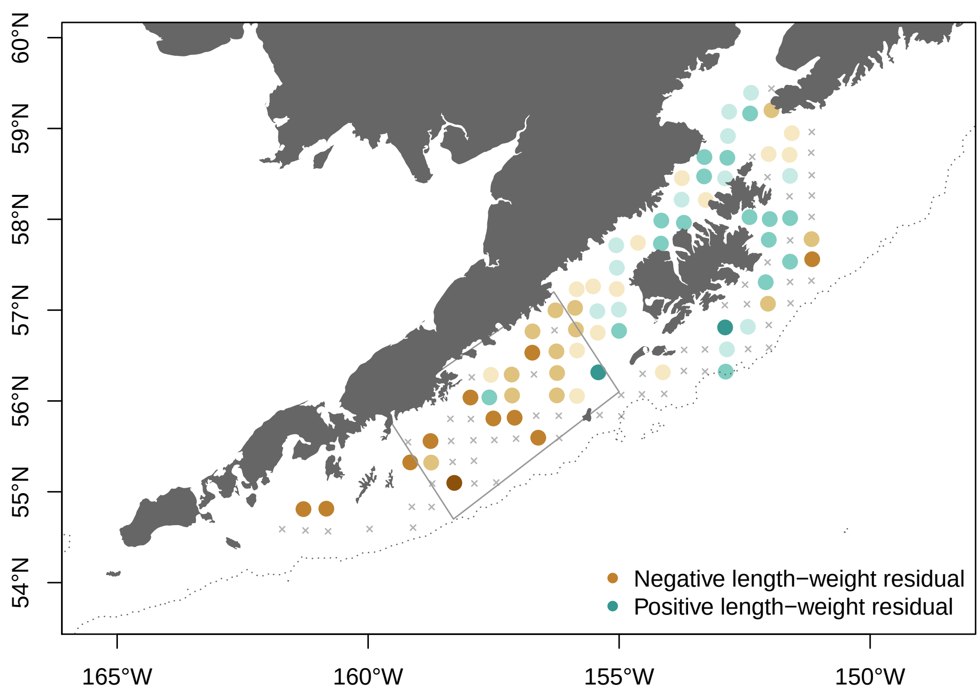


Figure 40: Station averages of age-0 pollock body condition measured in 2019. Color indicates whether condition was above (blue-green) or below (orange) average, whereas shading indicates the relative magnitude of residuals. Gray x's indicate stations where no age-0 pollock were caught or measured. Stations in the core Semidi area (gray box) have been most consistently sampled since 2000 and were used for constructing the condition index.

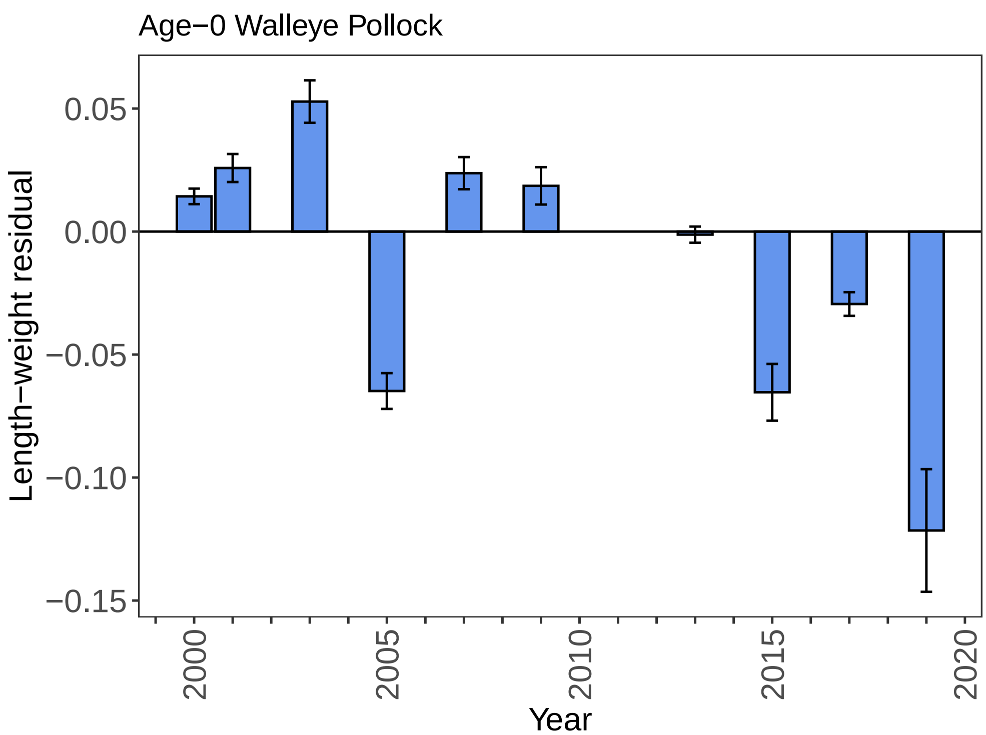


Figure 41: Average CPUE-weighted body condition of age-0 pollock in the core Semidi area (+/- 1 standard error).

Seabird-Derived Forage Fish Indicators from Middleton Island

Contributed by Scott A. Hatch[1], Mayumi Arimitsu[2], John F. Piatt[2]
[1] Institute for Seabird Research and Conservation, Anchorage, AK
[2] Seabird and Forage Fish Ecology Program, Marine Ecosystems Office, Alaska Science Center U.S. Geological Survey, Anchorage, AK
Contact: shatch.isrc@gmail.com
Last updated: September 2021

Description of indicator: The time series of forage fish population trends derived from seabird diet monitoring at Middleton Island in the north-central Gulf of Alaska are among the longest available from any Alaska location. Being situated near the continental shelf edge (lat 59.4375°N, lon -146.3277°W), Middleton's seabirds sample both neritic shelf habitat and deep ocean waters beyond the shelf break. Tagging data suggest the foraging range of seabirds at Middleton varies across years but can be approximated by a 100 km radius from the colony. Consequently, important shelf forage species (e.g., capelin, sand lance) figure prominently in seabird diets at Middleton, but additionally, certain other species of high ecological importance (e.g., myctophids) and/or economic concern (e.g., 0-age sablefish, pink and chum salmon) regularly occur in diets that have been monitored since the late 1970's.

Diet data collection began in 1978, and in most years since 2000 regurgitated food samples have been collected from adult and/or nestling black-legged kittiwakes (*Rissa tridactyla*) from April to August (>6,000 samples to date). The preferred metric for kittiwakes is prey relative occurrence (Hatch, 2013), for which the relevant sample unit (denominator for calculations of frequency) is total occurrences of identified prey types in a given collection of samples. Kittiwake diets reflect the availability of surface-oriented prey within their foraging range.

Rhinoceros auklet (*Cerorhinca monocerata*) diets are monitored by collecting bill-loads from chick-provisioning adults, about twice a week from early July through early or mid-August. Samples consist of whole prey specimens from one or more species, and therefore the reported data are simple calculations of percentage biomass per species. Since 1978, 5337 auklet prey samples have been collected on Middleton, and auklet diet monitoring provides the single best indicator of forage fish dynamics and forage community stability over time for the region (Hatch, 2013; Sydeman et al., 2017; Arimitsu et al., 2021).

Status and trends: 2021 Update: Totals of 440 kittiwake diet samples and 306 rhinoceros auklet samples were obtained in 2021. As in several prior years, hexagrammids (primarily kelp and rock greenlings) were important seabird prey in 2021–41% of prey biomass in rhinoceros auklets and 14% relative occurrence in kittiwakes. Pacific herring also extended their prominence as a prey species of auklets (17% the diet during chick-rearing), and especially kittiwakes (36% during chick-rearing [Figure 42], 45% prior to laying [not shown])—levels seen in few prior years at Middleton. Herring that were classified as age-1 or older fish predominated in 2021, with only trace amounts of age-0 fish occurring in the diet of rhinoceros auklets. Total length of age-1+ herring ranged from 120 to 180 mm, averaging 153 mm.

Capelin (5% of prey mass delivered to auklet nestlings, 13% relative occurrence in kittiwakes) made a modest showing in 2021. As is often the case at Middleton, many female capelin contained prominent egg masses in 2021. The spawning grounds of capelin brought to Middleton may vary from year to year as stable isotope analyses of mature capelin over time suggest both offshore and coastal sources.

Consumption of age-0 sablefish by Middleton seabirds (rhinoceros auklets and kittiwakes) varies greatly among years (Figure 43). Neither surface feeding or diving seabird species obtained sablefish readily in 2021—no occurrences in kittiwake diet samples and only trace amounts in auklets—presumably due to a lack of encounters with young-of-the-year sablefish in the birds' foraging areas.

On average, Middleton kittiwakes take about equal amounts of Pacific sand lance, capelin, and invertebrates, with lesser amounts of herring, sablefish, salmon, and myctophids, depending on stage of the season. The juxtaposition of time series for kittiwakes and rhinoceros auklets since 1978 (Figure 42) shows general agreement between a sustained decline of sand lance and, beginning in 2007, the emergence of capelin as a dominant forage species through the cool period that lasted through 2013. However, in years when neither sand lance nor capelin were prevalent (e.g., 2014–2017), the diets of surface feeding kittiwakes and diving auklets diverged in respect to behavioral prey-switching to alternate species such as myctophids, salmon, greenlings, sablefish, and herring.

Auklet data plotted separately by prey type highlight the interannual dynamics of particular species of interest (Figure 43). Sand lance were the overwhelmingly dominant forage species in the northern Gulf in the late 1970s through the early 1980s. Following a period of reduced availability in the mid 1990s, sand lance made a strong comeback by the end of that decade. However, sand lance steadily declined in importance after 2000 and contributed little to seabird diets from 2009 through 2015. The appearance of about 30% sand lance in the auklet diet in 2016 and 2017 is consistent with a known association of sand lance with warm-water conditions (Hatch, 2013; Sydeman et al., 2017). The re-emergence of sand lance continued in 2018, when this species constituted about 50% of the auklet diet by weight (Figure 43). In 2019, sand lance declined slightly as compared with the previous year, the difference being offset by a modest increase in capelin. Greenlings were prominent in the auklet and kittiwake diets during 2018-2021, to a consistent high degree not seen since sampling began (Figure 42). The occurrence of herring and other coastal species in seabird diets from Middleton possibly reflects greater use of nearshore/inner shelf habitats because of reduced availability of offshore prey resources. Indeed, GPS tracking of foraging seabirds conducted during chick-rearing reveal that in recent years birds from Middleton have commuted a considerable distance (∼80 km one-way) and foraged principally in nearshore waters, especially at the southern end of Montague Island.

Factors influencing observed trends: Seabird diets at Middleton reflect ecosystem shifts in the Gulf of Alaska. This includes specific events recorded and widely discussed in the ecological literature such as the notable shift from "warm" (positive Pacific Decadal Oscillation, PDO) conditions to "cold" (negative PDO) conditions around 1999–2000 (Greene, 2002; Peterson et al., 2003; Batten and Welch, 2004), a similar but stronger and more persistent shift in 2008 (Hatch, 2013; Sydeman et al., 2017), and a widely reported warm-water anomaly that dominated the system for several years beginning in late 2013 (Bond et al., 2015). A salient finding during the anomaly was the virtual disappearance of capelin from seabird diets on Middleton, following 6 prior years when capelin were predominant (Figure 42). An apparent trade-off between Pacific sand lance (warm conditions) and capelin (cold conditions) may have been a hallmark of the forage fish community in the region for several decades (Sydeman et al., 2017); however, this pattern apparently changed during the marine heatwave. Notably, large-scale seabird die-offs have occurred when seabird diets at Middleton suggested low availability of both capelin and sand lance at the same time, for example in 1993 (Piatt and Van Pelt, 1997) and in 2015–2016 (Piatt et al., 2020).

The PDO turned negative in early 2020 and has remained mostly so to the present time (September 2021), a development discussed elsewhere in relation to seabird responses on Middleton (see the Seabird Synthesis in this Report, p.152). Unlike previous intervals with cool-water conditions, capelin have not yet made any appreciable comeback in seabird diets. Rather, the salient response to date has been the ascendance of greenlings and other hexagrammids, as described above.

Implications: Seabird diets provide evidence that capelin disappeared in the ecosystem in recent warm years. Chick diets at Middleton may also be informative for sablefish studies. In recent years, the Alaska Fisheries Science Center began using specimens from seabird diet sampling at Middleton for phenology and growth studies of age-0 sablefish, which are difficult to sample by other means. Seabird diet indicators are potentially applicable to other management concerns in the region, including Pacific herring stocks, which crashed and have not recovered after the Exxon-Valdez Oil Spill in 1989, and year-class strengths of pink and chum salmon, which occur regularly in Middleton seabird diets.

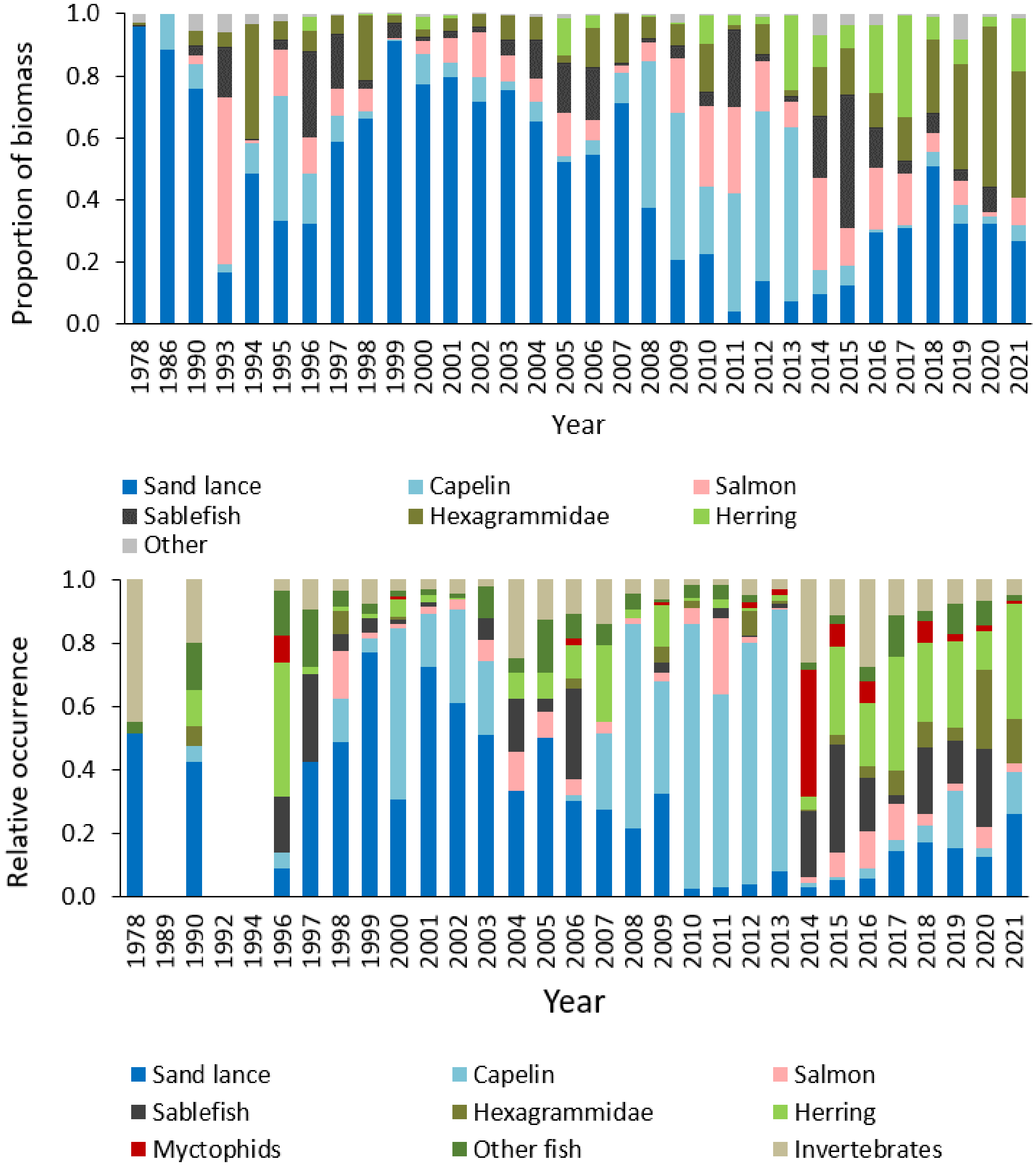


Figure 42: Interannual variation in diet composition of chick-rearing rhinoceros auklets (upper panel) and black-legged kittiwakes (lower panel) on Middleton Island, 1978–2021.

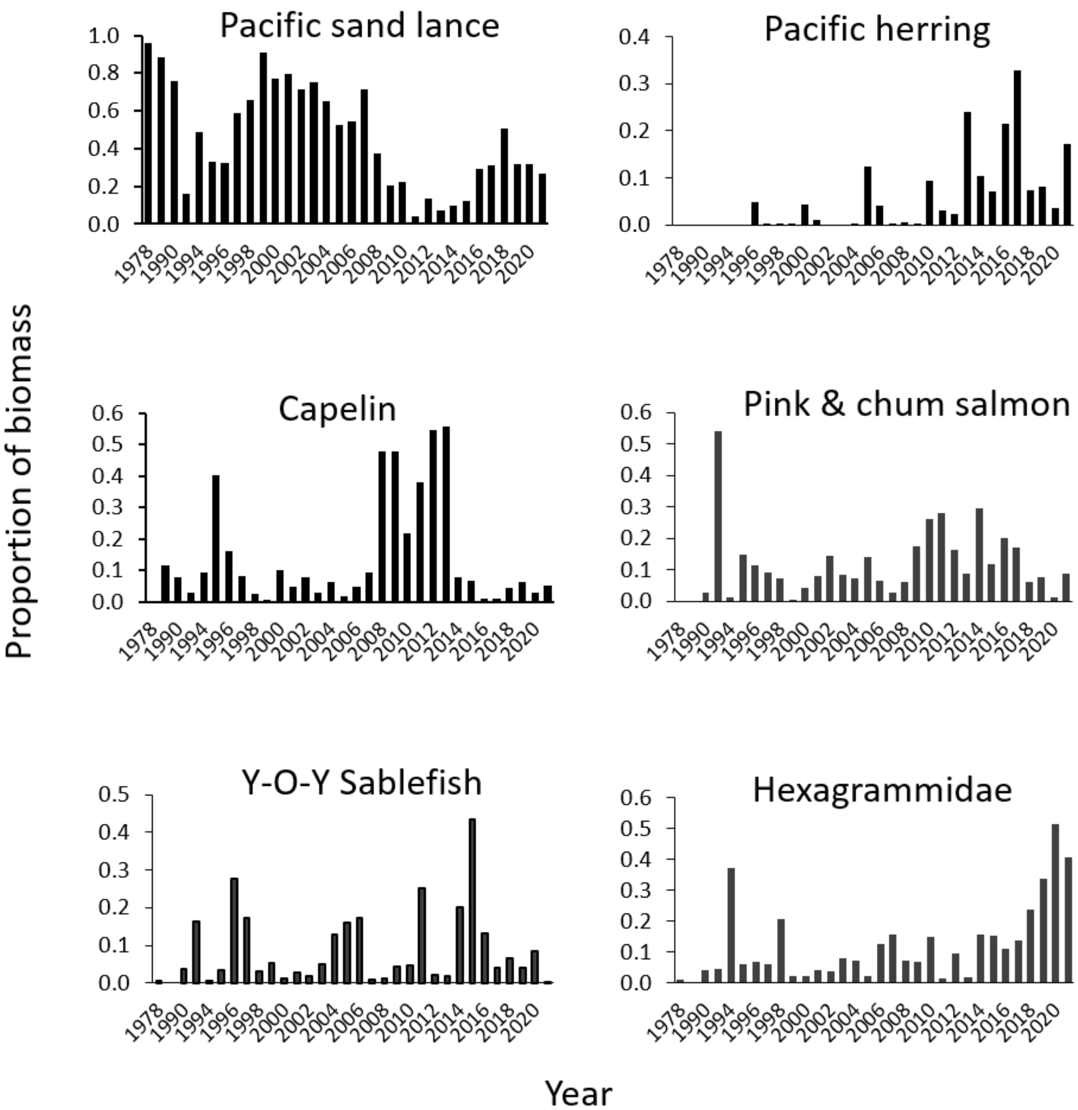


Figure 43: Yearly signal strength of selected prey species in the nestling diet of rhinoceros auklets on Middleton Island from 1978–2021.

Fisheries-independent Survey-based Indices of Capelin Relative Abundance

Contributed by David W. McGowan, Midwater Assessment and Conservation Engineering Program, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: david.mcgowan@noaa.gov
Last updated: October 2021

Description of indicator: Pacific capelin *Mallotus catervarius* are important prey for a number of top predators including Pacific cod, Pacific halibut, and piscivorous seabirds and whales (Aydin et al., 2007; Sydeman et al., 2017; McGowan et al., 2020). Survey-based indices of Pacific capelin relative abundance were derived from annual estimates of mean catch-per-unit-effort (CPUE, kg km^{-2}) from two fisheries-independent surveys conducted by the NOAA Alaska Fisheries Science Center designed for estimating abundances of age-1+ walleye pollock (*Gadus chalcogrammus*) and other groundfish species over the Gulf of Alaska (GOA) continental shelf and upper slope. Indices of mean CPUEs for age-1+ capelin (> 6 cm fork length; Arimitsu et al., 2021) were calculated from the summer GOA walleye pollock acoustic-trawl (AT) survey (2003–2021; Jones et al., 2019) and the summer GOA bottom trawl (BT) survey (2001–2021; von Szalay P.G. and Raring, 2018) following McGowan et al. (2020). Both surveys are conducted biennially in odd years, with no AT surveys conducted in 2007 or 2009. While these surveys were not designed specifically to sample capelin, they collectively track years of relatively high and low capelin abundance (Arimitsu et al., 2021; McGowan et al., 2020; Mueter and Norcross, 2002). The BT survey sampled the GOA shelf from ∼ 170°W near the Islands of Four Mountains to 133°W off Dixon Entrance in all years except 2001 when the survey ended at 147°W. The AT survey has consistently sampled from ∼ 170 to 140°W off Yakutat Trough since 2013; surveys prior to that had reduced spatial coverage (Guttormsen and Yasenak, 2007; Jones et al., 2015) and results should be interpreted with that in mind. In all years, both surveys have sampled the core areas around the Kodiak Archipelago where capelin have concentrated the past two decades (McGowan et al., 2020; Piatt et al., 2018). Mean capelin CPUEs were calculated using all available data from each survey for west and east of 147°W to produce separate indices for the western and eastern GOA.

Status and trends: Survey-based indices of mean density indicate that capelin relative abundance is higher in the western GOA in most years compared to the eastern GOA (Figure 44). Between 2001 and 2021, both surveys observed peaks in capelin densities in 2003 and 2013 in the western GOA. Capelin mean densities in the western GOA declined sharply from their peak in 2013 to the lowest values observed in 2015 for the BT survey and likely the AT survey; capelin densities were too low during AT surveys in 2015 and 2017 to be acoustically discriminated from other fish, which prevented estimation of their abundance. Low densities in the BT survey in 2015 persisted though 2017 at levels well below observations from 2005–2011 that followed the 2003 peak, but increased to levels near the 20-year index mean in 2019 and 2021. In contrast, the AT survey shows capelin mean densities have remained well below the 18-year index mean since 2019, declining to ∼ 90% below the index mean in summer 2021.

In the eastern GOA, both survey indices indicate capelin mean densities declined to low levels following relatively high to above-average levels in 2013, but at a different rate and duration compared to observations from the western GOA. The BT survey index shows capelin densities declined at a slower rate before reaching its 18-year low in 2017, and quickly rebounded to average levels in 2019

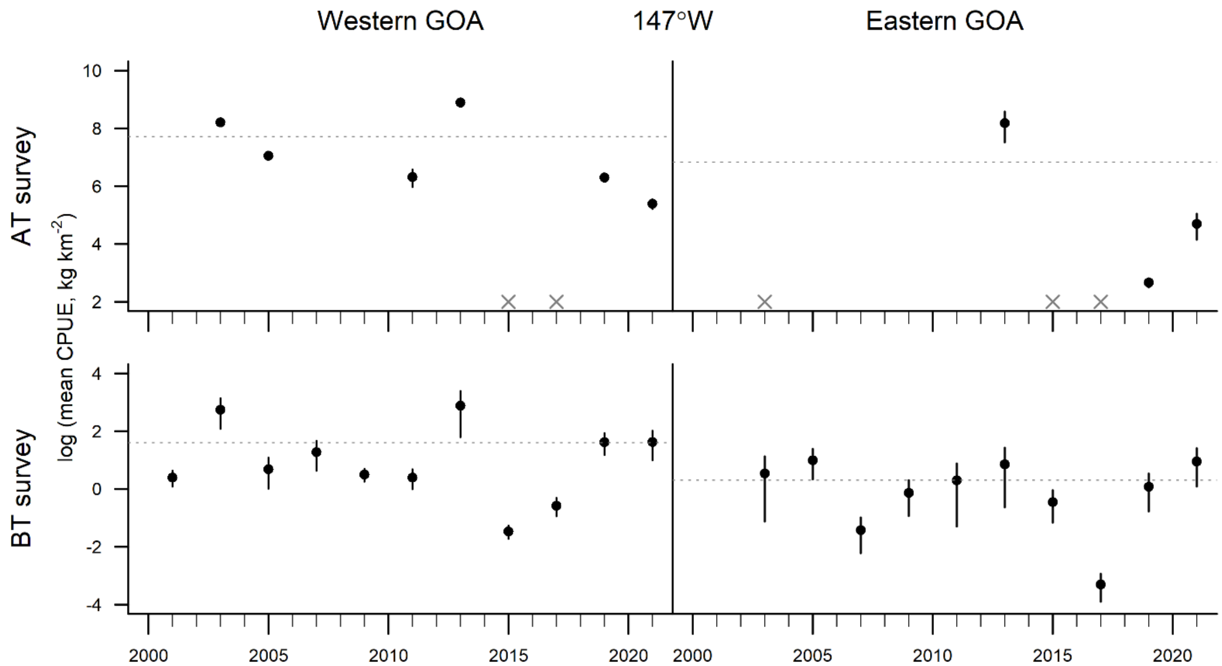


Figure 44: Survey-based indices of log-transformed mean catch per unit effort (mean ± SE CPUE, kg km^{-2}) of capelin in western and eastern Gulf of Alaska from summer acoustic-trawl (AT) and bottom trawl (BT) surveys. Index mean for each survey and region indicated by gray dotted line (eastern GOA index mean calculated for 2003–2021). Years in which capelin densities were too low to assess during AT surveys are indicated by “x”; there are no AT survey data for the eastern GOA in 2005 and 2011. Mean CPUEs are not corrected for potential spatial autocorrelation, and standard errors of the mean should be interpreted with caution.

and relatively high densities in 2021. The BT survey index also shows above-average densities from 2003–2005, followed by an abrupt decline in 2007 and gradual increase through 2013. Although the AT survey index is limited to a small number of observations in the eastern GOA, it shows that capelin densities remained very low in 2019 and increased this past summer, but remain well below levels observed in 2013. While actual numbers may vary between the two survey estimates, general trends point to little change from 2020 in the western GOA and an increase from 2020 in the eastern GOA.

Factors influencing observed trends: Current understanding of which factors contribute to changes capelin abundance in the Northeast Pacific is limited to observational studies. Historically, fluctuations in capelin abundance have coincided with large-scale shifts in ocean temperatures. The first well documented decline of capelin in the GOA was attributed to the onset of warmer ocean temperatures that followed the late 1970s regime shift (Anderson and Piatt, 1999). Over the past three decades, increases in capelin relative abundance and/or expansion of their distributions coincided with cooler temperatures in the GOA (Hatch, 2013; Mueter and Norcross, 2002; Sydeman et al., 2017) and eastern Bering Sea (Andrews et al., 2016). Both survey-based indices indicate that capelin abundance peaked in 2013, coinciding with the end of a period of cold years (2008–2013), the population collapsed during the 2014–2016 marine heatwave (Arimitsu et al., 2021; Bond et al., 2015), and that abundance levels have been recovering since 2019 during which ocean temperatures have fluctuated between warm and cold conditions (NOAA, 2021*a*). While these observations suggest capelin abundance does decrease/increase during extended periods of warm/cold conditions, it is unclear how the population responds to more frequent fluctuations in ocean temperatures. For example, both survey-based indices indicate abundance in the western GOA was relatively high in 2003 (and possibly 2005) during the onset of warm conditions, while abundance was low during cold conditions in 2011 (and possibly 2021). Therefor,e the availability of capelin to predators cannot be simply predicted based on current ocean conditions.

This uncertainty may in part reflect that neither survey was designed to sample capelin, nor have environmentally-driven changes in their availability to survey gears been examined (e.g., temperature-related shifts in vertical distribution). In the future, recently adopted design and analytical changes to the AT survey are expected to improve the accuracy of capelin estimates and allow for reanalysis of the 2015 and 2017 AT surveys during which capelin densities were too low to quantify.

Implications: Despite differences in sampling gear and designs, the AT and BT survey indices for the western GOA are mostly coherent over a two-decade period. While capelin are not formally assessed in the GOA, it's evident that the capelin population effectively collapsed across the GOA during the 2014–2016 marine heatwave and has been slowly recovering. Low densities in the western GOA in 2015 and 2017, particularly around the Kodiak Archipelago, suggest capelin abundance declined to the lowest levels observed during the past 20 years. This likely resulted in the greatest reduction in the availability of capelin to predators in the past 20 years, and is consistent with an abrupt decline in forage species hypothesized to be a major contributing factor to mass mortality of fish and apex predators in the Northeast Pacific from 2014–2017 (Arimitsu et al., 2021; Piatt et al., 2020). Estimates of current capelin abundance levels in the GOA are uncertain due to diverging trends observed by the AT (declining, below long-term mean) and BT surveys (stable, at or above long-term mean) in 2021.

Herring

Southeastern Alaska Herring

Contributed by Kyle Hebert and Sherri Dressel, Alaska Department of Fish and Game, Commercial Fisheries Division, P. O. Box 110024, Juneau, AK 99811-0024
Contact: kyle.hebert@alaska.gov
Last updated: August 2021

Description of indicator: Pacific herring (*Clupea pallasi*) stocks that reside in Southeast Alaskan waters are defined on a spawning-area basis. In recent decades there have been about nine spawning areas where spawning events have typically been annual and meaningful in size in terms of potential for commercial exploitation. These areas include Sitka Sound, Craig, Seymour Canal, Hoonah Sound Hobart Bay-Port Houghton, Tenakee Inlet, Ernest Sound, West Behm Canal, and Kah Shakes-Cat Island (Figure 45). Monitoring of spawning stock size has been conducted by the Alaska Department of Fish and Game at some of these areas for most years, since at least the 1980s, primarily by combining estimates of egg abundance with herring age and size information (Hebert, 2017). Starting in 2016, surveys and stock assessments were eliminated for many stocks in southeastern Alaska due to budget cuts. A large proportion of spawning biomass comes from these nine areas in southeastern Alaska, however, limited spawning also occurs throughout southeastern Alaska. Little or no stock assessment activity occurs at these minor locations other than occasional and opportunistic aerial surveys to document the miles of milt along the shoreline. The herring that spawn in all areas of Southeast Alaska are believed to be affected by the broad-scale physical and chemical characteristics of Gulf of Alaska waters, though the spawning areas directly exposed to the open coast (Sitka Sound, Craig, Kah Shakes-Cat Island) may be affected to the greatest extent or the most immediately.

Status and trends: Industrial-scale herring oil reduction fisheries and foreign fisheries operated in Southeast Alaska beginning in the early 1900s, with catch peaking in 1935. The most reliable estimates of biomass exist from data collected since 1980, which are discussed here. In aggregate (all nine consistently monitored spawning areas combined), the biomass of Southeast Alaska herring has generally increased since 1980 (Figure 46).

Following a period of generally low biomass during the 1980s through the mid-1990s, most Southeast Alaska stocks increased to relatively high levels between 2008–2011. Southeast stocks then declined substantially until 2016–2018. Although the two largest and most consistently abundant stocks, Sitka Sound and Craig, declined substantially from their peaks of 2009 and 2011, respectively, they continued to be at moderate levels and well above the thresholds established to allow commercial fisheries. They then increased dramatically in 2019 following the highest recruitment of age-3 herring documented for these areas. Based on limited aerial surveys, other Southeast Alaska stocks appear to have declined to low levels over the past several years and in some cases to small fractions of their historical abundance (e.g., Hoonah Sound, Seymour Canal, Ernest Sound). Current biomass levels for these areas are unknown because stock assessment surveys were suspended starting in 2016, due to budget reductions.

Currently, mature biomass for Sitka Sound and Craig herring is at a high level due to an extremely large recruitment event of age-3 herring observed in 2019. The 2019 recruitment event was by far

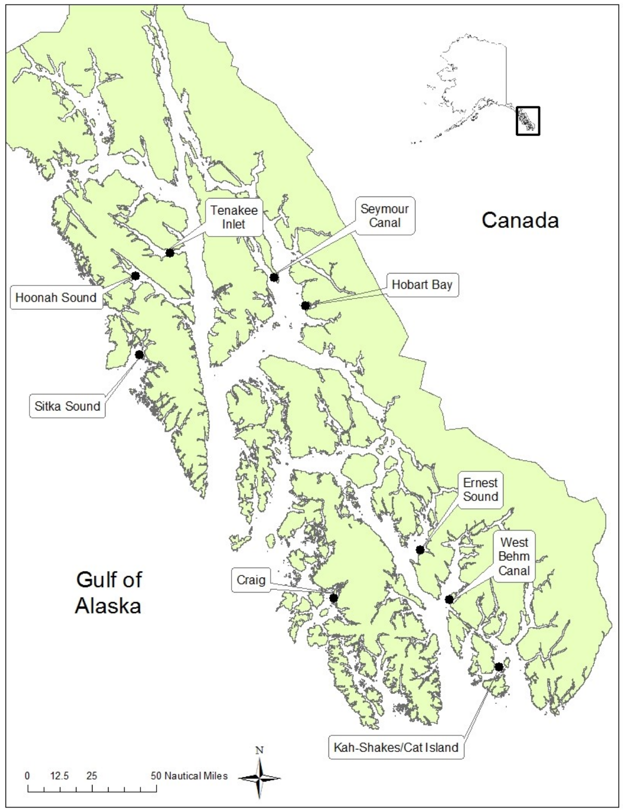


Figure 45: Location of nine Pacific herring spawning locations, historically surveyed in Southeast Alaska. Sitka Sound, Craig, and Kah-Shakes/Cat Island are considered "outside stocks" with greater ocean exposure, while all others are considered "inside stocks", less exposed to open ocean influence.

the largest recruit class in the Sitka Sound and Craig model time series (since 1976 for Sitka Sound and since 1988 for Craig). Results from 2020 indicate that mature biomass and the proportion of age-4 herring for Sitka and Craig stocks were very high, corroborating survey and model results from 2019 that the recruitment event in 2019 was indeed exceptional. A large percent of age-4 was also observed in 2020 for other southeast Alaska stocks (Kah Shakes-Cat Island and Seymour Canal) and in other Gulf of Alaska stocks (Prince William Sound and Kodiak Island). Of the twelve surveys conducted for Gulf of Alaska herring stocks in 2018 and 2019, nine showed large increases in relative abundance indices in 2019 corresponding to the large recruitment. Although biomass has not recently been estimated for most Southeast Alaska stocks other than Sitka Sound and Craig, limited aerial surveys of spawn events suggest that although there were increases due to the 2019 recruitment, they are still at relatively low levels compared to spawn mileage in 1990–2010.

Factors influencing observed trends: Herring population abundance is known to fluctuate dramatically, and is susceptible to environmental influences (Toresen, 2001). The underlying causes for the increase in the 1990's, the decrease during about 2010-2018, and the exceptional recruitment in 2019 remain unknown. Multiple plausible factors may be contributing, including increasing populations of predatory marine mammals, such as humpback whales and Stellar sea lions (Muto et al., 2016; Fritz et al., 2016), varying levels of predatory fish, or recent shifts in sea water temperatures, which could affect herring food sources, life history, spawn timing, and metabolism. While commercial fishing has occurred during some years for some stocks, the similar decline of inside

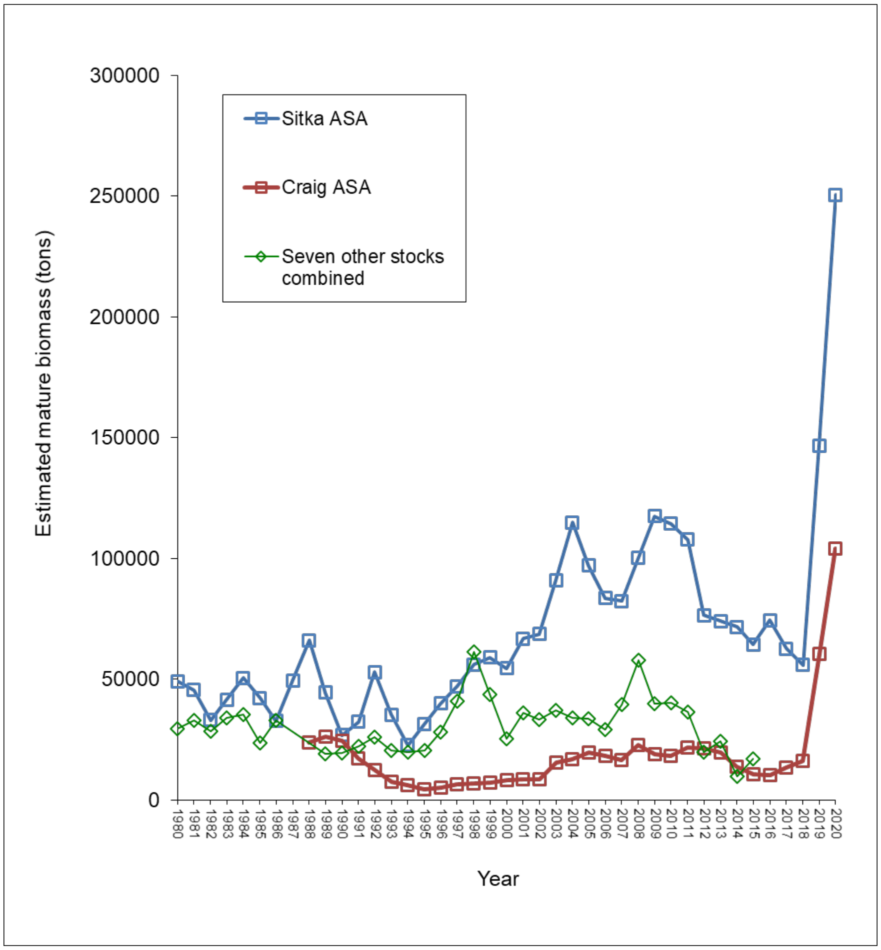


Figure 46: Estimated mature herring biomass (i.e., pre-fishery biomass) for nine important southeastern Alaska (SEAK) spawning areas, 1980–2020. Biomass estimates for Sitka Sound and Craig are based on age-structured assessment (ASA) models and those for all other stocks, where ASA model estimates are not available, were calculated by converting total egg deposition estimates to biomass using an estimate of eggs per ton of spawners. Results from 1987 and1988 were excluded for all other stocks because all stocks were not surveyed in those years. For years 2016–2020, biomass estimates were excluded for all other stocks because starting in 2016 stock assessment surveys were suspended for most areas due to budget reductions.

stocks, which for some occurred in the absence of fishing, suggests that the declines may have been primarily environmentally driven.

The very high recruitment event of 2019 is unprecedented, since standardized stock assessments have been conducted in Southeast Alaska. In Prince William Sound and Kodiak extremely high percentages of age-3 herring were also observed, indicating that the influencing factors occurred over a large spatial scale. One possibility is that the unusually warm water mass that circulated through the northern Pacific Ocean during 2014–2016 (Gentemann et al., 2017), known commonly as "the Blob", contributed to increased survival of larval and/or juvenile stages of the 2016 brood year. Ocean temperature has been positively correlated with recruitment in Atlantic herring *Clupea harengus* (Toresen, 2001), and Pacific herring (Zebdi and Collie, 1995).

Implications: There appears to be a gradient between patterns of herring biomass observed for Southeast Alaska spawning stocks exposed directely to Gulf of Alaska waters (outside stocks) and those found in inside waters. While all spawning stocks exhibited a decline from about 2010 to 2018, spawning stocks along the outer coast declined to moderate levels, while those of inside waters declined to low levels. The 2019 recruitment event has made the gradient appear much more pronounced. While all Southeast Alaska spawning stocks sampled exhibited high percentages of age-3 herring in 2019 and high percents of age-4 in 2020, the outside stocks increased from moderate to high biomass, whereas smaller inside stocks remained low. The high herring biomass along the outer coast is expected to be available to support marine predators and fisheries for the next two to three years as the strong 2016 year class ages. Lower abundance of herring in inside waters may not support predators that rely on herring to the same extent as in the 2010s, although there is not adequate information about populations of other forage species to understand the broader net impact on predators. The relatively short life-span of herring and the natural volatility of recruitment and stock levels make it difficult to speculate on the long-term implications for the ecosystem.

Salmon

Trends in Alaska Commercial Salmon Catch—Gulf of Alaska

Contributed by George A. Whitehouse, Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle, WA
Contact: andy.whitehouse@noaa.gov
Last updated: September 2021

Description of indicator: This contribution provides historic and current commercial catch information for salmon in the Gulf of Alaska. This contribution summarizes available information that is included in current Alaska Department of Fish and Game (ADF&G) agency reports (e.g., (Brenner et al., 2020) and on their website (`https://www.adfg.alaska.gov/`) .

Pacific salmon in Alaska are managed in four regions based on freshwater drainage basins (`http://www.adfg.alaska.gov/index.cfm?adfg=commercialbyfisherysalmon.salmonareas`), 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 salmon (*Oncorhynchus nerka*), pink salmon (*O. gorbuscha*), chum salmon (*O. keta*), Chinook salmon (*O. tshawytscha*), and coho salmon (*O. kisutch*).

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 47a).The commercial harvests of salmon 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 indicate a statewide total commercial salmon harvest of about 222.2 million fish (as of 20 September), which is well above the preseason projection of 190.1 million fish. The 2021 harvest was bolstered by the catch of 151.6 million pink salmon, primarily from Prince William Sound, and 55.8 million sockeye salmon, primarily from Bristol Bay.

Gulf of Alaska—The total commercial salmon harvests in the Gulf of Alaska are dominated by pink salmon which follow a cycle of strong odd years and weak even years (Figure 47b). In the Southeast region, the 2020 commercial salmon harvests totaled 14.6 million, which was less than half the total harvest in this region in 2019. The 2020 harvests of all five commercial salmon species in the GOA were below their respective long-term and recent 10-year averages. Preliminary data for 2021 indicate a rebound in the commercial harvest in the southeast region for all but Chinook salmon, with a total commercial harvest of more than 54 million. The 2021 southeast region preliminary total is buoyed by the harvest of 45 million pink salmon.

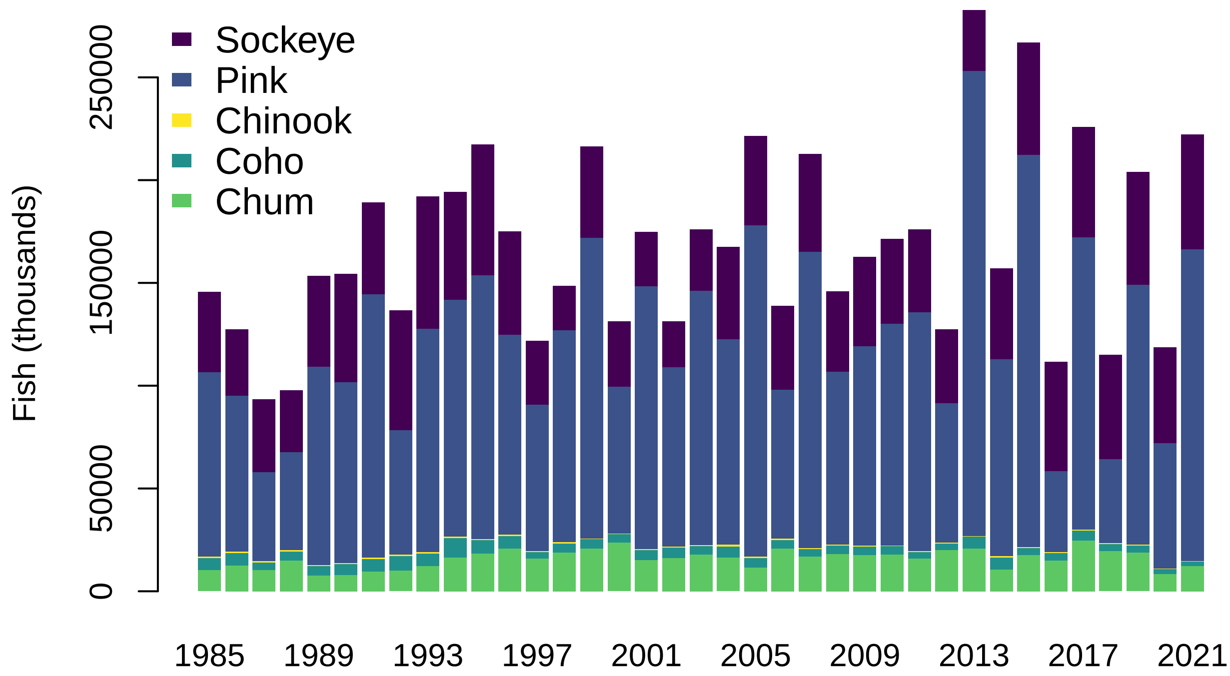
In the Kodiak management area, the 2020 total salmon harvest of 23.9 million fish was above the recent 10-year average harvest of 21.8 million fish. The 2020 sockeye salmon commercial harvest of 1.5 million fish was below the recent 10-year average of 2.3 million fish. The 2020 pink salmon harvest of 21.6 million was above the recent 10-year average harvest of 18.3 million fish. Preliminary data from ADF&G on the 2021 commercial harvest indicates the total 2021 harvest will increase to more than 29 million fish.

In the Prince William Sound Area of the Central region, the 2020 total commercial salmon harvest was 26.3 million fish, of which 23 million were pink salmon. The 2020 pink salmon harvest was 36% below the recent 5-year even-year average. Preliminary harvest numbers for 2021, indicate that pink salmon are continuing to follow the pattern of weak even years and strong odd years with a total commercial harvest of nearly 64 million.

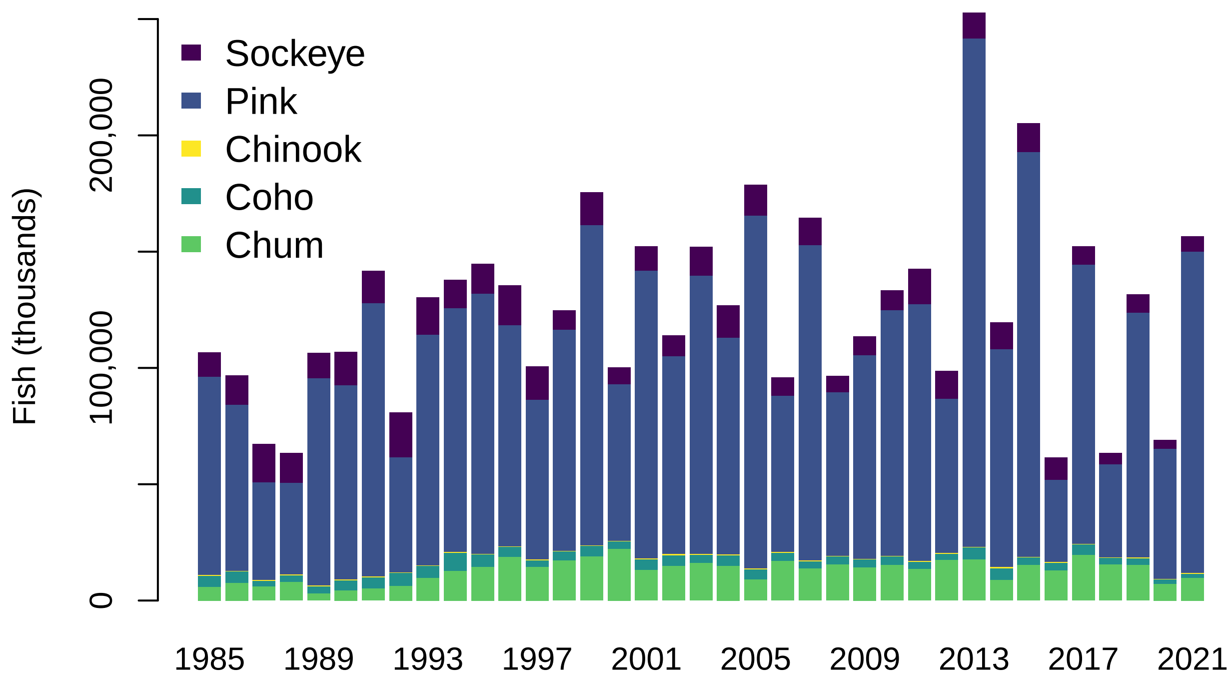
Factors influencing observed trends: Historically, pink salmon catches increased in the late 1970s to the mid-1990s and have generally remained high in all regions in the last decade (Figure 47a). While both natural and hatchery populations return to Prince William Sound, a large majority of the returning fish are hatchery fish; upwards of up to one half billion are released from four hatcheries (Kline et al., 2008). Pink salmon have an abbreviated life cycle, consisting of three phases: 1) brood year, 2) early marine year, and 3) return year (Kline et al., 2008). Interannual variation in Alaska statewide total salmon abundance is partly due to the even-year, odd-year cycle in pink salmon, which typically have larger runs in odd years.

Pink salmon run strength is established during early marine residence and may be influenced by diet and food availability (Cooney and Willette, 1997). Survival rates of Alaska pink salmon are positively related to sea surface temperatures and may reflect increased availability of zooplankton prey during periods with warmer surface temperatures (Mueter and Norcross, 2002). Interannual variation in Alaska statewide total salmon abundance is partly due to the even-year, odd-year cycle in pink salmon, which typically have larger runs in odd years. Chinook salmon 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).

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, affecting the body condition, growth, and survival of competitors (Ruggerone et al., 2003; Toge et al., 2011; Kaga et al., 2013). A negative relationship between seabird reproductive success and years of high pink salmon abundance has recently been demonstrated (Zador et al., 2013; Springer and van Vliet, 2014). Directed salmon fisheries are economically important for the state of Alaska. The overall abundance of salmon in Alaska has been high in recent decades and despite annual fluctuations, the trend in total statewide salmon catch in recent decades has been for generally strong harvests.



(a) Alaska



(b) Gulf of Alaska

Figure 47: Time series of commercial salmon harvest in Alaska (a) and GOA (b) from 1985-Sept 2021. Values from 2021 are preliminary. (Source: ADF&G, `http://www.adfg.alaska.gov`. ADF&G not responsible for the reproduction of data, subsequent analysis, or interpretation.)

Juvenile Salmon Abundance in Icy Strait, Southeast Alaska

Contributed by James Murphy[1], Wesley Strasburger[1], Andrew Piston[2], Steve Heinl[2], Jamal Moss[1], Emily Fergusson[1], and Andrew Gray[1]
[1]Auke Bay Laboratories Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
[2]Alaska Department of Fish and Game
Contact: jim.murphy@noaa.gov
Last updated: September 2021

Description of indicator: Juvenile salmon catch-per-unit-effort (CPUE), zooplankton abundance, and oceanographic conditions are collected during the Southeast Alaska Coastal Monitoring (SECM) surveys (Fergusson et al., 2021; Murphy et al., 2021). SECM data are used in a variety of research applications, however the information on juvenile salmon *(Oncorhynchus spp.)* CPUE is a key data product due to its use in harvest and run forecast models (Murphy et al., 2019). SECM surveys and salmon forecast models (Brenner et al., 2020) are part of a cooperative research effort by the Alaska Fisheries Science Center (AFSC) and the Alaska Department of Fish and Game (ADF&G) in support of salmon stocks and fisheries in SEAK.

Juvenile salmon CPUE indices are constructed from surface (0–20m) rope trawl catches in Icy Strait, the northern migratory corridor between the inside waters of SEAK and the Gulf of Alaska. CPUE indices are the peak monthly average log-transformed catch-per-unit-effort (CPUE, log-transformed catch per 20-min trawl set) in Icy Strait during the months of June and July. These indices are adjusted for fishing power differences between the survey vessels that have conducted SECM surveys over time (Wertheimer et al., 2010). CPUE data for juvenile pink (*O. gorbuscha*), chum (*O keta*), sockeye (*O. nerka*), and coho (*O. kisutch*) salmon are included in (Figure 48).

Status and trends: Peak CPUE has been consistently below average for all species of juvenile salmon in recent years: Chinook salmon since 2016; chum, pink, and sockeye salmon since 2017; and coho salmon since 2018 (Figure 48). Catch rates of juvenile pink salmon declined in 2021 to the second lowest level observed (0.88) since these surveys were initiated in 1997. Catch rates of other salmon species also declined slightly in 2021, with the exception of coho salmon, which increased slightly from 2020.

Factors influencing observed trends: Multiple factors contribute to the variation in juvenile salmon catch rates (CPUE) over time and the relative importance of these factors differ by species. Early life-history ecology and mortality are the primary factor influencing juvenile CPUE; however, spawner abundance and the migratory patterns of juveniles can also influence the year-to-year variation in juvenile CPUE. Spawner abundance goals have not been met in recent even-year runs of pink salmon within the northern inside region of SEAK (Piston and Heinl, 2020), and this is likely an important factor contributing to lower odd-year catch rates of juvenile pink salmon, including in 2021. Catch rates of juvenile pink salmon are corrected for temperature in harvest forecast models, and this correction is believed to reflect the influence of temperature on juvenile migration and juvenile pink salmon catch rates (Murphy et al., 2019). Juvenile pink salmon catches therefore reflect a combination of early life history ecology and mortality, escapement, and migration. Hatcheries accounted for approximately 87% of the chum salmon harvested in SEAK from 2010 to 2020; therefore, spawner abundance has minimal influence on juvenile chum salmon catch rates. Chinook, sockeye, and coho salmon spend at least one full year in freshwater before migrating to

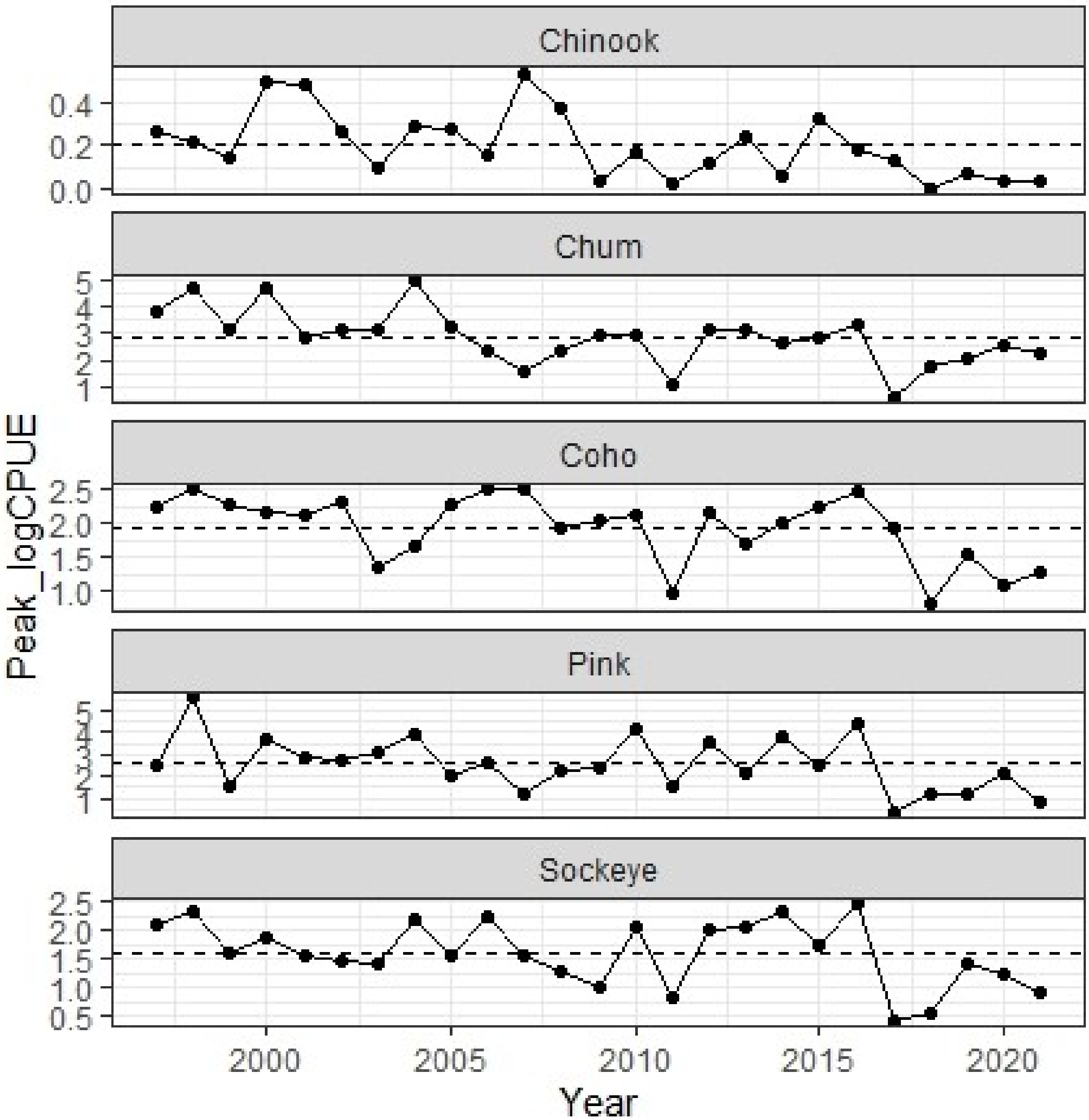


Figure 48: Catch-per-unit-effort (CPUE, log-transformed catch per 20-min trawl set) of juvenile salmon during Southeast Alaska Coastal Monitoring (SECM) surveys in Icy Strait, 1997–2021. The CPUE index is the peak monthly average catch rate during the months of June and July. The average index for each species is identified by the dashed line. The ADF&G is not responsible for the reproduction of data, subsequent analysis, or interpretation.

sea; therefore, both freshwater and early marine survival contribute to the juvenile catch rates of these species of salmon.

Implications: Juvenile pink salmon catch rates increased to average levels during 2020 (Figure

48); however, the harvest of SEAK pink salmon in 2021 (78,000 mt) was well above the recent 20-year average (58,000 mt; Figure 49). This may reflect improved offshore survival or reduced survey catchability (during juvenile migration) in 2020. The decline in juvenile pink salmon catch rates in 2021 indicates that pink salmon harvests will likely be below average in 2022. Although the relationship between juvenile and adult Chinook salmon abundance is weak (Orsi et al., 2016), the survival and harvest of northern SEAK Chinook salmon are unlikely to increase given the exceptionally low juvenile abundance observed in Icy Strait over the last four years. Catch rates of juvenile chum salmon improved after 2017, and this could contribute to improved harvests once those fish reach maturity after spending three to four years in offshore marine habitats.

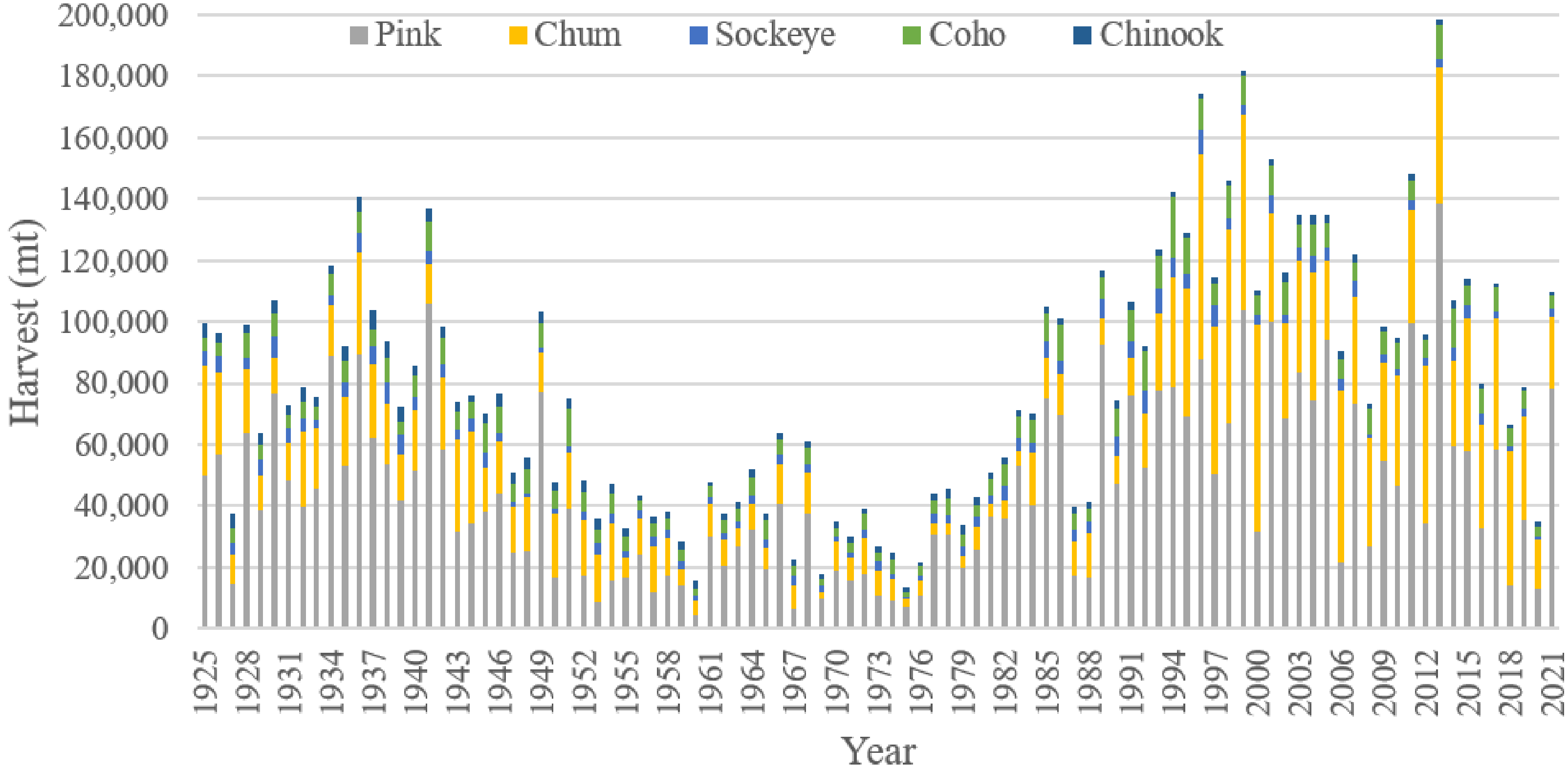


Figure 49: Commercial harvest (mt) of salmon in Southeast Alaska, 1925–2021. The 1925–2021 harvest data are provided by ADF%G and available at `https://npafc.org/statistics/`. The 2021 harvest data are preliminary data up to September 22, 2021, provided by ADF&G and available at `https://www.adfg.alaska.gov/index.cfm?adfg=commercialbyfisherysalmon.bluesheet`

.

Juvenile Salmon Size and Condition Trends in Icy Strait, Southeast Alaska

Contributed by Emily Fergusson, Jim Murphy, Wess Strasburger, Jamal Moss, and Andrew Gray,
Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: emily.fergusson@noaa.gov
Last updated: September 2021

Description of indicator: The Southeast Coastal Monitoring (SECM) project of Auke Bay Laboratories, AFSC, has been investigating how climate change may affect Southeast Alaska (SEAK) nearshore ecosystems in relation to juvenile salmon (*Oncorhynchus* spp.) and associated biophysical factors since 1997 (Fergusson et al., 2020*a*; Murphy et al., 2020). Juvenile pink (*O. gorbuscha*), chum (*O. keta*), sockeye (*O. nerka*), and coho (*O. kisutch*) salmon size and nutritional condition data have been collected annually in Icy Strait during monthly (June and July) fisheries oceanographic surveys. This Report presents July 2021 size data (fork length) and energy density data through 2020 for juvenile salmon in relation to the past trends in Icy Strait.

Status and trends: In 2021, juvenile salmon lengths did not show a clear trend in size when compared with 2020 values. For juvenile pink, sockeye, and coho salmon, length values decreased relative to 2020 and were at or below the 25-year average (Figure 50). Juvenile chum salmon length increased slightly from 2020 and remained above average.

In 2020, energy densities (kJ / g dry weight) of the four juvenile salmon species were at or above average. For juvenile pink and sockeye salmon, energy densities decreased from the 2019 values (Figure 51) while for juvenile chum and coho salmon energy densities increased.

Factors influencing observed trends: During early marine entry and residency, juvenile salmon must grow quickly to avoid predation while also acquiring enough lipid reserves to survive winter when food is severely limited (Beamish and Mahnken, 2001; Moss et al., 2005). The record low numbers of out-migrating juvenile pink and coho salmon in 2017 through 2019 may have resulted from low escapements in the previous years and/or low freshwater survival (Murphy et al., 2020).

Implications: The near-average and below-average size values observed for juvenile salmon in 2021 reflect the colder water temperatures experienced in their early marine residency in Icy Strait. Larger fish generally have increased foraging success and a decreased predation risk resulting in higher survival. Based on the 2021 length frequency results relative to the long-term averages by species, generally, juvenile salmon are entering the GOA in 2021 with an average size. Further growth and survival will be dependent on favorable over-winter conditions in the GOA. Juvenile salmon entered the Gulf of Alaska in 2020 with at or above average energy stores which may contribute to higher survival and escapement.

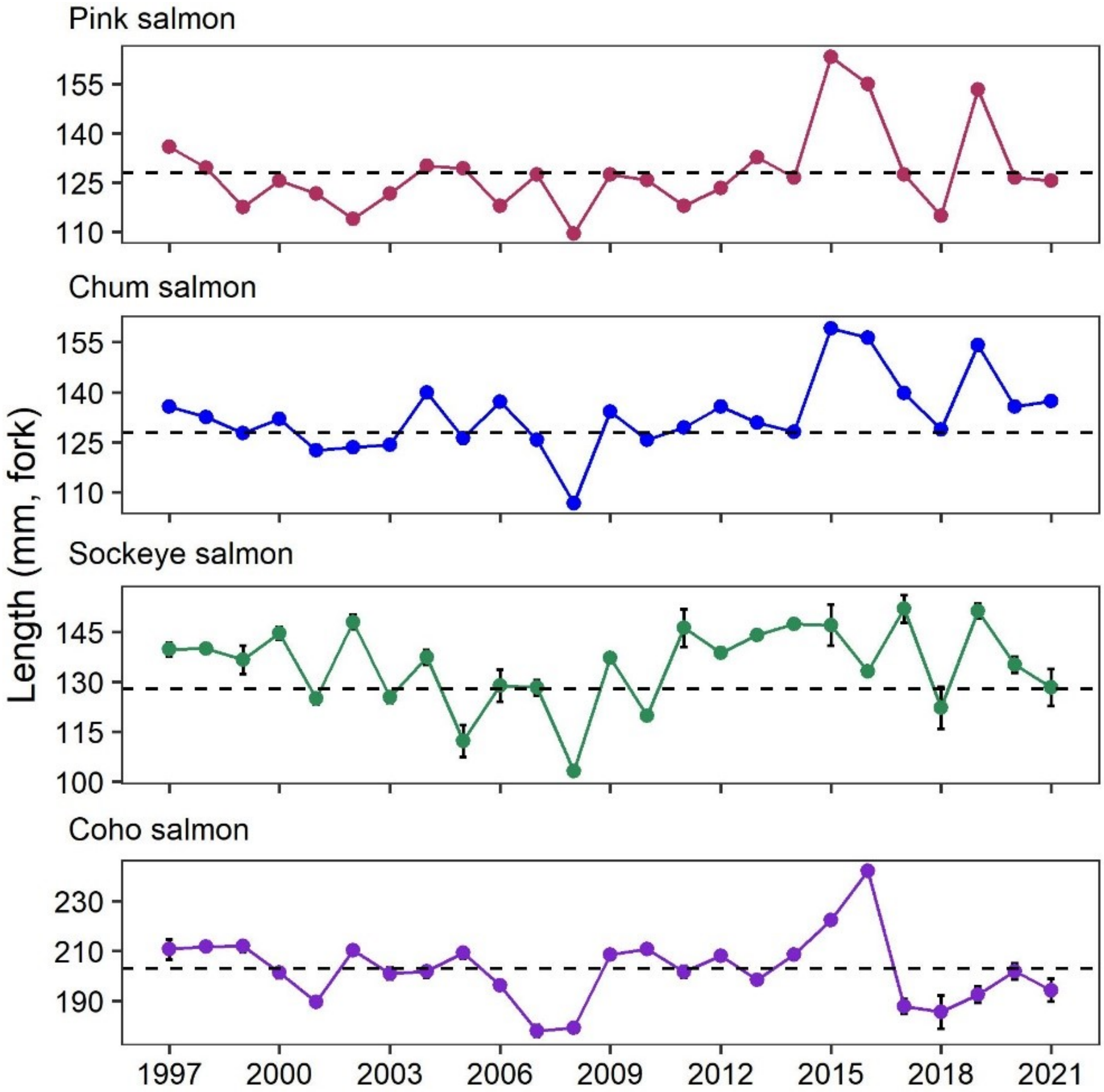


Figure 50: Average fork length (mm; ±1 standard error) of juvenile salmon captured in Icy Strait, AK by the Southeast Coastal Monitoring project, 1997–2021. Time series average is indicated by the dashed line.

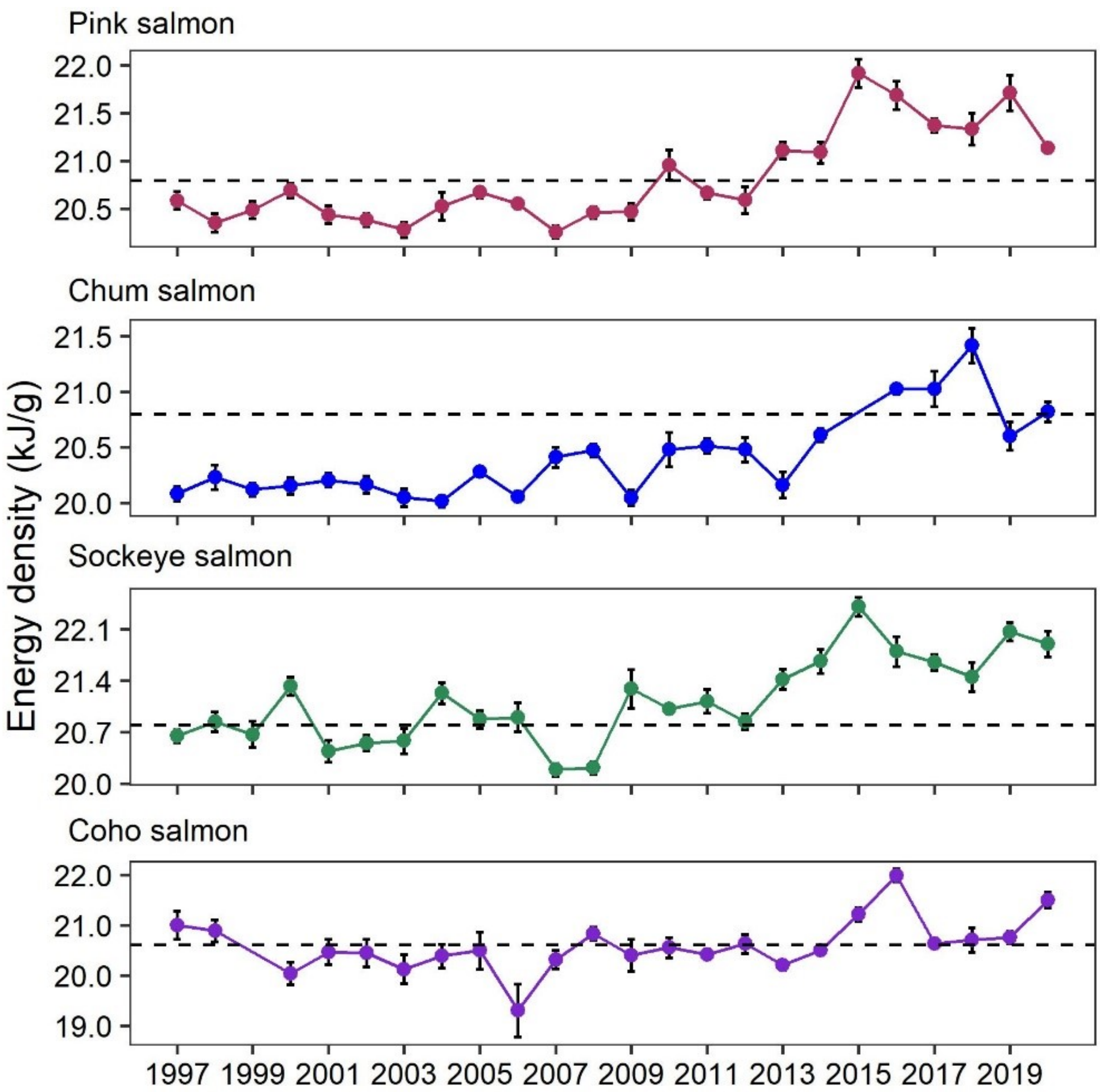


Figure 51: Average energy density (kJ/g, dry weight; ±1 standard error) of juvenile salmon captured in Icy Strait, AK by the Southeast Coastal Monitoring project, 1997–2020. Time series average is indicated by the dashed line.

Marine Survival Index for Pink Salmon from Auke Creek, Southeast Alaska

Contributed by Scott C. Vulstek, Joshua R. Russell, Auke Bay Laboratories Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: scott.vulstek@noaa.gov
Last updated: September 2021

Description of indicator: The time series of marine survival estimates for wild pink salmon from the Auke Creek Research Station in Southeast Alaska is the longest-running continuous series available in the North Pacific. The Auke Creek weir structure facilitates near-complete capture of all migrating pink fry and returning adults. It is the only weir capable of such on a wild system in the North Pacific. Marine survival is estimated as the number of adults (escapement) per fry. While no stock-specific harvest information is available for Auke Creek pink salmon, and there are possible influences of straying and intertidal production downstream of the weir structure, the precision of this long-term dataset is still unmatched and the series is an excellent choice for model input relating to nearshore and Gulf-wide productivity. The index is presented by fry ocean entry year.

Status and trends: The historical trend shows marine survival of wild pink salmon from Auke Creek varies from 1.1% to 53.3%, with an average survival of 11.6% from ocean entry years 1980–2020 (Figure 52). Marine survival for the 2020 ocean entry year was 28.9% and overall survival averaged 13.8% over the last 5 years and 16.2% over the last 10 years. 2021 saw the 10^{th} highest return of pink salmon to Auke Creek with 13337 returning adults (Figure 53).

Factors influencing observed trends: Factors that have influenced these observed trends include: migration timing, fishery effort and timing, predation, growth rates, maintained genetic variation, and stream conditions. Within the Auke Creek system, a system undergoing rapid climatic change, climate-induced phenological shifts have been shown to influence the trend of earlier migration of both the early and late run of pink adults, as well as juvenile fry migration (Kovach et al., 2013*b*; Shanley et al., 2015). The effect of fishing pressure on pink salmon has some obvious effects on marine survival, as well as unapparent impacts including decreases in body weight, variations in length, increases in earlier-maturing fish, and increases in heterozygosity at PGM (Hard et al., 2008).

During juvenile development, the local conditions of stream discharge and temperature are strong determinants of egg and fry survival. As pink salmon are one of the most numerous and available food sources of larger migrating juvenile salmon and other marine species, their early marine survival can be heavily impacted by predation (Parker, 1971; Landingham et al., 1998; Mortensen et al., 2000; Orsi et al., 2013). One resistance to this predation is that pink salmon fry are able to quickly outgrow their main predators of juvenile coho and sockeye salmon and become unavailable as a food resource due to their size (Parker 1971). In addition, many of these influencing factors have been shown to have a genetic component that can strongly influence survival (Geiger et al., 1997; McGregor et al., 1998; Kovach et al., 2013*a*).

Implications: The marine survival of Auke Creek pink salmon is related to large-scale ocean productivity indices and to important rearing habitats of many southeast Alaska groundfish species. The marine survival of indices of Auke Creek pink salmon provide quanitative data that allow for the examination of annual variation in habitat quality of rearing areas and general ocean conditions

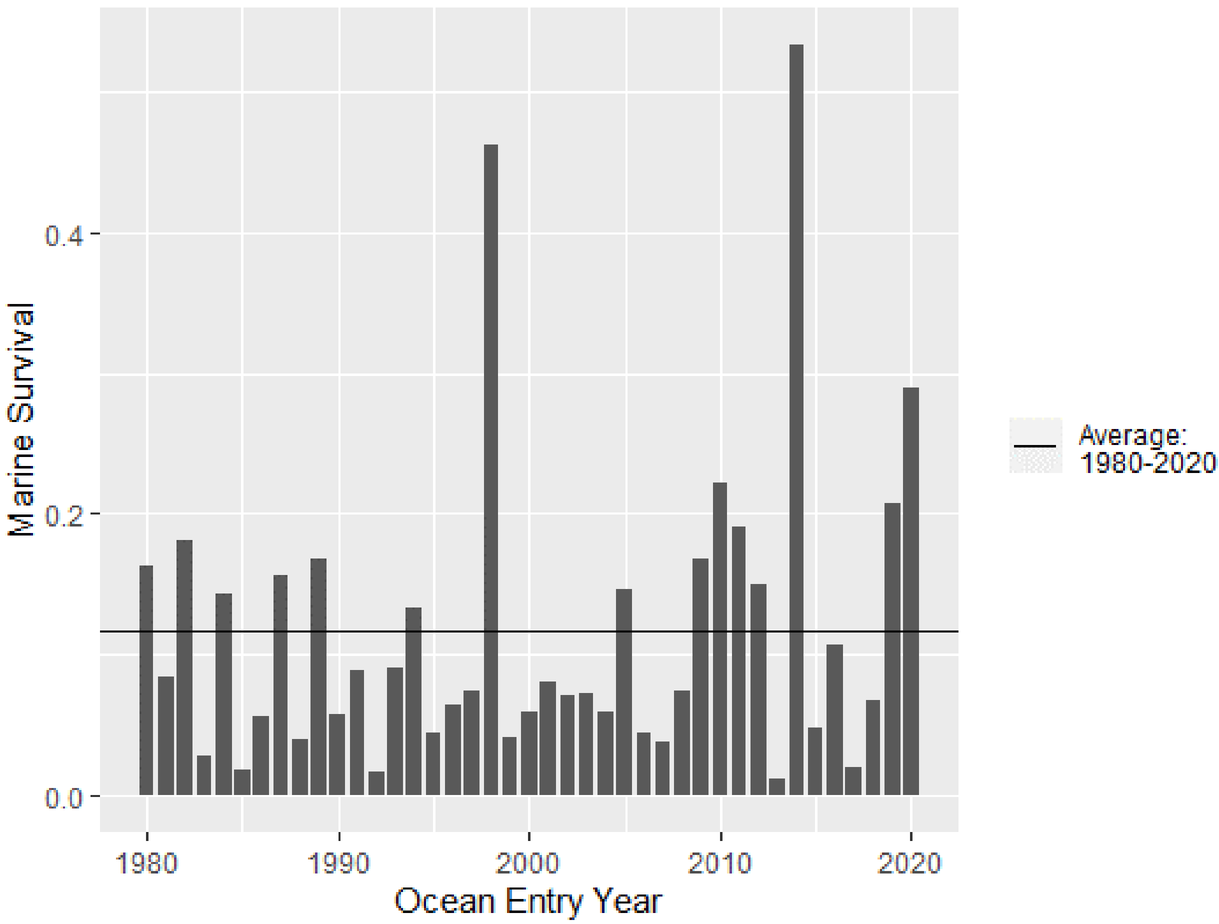


Figure 52: Auke Creek pink salmon marine survival index by ocean entry year.

and productivity. Due to the one-ocean-year life history of pink salmon, we can use their marine survival as a proxy for the general state of the Gulf of Alaska. Additionally, as pink fry are such an abundant food resource in southeast Alaska, their abundance and rate of predation allow for insights into the groundfish fisheries. Pink fry have been shown to be an important food resource for juvenile sablefish, making up a large percentage of their diet (Sturdevant et al. 2009, 2012). The growth and marine survival of Auke Creek pink salmon provide valuable proxies for Gulf of Alaska and southeast Alaska productivity, as well as the overwintering survival and recruitment of sablefish.

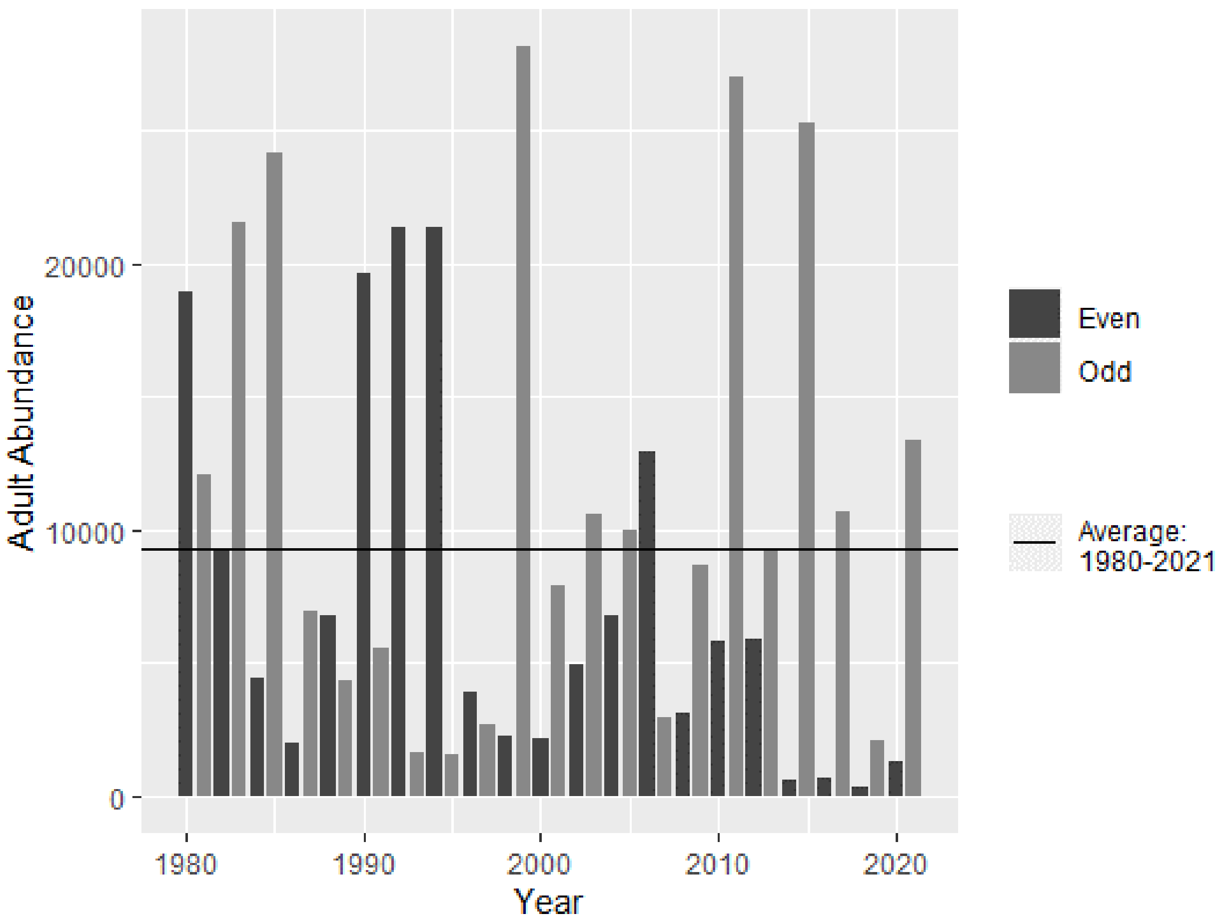


Figure 53: Auke Creek pink salmon adult returns by year.

Marine Survival Index for Coho Salmon from Auke Creek, Southeast Alaska

Contributed by Scott C. Vulstek, Joshua R. Russell, Ellen M. Yasumiishi, Auke Bay Laboratories Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: scott.vulstek@noaa.gov
Last updated: September 2021

Description of indicator: The time series of marine survival estimates for wild coho salmon from the Auke Creek Weir in Southeast Alaska is the most precise and longest-running continuous series available in the North Pacific. Auke Bay Laboratory began monitoring wild coho salmon survival in 1980. All coho salmon smolts leaving the Auke Lake watershed have been counted, subsampled for age and length, and injected with coded wire tags (CWT). Research studies over the last 42 years have captured and sampled virtually all migrating wild juvenile and adult coho salmon. These migrating fish included those with both 1 and 2 freshwater annuli and 0 or 1 ocean annuli. Marine survival is estimated as the number of adults (harvest plus escapement) per smolt. The index is presented by smolt (outmigration) year. The precision of the survival estimate is high due to 100% marking and high sampling fractions that minimize the variance in the survival estimate, which make the series an excellent choice for model input relating to nearshore and Gulf-wide productivity. It is the only continuous marine survival and scale data set in the North Pacific that recovers all returning wild, CWT coho salmon as ocean age-0 and age-1 classes.

Status and trends: The historical trend shows marine survival of wild coho salmon from Auke Creek varies from 5.1% to 47.8%, with an average survival of 21.7% from smolt years 1980–2020 (Figure 54; top panel). Marine survival for 2020 was the fourth lowest on record at 8.2%. Overall survival averaged 9.6% over the last 5 years and 12.9% over the last 10 years. The survival index for ocean age-1 coho varied from 3.9% to 36.6% from smolt years 1980–2020 (Figure 1; middle panel) and for ocean age-0 coho varied from 0.2% to 11.2% from smolt years 1980–2020 (Figure 54; bottom panel). Return data for 2021 returns are included, despite the fact that the run is not completely finished. These data are included because the marine survival for ocean age-1 coho at Auke Creek will likely again be among the lowest on record at ∼5% (marine survival was at 5.1% as of 20 September 2021, with recent fishery and escapement counts still ongoing).

Factors influencing observed trends: Factors influencing observed trends include: smolt age, smolt size, migration timing, fishery effort and location, and marine environmental conditions (Kovach et al., 2013*b*; Malick et al., 2009; Robins, 2006; Briscoe et al., 2005). Coho salmon marine survival is influenced by a number of life history parameters such as juvenile growth rate and size, smolt age and smolt ocean entry timing (Weitkamp et al., 2011). Recent studies have shown that climate change has shifted the median date of migration later for juveniles and earlier for adults (Kovach et al., 2013*b*). The marine survival of Auke Creek coho reflects nearshore rearing productivity and, as such, is utilized to infer regional trends in coho salmon productivity as one of four indicator stocks utilized by the Alaska Department of Fish and Game to manage coho salmon throughout southeast Alaska (Shaul et al., 2011). The marine survival of Auke Creek coho salmon and growth inferred by scales samples is influenced by and reflective of broad scale oceanographic indices in the Gulf of Alaska (Malick et al., 2009; Robins, 2006; Briscoe et al., 2005; Orsi et al., 2013).

Implications: The marine survival index of coho salmon at Auke Creek is related to ocean productivity indices and to important rearing habitats shared by groundfish species. The trends in coho salmon marine survival indices from Auke Creek provide a unique opportunity to examine annual variation in habitat rearing areas and conditions because ocean age-0 coho adults occupy only nearshore and strait habitats prior to returning to the creek. Ocean age-0 coho leave freshwater in May through June and return in August through October, the same time sablefish are moving from offshore to nearshore habitats. In contrast, ocean age-1 coho salmon occupy those nearshore habitats for only a short time before entering the Gulf of Alaska and making a long migratory loop. They return to the nearshore habitats on their way to spawning grounds after the first winter that age-0 sablefish spend in nearshore habitats. The relative growth and survival of ocean age-0 and age-1 coho salmon from Auke Creek may provide important proxies for productivity, overwintering survival of sablefish, and recruitment of sablefish to age-1.

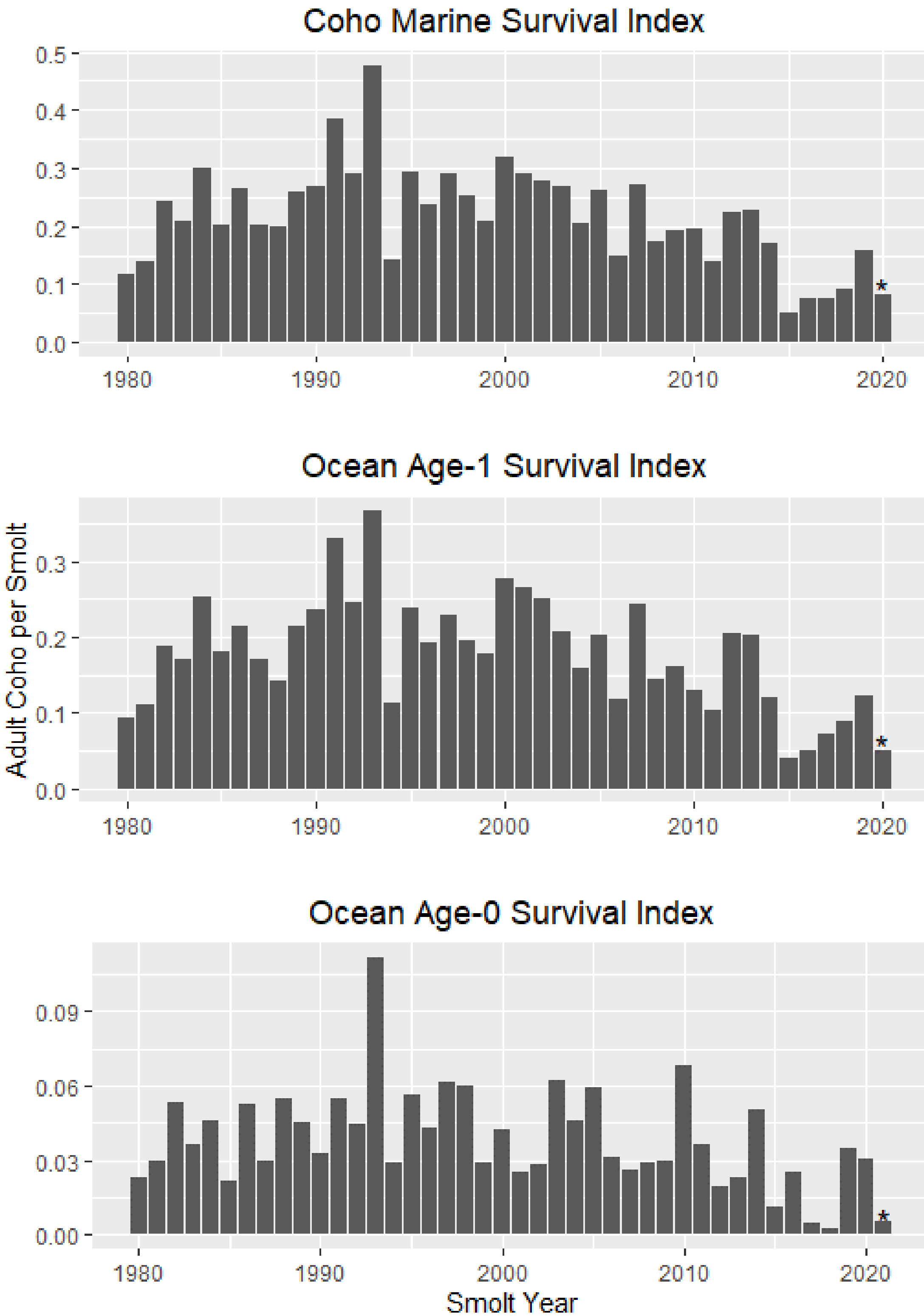


Figure 54: Auke Creek coho salmon marine survival indices showing total marine survival (ocean age-0 and age-1 harvest plus escapement; top panel), percentage of ocean age-1 coho per smolt (harvest plus escapement; middle panel), and percentage of ocean age-0 coho per smolt (escapement only; bottom panel) by smolt year. Return year 2021 data are denoted with an asterisk as these may change by the end of the coho return.

Wild Productivity and Escapement of Sockeye Salmon from Auke Creek, Southeast Alaska

Contributed by Joshua R. Russell and Scott C. Vulstek, Auke Bay Laboratories Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: joshua.russell@noaa.gov
Last updated: September 2021

Description of indicator: The time series of wild productivity and escapement for sockeye salmon from the Auke Creek Research Station in Southeast Alaska is the longest-running continuous series available in the North Pacific, spanning 42 years. The Auke Creek weir structure facilitates near-complete capture of all migrating sockeye smolt and returning adults. It is the only weir capable of such precision on a wild system in the North Pacific. While no stock-specific harvest information is available for Auke Creek sockeye salmon for a direct estimation of marine survival, the precision of this long-term dataset is still unmatched and the series is an excellent choice for model input relating to nearshore and gulf-wide productivity. We report out-migrating smolts and escapement (adult returns), and not marine survival indexas per the other Auke Creek salmon contributions, due to the multiple age classes outmigrating and varying years spent at sea.

Status and trends: The historical trend shows that the productivity of wild sockeye salmon smolts from Auke Creek varies from 1619 to 33616, with an average productivity of 16048 from ocean entry years 1980–2021. Productivity for the 2021 saw 3963 outmigrant smolts, the third lowest on record (Figure 55). Escapement of wild sockeye salmon smolts from Auke Creek has varied from 325 to 6123, with an average escapement of 2615 from return years 1980–2021. The 2021 season saw the tenth lowest escapement of sockeye salmon to Auke Creek with 1489 returning adults (Figure 56).

Factors influencing observed trends: Factors influencing observed trends include: smolt age, smolt size, migration timing, predation, and marine environmental conditions. Age and size at saltwater entry, along with regional sea surface temperate have been shown to influence juvenile mortality at ocean entry (Yasumiishi et al., 2016). Within the Auke Creek watershed, a system undergoing rapid climatic change, climate-induced phenological shifts have been shown to influence a trend of later migration of sockeye adults and age-1 smolts, while age-2 smolts are trending earlier (Kovach et al., 2013*b*; Shanley et al., 2015). Additionally, positive effects of temperature have been observed on sockeye biomass and length of age-2 smolts in the Auke Creek system (Kovach et al., 2014). In Southeast Alaska, sablefish have been observed to prey upon juvenile sockeye in early summer before more abundant food resources become available (Sturdevant et al., 2009).

Implications: The productivity and escapement of Auke Creek sockeye salmon is related to large-scale ocean productivity indices and to important rearing habitats of many southeast Alaska groundfish species. The productivity and escapement indices of Auke Creek sockeye salmon provide an opportunity for the examination of annual variation in habitat quality of rearing areas and general ocean conditions and productivity. Within Southeast Alaska, sockeye salmon productivity and escapement are of great interest to the Pacific Salmon Commission with relation to the Transboundary and Northern Boundary areas and indices such as Auke Creek help in assessment. Thus, the productivity and escapement of Auke Creek sockeye salmon provide valuable proxies for Gulf of Alaska and Southeast Alaska productivity, and may provide insight to the overwintering survival and recruitment of sablefish and other groundfish species.

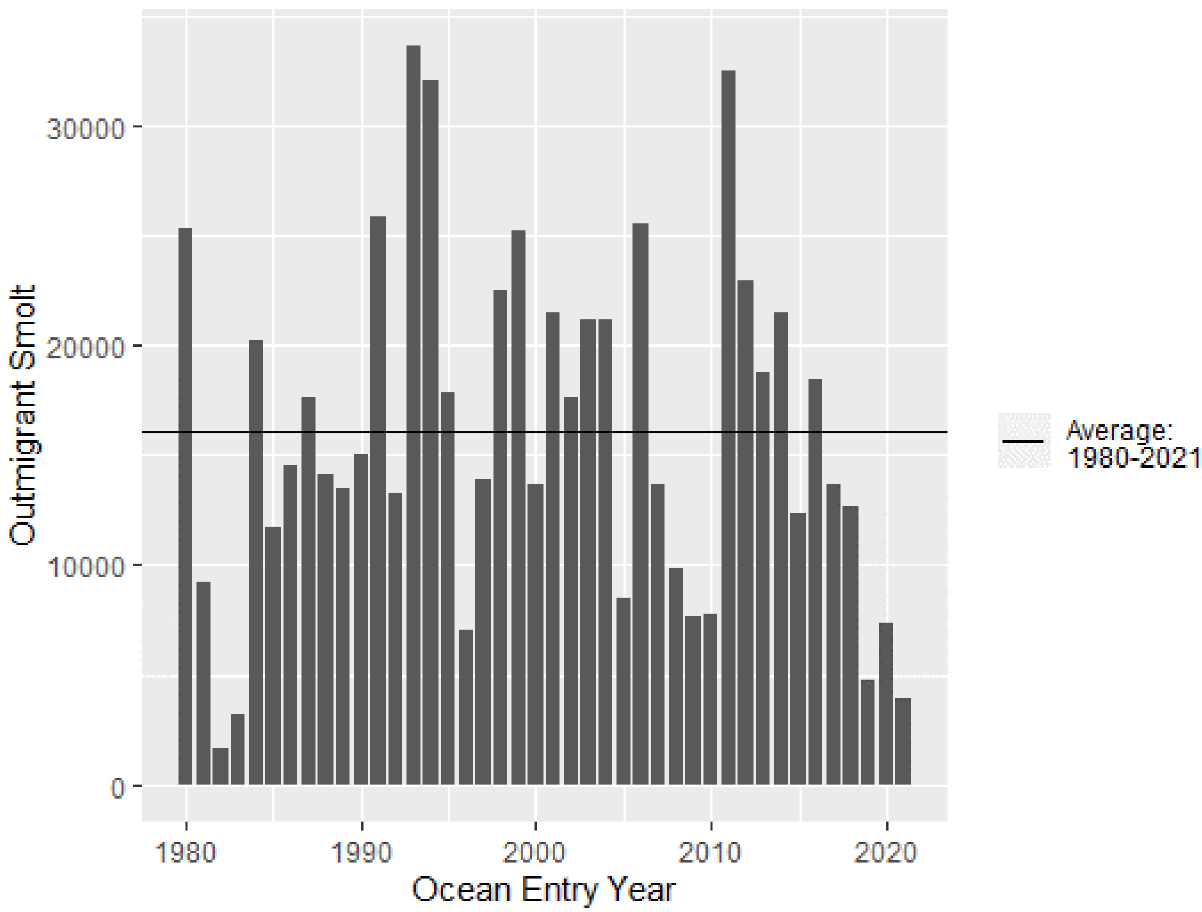


Figure 55: Auke Creek sockeye salmon smolt productivity by ocean entry year

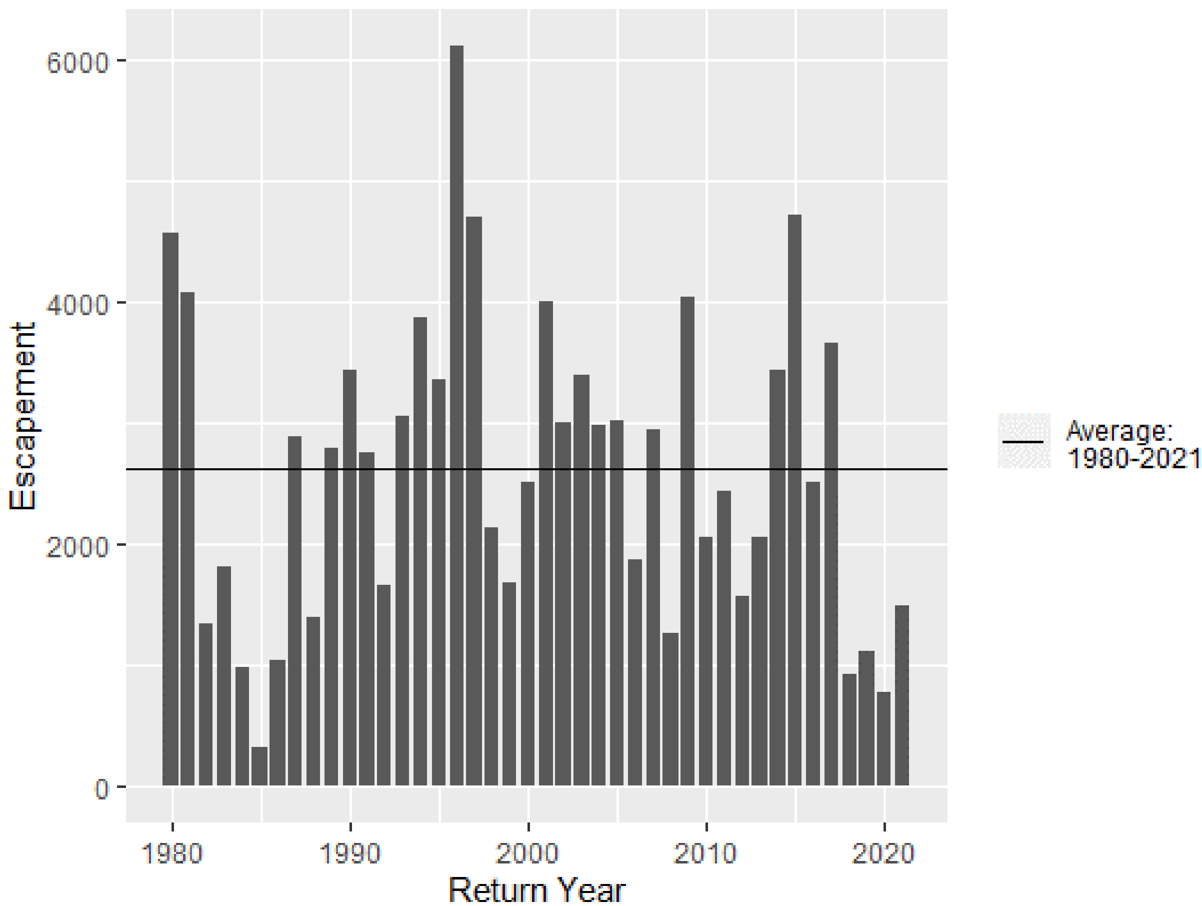


Figure 56: Auke Creek sockeye salmon adult returns by year.

Maturing Coho Salmon Weight as an Indicator of Offshore Prey Status in the Gulf of Alaska

Contributed by Leon D. Shaul[1], Gregory T. Ruggerone[2], and Justin T. Priest[3]
[1]1316 3rd St, Douglas, AK 99824; Contact: leondshaul@gmail.com
[2]Natural Resources Consultants, Inc., 4039 21st Avenue West, Suite 404, Seattle, WA 98199; Contact: GRuggerone@nrccorp.com
[3]Alaska Department of Fish and Game, Division of Commercial Fisheries, 304 Lake Street, Room 103, Sitka, Alaska 99835; Contact: Justin.Priest@alaska.gov
Last updated: September 2021

Description of indicator: Coho salmon returning to Southeast Alaska (SEAK) gain most of their mass during their final summer at sea in the Gulf of Alaska (Myers et al., 1996) where their rapid growth is closely tied with a single even- or odd-year line of epipelagic squid (principally *Berryteuthis anonychus* (Aydin, 2000; Kaeriyama et al., 2004). When available in sufficient abundance, these squid provide the majority of the energy-rich higher trophic level prey consumed by salmon in offshore waters (Davis et al., 1998) and are important prey for wide variety of marine fish, mammal and avian predators.

The SEAK coho weight indicator (Figure 57) is inferred to reflect, in substantial part, the trajectory and status of distinct even- and odd-year lines of maturing epipelagic squid in offshore waters of the Gulf of Alaska (GOA). The indicator is comprised of the weekly average weight of dressed (head-on, gutted) coho salmon landed by the Southeast Alaska troll fishery averaged over 11 statistical weeks (28–38) from early-July to mid-September.

Shaul and Geiger (2016) found that the majority of variation in this index of coho salmon weight over a 45-year period (1970–2014) was explained by the biomass of pink salmon commercially harvested in North America (excluding the Bering Sea and Aleutian Islands) and the average monthly PDO index during squid emergence and development (April-March), averaged at biennial lags (matching life cycles of pink salmon and squid) of up to four years. Squid populations appear to respond positively to warm conditions associated with positive PDO values whereas predation by maturing pink salmon exerts a negative influence. Together these variables appear to shape even- and odd-year lines of squid across multiple generations. An update of the SEAK coho weight model with five additional years of data provided a slightly improved fit, explaining two-thirds of variation in coho weight over a 50-year period from 1970–2019, with variable weightings of 0.555 for pink salmon biomass and 0.445 for the PDO index (Figure 58).

However, SEAK coho salmon weight subsequently reached record lows on the even-year line in 2020, while revisiting recent lows on the odd-year line in 2021, for reasons that are not explained by the predictive variables in the model: GOA pink salmon harvest biomass and the PDO index. The 2020 and 2021 deviations from forecast coho weight suggest that prey populations important to coho salmon growth have recently declined because of other (unidentified) causes.

Status and trends: Coho salmon weight was typically larger in odd-years during the 1970s (Figure 57), reaching a peak in 1977, before trending progressively lower on the odd-year line until the most recent decade. Even-year coho weight has displayed a substantially more level trend, increasing from the 1970s to a peak in 1984 and later decreasing to a low in 2012–2014 before increasing to near-average in 2016–2018. The even-year line subsequently fell to a new record low weight of 2.65

kg in 2020, that was 0.53 kg (16.7%) below the long-term mean for that line (3.18 kg). In 2021, the average coho weight of 2.42 kg fell between the two previous lowest values of 2.41 kg in 2011 and 2.43 kg in 2017, and was 0.49 kg (16.7%) below the 1971–2019 odd-year average of 2.95 kg. The low average coho weight in both years fell far below the model forecasts based on trailing PDO and GOA pink salmon biomass values, by 0.90 kg (25.3%) in 2020 and 0.43 kg (14.8%) in 2021 (Figure 58). Forecast errors for both years far exceeded the average magnitude of model residuals for the 50-year period from 1970–2019 of 0.14 kg (4.5% of modeled weight).

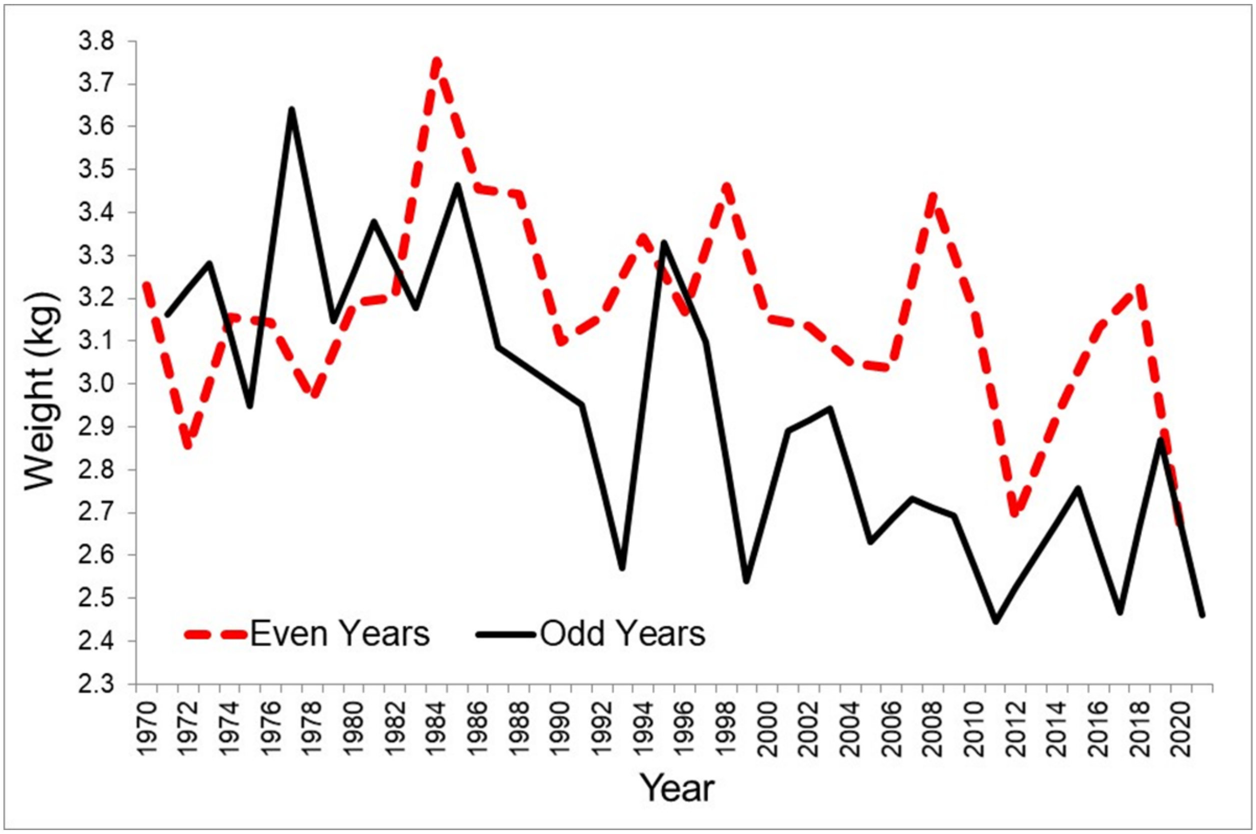


Figure 57: The dressed weight of troll caught coho salmon in Southeast Alaska in even and odd years, 1970–2021.

Factors influencing observed trends: The predominant offshore cephalopod prey of coho salmon in the GOA and central North Pacific (*B. anonychus*) appears to respond positively to warmer conditions associated with high PDO index values during emergence and development, and to be susceptible to population depletion through predation by maturing adults of pink salmon. Other investigators have also reported evidence of control by pink salmon of squid populations (Ito, 1964; Davis, 2003), growth of coho salmon (Ogura et al., 1991) and growth of sockeye salmon (Ruggerone et al., 2005), based on opposing biennial patterns.

The biennial pattern is likely enhanced by a coincident biennial life cycle, with distinctive even- and odd-year population lines in both predator (pink salmon) and prey (squid; Jones et al., 2011). Therefore, differential predation by separate lines of pink salmon (exhibiting a persistent pattern of cyclic dominance) can lead to distinctive line-specific trajectories in squid prey that are evident

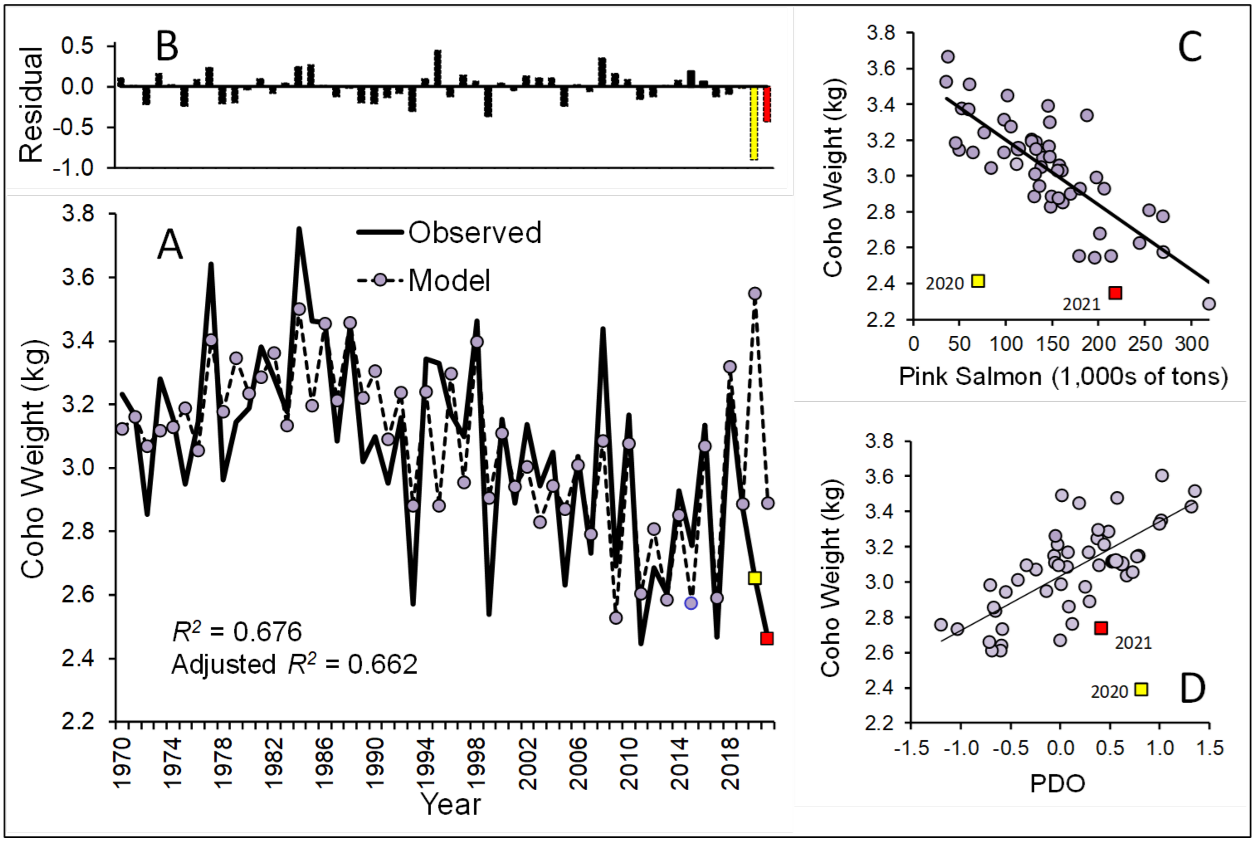


Figure 58: Southeast Alaska troll-caught coho salmon average dressed weight compared with modeled weight (A) based on a multiple regression model with two variables: the standardized April-March PDO Index (average for lag 0, 2, and 4 years; 0.445 weighting based on the regression coefficient) and the standardized average commercial catch of pink salmon in North America (excluding the Bering Sea and Aleutian Islands) lagged by 2 and 4 years (0.555 weighting). The model residual is shown (B), as well as partial residual plots for pink salmon (C) and the PDO index (D). The model developed by Shaul and Geiger (2016; using 1970–2014 data) is refitted for 1970–2019, with 2020 and 2021 forecasts indicated on the partial residual plots by yellow and red squares, respectively.

in size-at-maturity of age 1-ocean coho salmon that achieve the majority of their growth from maturing individuals of a single even or odd-year cohort of squid. Shaul and Geiger (2016) found that Southeast Alaska coho weight had a negative relationship with GOA pink salmon harvest biomass, averaged at lags of 2 and 4 years, although not with pink salmon returning in the current year— likely because pink salmon are only large enough to feed effectively on squid late in their offshore residence, after coho salmon have achieved much of their growth from the same cohort of squid.

Coho salmon weight exhibits a positive relationship with the average monthly PDO index during April-March, averaged at lags of 0, 2, and 4 years, suggesting that squid benefit from warmer conditions during emergence and development. Both variables (GOA pink salmon harvest biomass and the PDO index) exhibited a strong positive correlation during 1970–1990, as pink salmon harvests followed the PDO index higher after the 1977 regime shift. However, the two variables were uncorrelated after 1990 when abundant pink salmon returns occurred in combination with a return to cooler conditions (Shaul and Geiger, 2016).

Coho salmon weight was predominantly odd-year dominant prior to 1983, but shifted to even-year dominance beginning in 1982–1983 two biennial cycles after the GOA pink salmon harvest shifted in the opposite direction to odd-year dominance. A series of peak even-year coho salmon weights (1984, 1986, 1988) coincided with moderate trailing pink salmon harvests and warm conditions that appeared to benefit squid. Prior to 2020, even-year weight exhibited a stable trend, except for a decrease to near the odd-year trend in 2012 after a protracted cold period with negative PDO index values and following a high 2010 GOA pink salmon harvest of 181.7 thousand metric tons (of which 62% was comprised of Prince William Sound hatchery fish). Following the abrupt decrease in size in 2012, even-year coho weight recovered over sequential biennial cycles through 2018 under warming conditions and lower pink salmon returns, before plummeting to a new even-year low of 2.65 kg in 2020. The abrupt recent decrease is unexplained by the model variables, which predicted that returning coho salmon would average very large (3.55 kg) in 2020 (following a favorably warm conditions during 2016–2020 and poor GOA pink salmon returns on the even-year line in 2016 and 2018).

While reasons for the inferred decrease in prey are unknown, potential explanations include a decrease in overall productivity in the offshore GOA extending to squid populations from lower trophic levels (and influencing salmon forage across multiple trophic levels), or a potential change in the level of interaction by highly abundant Asian pink salmon stocks that have not previously been identified as a factor in SEAK coho weight.

Although high seas tagging data indicate that Asian pink salmon populations have historically remained west of the range of SEAK coho salmon (limited within the GOA), it is possible that the range of Asian pink salmon expanded eastward into the GOA, given the two highest Russian pink salmon harvests on record in 2018 and 2019, years that could potentially have affected squid availability to coho salmon two years later in 2020 and 2021. Whereas historical tag recovery data for Eastern Kamchatka pink salmon reflects primarily the highly dominant odd-year line, the presence of genetically isolated pink salmon lines suggest that the unusually large even-year return of Eastern Kamchatka pink salmon in 2018 could have ranged into different areas, including the Gulf of Alaska. Finally, although the range and movements of potentially distinctive *B. anonychus* populations is unknown, ocean circulation patterns suggest that some westward movement likely occurs with the Alaska Current (toward the usual range of Asian pink salmon stocks) at the early paralarva stage (Jones et al., 2011), that could potentially be followed by return eastward movement over the 2-year life cycle of the species. Although substantial influence on central GOA prey populations by Russian pink salmon appears unlikely, it certainly cannot be ruled out.

It is also possible that a reduction in higher trophic level salmon prey reflects a more general decline in productivity in the Gulf of Alaska across multiple trophic levels including both zooplankton and micronekton. This hypothesis is supported by reports of below-average adult size-at-age in 2020 and 2021 across multiple salmon species, including chum salmon which heavily utilize gelatinous zooplankton but consume very few maturing squid. A positive relationship between the PDO index and SEAK coho weight suggests that *B. anonychus* prefers warmer conditions. Close tracking of observed weight with the model throughout anomalous warming in 2014–2016 and immediately afterward through 2019 suggests that this warming did not result in an immediate tipping point for squid. However, the large recent negative deviations in coho weight in 2020 and 2021 could reflect a lagged ecosystem response to earlier intense warming associated with the North Pacific "Blob".

Implications: In its role as a flexible planktivore that feeds at different trophic levels (zooplankton and squid), the pink salmon functions as a keystone predator that controls energy flow in the offshore ecosystem in a "trophic triangle" involving salmon, squid and zooplankton (Aydin, 2000). An increasing trend in abundance of both natural and hatchery-produced pink salmon in the North Pacific (Ruggerone and Irvine, 2018), combined with their apparent ability to control squid populations, has important implications for not only higher trophic level salmon species like coho, chinook, steelhead, and older (age 3-ocean) sockeye salmon, but also for a wide variety of fish, birds and marine mammals that depend upon epipelagic squid.

While the SEAK coho salmon weight model explains about two-thirds of variation in Southeast Alaska coho weight over a half century (1970–2019), recent unexplained decreases in average weight indicate that one or more new controlling factors have likely contributed to reduced populations of maturing squid in 2020 and 2021. The importance of epipelagic squid to many species in the offshore ecosystem suggests that priority should be given to identification of these factors.

Groundfish

Gulf of Alaska Groundfish Condition

Contributed by Cecilia O'Leary, Ned Laman, and Sean Rohan, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: ned.laman@noaa.gov
Last updated: October 2021

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 represent an integration of prior prey availability and growth conditions. 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). Fish condition calculated as length-weight residuals reflects fish growth trajectories which can have implications for biological productivity due to growth, reproduction, and mortality (Paul and Paul, 1999; Boldt and Haldorson, 2004). In addition, variability in growth and consequent body condition can act as a key indicator of population health reflecting how populations respond to environmental and anthropogenic factors (Brosset et al., 2017).

Paired lengths and weights of individual fishes were examined from the Alaska Fisheries Science Center biennial Resource Assessment and Conservation Engineering (AFSC/RACE) - Groundfish Assessment Program's (GAP) bottom trawl survey of the Gulf of Alaska (GOA). Analyses focused on walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), arrowtooth flounder (*Atheresthes stomias*), southern rock sole (*Lepidopsetta bilineata*), northern rockfish (*Sebastes polyspinis*), Pacific ocean perch (*Sebastes alutus*), and dusky rockfish (*Sebastes variabilis*) collected in trawls with satisfactory performance at standard survey stations. Data were combined in the former International North Pacific Fisheries Commission (INPFC) strata; Shumagin, Chirikof, Kodiak, Yakutat and Southeast (Figure 59).

Length-weight relationships for each of the seven species were estimated within each stratum across all AFSC/RACE GAP GOA bottom trawl survey years where data were available (1984—2021). Groundfish condition was calculated from a linear regression of log-transformed exponential growth, W = aLb, where W is weight (g) and L is fork length (mm) and a bias correction was applied when predicting weights priori to calculating residuals. Stratum mean residuals were weighted in proportion to stratum biomass and stratum-year combinations with samples sizes <10 were eliminated from indicator calculations although they were included when establishing length-weight relationships. A different slope was estimated for each stratum to account for spatial-temporal variation in growth and bottom trawl survey sampling. Length-weight relationships for 100—250 mm fork length (1—2 year old) walleye pollock were established independent of the adult life history stages caught. Bias-corrected weights-at-length (log scale) were estimated from the model and subtracted from observed weights to compute individual residuals per fish. Length-weight residuals were averaged for each stratum and weighted in proportion to INPFC stratum biomass based on stratified area-swept expansion of summer bottom trawl survey catch per unit effort (CPUE). Average length-weight residuals were compared by stratum and year to evaluate spatial variation in fish condition. As in previous years, confidence intervals for the condition indicator reflect uncertainty based on length-weight residuals, but now better reflect sample sizes and stratum biomasses among years. Confidence intervals do not account for uncertainty in stratum biomass estimates. Combinations of stratum and year with ¡10 samples were used for length-weight relationships but excluded from indicator calculations. Code used to calculate the condition indicator is available at (`https://www.github.com/sean-rohan-noaa/akfishcondition`).

Methodological Changes: The method used to calculate groundfish condition this year (2021) is the same as the method that was adopted in 2020, and differs from ESR's prior to 2019 in that: 1) different regression slopes were estimated for each stratum, 2) a bias-correction was applied to estimated weights prior to calculating residuals, 3) stratum mean residuals were weighted in proportion to stratum biomass, and 4) stratum-year combinations with sample size < 10 were not used in indicator calculations.

Status and trends: Residual body condition varied among survey years for all species considered (Figure 60). Fish condition indicators for all seven species were below average in 2021, but with the same condition or reduction in magnitude for most species in 2021 relative to 2019. Residual body condition for pollock, Pacific cod, and arrowtooth flounder remained constant relative to 2019. Southern rock sole residual body condition improved over the last four years, but the final two years remained a constant below average condition. Residual body condition for dusky and northern rockfish also improved, but are still below average. Finally, Pacific ocean perch residual body condition is below average and trending downward in the final four years. Prior to 2015, residual body condition indexes of these GOA species vary from survey to survey, cycling between negative and positive residuals with no clear temporal trends. Residual body condition of 100—250 mm walleye pollock in the GOA is strikingly positive during early years in the time series, but has remained mostly neutral or slightly negative since the early 1990s. Overall, GOA fish condition remains below average.

The general patterns of above and below average residual body condition index across recent survey years for the GOA as described above were also apparent in the spatial condition indicators across INPFC strata (Figure 61). The relative contribution of stratum-specific residual body condition to the overall trends (indicated by the height of each colored bar segment) does not demonstrate a clear pattern. Although, for many species, the direction of residual body condition (positive or negative) was synchronous among strata within years. For example, residual body condition for small pollock (100—250 mm) in Shumagin and Southeast were positive while other locations trended negative. Residual body condition for southern rock sole in Yakutat and Southeast were also positive, while the rest of the regions trended negative. While Pacific cod residuals trended negative again, residual body condition in the Kodiak strata remained positive. All other fish residual body condition was negative across all strata. Patterns of fish distribution are also apparent in the stratum condition indexes. For example, northern rockfish have primarily been collected from the Shumagin and Chirikof strata in recent surveys.

Factors influencing observed trends: Factors that could affect residual fish body condition presented here include temperature, trawl survey timing, stomach fullness, movement in or out of the survey area, or variable somatic growth. Following an unprecedented warming event from 2014–2016 (Bond et al., 2015; Stabeno and Bell, 2019; Barbeaux et al., 2020*b*), there has been a general trend of warming ocean temperatures in the survey area and sea surface temperature anomaly data continue to reflect temperatures above average historical conditions through 2021 (NOAA, 2021*b*); these warmer temperatures could be affecting fish growth conditions in this region. Changing ocean conditions along with normal patterns of movement can cause the proportion

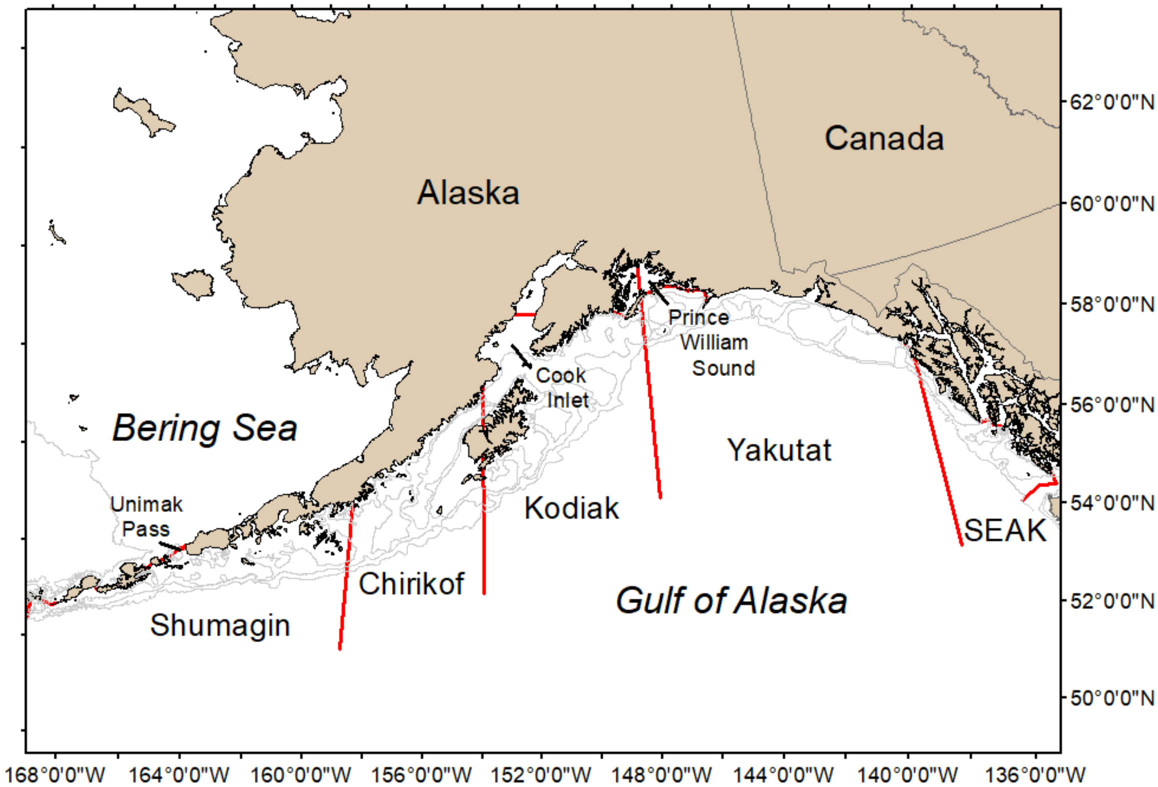


Figure 59: National Marine Fisheries Service (NMFS) Alaska Fisheries Science Center Gulf of Alaska summer bottom trawl survey area with International North Pacific Fisheries Commission (INPFC) statistical fishing strata delineated by the red lines.

of the population resident in the sampling area during the annual bottom trawl survey to vary. Recorded changes attributed to the marine heatwave included species abundances, sizes, growth rates, weight/body condition, reproductive success, and species composition (Suryan et al., 2021). Warmer ocean temperatures can lead to lower energy (leaner) prey, increased metabolic needs of younger fish, and therefore slower growth for juveniles, as observed in Pacific cod (Barbeaux et al., 2020*b*). Additionally, spatial and temporal trends in fish growth over the season become confounded with survey progress since the first length-weight data are generally collected in late May and the bottom trawl survey is conducted throughout the summer months moving from west to east. In addition, spatial variability in residual condition may also reflect local environmental features which can influence growth and prey availability in the areas surveyed (e.g., warm core eddies in the central GOA; Atwood et al., 2010). The fish condition computations presented here begin to, but do not wholly, account for spatio-temporal trends in the data contributed by survey sampling logistics nor do they resolve sources of variability in the underlying populations.

Implications: Variations in body condition likely have implications for fish survival. In Prince William Sound, the condition of herring prior to the winter may influence their survival (Paul and

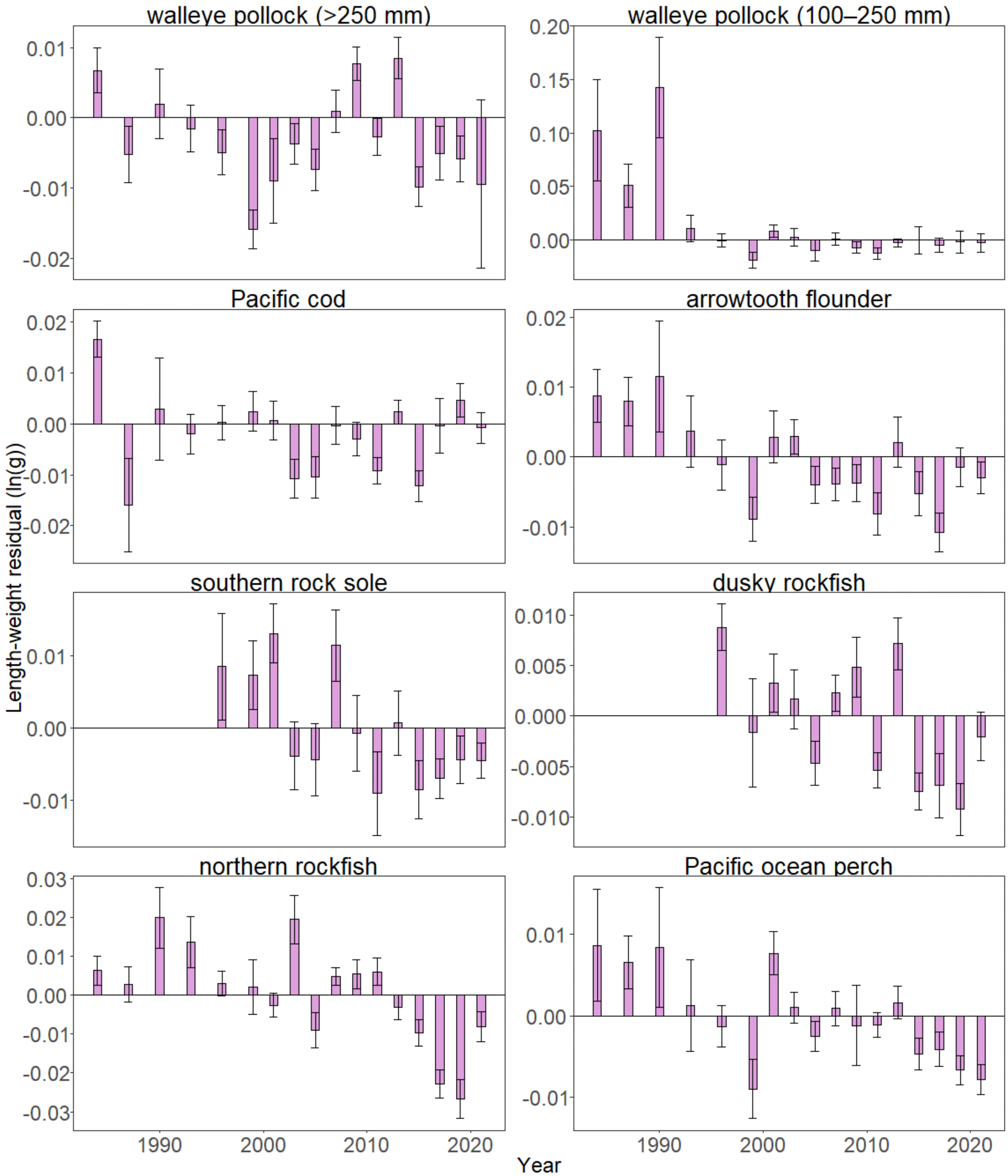


Figure 60: Biomass-weighted residual body condition index across survey years (1984–2021) for seven Gulf of Alaska groundfish species collected on the National Marine Fisheries Service, Alaska Fisheries Science Center standard summer bottom trawl survey. Filled bars denote weighted length-weight residuals, error bars denote two standard errors.

Paul, 1999). The condition of GOA groundfish may similarly contribute to survival and recruitment.

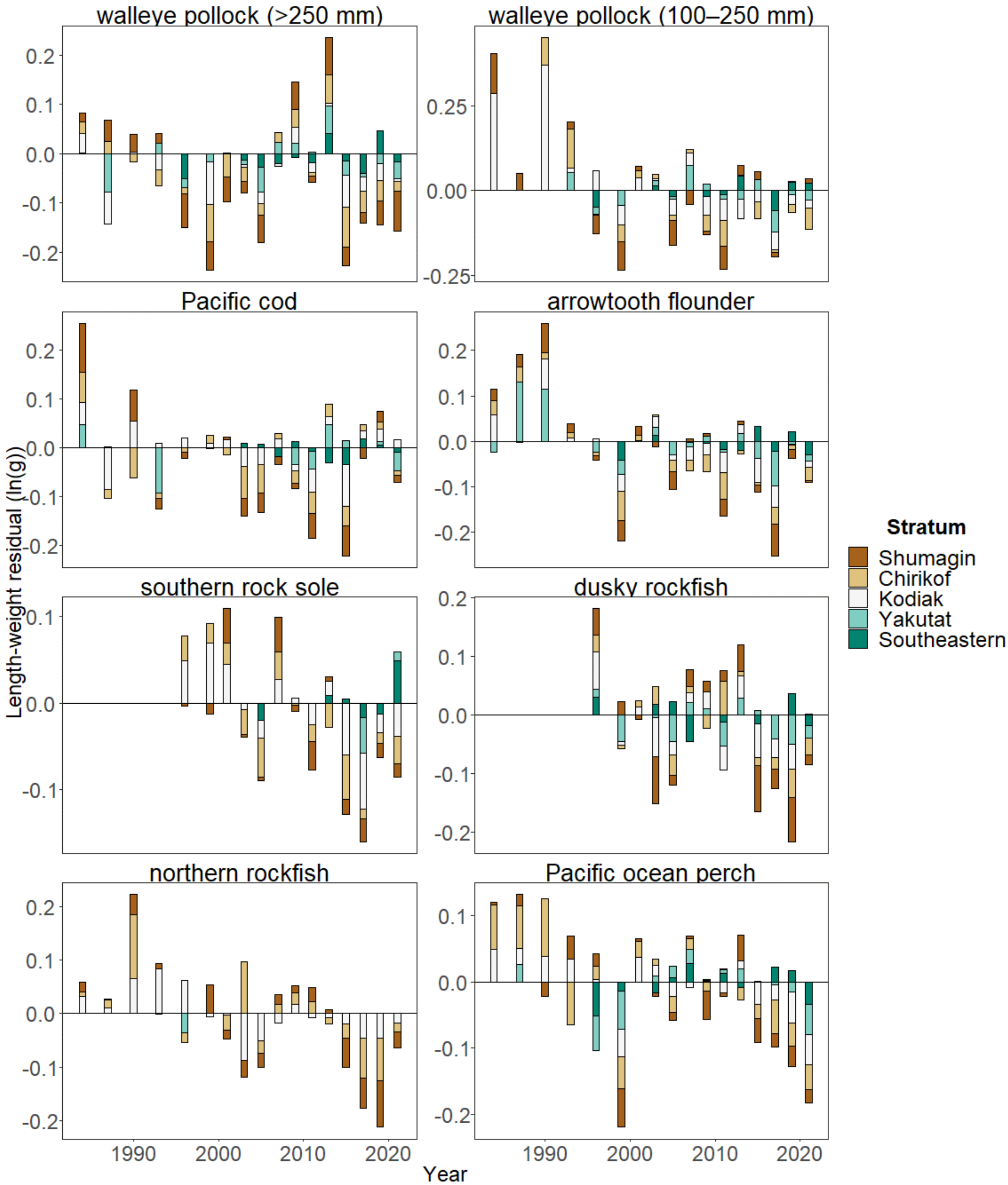


Figure 61: Residual body condition index for seven Gulf of Alaska groundfish species collected on the National Marine Fisheries Service Alaska Fisheries Science Center standard summer bottom trawl survey (1984—2021) grouped by International North Pacific Fisheries Commission (INPFC) statistical sampling strata.

As future years are added to the time series, the relationship between length-weight residuals and subsequent survival will be examined further. It is important that residual body condition for most species in these analyses was computed for all sizes and sexes combined. Requirements for growth and survivorship differ for different fish life stages and some species have sexually dimorphic or even regional growth patterns. It may be more informative to examine life-stage (e.g., early juvenile, subadult, and adult phases) and sex-specific body condition in the future.

The trend toward lowered body condition for many GOA species over the last three to four RACE/AFSC GAP bottom trawl surveys is a potential cause for concern. It could indicate poor overwinter survival or may reflect the influence of locally changing environmental conditions depressing fish growth, local production, or survivorship. Indications are that the 2014-2016 marine heatwave (Bond et al., 2015; Stabeno and Bell, 2019) has been followed by subsequent years with elevated water temperatures (Barbeaux et al., 2020*b*; NOAA, 2021*b*) which may be related to changes in fish condition in the species examined. As we continue to add years of fish condition to the record and expand on our knowledge of the relationships between condition, growth, production, and survival, we hope to gain more insight into the overall health of fish populations in the GOA.

ADF&G Gulf of Alaska Trawl Survey

Contributed by Carrie Worton, Alaska Department of Fish and Game, 211 Mission Road, Kodiak, AK 99615
Contact: carrie.worton@alaska.gov
Last updated: September 2021

Description of indicator: The Alaska Department of Fish and Game conducts an annual trawl survey for crab and groundfish in Gulf of Alaska targeting areas of crab habitat around Kodiak Island, the Alaska Peninsula, and the Eastern Aleutian Islands (Spalinger, 2020). Parts of these areas have been surveyed annually since 1984, but the most consistent time series begins in 1988. In 2021, a total of 150 stations were sampled from June 18 through July 15. While the survey covers a large portion of the central and western Gulf of Alaska, results from Kiliuda and Ugak Bays (inshore) and the immediately contiguous Barnabas Gully (offshore) are generally representative of the survey results across the region (Figure 62). The trawl survey uses a 400-mesh eastern otter trawl constructed with stretch mesh ranging from 10.2 cm in the body, decreasing to 3.2 cm in the codend. Constructed ideally to sample crab, it can also reliably sample a variety of fish species and sizes, ranging from 15 cm to adult sizes, but occasionally capturing fish as small as 7 cm for some species. The survey catches (mt/km) from Kiliuda and Ugak Bays and Barnabas Gully were summarized by year for selected species groups (Figure 63). Using a method described by (Link et al., 2002), standardized anomalies, a measure of departure from the mean catch (kg) per distance towed (km), were also calculated for selected species; arrowtooth flounder *Atheresthes stomias*, flathead sole *Hippoglosoides elassodon*, Tanner crab *Chionoecetes bairdi*, Pacific cod *Gadus macrocephalus*, skates, walleye pollock *G. chalcogrammus* and Pacific halibut *Hippoglossus stenolepis* (Figure 64).

Status and trends: A sharp decrease in overall biomass is apparent from 2007 to 2017 from the years of record high catches occurring from 2002 to 2005 (Figure 63). Although still at relatively low levels, 2021 survey data showed a slight increase in overall biomass in the inshore and offshore stations. Arrowtooth flounder and Tanner crab have been the predominant species in the ADF&G

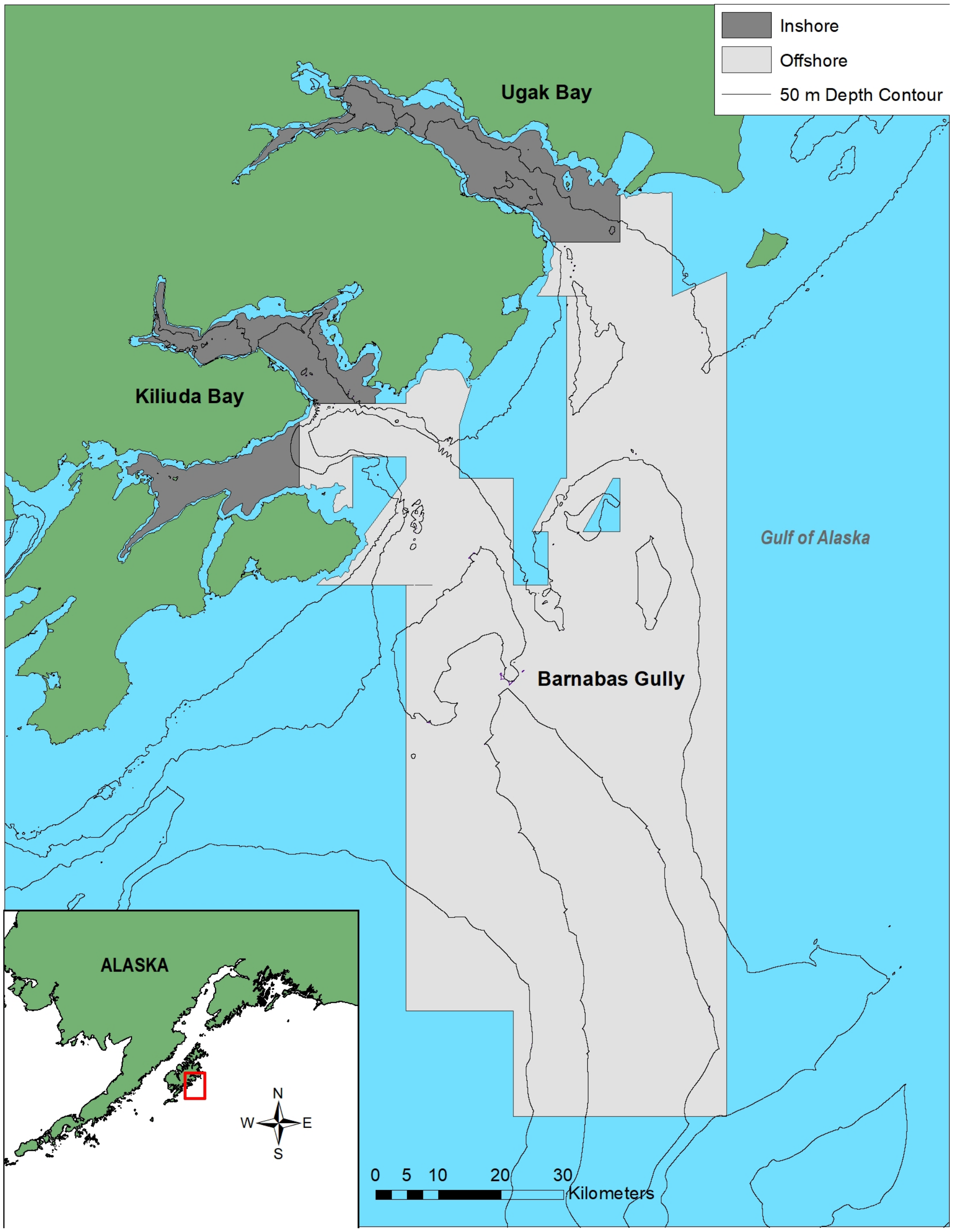
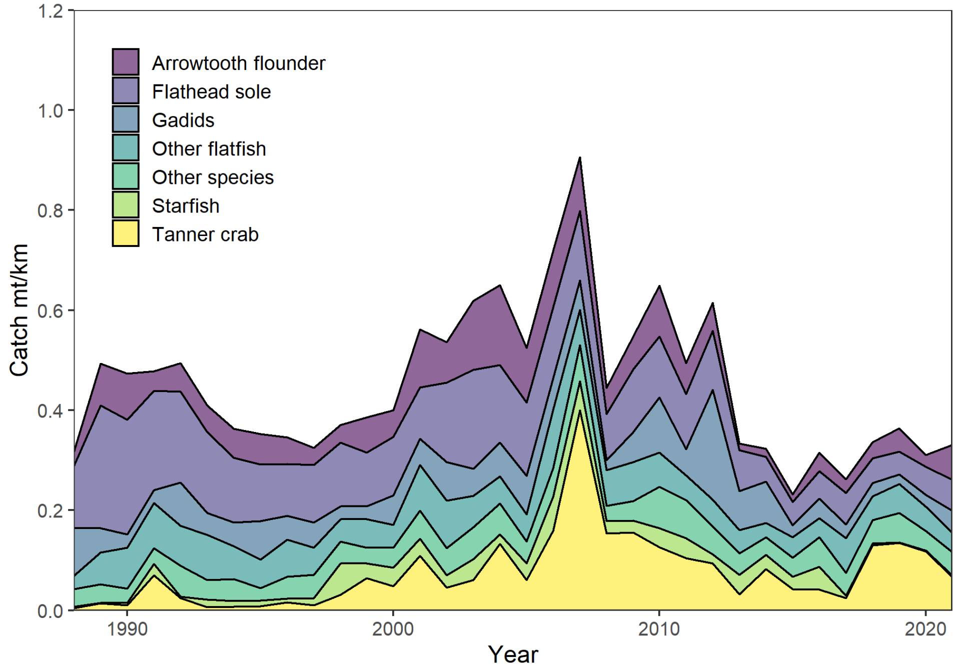


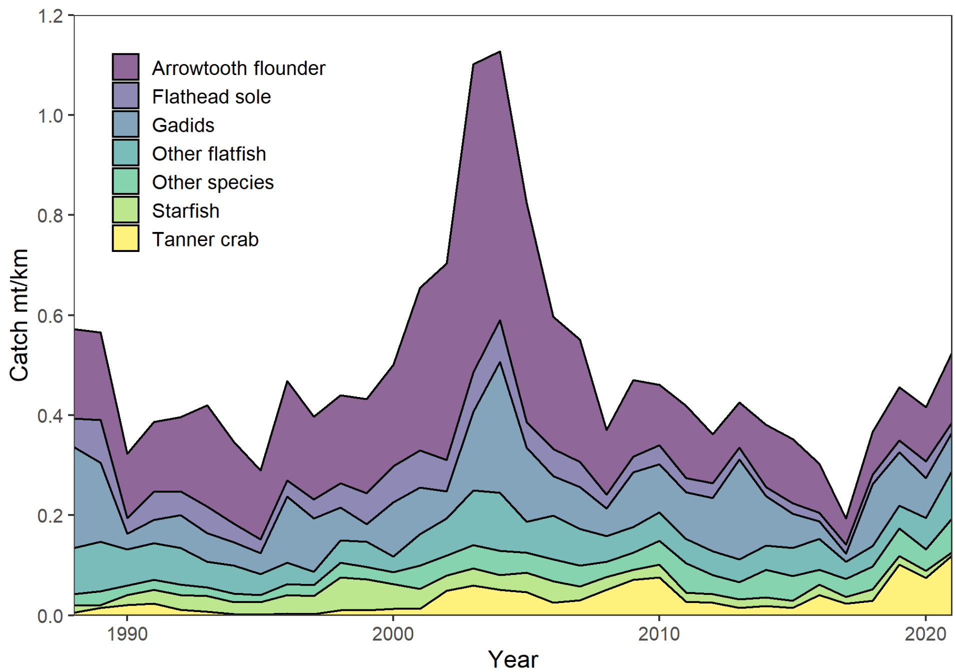
Figure 62: Kiliuda Bay, Ugak Bay, and Barnabus Gully survey areas used to characterize inshore (dark gray, 14 stations) and offshore (light gray, 33 stations) trawl survey results.

trawl survey catches in the last 3 years, with significant increases in the offshore stations. Flathead sole showed a slight increase in 2021, from the lower catches in recent years. Starfish catches have significantly decreased since 2017 and continue to remain low in 2021.

Prior to the start of our standard trawl survey in 1988, Ugak Bay was the subject of an intensive seasonal trawl survey in 1976–1977 (Blackburn, 1977). Today, the Ugak Bay species composition is markedly different than in 1976. Red king crabs *Paralithodes camtschaticus* were the main



(a) Kiliuda and Ugak Bay



(b) Barnabas Gully

Figure 63: Total catch per km towed (mt/km) of selected species from Kiliuda and Ugak Bay (a) and Barnabas Gully (b) survey areas off the east side of Kodiak Island, 1987–2021.

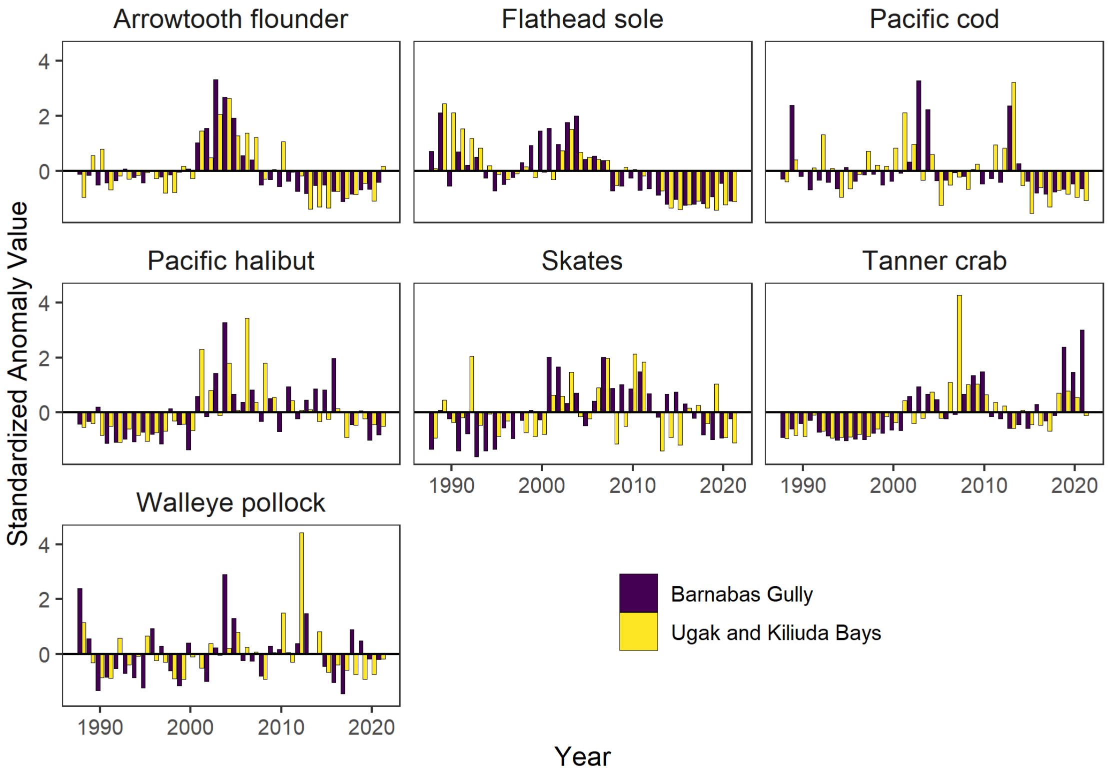


Figure 64: A comparison of standardized anomaly values, based on catch (kg) per distance towed (km) for selected species caught from 1988 to 2021 in Barnabas Gully and Kiliuda and Ugak Bays during the ADF&G trawl survey.

component of the catch in 1976 –1977, but now are nearly non-existent. Flathead sole, skate, and gadid catch rates have all increased roughly 10-fold. While Pacific cod made up 88% and walleye pollock 10% of the gadid catch in 1976–1977, catch compositions have reversed with Pacific cod making up 8% of catch and walleye pollock 92% in 2021.

Below average anomaly values for arrowtooth flounder and flathead sole were recorded again in 2021 for the offshore areas, while arrowtooth was slightly above the average in the inshore areas (Figure 64). Pacific cod, Pacific halibut, skates, and walleye pollock were all below average for both inshore and offshore. The above average anomaly values for Tanner crab continued in 2021 in offshore areas, due to a large recruitment event (Spalinger, 2020).

Temperature anomalies for both inshore and offshore stations were below average in 2020 and 2021, in contrast to previous years. The higher than average temperatures in past years frequently occured during moderate and strong El Niño years (`http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml`).

Factors influencing observed trends: It appears that significant changes in volume and composition of the catches on the east side of Kodiak are occurring, but it is unknown to what extent predation, environmental changes, and fishing effort are contributing. The lower overall catch from 1993 to 1999 (Figure 63) may reflect the greater frequency of El Niño events on overall production, while the period of less frequent El Niño events, 2000 to 2003, corresponds to years of increasing production and corresponding catches. Lower than average temperatures have been recorded from 2006 to 2009 along with decreasing overall abundances in 2008 and 2009. This may indicate a possible lag in response to changing environmental conditions or some other factors may be affecting abundance that are not yet apparent. Declines in Pacific cod abundance during the 2014–2016 period of the anomalously warm water event ("the Blob") in the GOA are well documented (Barbeaux et al., 2020*a*; Suryan et al., 2021). Recent increases in Tanner crab abundance are likely influenced by the decrease in predation, where years with lower than average Pacific cod, arrowtooth flounder, and flathead sole catches favor Tanner populations in Kodiak Area.

Implications: Although trends in abundance in the trawl survey appear to be influenced by major oceanographic events such as El Niño, local environmental changes, predation, movements, and fishery effects may influence species specific abundances. Monitoring these trends is an important process used in establishing harvest levels for state water fisheries. This survey data is used to establish guideline harvest levels of state managed fisheries and supply abundance estimates of the nearshore component of other groundfish species such as Pacific cod and pollock. Decreases in species abundance will most likely be reflected in decreased guideline harvest levels.

Distribution of Rockfish Species in Gulf of Alaska Trawl Surveys

Contributed by Wayne Palsson, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: wayne.palsson@noaa.gov
Last updated: October 2021

Description of indicator: In a previous analysis of rockfish from 14 bottom trawl surveys in the Gulf of Alaska and Aleutian Islands (Rooper, 2008), five species assemblages were defined based on similarities in their distributions along geographical position, depth, and temperature gradients. The 180 m and 275 m depth contours were major divisions between assemblages inhabiting the shelf, shelf break, and lower continental slope. Another noticeable division was between species centered in southeastern Alaska and those found in the northern Gulf of Alaska and Aleutian Islands.

In this time series, the mean-weighted distributions of six rockfish (five *Sebastes* spp. and *Sebastolobus alascanus*) species along the three environmental gradients (depth, temperature, and position) were calculated for the Gulf of Alaska and Aleutian Islands. A weighted mean value for each environmental variable was computed for each survey as:

$$Mean = \frac{\sum(f_i x_i)}{\sum f_i},$$

where f_i is the CPUE of each rockfish species group in tow i and x_i is the value of the environmental variable at tow i. The weighted standard error (SE) was then computed as:

$$SE = \frac{\sqrt{\frac{(\sum(f_i x_i^2)) - ((\sum f_i) * mean^2)}{(\sum f_i) - 1}}}{\sqrt{n}},$$

where n is the number of tows with positive catches. Details of the calculations and analyses can be found in Rooper (2008). These indices monitor the distributions of major components of the rockfish fisheries along these environmental gradients to detect changes or trends in rockfish distribution. Changes in geographic position are referenced to Hinchinbrook Island in the Gulf of Alaska.

Status and trends: In the Gulf of Alaska, there are no significant trends in the distribution of rockfish with temperature (Figure 65) in the 2021 analysis, and these results are similar as those observed in the 2017 and 2019 analyses. However, there were slight and significant decreases in depth (shallowing) for northern rockfish (slope= -0.424, $p \leq 0.009$) and shortspine thornyhead (slope = -0.763, $p \leq 0.036$). For the first time, there was a significant increase in distance from the reference point for northern rockfish (slope = 7.88, $p \leq 0.015$) indicating a westward shift in distribution. While the statistical analysis of temperature found no significant changes in temperatures experienced by rockfish, most ambient temperatures experienced by rockfishes were higher for rockfish in 2015 and 2019 than during earlier surveys.

Factors causing observed trends: In the Gulf of Alaska, the stability of the distribution indicates that each of the species occupy a fairly specific geographical distribution and generally the same depth distribution. This is seen in the flat line time series of distribution across areas and depths despite the variability in temperature, especially recently. As temperatures rise and fall around the mean, the depth distribution does not change, indicating that most rockfishes are not changing their habitat or distribution to maintain a constant temperature. This is in agreement with a recent analysis showed that Pacific ocean perch did not respond to marine heatwaves by changing depth in the central GOA (Yang et al., 2019). The slight decrease in depth over time for northern rockfish and shortspine thornyhead and the westward shift of northern rockfish warrant further investigation or additional surveys to determine if this is a consistent long-term trend.

Implications: The trends in the mean-weighted distributions of rockfish should continue to be monitored, with special attention to potential causes of the shift in depth and position distributions of rockfish, especially as they relate to changing temperatures.

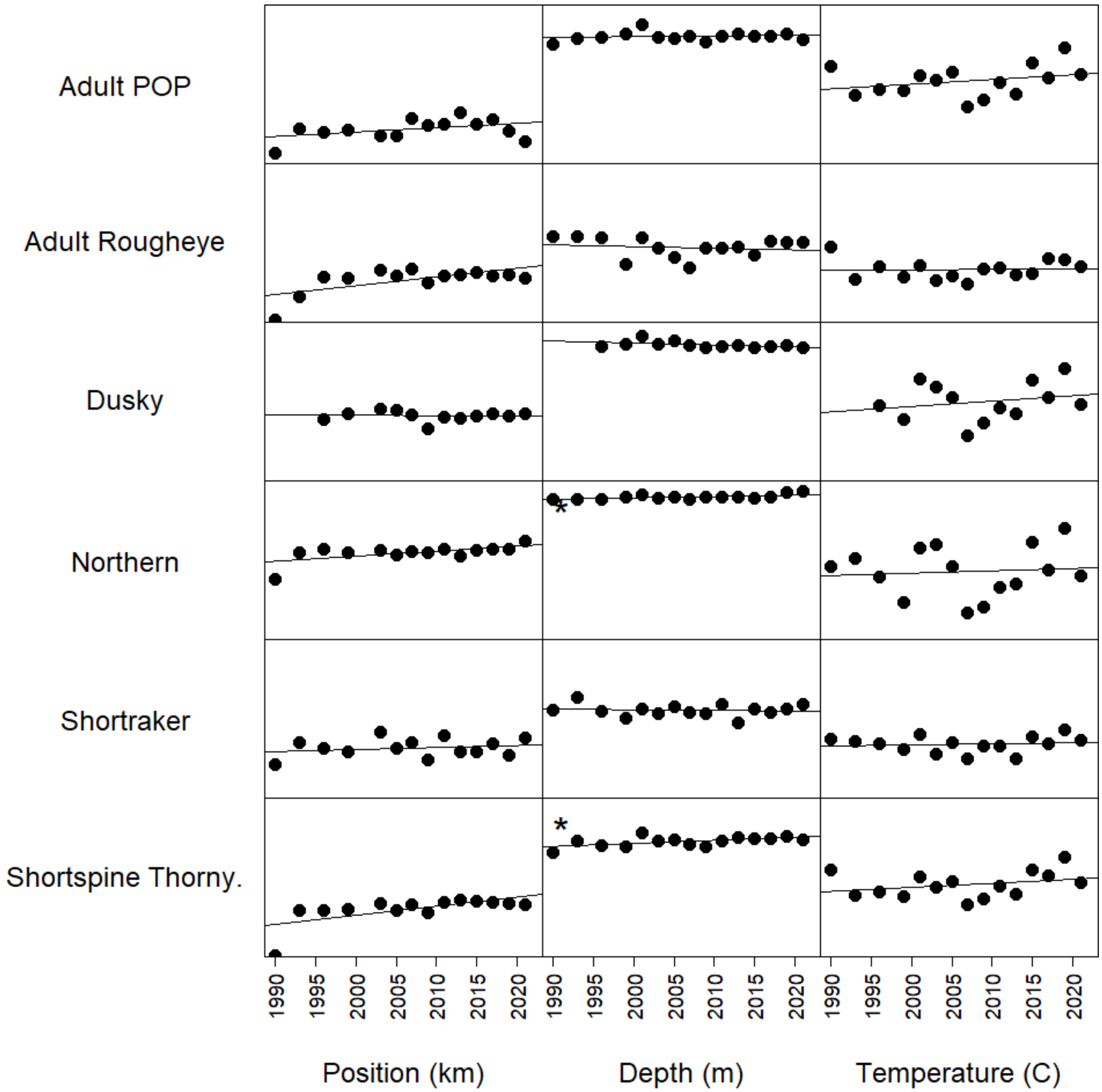


Figure 65: Plots of mean weighted (by catch per unit effort) distributions of six rockfish species-groups along three environmental variables in the Gulf of Alaska. Mean weighted distributions of rockfish species-groups are shown for A) position, B) depth, and C) temperature. Position is the distance from Hinchinbrook Island, Alaska, with positive values west of this central point in the trawl surveys and negative values in southeastward. Asterisk indicates significant trend over the time series.

Multispecies model estimates of time-varying natural mortality of groundfish in the Gulf of Alaska

Contributed by Grant Adams[1], Kirstin Holsman[2], Kerim Aydin[2], Steve Barbeaux[2], Martin Dorn[2], Anne Hollowed[2], Jim Ianelli[2], André Punt[1], Ingrid Spies[2]

[1]School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA
[2]Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: adamsgd@uw.edu
Last updated: November 2021

Description of indicator: We report trends in age-1 total natural mortality for walleye pollock *Gadus chalcogrammus*, Pacific cod *Gadus macrocephalus* and arrowtooth flounder *Atheresthes stomias*, from the Gulf of Alaska (GOA). Total natural mortality rates are based on model estimated sex-specific, age-invariant residual mortality (M1) and model estimates of annual predation mortality (M2) 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 Holsman and Aydin, 2015). CEATTLE has been modified for the GOA and implemented in Template Model Builder (Kristensen et al., 2015) to allow for the fitting of two-sex models, multiple sources of data, time-varying selectivity, time-varying catchability, and random effects. The model is based, in part, on the parameterization and data used for recent stock assessment models of each species (Barbeaux et al., 2018; Dorn et al., 2018; Spies and Palsson, 2018). The model is fit to data from five fisheries and seven surveys, including both age and length composition assumed to come from a multinomial distribution and includes inputs of abundance-at-age from recent stock assessment models of Pacific halibut scaled to the proportion of age-5+ biomass in IPHC management area 3 (Stewart and Hicks, 2019). Model estimates of M2 are empirically driven by bioenergetics based consumption information and diet data from the GOA to inform predator-prey suitability (Holsman and Aydin, 2015; Holsman et al., 2019). The model was fit to data from 1977 to 2021.

Status and trends: The climate-enhanced multispecies model (CEATTLE) for the Gulf of Alaska (GOA) estimates that age-1 pollock, Pacific cod, and arrowtooth flounder total natural mortality has declined in recent years and is below the long-term mean. Similarly, estimates of biomass consumed of pollock, Pacific cod, and arrowtooth flounder as prey across all ages is currently below the long term mean, but has increased for pollock.

Estimated age-1 total natural mortality (M = M1 + M2) for walleye Pollock, Pacific cod, and arrowtooth flounder peaked between 1990 and 2010. At an average of 1.322 yr^{-1}, age-1 M estimated by the model was greatest for pollock and lower for Pacific cod and arrowtooth (females and males), which had averages of 0.373 (arrowtooth females), 0.463 (arrowtooth males), and 0.847 yr^{-1} (Pacific cod). After decreasing in recent years, pollock age-1 M remained slightly lower in 2021 relative to the long-term mean and the values used for single species assessment (age-1 M = 1.39; Figure 66). Additionally, Pacific cod and arrowtooth flounder age-1 M were below the long-term mean after decreasing in recent years, but above the values used/estimated for the single species assessment of 0.2 (arrowtooth females), 0.35 (arrowtooth males), and 0.50 (Pacific cod) in 2018.

On average 210,821 mt of age-1 pollock, 6,802 mt of age-1 arrowtooth flounder, 3,380 mt of age-1 Pacific cod was consumed annually by species included in the model. Across all ages 1,486,512 mt of walleye pollock, 68,700 mt of arrowtooth flounder, and 12,691 mt of Pacific cod was consumed annually by species included in the model (Figure 67). The total biomass of pollock consumed as prey across all ages increased in 2021 compared to 2020, while the total biomass of arrowtooth flounder and Pacific cod consumed has decreased in recent years. The total biomass of pollock, Pacific cod, and arrowtooth flounder consumed as prey across all ages is currently below the long term mean (Figure 70).

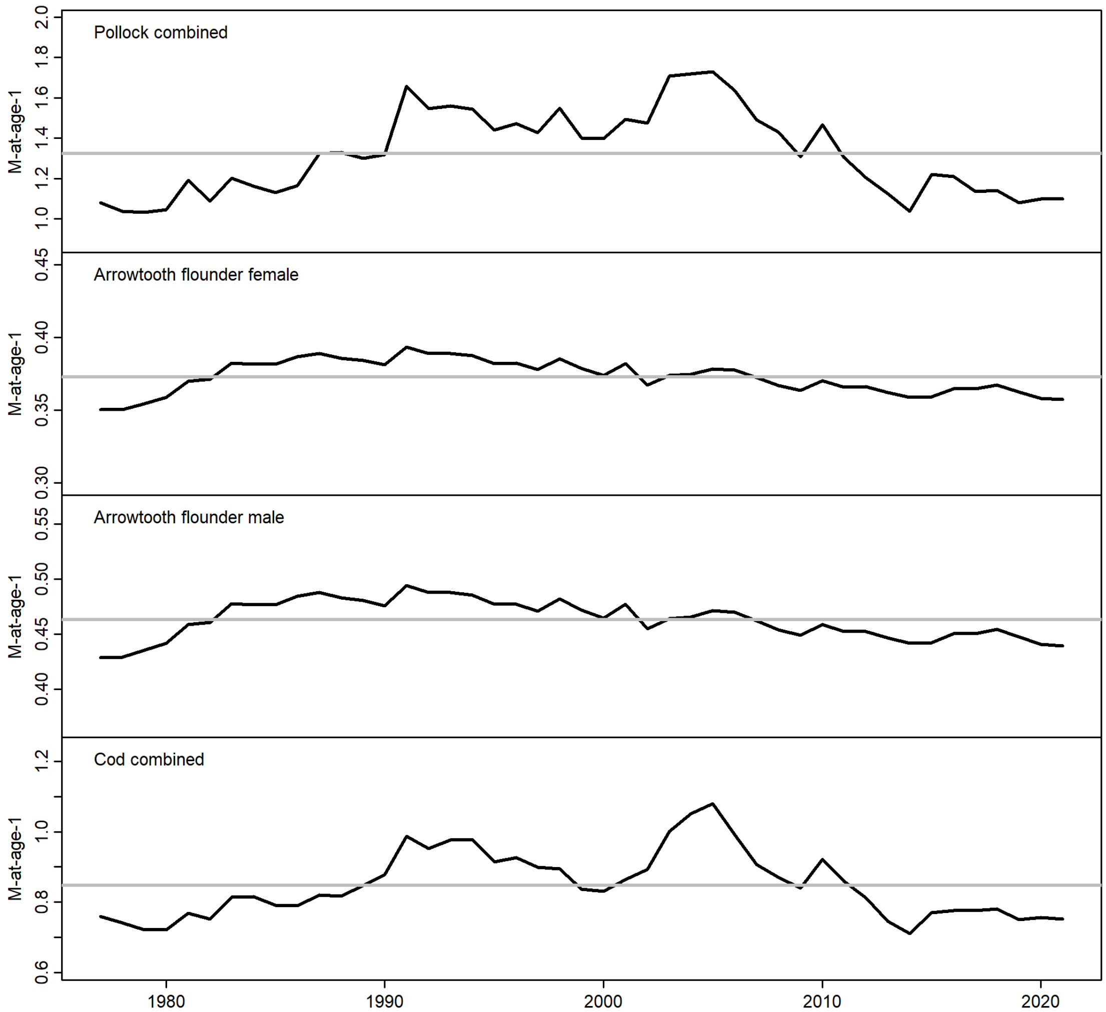


Figure 66: Annual variation in (black line) and average (grey line) total natural mortality (M1 + M2) for age-1 pollock, Pacific cod, and arrowtoth flounder (females and males) estimated from the multi-species GOA CEATTLE model between 1977 and 2021. Note: y-axis differ.

Factors influencing trends: Temporal patterns in total natural mortality reflect annually varying changes in predation mortality that primarily impact age-1 fish (but also impact older age classes). Predation mortality at age-1 for all species was primarily driven by arrowtooth flounder (Figure 68) and arrowtooth flounder biomass has declined and remained relatively constant in recent years. Arrowtooth flounder was the primary consumer of all prey biomass across ages and species included in the model (Figure 69) . Increases in biomass consumed of walleye Pollock in 2021 relative to 2020 reflect elevated recruitment of age-1 Pollock in 2021 that is available to predators.

Implications: We find evidence of continued decline in predation mortality on age-1 pollock, Pacific cod and arrowtooth flounder. Declines in total predator biomass are contributing to an overall decline in total consumption and therefore reduced predation mortality. Between 1990 and 2010, relatively high natural mortality rates reflect patterns in annual demand for prey from arrowtooth flounder, whose biomass peaked during this time period. A strong recruitment of age-1

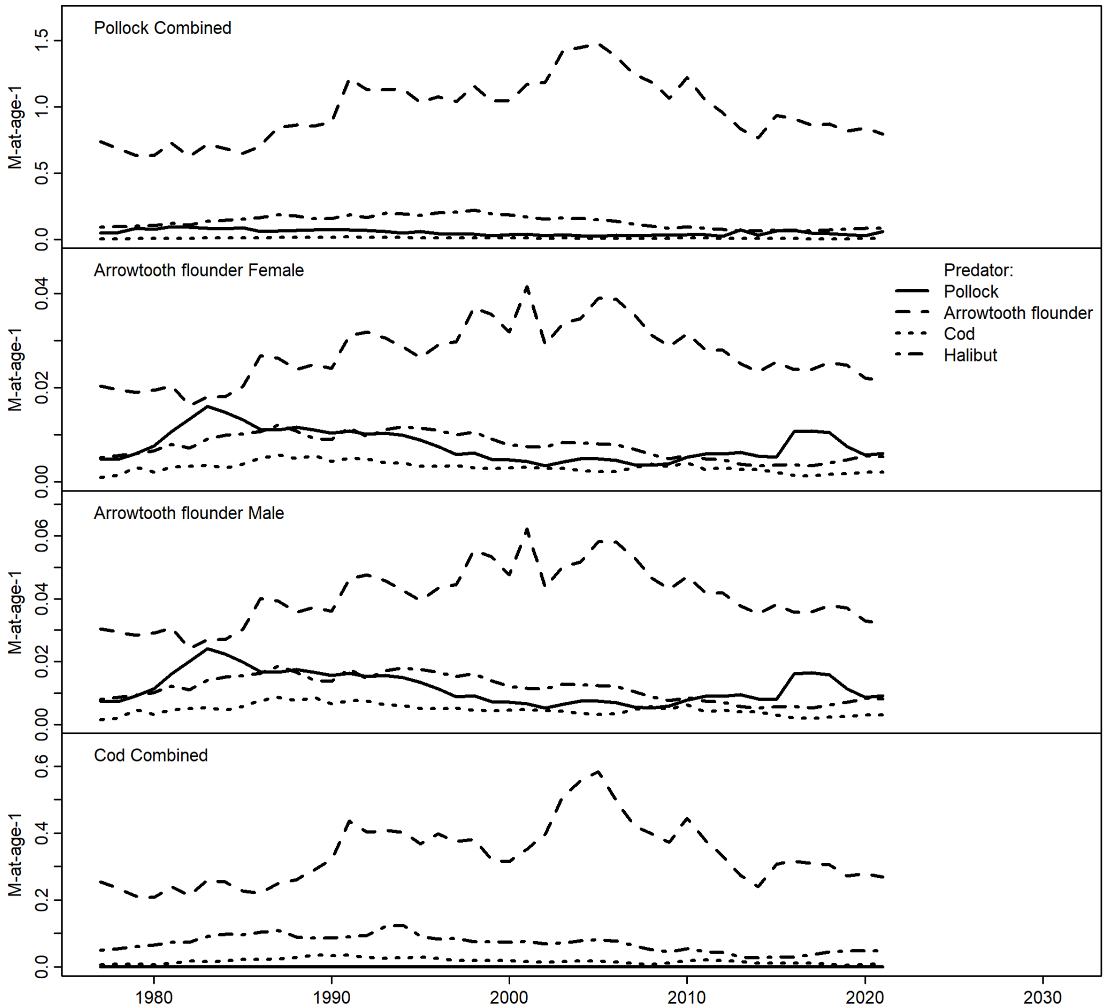


Figure 67: Multispecies estimates of pollock, Pacific cod, and arrowtooth flounder biomass, at all ages, consumed by all predators in the multi-species GOA CEATTLE model. Gray lines indicate mean estimates for each species across all years.

pollock in 2021 led to an increase in biomass of pollock being consumed by predators. Decreases in predation mortality in recent years suggest that the disappearance of the large age-1 recruitment of pollock in 2019 was not due wholly to predation by species included in the model (Figure 70).

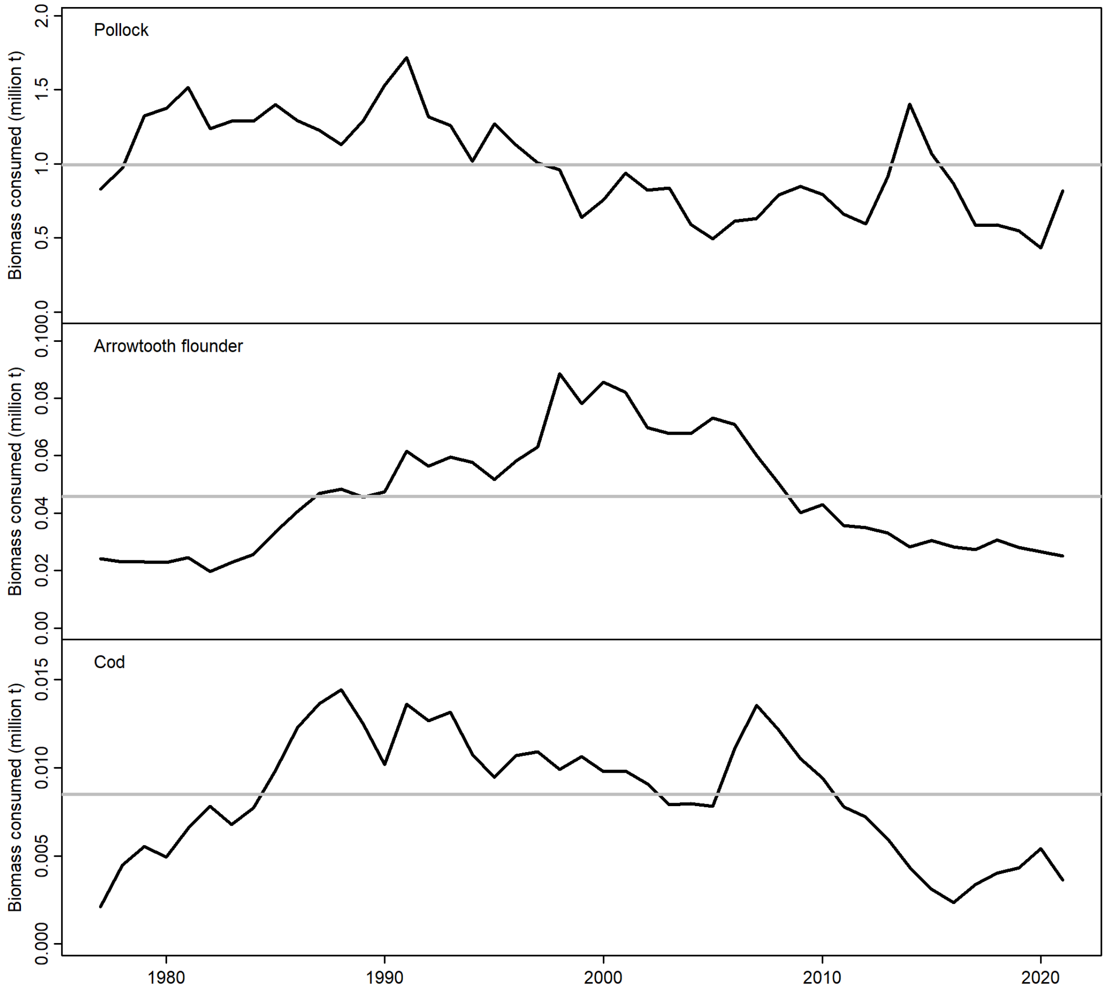


Figure 68: Proportion of total age-1 predation mortality (M2) from pollock, Pacific cod, and arrowtoth flounder (females and males) estimated from the multi-species GOA CEATTLE Model between 1977 and 2018.

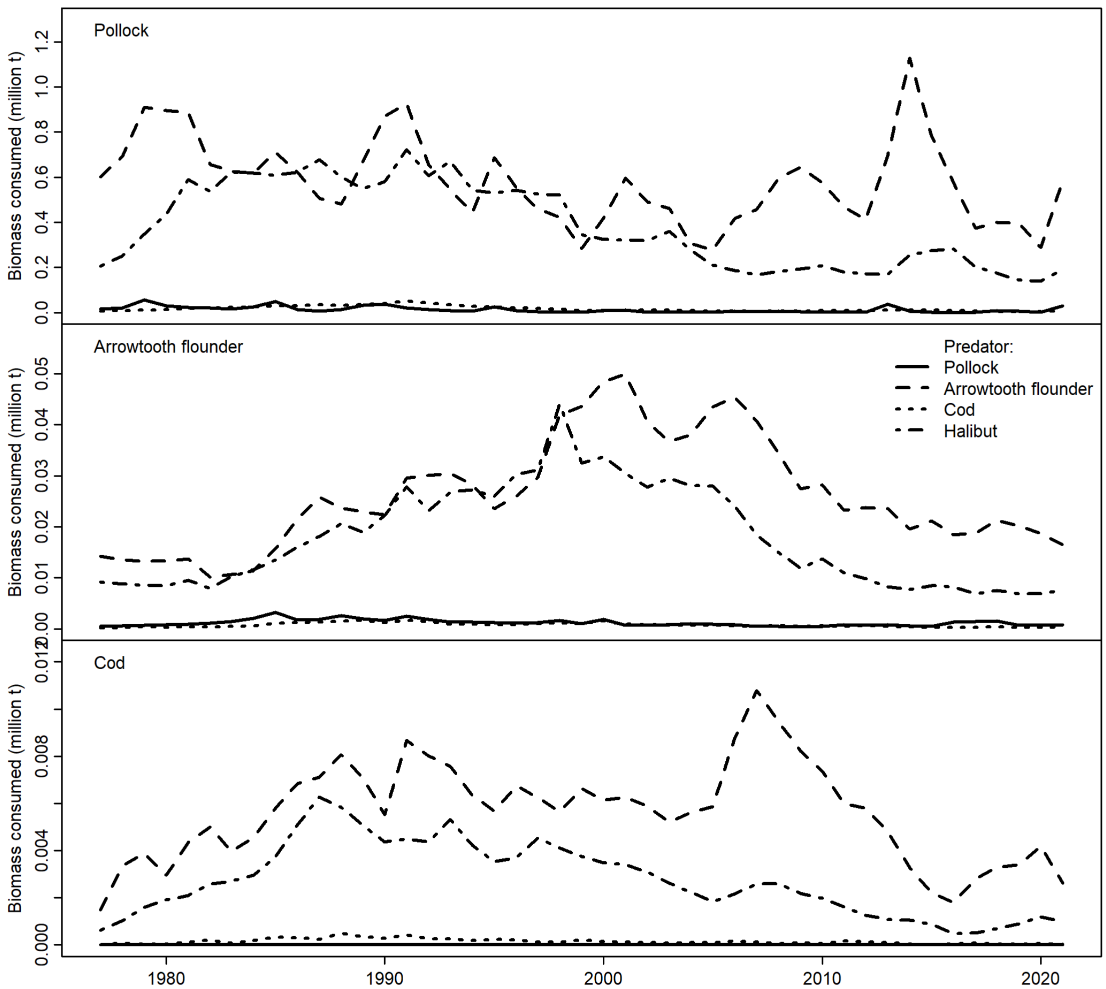


Figure 69: Multispecies estimates of pollock, Pacific cod, and arrowtoth flounder biomass consumed by predator in the multi-species GOA CEATTLE model.

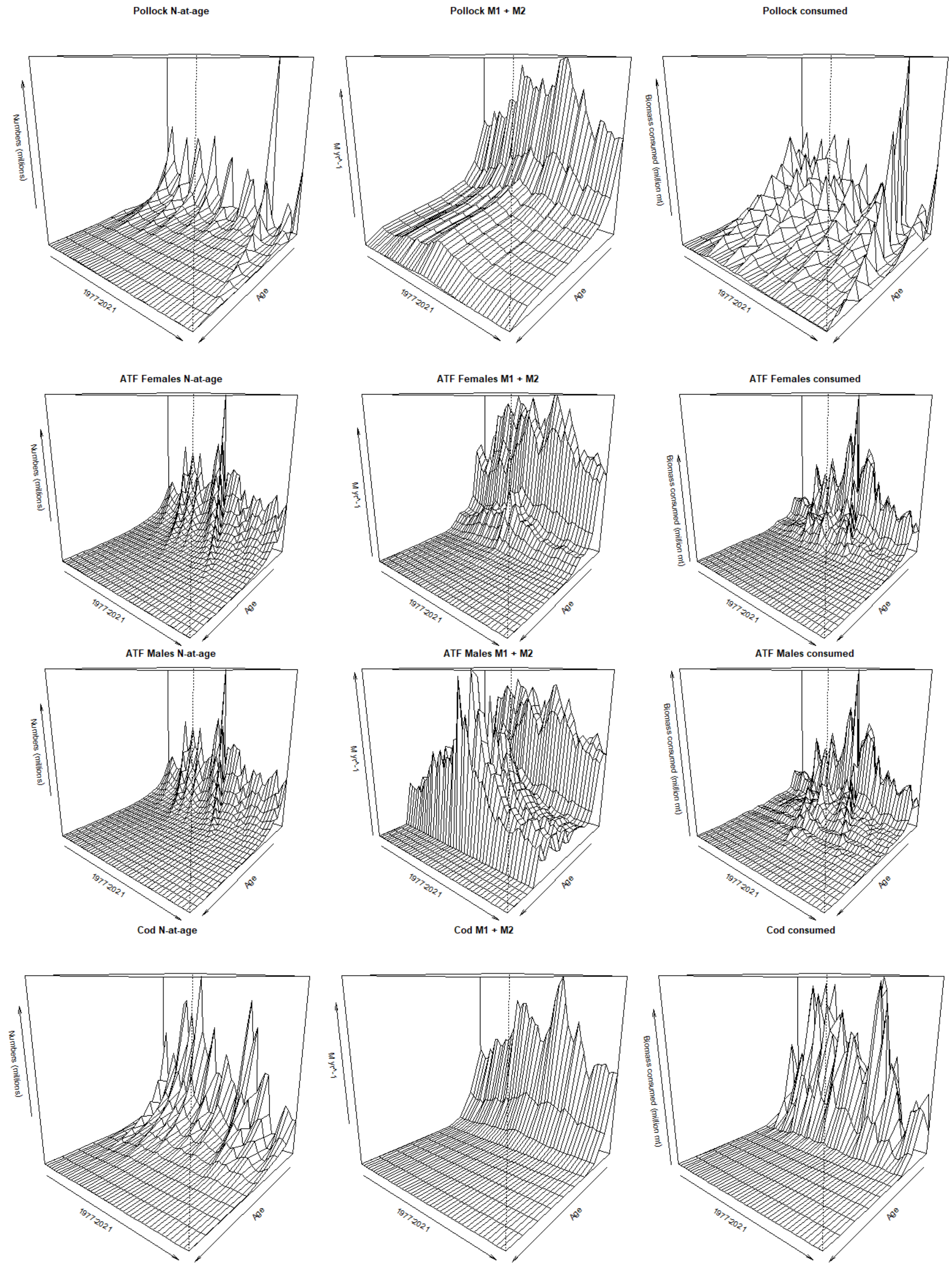


Figure 70: Estimates of pollock, Pacific cod, and arrowtooth flounder (ATF) numbers-at-age, total natural mortality-at-age, and biomass consumed as prey by age from predators in the multi-species CEATTLE model between 1977 and 2021.

Benthic Communities and Non-target Fish Species

Miscellaneous Species—Gulf of Alaska Bottom Trawl Survey

Contributed by Wayne Palsson, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: Wayne.Palsson@noaa.gov
Last updated: October 2021

Description of indicator: RACE bottom trawl surveys in the Gulf of Alaska (GOA) are designed primarily to assess populations of commercially important fish and invertebrates. However, many other species are identified, weighed and counted during the course of these surveys and these data may provide a measure of relative abundance for some of these species. Many of these species are not sampled well by the gear or occur in areas that are not well sampled by the survey (hard, rough areas, mid-water etc.); thus they are encountered in small numbers which may or may not reflect their true abundance in the GOA. The fishing gear used aboard the Japanese vessels that participated in all GOA surveys prior to 1990 was very different from the gear used by all vessels since. This gear difference almost certainly affected the catch rates for some of these species groups. For each species group, the catches for each year were scaled to the largest catch over the time series (which was arbitrarily scaled to a value of 100). The standard error (± 1) was weighted proportionally to the CPUE to get a relative standard error. The percentage of positive catches in the survey bottom trawl hauls was also calculated.

Status and trends: Echinoderm catches are frequent in bottom trawls conducted in all regions where they usually occur in over 80% of catches in each region; however, the trends in relative CPUE have differed among the five regions (Figure 71). During 2021, echinoderms occurred in low abundance in the Shumagin, Yakutat, and Southeastern regions while in the Chirikof and Kodiak regions, 2021 CPUEs were higher than the 2019 values. An increasing CPUE trend is suggested in the Kodiak region. Shrimp CPUEs have been increasing in the Chirikof, Yakutat, and Southeastern regions over the last few surveys, while they have declined in relative abundance in the other areas with respect to historic peaks. Shrimp occurs more frequently in Yakutat and Southeastern catches compared to frequencies farther west. Eelpout CPUE has been variable, with peak abundances occurring in 1993, 2001, 2009, and 2021 in the Shumagin area but were at their lowest observed level in 2019. High abundances of eelpouts were observed in 2003 in the central GOA (Kodiak and Chirikof areas) and have been relatively stable during recent surveys in those regions. Eelpout CPUE in the Yakutat area had the highest ever abundance in 2019 but declined in 2021, closer to historic values. Poacher CPUE's peaked in 1993 and 2015 in the Shumagin area. Poachers have been uniformly in low abundance in the Chirikof, Yakutat, and Southeastern areas and have been variable, but somewhat vary greatly in the Kodiak region where the 2021 CPUE was very low following an historic high in 2019. The CPUE is also highly variable in the Shumagin region but was higher in 2021 than in 2019.

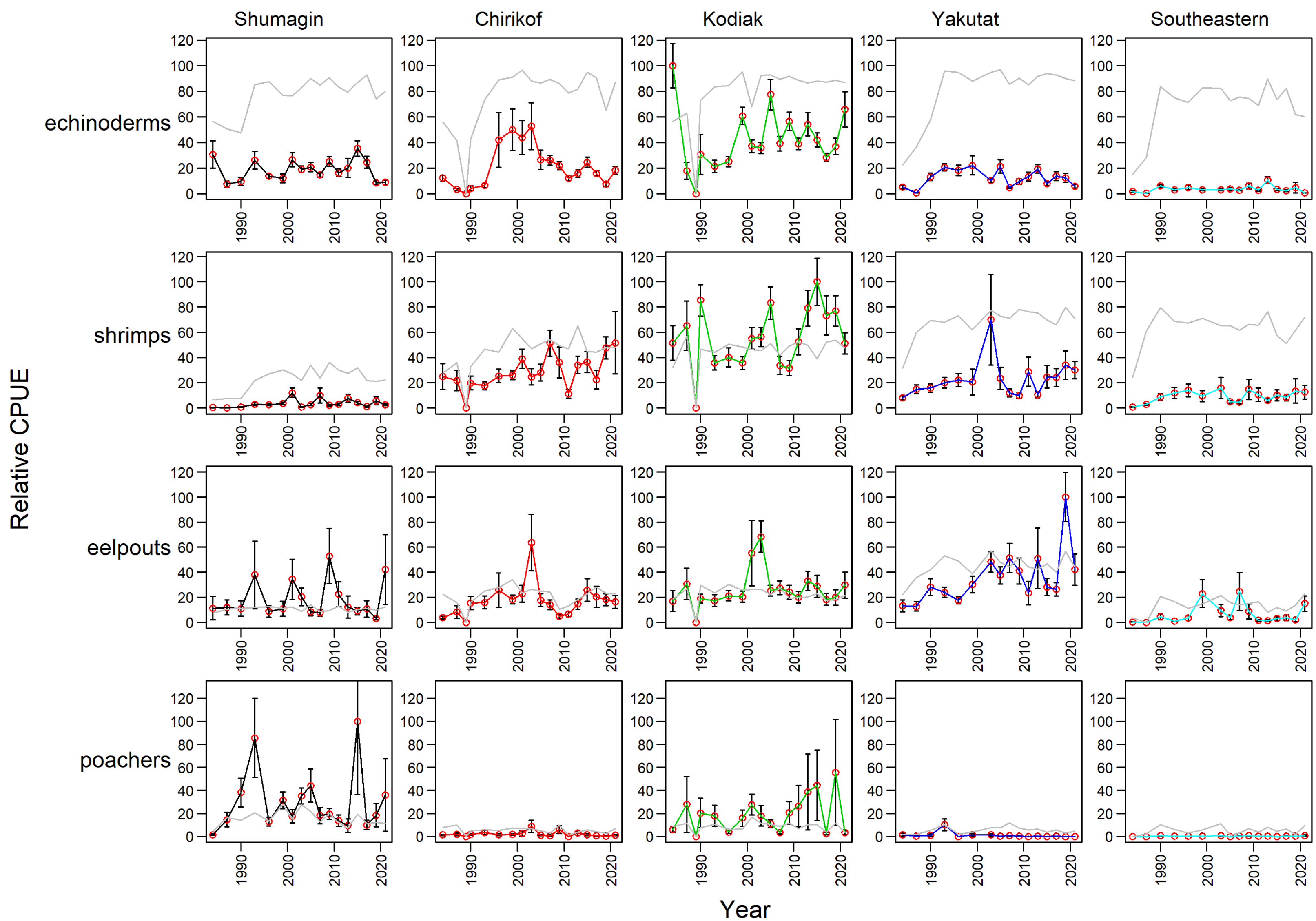


Figure 71: Relative mean CPUE of miscellaneous species by area from RACE bottom trawl surveys in the Gulf of Alaska from 1984 through 2021. Error bars represent standard errors. The gray lines represent the percentage of non-zero catches.

Factors influencing observed trends: Unknown

Implications: The trends in other species in the bottom trawl survey do not appear consistent over time, with the possible exception of recent decreases in echinoderms in the Shumagin, Yakutat, and Southeastern regions.

Seabirds

Seabird Synthesis

Contributed by Mayumi Arimitsu[1], Daniel Cushing[2], Brie Drummond[3], Scott Hatch[4], Tim Jones[5], John F. Piatt[1], Heather Renner[3].
Synthesis compiled by Jane Dolliver[6]
[1]U.S. Geological Survey, Alaska Science Center; Contact: marimitsu@usgs.gov
[2]U.S. Fish and Wildlife Service, Migratory Birds - Alaska; Contact: dan.cushing@gmail.com
[3]U.S. Fish and Wildlife Service, Alaska Maritime National Wildlife Refuge; Contact: Brie_Drummond@fws.gov
[4]Institute for Seabird Research and Conservation; Contact: shatch.isrc@gmail.com
[5]University of Washington, Coastal Observation and Seabird Survey Team; Contact: timothy.t.jones@googlemail.co
[6]Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Last updated: October 2021

Summary Statement: Overall, the status of seabirds in the Gulf of Alaska in 2021 was good (Figure 72). Colonies saw an early onset of breeding (e.g., pelagic cormorants, Middleton Island), generally strong reproductive success across foraging guilds (e.g., glaucous-winged gulls, common murres—3 separate sites), and in several cases, banner years (e.g., tufted puffins, Chowiet Island). These successes indicate, in general, good availability of small forage fish in the Western Gulf. Plankton feeders had mixed reproductive success, within and between species, indicating variability in the availability of lipid-rich plankton. No large-scale mortality event(s) were recorded via monthly beach surveys in the Western Gulf of Alaska but a localized botulism event did occur on Middleton Island affecting kittiwakes and gulls (see Schoen et al. in this Report, p.24). This appears to be the first published instance of botulism type C disease affecting gull family, *Laridae*, in Alaska (Hubálek, 2021)—a pathogen linked to temperature/latitude (Soos and Wobeser, 2010).

Description of indicator: Seabirds are sensitive indicators of changes in the productivity of marine ecosystems, and their populations can signal processes affecting the availability of prey for commercial fish stocks (Warzybok et al., 2018). From field data and observations collected by 5 government, university and non-profit partners, we provide a summary of the best available data on seabirds in the Gulf of Alaska in 2021. We forefront environmental impacts on seabirds (e.g., heatwaves) and interpret changes in seabird mortality, attendance, and reproduction as a reflection of ecosystem productivity and prey availability (Koehn et al., 2021).

In this synthesis, we divide seabirds by preferred prey: fish or plankton, and foraging location: deep or surface because each group responds to a different part of the ocean ecosystem. To describe the status of seabird groups we use three types of information that represent different spatial and temporal scales of seabird responses:

1. **Breeding timing** can represent conditions prior to breeding and/or phenological variation in the environment. Birds arriving to breed at a later date can reflect poor winter and/or spring foraging conditions, or later peaks in ocean productivity.

2. **Reproductive success** which can represent food availability around the colony during the breeding season (summer), with a lower number of fledged chicks generally reflecting a decrease in the local abundance of high-quality prey.

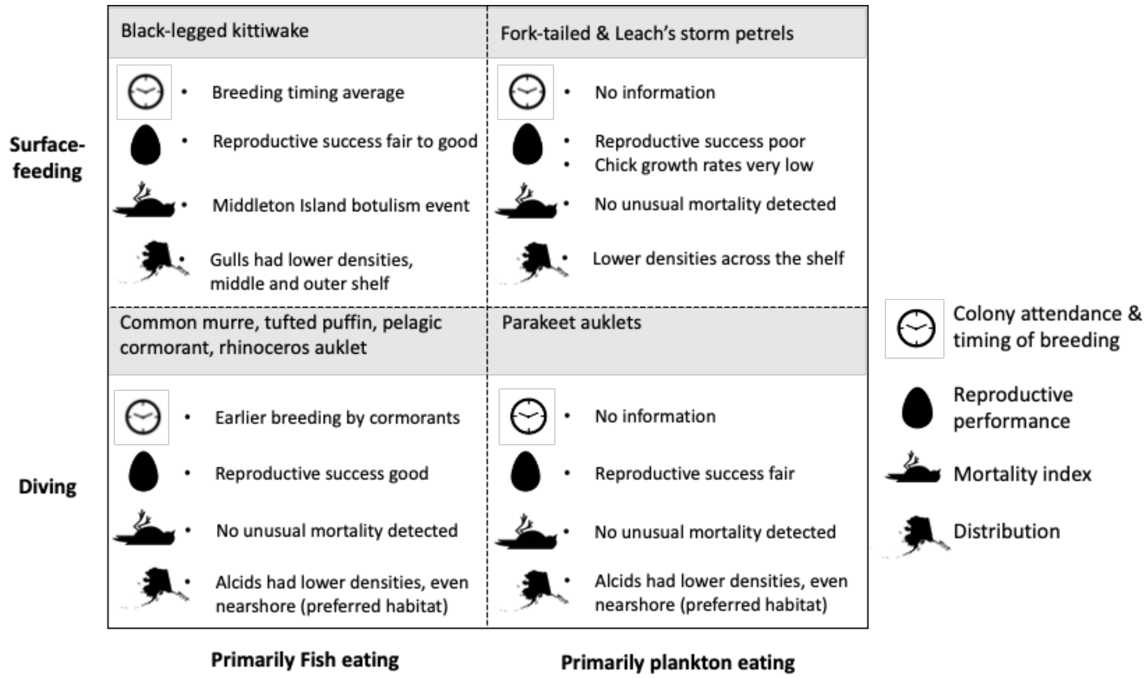


Figure 72: Summary of 2021 status for all seabird feeding guilds (surface-feeding and diving, fish and plankton-eating) in the Gulf of Alaska

3. **Mortality** which gives insight into environmental conditions and ecosystem impacts beyond breeding colonies and the breeding season. Unusual mortality events in the Gulf of Alaska have been linked to declines in prey abundance and quality during recent marine heatwaves (Piatt et al., 2020).

4. **Distribution** which provides area-specific and season-specific index of use as a function of physical environmental drivers that affect the characteristics of the habitat and influence the distribution and availability of prey.

Status and trends:

Fish-eating, surface feeding seabirds: Fish-eating, surface feeding seabirds in the Gulf of Alaska include black-legged kittiwakes *Rissa tridactyla* and glaucous-winged gulls *Larus glaucescens*. These species feed on small schooling fish that are available at the surface (e.g., sand lance, sablefish, capelin and herring), making them potential indicators of processes affecting juvenile groundfish that migrate to the surface to feed.

Breeding timing: *Breeding timing appeared average in 2021.* The timing of breeding by black-legged kittiwakes was average at Middleton Island. Birds part of the experimental, supplemental feeding program laid eggs, on average 7 days earlier (average: ±4 days, range: 0 to + 9), suggesting foraging conditions during the pre-lay period (April through mid-May) were relatively poor in 2021.

Reproductive success: *Reproductive success appeared average in 2021.* All three glaucous-winged gull colonies had above average years in the Gulf (Chowiet, East Amatuli, Saint Lazaria, Figure 73). Naturally foraging, un-fed black-legged kittiwakes showed slightly below average reproductive success in 2021 (Figure 75). Classification of 2021 as a "poor" chick production year on Middleton

Island (Figure 75, Fed-unfed for 2021) is attributed to warmer midsummer ocean conditions and low numbers of energy-rich capelin *Mallotus villosus*. Productivity of black-legged kittiwakes on Chowiet follows a similar pattern. High egg lay rates (reflective of good spring prey conditions) but low hatching success and relatively high chick loss (reflective of diminishing prey availability in the summer). For Chowiet kittiwakes, reproductive success remains below long-term mean although increased from 2019 (Figure 74).

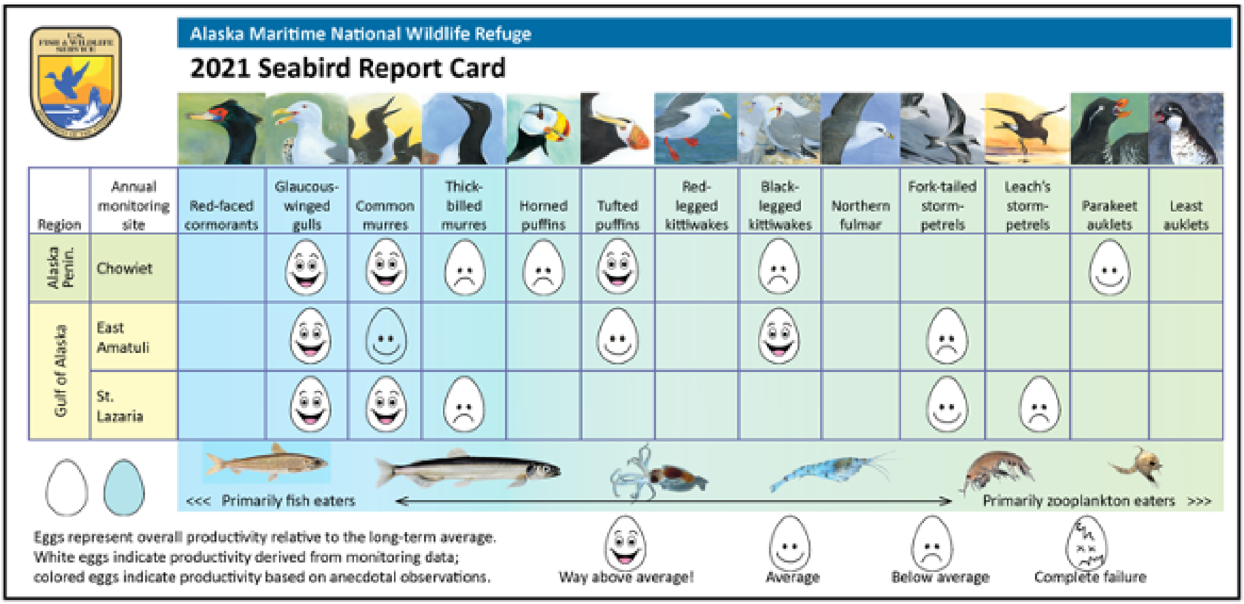


Figure 73: Reproductive success of Gulf of Alaska seabird species, relative to the long-term mean, as assessed by the Alaska Maritime National Wildlife Refuge.

Mortality: *One, localized mortality event occurred on Middleton Island in 2021.* Carcasses submitted to the National Wildlife Health Center tested positive for avian botulism type C, a pathogen often associated with a single, high-use fresh water source and low upland scavenging rates typical of islands (Work et al., 2010, see Schoen et al. in this Report, p.24)

No large-scale mortality event of fish-eating surface-feeding birds was recorded in 2021 based on beach surveys in the western GOA (Figure 76). Like much of Alaska, beach surveys show a late summer, post-breeding mortality pattern, with 2013 reflecting an unusually good reproductive season in the GOA (Figures 76 and 75)

Distribution: *Gulls, terns, and kittiwakes* Laridae *had lower densities in early-May* compared to the long-term mean (2007–2021), particularly on the middle and outer shelf (Figure 77). This continues a trend away from the middle and outer shelf (2017–2021) following the marine heat wave (2014–2016) and stable usage of the inner and oceanic domains (Figure 77).

Fish-eating, diving seabirds: Fish eating, diving seabirds in the Gulf of Alaska include common murres *Uria aalge*, rhinoceros auklets *Cerorhinca monocerata*, tufted puffins *Fratercula cirrhata* and pelagic cormorants *Phalacrocorax pelagicus*. The status of this group is impacted by changes in the availability of small, schooling fish up to ∼ 90 m (300 feet) below the surface, making them potential indicators of feeding conditions that may affect fish-eating groundfish species.

Breeding timing: *Breeding timing was early (pelagic cormorants) in 2021.* Breeding timing of pelagic cormorants on Middleton Island was earlier than the long-term mean (2002-2021), continuing a 10-year trend after progressive delays in breeding, 2002-2011.

Reproductive success: Reproductive success was strong for most fish-eating, diving seabirds in 2021. Pelagic cormorants breeding on Middleton Island fledged the greatest number of chicks in the last 20 years (Figure 78). Rhinoceros auklets also had above-average reproductive success on Middleton, highest in the last 11 monitored years (Figure 79). Though chick production was high, on St Lazaria, rhinoceros auklet chick growth on St Lazaria was below average, reflective of a general trend toward prey-limited conditions in late summer. Common murres (St Lazaria, Chowiet) and Tufted Puffins (Chowiet) continued 4-5 years of above average success (greater than 1SD above average in 2019 and 2021 for tufted puffins) (Figure 74). The below-average success for murres at St. Lazaria and E. Amatuli colonies in 2021 can be attributed to small sample size, and/or extremely local variables (e.g., disturbance, predation).

Mortality index: *No large-scale mortality event was recorded for fish-eating, diving seabirds based on beach surveys in the Western Gulf of Alaska in 2021.* This marks five years since the mass mortality event of common murres linked to the 2014-2016 marine heatwave (red bars - Figure 80).

Distribution: murres, murrelets, puffins and auklets (Alcidae family) had lower densities in early-May compared to the long-term mean (2007–2021), on the outer and oceanic shelf and the inner shelf where they are historically most common (Figure 77). This continues a trend away from the oceanic and outer shelves (2017–2021) following the marine heat wave (2014–2016) (Figure 77). Unlike 2017–2018, 2019–2021 saw no corresponding increase in densities along the inner shelf indicating population reduction without rebound or large-scale shift in spring distributions (Figure 77).

Plankton-eating seabirds: Plankton-eating seabirds in the Gulf of Alaska include surface-feeding species such as Leach's and fork-tailed storm petrels, and diving species such as parakeet auklets (*Aethia psittacula*). The status of these groups are impacted by changes in plankton production, making them potential indicators of feeding conditions that may affect planktivorous groundfish species, including the larvae and juveniles of fish-eating species.

Breeding timing: *No information on breeding timing provided in 2021.*

Reproductive success: *Reproductive success was average for plankton-eating seabirds in 2021.* Parakeet Auklets had average success on Chowiet, continuing a positive, above average trend from 2019 (Figure 74). Saint Larazia fork-tailed storm-petrels also had average reproductive success, althought 2021 continues a declining trend since a high in 2016 (Figure 74), but Leach's storm-petrels did poorly in 2021 as did fork-tailed storm petrels on East Amatuli. With no consistent pattern by species or location, planktonic prey appears patchy in 2021, with the earlier breeding fork-tailed storm petrel consistently outperforming the later- arriving leach's storm-petrel, 2016–2021 (Figure 74).

Mortality index: *No large-scale mortality event was recorded for plankton-eating seabirds based on beach surveys in the Gulf of Alaska in 2021.* The encounter rate of fork-tailed storm-petrels in the Gulf of Alaska was normal in 2021; Leach's storm-petrels are rare in this dataset. Crested auklets last appeared dead on beaches, 2015–2016, following the marine heatwave; no least auklets have been found in the GOA.

Distribution: storm-petrels, shearwaters, fulmars and albatross (Procelariiformes family) had lower densities in early-May compared to the long-term mean (2007–2021) across all domains (inner, middle and outer shelves, oceanic - Figure 5d). This continues a trend away from the middle and outer shelf (2017–2021) following the marine heat wave (2014–2016).

Factors influencing trends and implications for ecosystem productivity: Strong breeding performance observed in many of the fish-eating seabird populations in the Western Gulf of Alaska (both surface-feeders and divers) reflects good availability of small schooling fish in the region. Geographically dispersed populations experienced exceptionally high reproductive outputs in 2021: pelagic cormorants and rhinoceros auklets on Middleton Island, common murres and glaucous-winged gulls breeding on the Alaska Peninsula and in the Western Gulf.

Some closely related species had surprisingly different trends:

1. Common murres had great reproductive success at all locations; thick-billed murres did not. For St Lazaria, sample size may be a factor for thick-billed murres and not expressive of the eastern Gulf at-large.

2. Leach's and fork-tailed storm petrels had mixed success on St Lazaria, Eastern Gulf. While fork-tailed storm-petrels had average productivity this year, the species initiates breeding, on average, 3-4 weeks prior to Leach's storm-petrels. Chick growth rates for both species were the lowest recorded in 30 years, suggesting fork-tailed storm petrels benefited from fair-to-good zooplankton availability in the spring which decreased sharply and significantly during the summer, causing adults of both species to struggle to feed chicks.

3. Black legged kittiwakes had below average reproductive success on Middleton and Chowiet but an above average success on East Amatuli. Many reproductive failures happened in the second half of the seaon in 2021. This may be due to a lack of smaller, age-0 fish (e.g., pollock, herring) available for parents to feed small chicks. Prey was limited at Middleton Island, given the large difference in reproductive success between naturally-fed and supplementally-fed pairs (Figure 75).

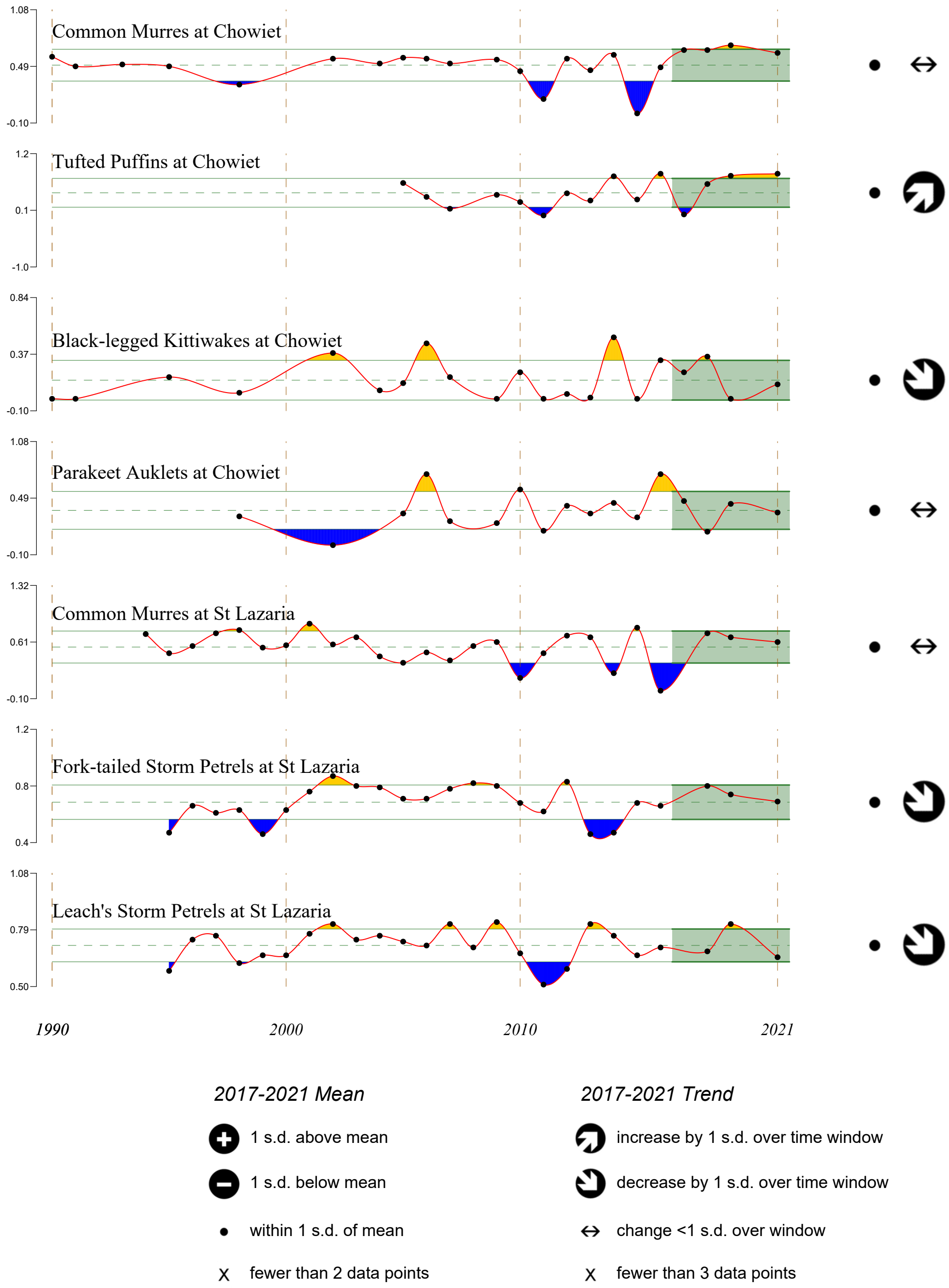


Figure 74: Time series of reproductive success of some piscivorous and zooplanktivorous seabird species at Chowiet (western GOA) and St Lazaria (eastern GOA).

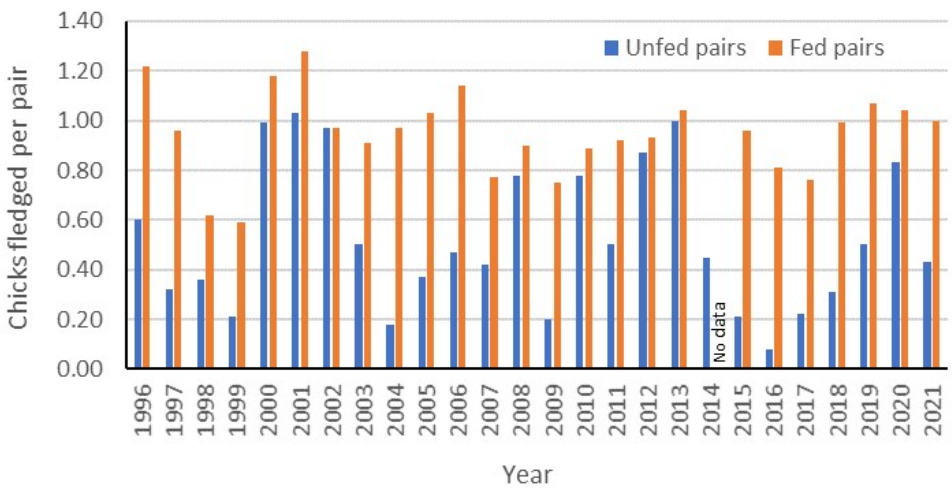


Figure 75: Annual reproductive output for black-legged kittiwakes on Middleton Island. Figure provided by the Institute for Seabird Research and Conservation, September 2021.

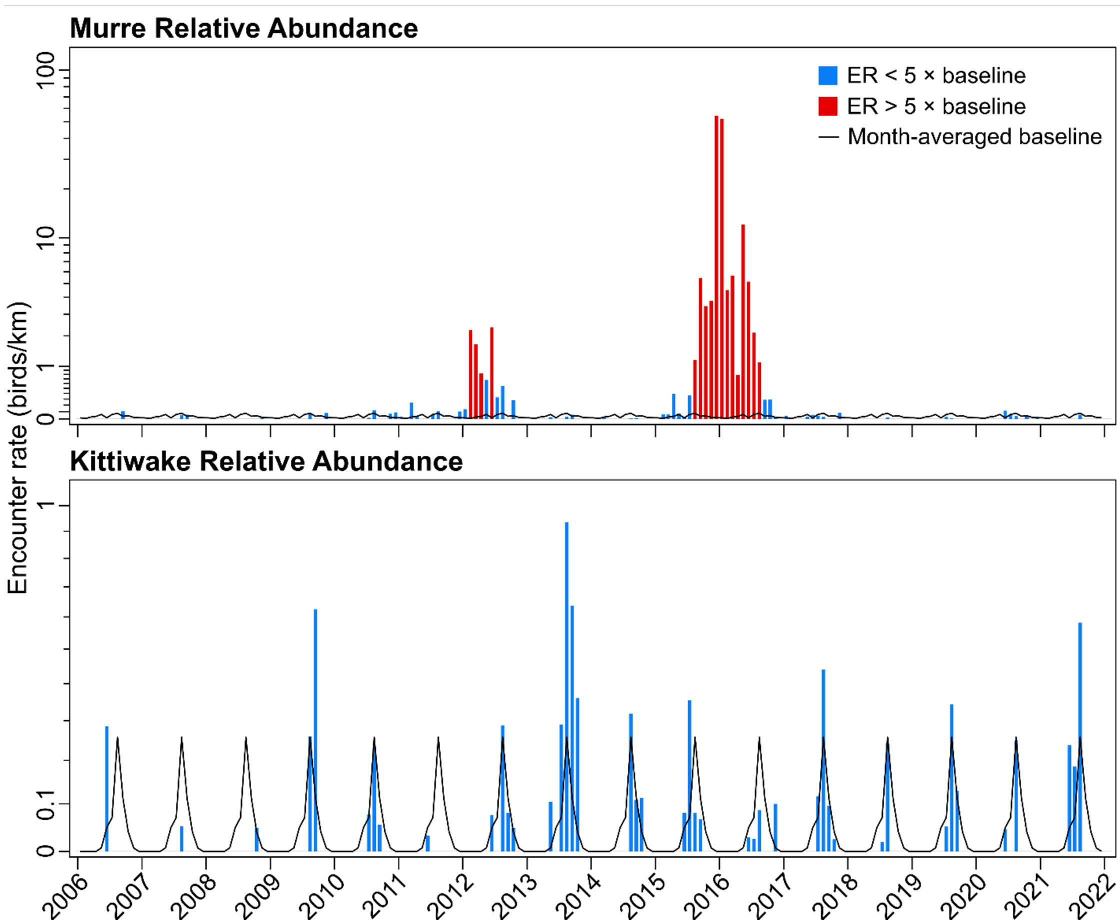


Figure 76: The number of dead kittiwakes encountered per km of beach surveyed by citizen scientists in the Gulf of Alaska. The black line is the month-averaged baseline, blue bars are single month averages. Red bars (none present) would indicate single month averages reflecting regional mortality events at 5x the baseline encounter rate. Surveys reflect regional trends, but are biased toward more accessible beaches in areas of higher population density. Figure provided by the Coastal Observation and Seabird Survey Team (COASST), October 2021.

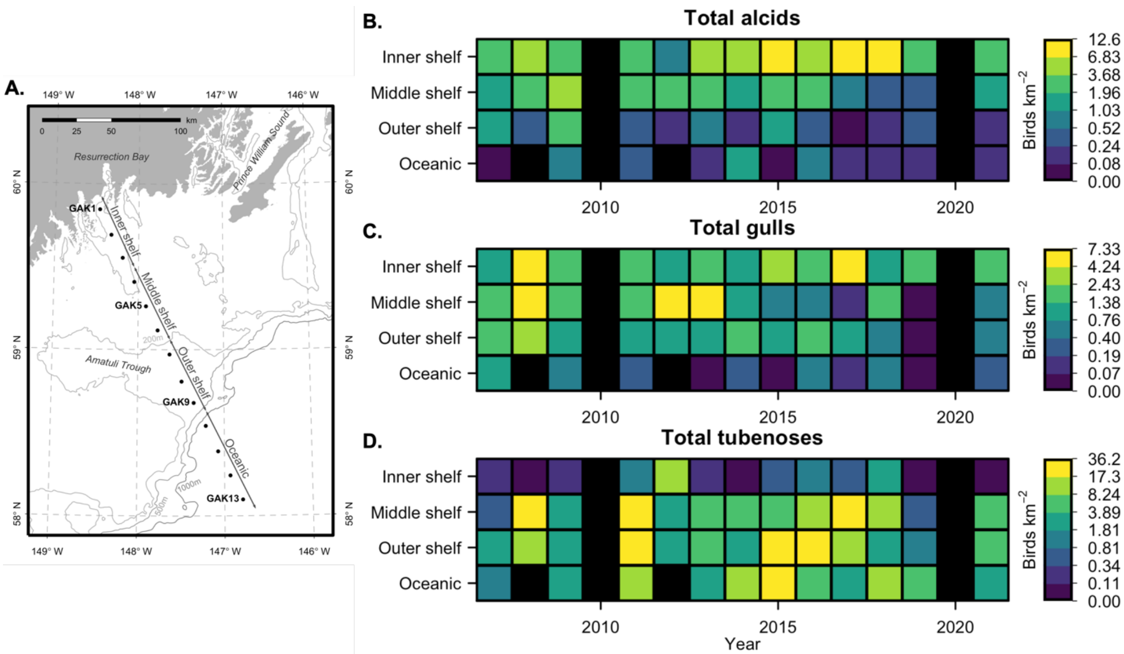


Figure 77: The spring Seward Line in the northern GOA, and four domains used for analysis (5a). Mean densities (birds km^{-2}) of major seabird taxonomic groups within domains during spring Seward Line cruises, 2007–2021 (5b-d). Black indicates no seabird surveys were conducted.

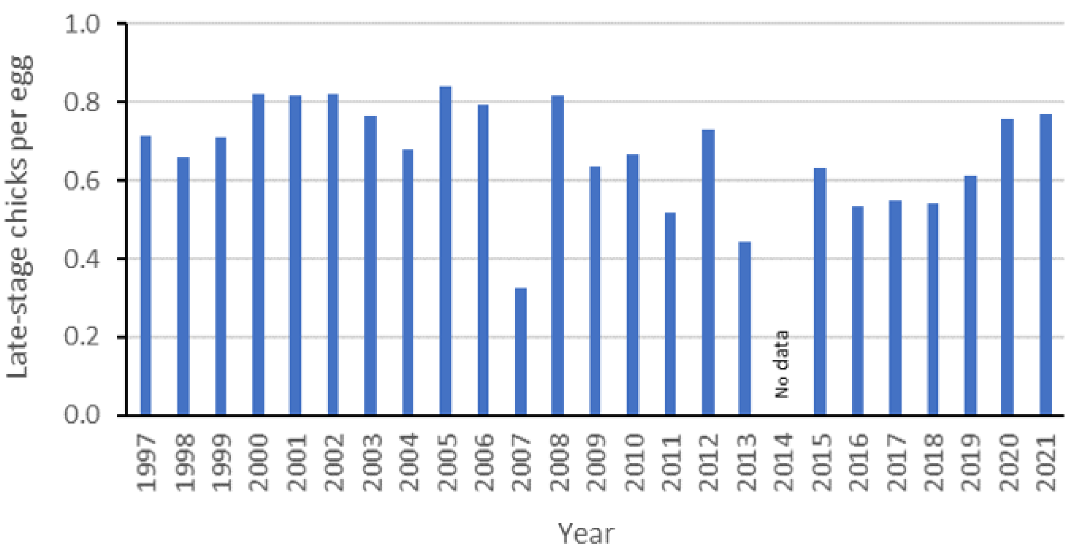


Figure 78: Reproductive success of pelagic cormorants breeding on Middleton Island. Figure provided by the Institute for Seabird Research and Conservation, October 2021.

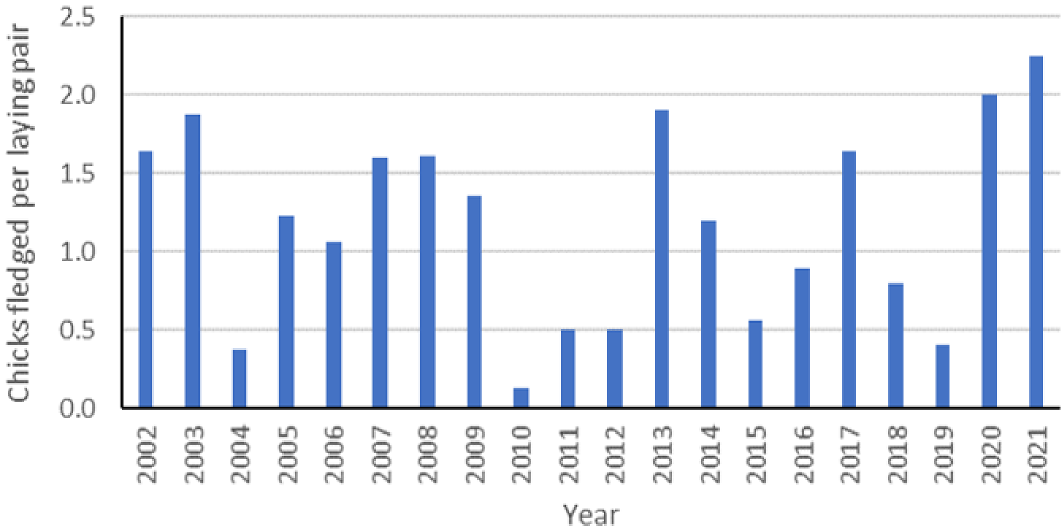


Figure 79: Reproductive success of rhinoceros auklets breeding on Middleton Island. Figure provided by the Institute for Seabird Research and Conservation, October 2021.

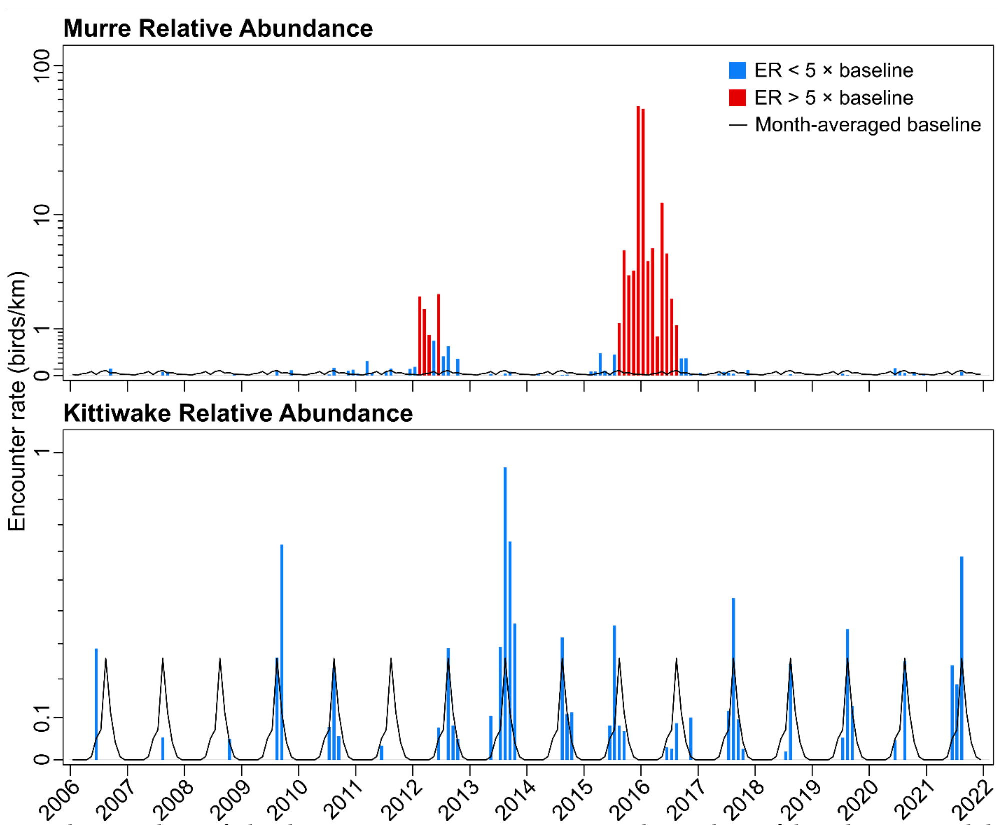


Figure 80: The number of dead common murres encountered per km of beach surveyed by citizen scientists in the Gulf of Alaska. The black line is the month-averaged baseline, blue bars are single month averages, red bars are single month averages reflecting regional mortality events at 5x the baseline encounter rate. Data show regional trends, but are biased toward more accessible beaches in areas of higher population density. Figure provided by the Coastal Observation and Seabird Survey Team (COASST), October 2021.

Methods:

- The Coastal Observation and Seabird Survey Team (COASST) and regional partners provided a standardized measure of relative beached bird abundance collected by citizen scientists. Information for the two most data-rich species are included in this Report: common murres and black-legged kittiwakes, representatives of the diving, fish eating group and the surface feeding, fish eating group respectively. Note that data collection is biased toward accessible beaches close to population centers (Figure 81).

- The Institute for Seabird Research and Conservation (ISRC) provided data on breeding timing and/or reproductive performance of pelagic cormorants, rhinoceros auklets and black-legged kittiwakes on Middleton Island (Figure 81). These data have been collected since the mid-1990s, including an experiment involving feeding a group of kittiwakes to highlight the effect of food availability on the reproductive performance of wild-foraging birds.

- USFWS used vessel-based seabird surveys conducted as a component of multidisciplinary sampling of the Seward Line, during spring (typically the first 10 days of May), 2007–2021, to examine cross-shelf distribution of numerically dominant seabird taxonomic groups. Seabird surveys were conducted while the vessel was underway using USFWS modified strip transect protocol (Kuletz et al., 2008), subsequently divided into $\sim$ 3 km transects. For each year, transects within 10 km of each of the 13 stations along the Seward Line were used to calculate densities (birds km^{-2}) for each station-centered cell; these station-centered values were then averaged within each of 4 domains (Inner shelf, Middle shelf, Outer shelf, Oceanic). Alcids (murres, murrelets, puffins, auklets) are sub-surface divers that exploit prey in the water-column but have high energetic costs of flight. The most abundant alcid species in this region are primarily fish-eaters. Gulls (kittiwakes, gulls, terns) have highly maneuverable low-speed flight and forage on prey (primarily fish) at and near the water surface. Tubenoses (Procelariiformes: storm-petrels, shearwaters, fulmars, and albatrosses) have efficient long-range flight and use their acute olfactory sense to locate food. They feed on squid and other invertebrates and a variety of fish. Two abundant local breeders (fork-tailed storm-petrel and northern fulmar) are surface-feeders, while migratory shearwaters feed both at the surface and dive for prey.

- The Alaska Maritime National Wildlife has monitored seabirds at colonies around Alaska in most years since the early to mid-1970's. Time series of annual breeding success and phenology (and other parameters) are available from over a dozen species at eight Refuge sites in the Gulf of Alaska, Aleutian Islands, and Bering and Chukchi Seas. Monitored colonies in the Gulf of Alaska include Chowiet (Semidi Islands), East Amatuli (Barren Islands), and St. Lazaria (southeast Alaska) islands (Figure 81). Egg icons are determined using a nonparametric bootstrap approach. For each species and location, using all previous years' data, mean bootstrap quartiles were generated using 1000 bootstrap samples and delineated as follows: current year's values above the mean 75th percentile received "big smiley" faces; current year's values between the mean 25th–75th percentile received "smiley" faces; current year's values below the mean 25th percentile received "frowny" faces; current year's values below .01 received "broken" faces.

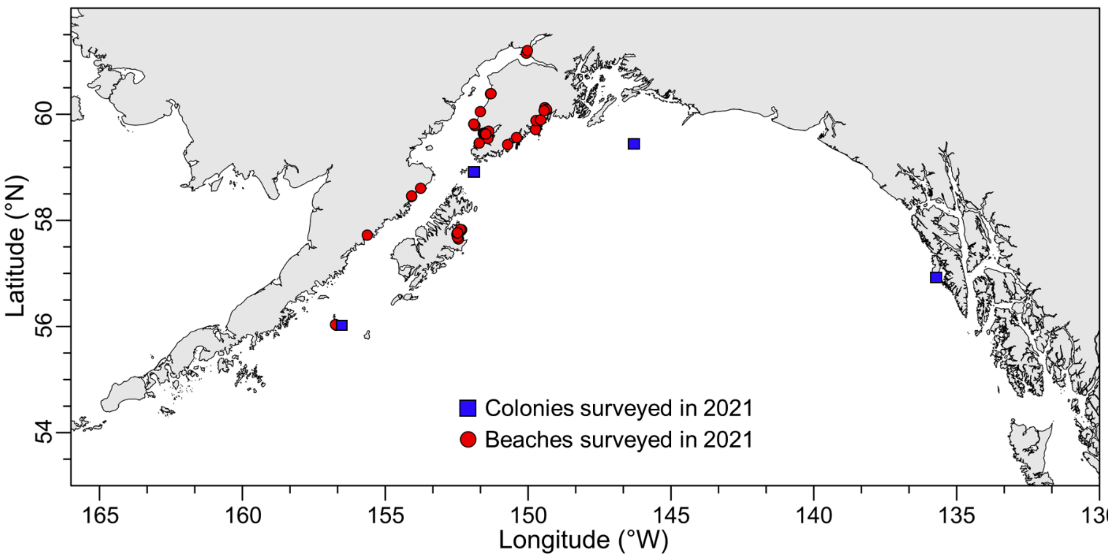


Figure 81: Location of seabird information provided in 2021. Red circles represent beaches surveyed for dead birds by citizen scientists as part of the COASST program in 2021, in the Gulf of Alaska. Sheltered, interior Southeast Alaska beaches not included on map or in Gulf of Alaska encounter rate calculations. Blue squares indicate the locations of seabird colonies where information was collected on colony attendance and/or reproductive performance in 2021 by other partners (ISRC: Middleton Island; USFWS: Alaska Maritime National Wildlife Refuge). Base map provided by COASST.

Marine Mammals

Trends in Humpback Whale Calving in Glacier Bay and Icy Strait

Contributed by Christine Gabriele, Janet Neilson, and Andrea R. Bendlin, Glacier Bay National Park and Preserve, P.O. Box 140, Gustavus, AK 99826
Contact: chris_gabriele@nps.gov
Last updated: September 2021

Description of indicator: Humpback whales and groundfish target the same lipid-rich prey (i.e., forage fish and euphausiids), therefore trends in whale reproductive success may indicate changes in prey quantity and/or quality available for both groundfish and humpback whales in the eastern Gulf of Alaska. From 1985–2021, we used consistent methods and levels of effort to monitor individually-identified humpback whales annually from June 1–August 31 in Glacier Bay and Icy Strait (Gabriele et al., 2017). We photographically identified and counted the number of different whales and documented the number of calves-of-the-year. From these data we can document 1) number of whales; 2) number of calves; 3) crude birth rate (CBR) (defined as the number of calves divided by the total whale count for each year); 4) within-season calf survival; and 5) return rate of calves in subsequent years as juveniles and adults; and 6) indicators of health/body condition for mothers and calves.

Status and trends: Humpback whale productivity and juvenile survival in Glacier Bay and Icy Strait declined sharply beginning in 2014 (Neilson et al., 2017; Gabriele and Nielson, 2018, 2019; Gabriele et al., 2021) after many years of steady reproductive success (Gabriele et al., 2017), likely due to ecological disruptions brought on by warm ocean conditions including the 2014–2016 marine heatwave (Piatt et al., 2020; Arimitsu et al., 2021; Suryan et al., 2021). In 2020 and 2021, humpback whale calving and juvenile return rates returned to more typical levels as compared to 1985–2013 (Table 3, Figure 82).

Table 3: Humpback whale calf production and survival observations in Glacier Bay and Icy Strait, Alaska. *None have been re-sighted as juveniles. Crude birth rate is calculated by dividing the number of calves by the total number of whales. **Overall calf disappearance rate for 2014–2019 is 7 out of 37 (18.9%).

Time Period	Number of Calves	Crude Birth Rate (CBR)	Number of calves lost (%)**
1985–2013	mean 9.3 (range 2–21)	mean 9.3 (range 3.3–18.2)	8 (4%)
2014	14*	8	5 (36%)
2015	5*	3	0
2016	0*	0.6	0
2017	2*	1.6	1 (50%)
2018	1*	1.0	1 (100%)
2019	2	1.3	0
2020	12	7.4	0
2021	11	6.6	1(9%)

We observed 11 cow/calf pairs in June-August 2021 and no additional ones outside this main study period. We computed a CBR of 6.6% based on a preliminary whale count of 166 whales. The 2021 CBR represents a positive trend compared to the 2014-2019 period (including 2014-2016 and 2019 marine heatwave years; mean = 2.5%), yet lower than typical CBRs prior to 2014 (1985-2013 mean = 9.3%; Table 3, Figure 82).

Most mothers in 2021 appeared to be in sub-optimal body condition based on visible scapulae, an overall "angular" appearance, the presence of a post-cranial depression, and rough skin (Figure 83). In the 1990s and 2000s, it was typical to see a few mothers that looked moderately emaciated in the spring but by mid to late summer their body condition would improve. In recent years including 2021, many of the mothers still looked emaciated at the end of summer. All calves in 2021 appeared to be in relatively good physical condition throughout the summer. However, we saw one incidence of apparent mid-season calf mortality this year, which is uncommon but has occurred more frequently in recent years (Table 3).

We documented two yearlings in 2021 (#2659, calf of #1295 and #2689, calf of #1479) and a two year-old (#2652, calf of #219, born in 2019). None of the other Glacier Bay/Icy Strait calves born since 2014 have been documented as juveniles in Southeast Alaska or elsewhere. Sightings outside our study area relied on the geographically expanded matching effort using the HappyWhale automated matching system.

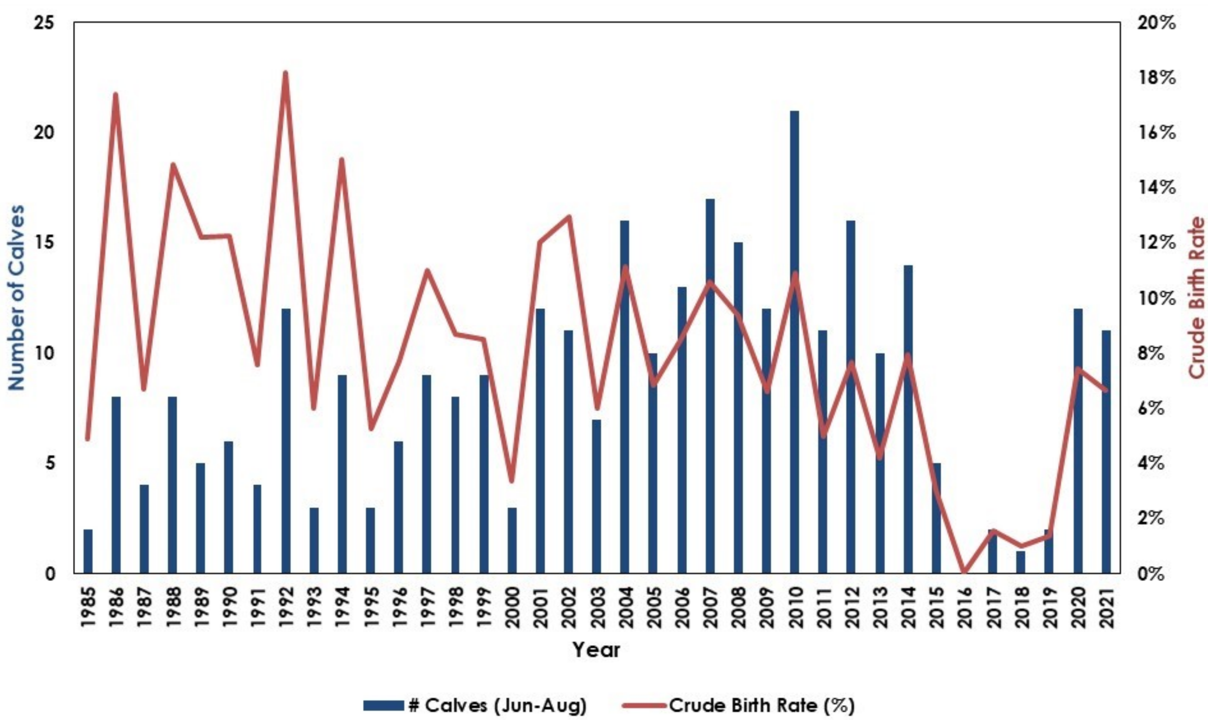


Figure 82: Annual number of calves (blue bars) and crude birth rate (CBR, red line) in Glacier Bay-Icy Strait, 1985-2021. The preliminary CBR for 2021 is 6.6% based on a whale count of 166 individually identified whales for June-August.

Factors influencing observed trends: A major factor influencing the relatively high number of calves in 2021 is that very few females had calves in 2015–2019. Prior research indicates that in Southeast Alaska, adult female humpback whales tend to have a calf every 2–3 years (Gabriele et al., 2017). The sharp decline in calving since 2015 (Gabriele et al., 2021) meant an unusually high number of available females in the winter 2019–2020 breeding season, thus creating an opportunity for good calving numbers in 2021. Eight of the eleven 2021 mothers were sighted in the study area every year since 2016, but the return of three additional reproductive females to the study area was also a factor in the observed trend.

Three of this year's mothers had not previously been observed with a calf. One new mother was of known age (age 11) and the other two mothers' estimated ages were 10 years. Therefore, recruitment of new mothers into the breeding population is also a factor in the observed calving trend. The typical age at first calving for this population has been estimated at 12 years (Gabriele et al., 2007, 2017). The ages of the other eight mothers were 21–33 years.

Food and feeding are clearly important factors in whale reproduction and survival, but in the absence of standardized forage species monitoring in Glacier Bay and Icy Strait, we are not able to comment definitively on foraging conditions in 2021. The increase in calf production in 2020–2021 suggests sufficiently good feeding conditions for females prior to conception, as well as during pregnancy and lactation. Relying on indirect indicators of positive foraging conditions, in 2021 we saw a continuation of the 2020 trend (Neilson and Gabriele, 2021) toward pairs, trios and larger groups of whales that were conspicuously absent in 2014–2018.

Implications: The observed improvement in humpback whale productivity and apparent feeding conditions may indicate that groundfish also experienced better prey availability. The 2020 and 2021 observations of a more typical rate of calf production and survival are signs of population resiliency that may continue, assuming a prey base that promotes whale health and reproduction. However, the lasting ecological effects of the 2014–2016 marine heatwave and the persistence of warm conditions through 2019 make it unclear if the Gulf of Alaska will return to pre-heatwave conditions (Suryan et al., 2021).

Figure 83: Health assessment photographs of mother #1896 on showing visible scapula (A) and moderately mottled skin (B) that characterize poor body condition. This female lost her calf in late July and was seen feeding alone for the rest of the summer.

Cetacean distribution in the Gulf of Alaska – results from the 2021 PacMAPPS survey

Contributed by Jessica Crance, Kim Goetz, and Robyn Angliss
Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: jessica.crance@noaa.gov
Last updated: September 2021

Description of indicator: Cetaceans can be indicators for ecosystem health because they feed on a variety of prey, including euphausiids, amphipods, and forage fish, but also commercially important fish such as sablefish. Additionally, many large baleen whale species target the same lipid-rich prey as groundfish (i.e., forage fish and/or euphausiids). As such, the distribution of cetaceans throughout a region may be indicative of trends in their corresponding prey fields. To determine the distribution of cetaceans in the Gulf of Alaska, a large scale visual and passive acoustic marine mammal survey supported by the U.S. Navy and the AFSC was conducted in August of 2021 in the northern Gulf of Alaska. The survey area was split into two different strata: coastal (30 m to 500 m isobath) and slope (500 m to 4000 m). Tracklines were randomly generated throughout the survey area. Marine mammals were visually sighted and identified using 25x big eye binoculars to obtain distribution, density, and abundance information. Mark-recapture distance sampling methods via independent double platforms were used to estimate g(0) (trackline detection probability, and correction factor for possible missed sightings) (Borchers et al., 1998). Real-time passive acoustic monitoring was conducted via sonobuoys deployed every ∼30 nm to obtain an even census of vocalizing marine mammal distribution using methods described in Crance et al. (2017). The following is a description of the field project and basic observations; analytical results will be provided in 2022.

Status and trends: Marine mammals were sighted in both strata of the survey area. A total of 667 sightings (including duplicates and possible resights) of cetaceans occurred during the survey (Figure 84). The two most commonly sighted large whale species were humpback (*Megaptera novaeangliae*) and fin (*Balaenoptera physalus*) whales, with a total of 137 and 98 sightings, respectively. Humpback, gray (*Eschrichtius robustus*), and North Pacific right (*Eubalaena japonica*) whales were only sighted in the coastal strata (Table 4). Large concentrations of humpbacks were sighted in the nearshore waters around Kodiak Island, particularly around Albatross Bank (Figure 84), which was identified as a Biologically Important Area for feeding for humpbacks in 2015 (Ferguson et al., 2018). Fin whales were primarily sighted in the coastal strata, but were also occasionally sighted in the slope strata. Killer whales were primarily sighted in the coastal strata; note these sightings have not yet been separated out by ecotype. Sperm whales were found almost exclusively in the slope strata, in waters deeper than 500 m. Very few sightings occurred in the slope 3 stratum, the farthest east (Figure 84). Acoustic detections are in good agreement with visual sighting results, and as such are not included here.

Four unique right whales, two during each of two sightings, were found during the survey, more than in any other cetacean survey in the Gulf of Alaska. Both right whale sightings occurred along Albatross Bank, an area known for being highly productive and having high concentrations of zooplankton. This area was identified as a Biologically Important Area for feeding for North Pacific right whales in 2015 (Ferguson et al., 2018). There was evidence of feeding (feces present, water being expelled from the mouth) during both right whale sighting events.

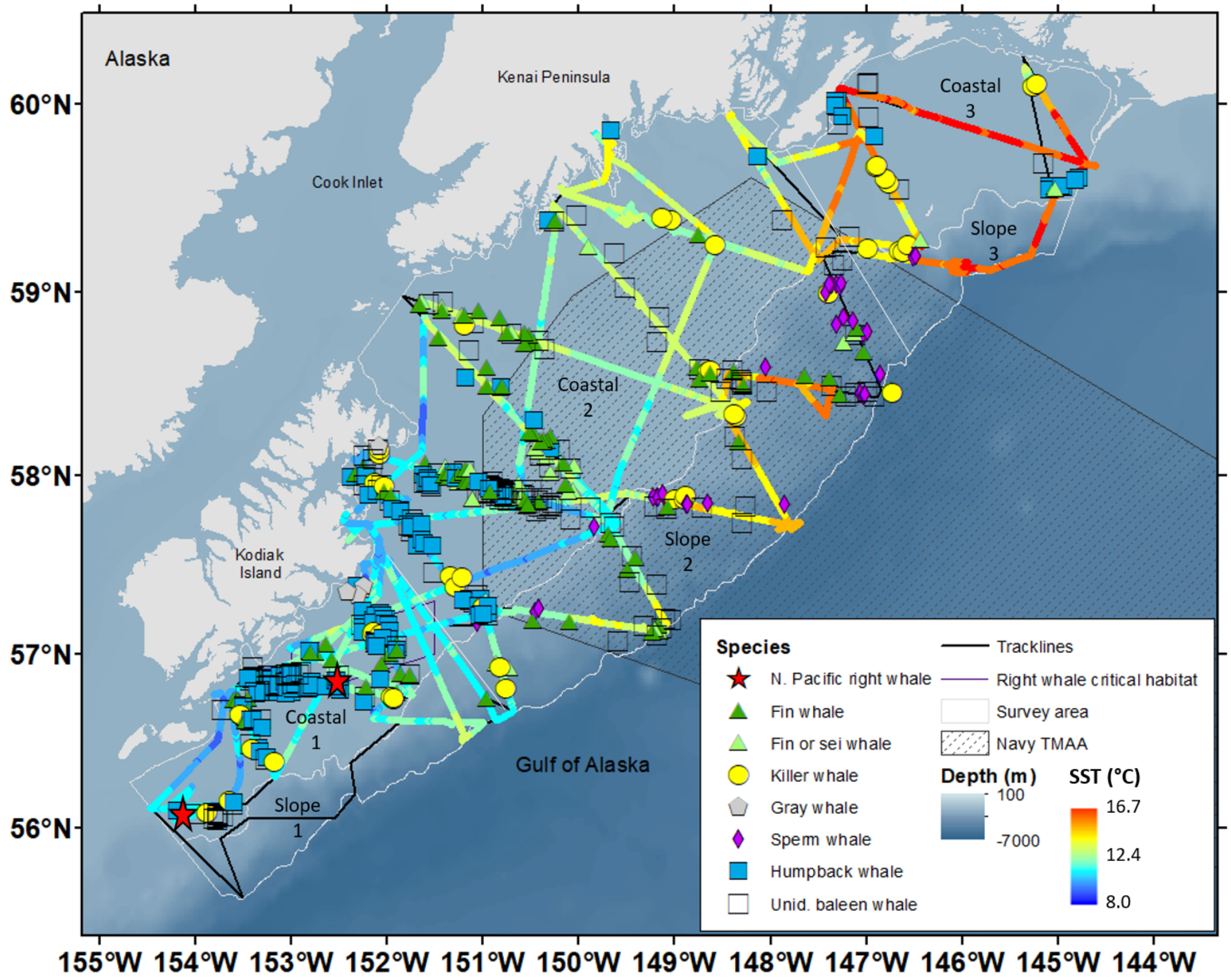


Figure 84: Sighting locations of all whale species (includes duplicate sightings and possible resights) plotted against sea surface temperature (collected via underway sampling system) during the 2021 PacMAPPS survey. Light gray lines = survey area, divided into coastal (1, 2, and 3) and slope (1, 2, and 3) strata.

Preliminary sea surface temperature (SST) data showed a minimum of 8.0°C, and a maximum of 16.7°C (Figure 84) throughout the PacMAPPS survey area.

Factors influencing observed trends: The distribution of cetaceans throughout the Gulf of Alaska is consistent with what is known about their distribution and preferred habitat (e.g., Mellinger et al., 2004; Ferguson et al., 2018; Rone et al., 2017; Rice et al., 2021). The large baleen whales were predominantly found in coastal areas of known upwelling and high concentrations of primary production (Stabeno et al., 2004). North Pacific right and gray whales were only seen in the nearshore waters of Kodiak Island, in known feeding Biologically Important Areas (Ferguson et al., 2018). Although oceanographic and prey data have not yet been analyzed, preliminary results show cetacean sightings occurred in temperatures less than 15.6°C (Figure 84), with most sightings occurring in temperatures less than 13°C.

Table 4: Number of sightings (including duplicates and possible resights) per whale species per stratum during the 2021 PacMAPPS survey. This does not include number of individuals seen per sighting event. Note: there was no effort conducted in the Slope 1 stratum. See Figure 84 for different stratum outlines.

	Stratum					
Species	Coastal 1	Coastal 2	Coastal 3	Slope 2	Slope 3	Total
Humpback whale	84	42	11	0	0	137
Fin whale	27	52	0	19	0	98
Fin/sei	2	26	2	6	1	37
Gray whale	4	1	0	0	0	5
North Pacific right whale	2	0	0	0	0	2
Killer whale	12	14	10	9	0	45
Sperm whale	0	2	0	31	2	35
Unid. baleen whale	39	83	6	33	0	161
TOTAL	170	220	29	98	3	520

Implications: Preliminary data suggest that cetacean distribution is likely influenced by oceanographic conditions, as has been shown previously (e.g., Friday et al., 2012; Zerbini et al., 2015). Given many cetacean species share a prey source with groundfish, concentrations of large whales may also be a proxy for the distribution of groundfish. Data have not yet been analyzed for comparison with previous years; however, the distribution of cetaceans in the northern Gulf of Alaska appears to be broadly consistent with results from previous surveys (Rone et al., 2017).

Marine Mammal Strandings in the Gulf of Alaska

Contributed by Mandy Keogh and Kate Savage, Alaska Regional Office, National Marine Fisheries Service, NOAA
Contact: mandy.keogh@noaa.gov
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 is 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.

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, 108 stranded marine mammals have been reported (confirmed reports) in the Gulf of Alaska, the majority of reports being from populated areas (Figure 85) where AMMSN members and NMFS Office of Law Enforcement members are located. Further, increased outreach and dedicated surveys (e.g., Cook Inlet and Kodiak Island) associated with high priority species or events (e.g., Cook Inlet beluga, 2019 gray whale Unusual mortality event) likely contributed to reported strandings in some area and years. Reported strandings in the Gulf of Alaska since 2016 varied between years without an overall pattern or consistent increase in reports (Table 5). The 2021 stranding data includes confirmed strandings reported between January 1, 2021 and September 18, 2021. **Factors influencing observed trends:** It is important to recognize that stranding reports represent effort that has varied substantially over time and location and overall has increased over time and with areas with higher human population densities. Unusual Mortality Events (UME) including the 2019 gray whale UME can have large influence on variability between years in this area (Table 5). 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.” Other factors that may influence the number and species of marine mammals being reported include changing populations of some species and increased public awareness through outreach suck as with the endangered Cook Inlet beluga, a species in the spotlight. Further, the number of stranded marine mammals in an area can vary due to potential conflict with fishery resources either directly through prey competition or indirectly through interactions with fishing gear such as increased whale entanglements in fishing gear.

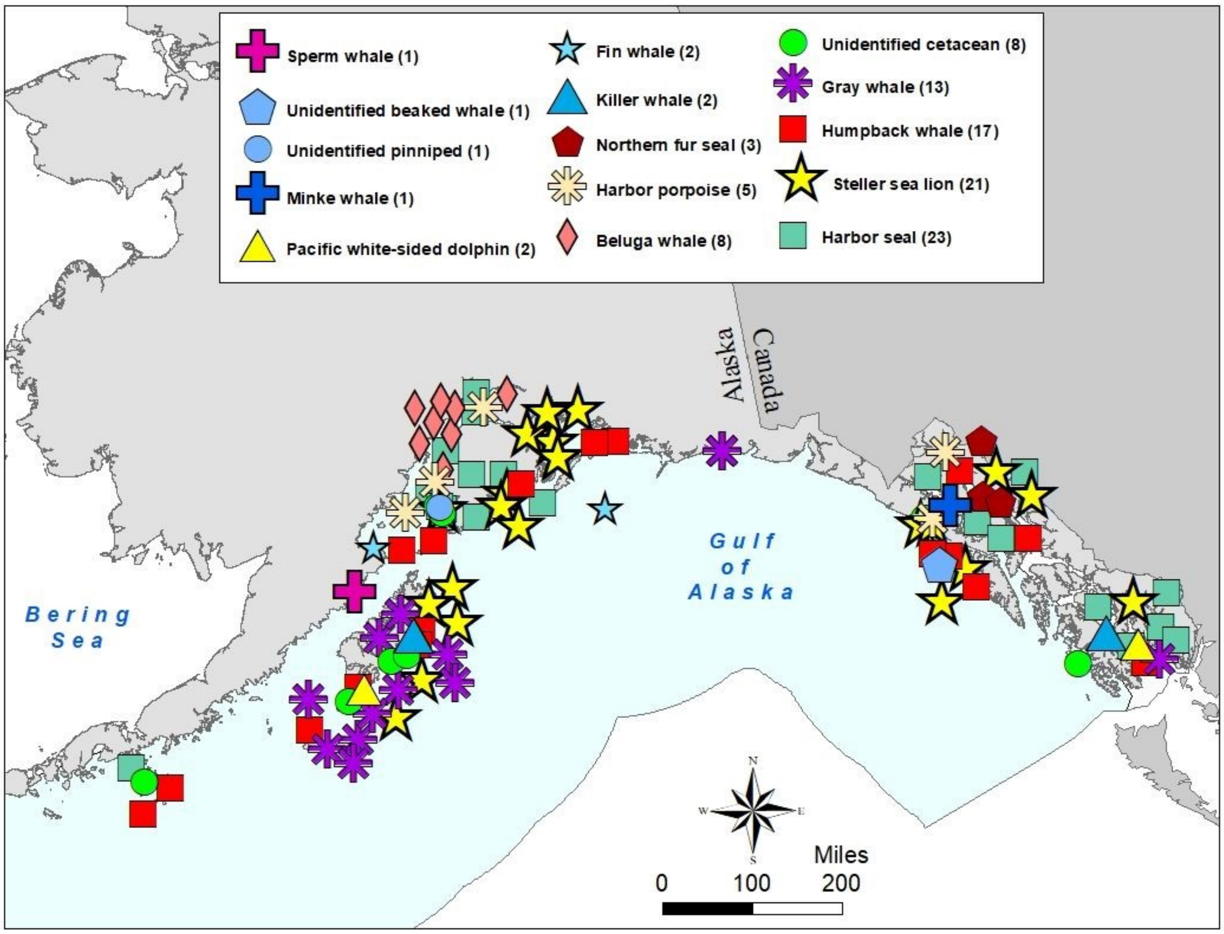


Figure 85: Reported stranded marine mammals in 2021.

Table 5: Reported stranded NMFS marine mammal species for the last five years in the Gulf of Alaska by species and year.

Species	2016	2017	2018	2019	2020	2021
Blue whale	-	-	-	1	-	-
Cook Inlet beluga	8	13	7	13	13	8
Dall's porpoise	3	3	2	1	2	-
False killer whale	-	-	1	-	-	1
Fin whale	2	1	1	-	2	2
Gray whale	6	4	4	22	26	13
Harbor porpoise	12	6	5	5	4	5
Killer whale	3	1	-	-	3	2
Sperm whale	1	2	2	1	-	1
Cuvier's beaked whale	-	-	-	-	2	-
Unidentified beaked whale	-	-	-	-	1	1
Minke whale	-	-	1	-	-	1
Pacific white-sided dolphin	-	-	-	-	-	2
Unidentified whale	4	8	5	-	11	-
Unidentified cetacean	6	2	2	13	2	8
Total cetaceans	70	54	43	65	80	60
California sea lion	1	-	1	-	-	-
Harbor seal	25	31	27	28	23	23
Northern fur seal	-	-	-	-	1	3
Guadalupe fur seal	1	-	-	-	-	-
Steller sea lion	35	30	28	46	35	21
Ringed seal	-	-	-	-	-	-
Steller sea lion	-	-	-	-	-	-
Unidentified pinniped	1	1	2	2	-	1
Unidentified marine mammal	-	-	1	1	-	-
Total pinnipeds	63	62	59	77	58	48
Total Cetaceans and Pinnipeds	113	116	102	142	139	108

Ecosystem or Community Indicators

Foraging Guild Biomass—Gulf of Alaska

Contributed by George A. Whitehouse[1] and Kerim Y. Aydin[2]
[1]Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle WA
[2]Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: andy.whitehouse@noaa.gov
Last updated: October 2021

Description of indicator: Foraging guilds are non-taxonomic groups of species with similar diet compositions (Root, 1967). We present time trends in biomass of two foraging guilds in the eastern and western GOA: motile epifauna and apex predators. Foraging guild biomass is based on catch data from the NMFS/AFSC biennial summer bottom-trawl survey of the GOA shelf and upper continental slope (< 501 m), modified by an Ecopath-estimated catchability coefficient that takes into account the minimum biomass required to support predator consumption (for details, see Appendix 1 in Boldt, 2007).

This year's foraging guild biomasses reflect the recent shift in division between the eastern and western GOA ESRs from 144°W to 147°W. This has decreased the total area in the western GOA and increased the area in the eastern GOA. We use the division between the Kodiak and Yakutat sub-regions in the AFSC bottom trawl survey strata to separate the eastern and western GOA in the survey data because it closely approximates 147°W (see Appendix A in von Szalay and Raring (2018) for details). We limit the bottom-trawl survey data included in the guild biomasses to strata < 501 m depth. Deeper strata make up a much smaller proportion of the total survey area, fewer stations are sampled in deeper strata, and those strata have not been sampled in each year the survey was conducted. New this year, foraging guild biomass is weighted by strata area (km^2). We no longer include species in the guild biomass that lack time series and were previously represented by a constant biomass equal to the mid-1990s mass balance level estimated in Aydin et al. (2007). Lastly, starting this year rougheye/blackspotted rockfish are now included in the apex predators guild. These methodological changes have resulted in a minor shift in the biomass values from reporting in previous years but the trends and patterns remain the same.

Status and trends: Motile epifauna in the east and west GOA are both below their long term mean but within one standard deviation (Figure 86). Apex predators in the east and west GOA are both about 1.1 standard deviations below their long term mean (Figure 86).

Western GOA Motile epifauna: The biomass of motile epifauna decreased from 2019 to 2021 and is below the long term mean (1984–2021) but within one standard deviation. The biomass of this guild is dominated by hermit crabs, brittle stars, other echinoderms, and octopus. In 2021, hermit crabs, brittle stars, and octopus are below their long-term means while other echinoderms are above their long term mean.

Western GOA Apex predators: The biomass of apex predators in the western GOA increased from 2019 to 2021 but remains below the long term mean. The biomass trends for apex predators are primarily driven by arrowtooth flounder, Pacific cod, Pacific halibut, and sablefish. In 2021, Pacific

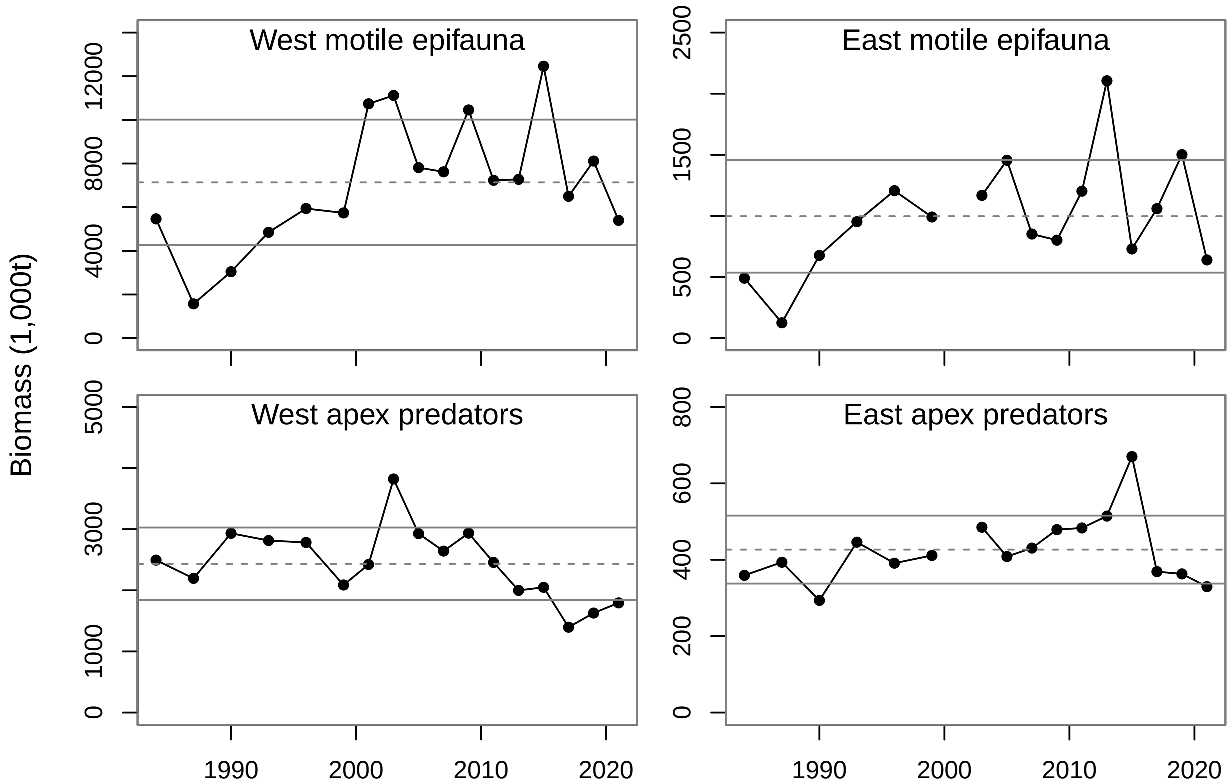


Figure 86: The biomass of apex predator and motile epifauna foraging guilds in the western and eastern GOA shelf from 1984–2021 (data from the NMFS AFSC biennial summer bottom trawl survey). The dashed line is the long-term mean and solid straight lines are ± 1 standard deviation.

cod continue to stay above their low in 2017 but remain below their long term mean. Arrowtooth flounder have trended upward since their low in 2017 but also remain below their long-term mean. In contrast, sablefish are well above their long term mean at their second highest value over the time series.

Eastern GOA Motile epifauna: The biomass of motile epifauna in the eastern GOA has decreased from 2019 to 2021 and is below the long term mean. Hermit crabs, brittle stars, and other echinoderms are dominant components of this guild and are all below their long term means. Eelpouts have also decreased from 2019 to 2021 but remain above their long term mean.

Eastern GOA Apex predators: The biomass of apex predators in the eastern GOA has trended downward from a high in 2015 to their second lowest value over the time series in 2021. The decrease over this time period has largely been driven by arrowtooth flounder which are at their lowest value over the time series, more than one standard deviation below their long term mean. Other dominant species in this guild including Pacific halibut, sablefish, and Pacific cod, have all increased from 2019 and are above their long term means.

Factors influencing observed trends: The 2014–2016 marine heatwave followed by multiple years of moderately warm conditions has had lasting impacts across trophic levels in the GOA (Suryan et al., 2021) and may be a contributing factor in the current lower apex predator biomass. The marine heatwave was a major perturbation to pelagic primary and secondary production throughout the GOA altering phenology, community composition, and abundance at lower trophic levels (Batten et al., 2018; Suryan et al., 2021). These changes may have impacted the abundance and energetic content of key pelagic forage fish that are critical prey to apex predators (Arimitsu et al., 2021). Pacific cod are a prominent component of the apex predator guild in the GOA. The marine heatwave and its attendant ecosystem effects reduced the amount of suitable spawning and larval habitat for Pacific cod, increased their metabolic demands, and reduced the quantity and quality of prey available to Pacific cod helping explain their low abundance in the years since the heatwave (2017–2021) (Barbeaux et al., 2020*b*; Laurel and Rogers, 2020; Laurel et al., 2021). Arrowtooth flounder are a primary driver of the apex predator guild in both the western and eastern GOA, accounting for 52% and 43% of apex predator biomass respectively. Their biomass in 2021 is below their long term mean in both the eastern and western GOA.

The motile epifauna guild remains within one standard deviation of the long term levels in both the eastern and western GOA. Interannual variation in motile epifauna biomass is primarily driven by short term fluctuations in dominant groups, including hermit crabs, brittle stars, other echinoderms, and eelpouts.

Implications: The relatively low biomass of apex predators in the years since the marine heatwave warrants caution in management decisions and continued monitoring of apex predator status and the status of key prey groups.

Stability of Groundfish Biomass in the Gulf of Alaska

Contributed by George A. Whitehouse, Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle WA
Contact: andy.whitehouse@noaa.gov
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. 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.

The biomass index for groundfish species was calculated from the catch of the NMFS/AFSC biennial summer bottom-trawl survey of the Gulf of Alaska (GOA). Initially, the GOA groundfish survey was conducted on a triennial basis from 1984 through 1999. Starting in 2001 the survey has been conducted on a biennial basis; however, the eastern GOA was not surveyed in 2001. Since 10 years of data are required to calculate this metric, the indicator values start in 2007 for the western GOA and in 2009 for the eastern GOA, the tenth time the regions were surveyed in the trawl survey time series (1984–2021).

This indicator specifically applies to the portion of the demersal groundfish community efficiently sampled with the trawling gear used by NMFS during the summer bottom-trawl survey of the GOA (for complete survey details see von Szalay P.G. and Raring, 2018). Species that are predominately found in the pelagic environment (e.g., capelin, pelagic smelts), are infrequently encountered (e.g., sharks, grenadiers, myctophids) or otherwise not efficiently caught by the bottom-trawling gear are excluded from this indicator.

The survey index used here is the same as that used for the apex predator and motile epifauna indices in the "Foraging Guild Biomass" contribution (Whitehouse in this Report, p.174) and in the Report Card (p.3 and p.4). There were some methodological changes made to the way this survey index was calculated this year: 1) the division between the eastern and western GOA moved from 144°W to 147°W, 2) we limit survey data to strata less < 501m depth, 3) biomass is weighted by strata area (km^2), and 4) we have added rockfish species including, Pacific ocean perch (POP), sharpchin rockfish, northern rockfish, dusky rockfish, shortraker rockfish, rougheye/blackspotted rockfish, other *Sebastes*, and shortspine thornyhead.

Several species of pelagic forage fishes are abundant in the GOA and their populations may vary substantially which could drive the value of this indicator. While many species of pelagic forage fish are occasionally encountered during the survey, most are not consistently sampled well enough to be included in the survey biomass index, including sandlance, capelin, and other pelagic smelts. Herring and eulachon are included in the survey index, so I have recalculated this indicator with and without herring and eulachon to examine their influence on this indicator.

Status and trends: The stability of groundfish biomass in the western Gulf of Alaska is at time series highs for both the series with eulachon and herring (Figure 87) and the series without (Figure 87). Both series have generally trended upward since 2007. When herring and eulachon are removed, this indicator has slightly higher values from 2007–2017 (Figure 87), and follows the same overall trends of the indicator with herring and eulachon. In 2019 and 2021, the series with eulachon and herring has higher stability.

In the eastern Gulf of Alaska, this indicator has been stable over the time series with only minor fluctuations between survey years (Figure 87). When herring and eulachon are excluded from the indicator, the values are slightly lower indicating more variability in total groundfish biomass (Figure 87).

Factors influencing observed trends: Fishing is expected to influence this metric as fisheries can selectively target and remove larger, long-lived species effecting 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, and patchy spatial distribution for some species. This metric, as calculated here with trawl-survey data, reflects the stability of the groundfish community that is represented in the catch of the GOA summer bottom-trawl survey. In general, as total biomass decreases, species spatial distribution may contract or have increasingly isolated patches, both of which may lead to increased CV (Shin et al., 2010).

The index of groundfish stability in the western GOA with herring and eulachon included, reached

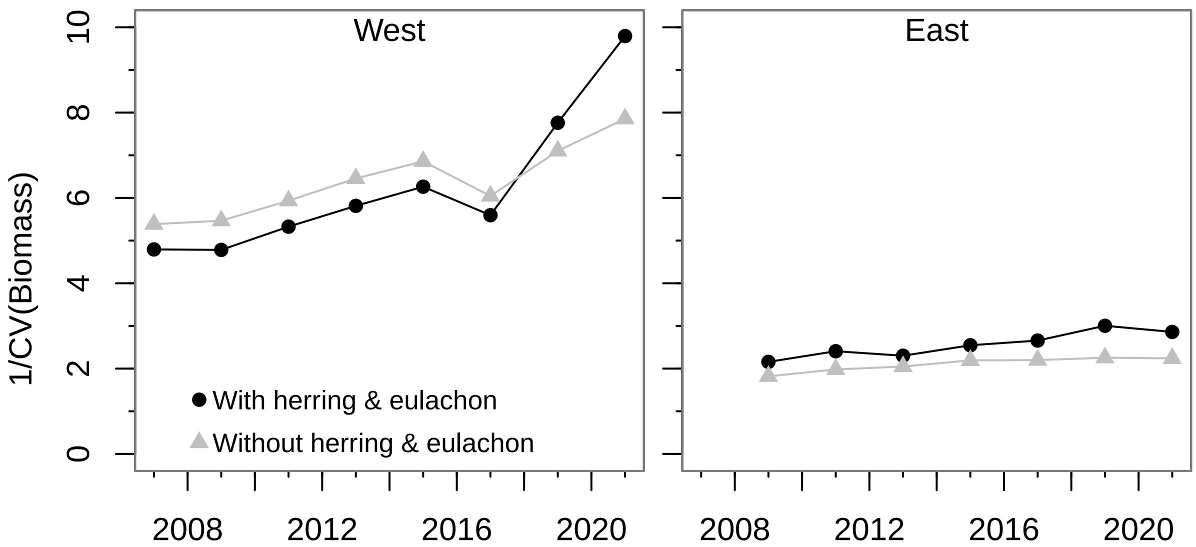


Figure 87: The stability of groundfish in the western and eastern GOA represented with the inverse biomass coefficient of variation (1/CV[B]), 1984-2021. Ten years of data are required to calculate this metric, so this time series begins in 2007 for the western GOA and in 2009 for the eastern GOA (no survey in 2001) after the tenth occurrence of the NMFS/AFSC summer bottom-trawl survey. The black circles are the series with herring and eulachon included in the index, and the gray triangles are the same series with herring and eulachon excluded.

its highest level in 2021, reflecting the relative stability of the groundfish biomass index in the most recent ten survey years. POP and herring are both biomass dominant species in the western GOA and have had contrasting biomass dynamics since 2017, where one species had relatively high biomass while the other was low and vice versa. The net result of these contrasting biomass dynamics was for very stable total biomass in the series with herring and eulachon included. Similarly, in the eastern GOA there is very little difference between the two series, but the one with herring and eulachon included was slightly higher than without.

This indicator has lower values in the eastern GOA than in the western GOA for both series, with and without herring and eulachon. While greater variability in groundfish biomass in the eastern GOA has resulted in lower overall indicator values than in the western GOA, the level of variability has been relatively steady resulting in the nearly flat trajectories for this indicator in the eastern GOA.

Implications: The stability of groundfish biomass in the eastern GOA has been relatively constant over the time series and the stability in the western GOA has been increasing. The groundfish biomass in the eastern GOA is less stable than the west and may be more sensitive than the western GOA to perturbations.

Mean Length of the Fish Community in the Gulf of Alaska

Contributed by George A. Whitehouse[1] and Geoffrey M. Lang[2]
[1]Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle WA

[2]Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: andy.whitehouse@noaa.gov
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 biennial bottom trawl survey of the Gulf of Alaska. Initially the survey was conducted on a triennial basis from 1984 to 1999 before switching to a biennial schedule in 2001.

Species-specific mean lengths are calculated for groundfish species from the length measurements collected during the trawl survey. The mean length for the groundfish community is calculated with the species-specific 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 efficiently sampled with the trawling gear used by NMFS during the summer bottom-trawl survey of the GOA and have their lengths regularly sampled (for complete survey details see von Szalay P.G. and Raring, 2018). This includes species of skates, flatfishes, roundfishes (e.g., cods, sculpins, eelpouts), and rockfish. Species that are predominately found in the pelagic environment (e.g., capelin, pelagic smelts), are infrequently encountered (e.g., sharks, grenadiers, myctophids) or otherwise not efficiently caught by the bottom-trawling gear are excluded from this indicator.

The survey index used here is the same as that used for the apex predator and motile epifauna indices in the "Foraging Guild Biomass" contribution (Whitehouse in this Report, p.174) and in the Report Card (p.3 and p.4). There were some methodological changes made to the way this survey index was calculated this year: 1) the division between the eastern and western GOA moved from 144°W to 147°W, 2) we limit survey data to strata less $<$ 501m depth, 3) biomass is weighted by strata area (km^2), and 4) we have added rockfish species including, Pacific ocean perch (POP), sharpchin rockfish, northern rockfish, dusky rockfish, shortraker rockfish, rougheye/blackspotted rockfish, other *Sebastes*, and shortspine thornyhead. Several species of pelagic forage fishes are abundant in the GOA and their populations may vary substantially which could drive the value of this indicator. While many species of pelagic forage fish are occasionally encountered during the survey, most are not consistently sampled well enough to be included in the survey biomass index, including sandlance, capelin, and other pelagic smelts. Herring and eulachon are included in the survey index, so this indicator is calculated with and without herring and eulachon, to examine their influence on the indicator state and trends.

Status and trends: *With herring and eulachon*—The mean length of the groundfish community in the western Gulf of Alaska is 35.9 cm, up from 32.1 cm in 2019 (Figure 88). The 2021 value is less than the long-term mean of 37.7 cm. In the eastern Gulf of Alaska, the mean length of the groundfish community is 32.9 cm, up from 26.4 cm in 2019, and is above the long term mean (Figure 88). Despite declines in this indicator in both regions from 2015 to 2019, this indicator has generally been stable over the years examined.

Without herring and eulachon—The mean length of the groundfish community in the western GOA with herring and eulachon excluded is only slightly higher (Figure 88) than when they are included. In the eastern GOA there is a larger difference between the status of the two series, with the series without herring and eulachon being higher (Figure 88). The value in 2021 is 42.7 cm which is above the long term mean of 41.7 cm, but down from the series high of 53.9 cm in 2019.

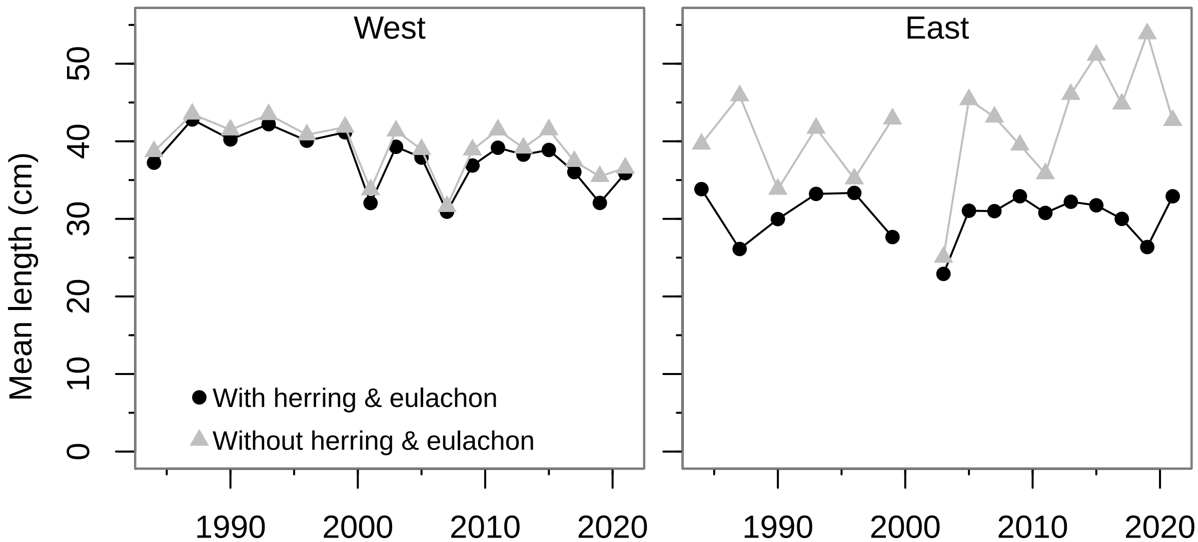


Figure 88: Mean length of the groundfish community sampled during the NMFS/AFSC summer bottom-trawl survey of the Gulf of Alaska (1984–2021). The groundfish community mean length is weighted by the relative biomass of the sampled species. The black dots represent the indicator series with herring and eulachon included and the gray triangles are the indicator series with herring and eulachon excluded.

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. Additionally, density dependent factors could contribute to size reductions.

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. The decline in this indicator from 2015 to 2019, in both series in the western GOA and when herring and eulachon were included in the eastern GOA, was initially concerning as it coincided in time with the "blob" marine heatwave. The indicator values in these three series have all increased in 2021 and are near long term means.

Fluctuations in this indicator are in part due to variation in the biomass indices of forage species who have shorter mean lengths and are not efficiently caught by the bottom-trawl. In the eastern GOA, herring have mean lengths shorter than much of the groundfish community, are a dominant component of the biomass index and can have large fluctuations in abundance from year to year.

Years with low mean groundfish length in the eastern GOA typically coincide with years of higher than average herring biomass. When herring are removed from this indicator, the values are higher.

In the series without herring and eulachon in the eastern GOA, recent low indicator values in 2003 and 2011 were years with high biomass of other forage fish (e.g., Pacific sandfish (*Trichodon trichodon*) and pricklebacks) which have generally shorter lengths.

Implications: The mean length of the groundfish community in the western and eastern GOA has been generally stable over the bottom-trawl time series (1984–2021). Low indicator values are broadly attributed to peaks in the biomass index of smaller, shorter-lived forage species. The downward trend from 2015–2019 that aligned with the presence of warmer water ("the blob") and was noted as a concern last year has corrected this year with indicator values near long term means.

Mean Lifespan of the Fish Community in the Gulf of Alaska

Contributed by George A. Whitehouse[1] and Geoffrey M. Lang[2]
[1]Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle WA
[2]Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: andy.whitehouse@noaa.gov
Last updated: October 2021

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 biennial summer bottom-trawl survey of the Gulf of Alaska were retrieved from the AFSC Life History Database (`https://access.afsc.noaa.gov/reem/LHWeb/Index.php`). The groundfish community mean lifespan is weighted by the relative biomass of groundfish species sampled during the summer bottom-trawl survey. Initially, the GOA bottom trawl survey was conducted triennially from 1984 to 1999, and then switched to a biennial schedule beginning in 2001.

This indicator specifically applies to the portion of the demersal groundfish community efficiently sampled with the trawling gear used by NMFS during the summer bottom-trawl survey of the GOA (for complete survey details see von Szalay P.G. and Raring, 2018). This includes species of skates, flatfishes, roundfishes (e.g., cods, sculpins, eelpouts), and rockfish. Species that are predominately found in the pelagic environment (e.g., capelin, pelagic smelts), are infrequently encountered (e.g., sharks, grenadiers, myctophids) or otherwise not efficiently caught by the bottom-trawling gear are excluded from this indicator.

The survey index used here is the same as that used for the apex predator and motile epifauna indices in the "Foraging Guild Biomass" contribution (Whitehouse in this Report, p.174) and in the Report Card (p.3 and p.4). There were some methodological changes made to the way this survey index was calculated this year: 1) the division between the eastern and western GOA moved from 144°W to 147°W, 2) we limit survey data to strata less $<$ 501m depth, 3) biomass is weighted by strata area (km^2), and 4) we have added rockfish species including, Pacific ocean perch (POP), sharpchin rockfish, northern rockfish, dusky rockfish, shortraker rockfish, rougheye/blackspotted rockfish, other *Sebastes*, and shortspine thornyhead. Several species of pelagic forage fishes are abundant in the GOA and their populations may vary substantially which could drive the value of this indicator. While many species of pelagic forage fish are occasionally encountered during the survey, most are not consistently sampled well enough to be included in the survey biomass index, including sandlance, capelin, and other pelagic smelts. Herring and eulachon are included in the survey index, so we have recalculated this indicator with and without herring and eulachon, to examine their influence on the indicator state and trends.

Status and trends: The mean lifespan of the western GOA demersal fish community in 2021 with herring and eulachon included is 42.0, which is up from 33.8 in 2019, and is the second highest over the time series (Figure 89). When herring and eulachon are excluded from the series, the indicator status and trends follows the same general pattern but with the values shifted slightly higher.

In the eastern GOA, the mean lifespan in 2021 with herring and eulachon included is 36.3, up from 29.3 in 2019 (Figure 89). When herring and eulachon are removed from the series, the indicator values are shifted higher but follow similar overall trends. Both series in the eastern GOA are near long term mean levels.

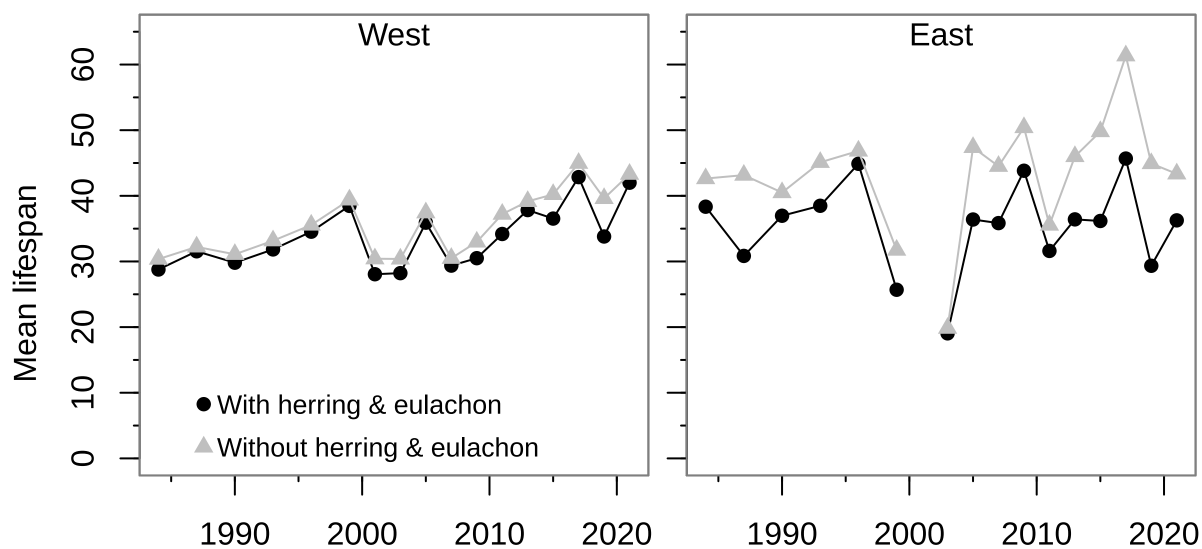


Figure 89: The mean lifespan of the eastern and western Gulf of Alaska demersal fish communities, 1984–2021, weighted by relative biomass calculated from the NMFS/AFSC summer bottom-trawl survey. The black dots represent the indicator series with herring and eulachon included and the gray triangles are the indicator series with herring and eulachon excluded.

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 also be influenced by the spatial distribution of species and the differential selectivity of species 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 the relative abundance of age classes and species.

In the western GOA, recent low indicator values in 2001, 2003, 2007, and 2019 were years with high biomass indices for Pacific herring, eulachon, and other managed forage species which reduced the mean lifespan for the groundfish community. Recent high values in mean lifespan are driven by higher biomass of long-lived species, including POP, dusky rockfish, and sablefish.

In the eastern GOA, low mean lifespan in 1987, 1999, 2003, and 2019 in the series with herring and eulachon corresponded to years with high biomass indices for Pacific herring and/or other managed forage fish (Figure 89). The high mean lifespans in 1996, 2009, and 2017 in the series with herring and eulachon corresponded to years with low herring biomass and/or high biomass in long-lived rockfish, such as shortraker rockfish. When herring and eulachon are excluded, high mean lifespans in the eastern GOA in 2009 and 2017 are driven by long-lived rockfishes, including shortraker rockfish, rougheye/blackspotted rockfish, and shortspine thornyhead (Figure 89).

Implications: The groundfish mean lifespan in the GOA has shown interannual variability over the time series, with years of low indicator values corresponding to years with high biomass indices for shorter-lived forage species, such as herring and other managed forage fish. 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).

Aggregated Catch-Per-Unit-Effort of Fish and Invertebrates in Bottom Trawl Surveys in the Gulf of Alaska, 1993–2021

Contributed by Franz Mueter[1] and Wayne Palsson[2]
[1]University of Alaska Fairbanks, 17101 Point Lena Road, Juneau, AK 99801
[2]Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: fmueter@alaska.edu
Last updated: October 2021

Description of indicator: This index provides a measure of the overall biomass of benthic, demersal, and semi-demersal fish and invertebrate species. We estimated mean catch-per-unit-effort (CPUE in kg ha^{-1}) of fish and major invertebrate taxa by year based on all successful hauls completed during standardized bottom trawl surveys on the Gulf of Alaska shelf (GOA), 1993–2021. Total CPUE for each haul was computed as the sum of the CPUEs of all fish and invertebrate taxa. To obtain an index of mean CPUE by year, we modeled log-transformed total CPUE (N = 7559 and 1909 hauls in the western (west of 147°W) and eastern GOA, respectively) as smooth functions of depth, alongshore distance and sampling stratum with year-specific intercepts using Additive Models. Hauls were weighted based on the area represented by each stratum. To avoid biases due to gear and vessel issues, data prior to the 1993 survey was not included in the analysis.

Status and trends: Total log(CPUE) in both the eastern and western GOA decreased from recent high values to their lowest (west) or second lowest value (east) in 2017 and increased somewhat from 2017 to 2021 in both areas (Figure 90). There was no significant long-term trend over time from 1993 to 2021 in either region (Generalized least squares regression with first-order autoregressive residual autocorrelation, $p > 0.2$), but total CPUE decreased significantly by 30–40% from 2009 to 2017 in the western GOA and from 2013 to 2017 in the eastern GOA. Total log(CPUE) in both regions increased slightly from 2017 to 2019 due to increases in Pacific cod, walleye pollock, sablefish, and several flatfish and rockfish species.

Factors influencing observed trends: Commercially harvested species account for over 70% of total 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, and distribution. Substantial declines in many species from 2013 to 2017 may be associated with the unusual warm conditions in the GOA in 2014–2015, which appeared to affect prey availability and were associated with unusual mortality events in seabirds and marine mammals. The subsequent increase in CPUE from 2017 to 2021 suggests improved conditions for growth and recruitment.

Implications: This indicator can help address concerns about maintaining adequate prey for upper trophic level species and other ecosystem components. A sharp drop in total biomass of demersal fish and invertebrates affecting commercial and non-commercial species, suggests poor availability of zooplankton prey for these species and a reduced prey base for upper trophic level species following the 2014/15 warm event, but recent trends suggest that prey availability has improved somewhat.

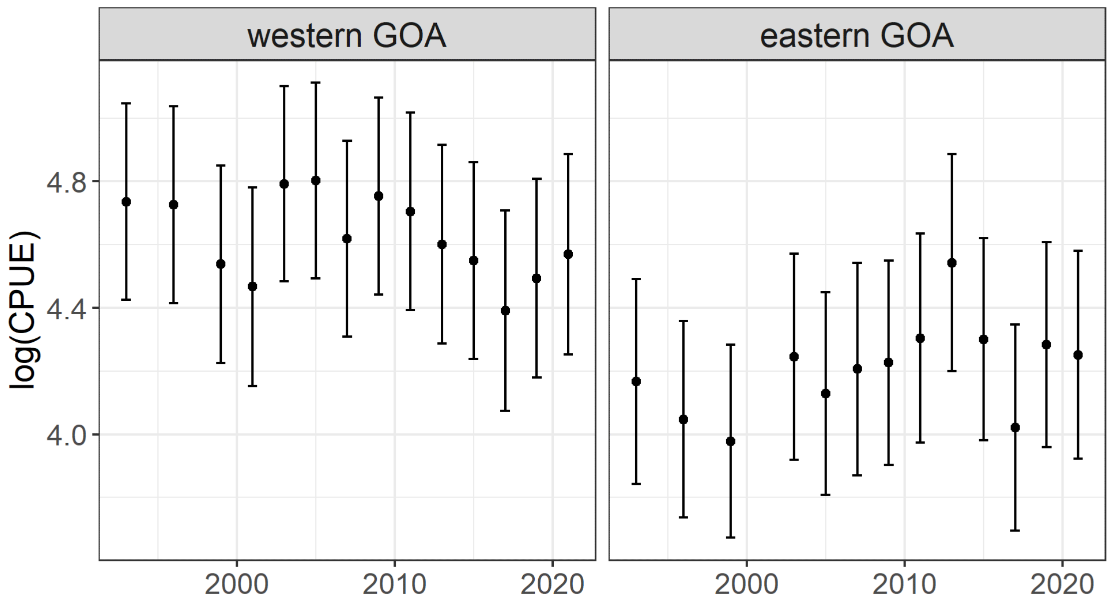


Figure 90: Model-based estimates of total log(CPUE) for major fish and invertebrate taxa captured in bottom trawl surveys from in the western (west of 147°W) and eastern Gulf of Alaska by survey year with approximate 95% confidence intervals. Estimates were adjusted for differences in depth and sampling locations (alongshore distance) among years. No sampling in the eastern Gulf of Alaska in 2001.

Species Richness and Diversity of the Gulf of Alaska Groundfish Community

Contributed by Franz Mueter, University of Alaska Fairbanks, 17101 Point Lena Road, Juneau, AK 99801
Contact: fmueter@alaska.edu
Last updated: October 2021

Description of indicator: Indices of local species richness and diversity are based on standard bottom trawl surveys in the western (west of 147°W) and eastern GOA. 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 GOA were based on 76 fish and common invertebrate taxa that have been consistently identified since the early 1990s. 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 a Generalized Additive Model that accounted for the effects of variability in geographic location (latitude/longitude) and depth with year-specific intercepts. In addition to trends in the indices over time, we mapped average spatial patterns for each index across the survey region.

Status and trends: Richness and diversity were generally higher in the eastern GOA than in the western GOA with, on average, 2–3 additional species per haul in the east (Figure 91). Richness and diversity have been relatively stable in the western GOA with slightly higher local richness in the 2015–2021 surveys compared to the 2011/2013 surveys. Local species richness in the eastern Gulf increased substantially in 2013, declined by more than 2 species per haul in 2015 during the heatwave and increased to relatively high levels in 2017–2021. Diversity in the eastern GOA declined from 2007 to 2015, but increased in 2017–2021, associated with the increase in local richness (Figure 91). Species diversity in both areas in 2019 and 2021 was at or near the maximum observed values. Both richness and diversity tend to be highest along the shelf break and slope (Figure 92), with richness peaking at or just below the shelf break (200–300m), and diversity peaking deeper on the slope (300m +), as well as in some shallow water regions (< 100m). Notably, both richness and diversity are high off the Kenai Peninsula.

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. 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 (Figure 91) and spatial patterns (Figure 92) in species diversity differ from those in species richness. Diversity typically increases with species richness and decreases when the abundance of a dominant species increases. For example, the decreasing trend in diversity in the eastern GOA since 2007 appears to be due to an increase in the abundance and dominance of a few species, including arrowtooth flounder, walleye pollock and Pacific ocean perch. The unusual increase in local species richness in the eastern GOA in 2013 appears to have resulted from increased catches of a number of fish and invertebrate species, including walleye pollock, several *Sebastes* species, skates, grenadiers, sea stars and others. The increase in richness and diversity in 2017 reflects reduced dominance of many of these species and possibly a more even distribution across space.

Implications: There is evidence from many systems that diversity is associated with ecosystem

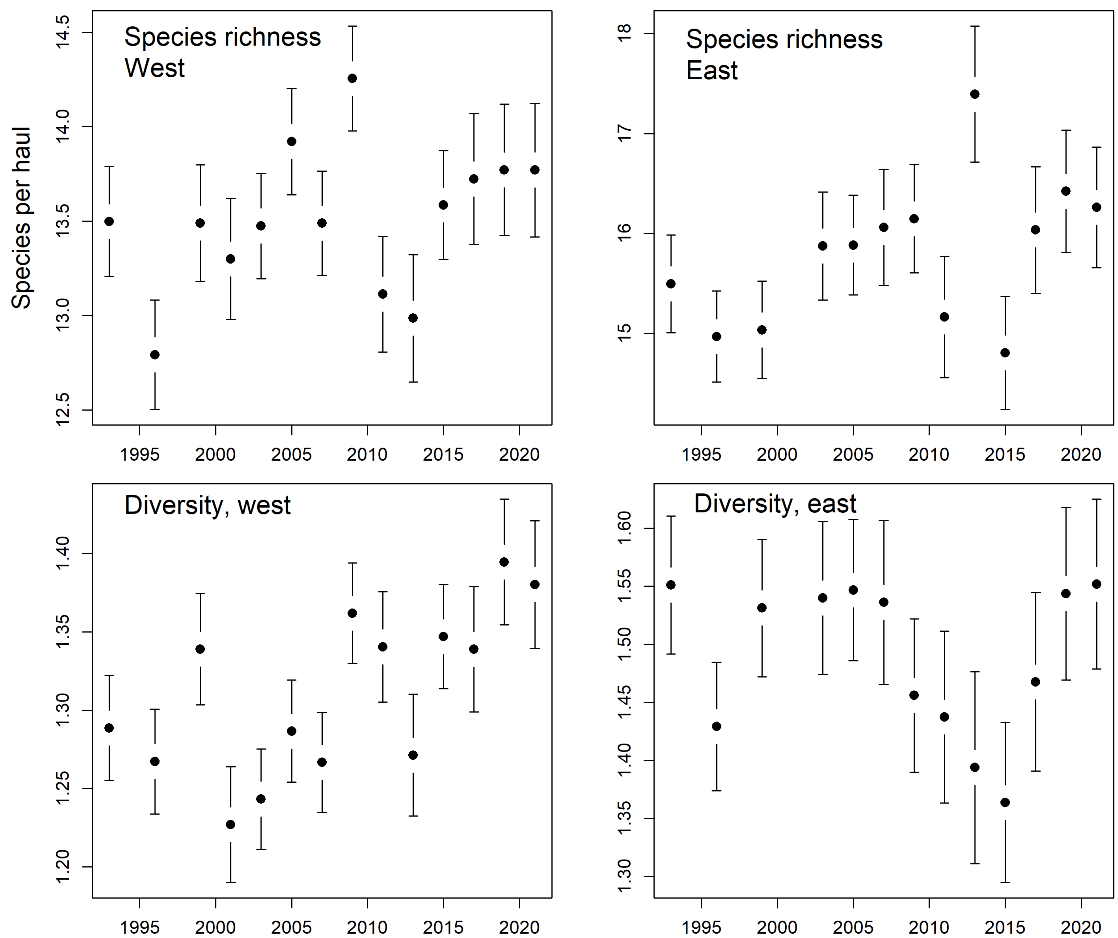


Figure 91: Model-based annual averages of species richness (average number of species per haul, top panels) and species diversity (Shannon index, bottom panels), 1993–2021, for the western (left) and eastern (right) Gulf of Alaska based on, respectively, 74 and 73 fish and invertebrate taxa collected by standard bottom trawl surveys with 95% pointwise confidence intervals. Model means were adjusted for differences in depth, date of sampling, and geographic location.

stability, which depends on differential responses to environmental variability by different species or functional groups (McCann, 2000). To our knowledge, such a link has not been established for marine fish communities.

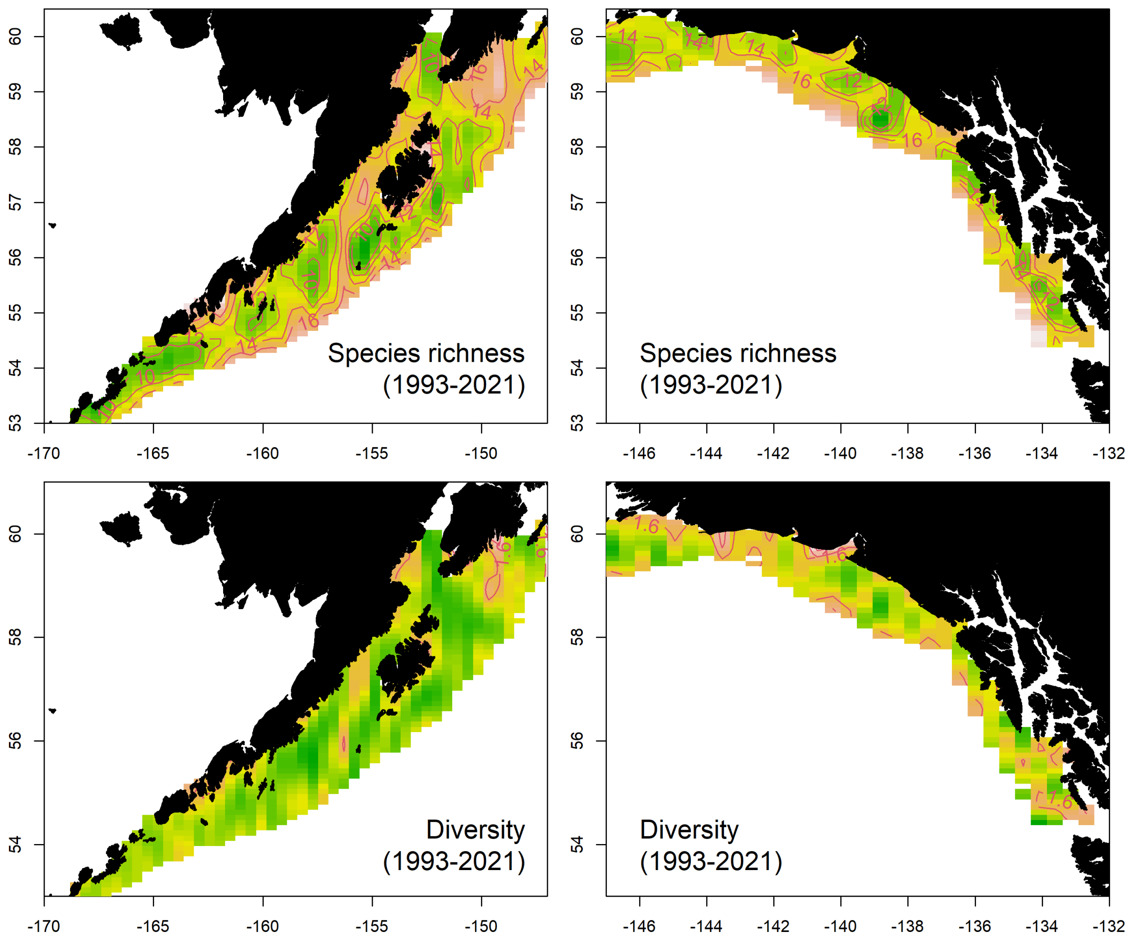


Figure 92: Average spatial patterns in local species richness (species per haul, top panels) and Shannon diversity (bottom panels) for the Western (left) and Eastern (right) Gulf of Alaska. Green colors are lower values and warmer colors are higher values for both plots).

Disease & Toxins Indicators

Harmful Algal Blooms in the Gulf of Alaska

Contributed by Thomas Farrugia[1], Darcy Dugan[1], Rosie Masui[2], Dom Hondolero[3], Grace Ellwanger[4], Annette Jarosz[5], Steve Kibler[6] , Kari Lanphier[7], Chandra Poe[8], Natalie Rouse[9], Courtney Hart[10], Bruce Wright[11], Sarah Schoen[12].
[1] Alaska Ocean Observing System, 1007 W. Third Avenue, Suite 100, Anchorage, AK 99501
[2] Kachemak Bay National Estuarine Research Reserve, 2181 Kachemak Dr, Homer, AK 99603
[3] NOAA NOS Kasitsna Bay Lab, Seldovia, AK 99603
[4] Kodiak Area Native Association, 3449 E Rezanof Dr, Kodiak, AK 99615
[5] Alutiiq Pride Marine Institute, 101 Railway Ave, Seward, AK 99664
[6] NOAA NOS Beaufort Lab, Beaufort, NC, 28516
[7] Sitka Tribe of Alaska, Sitka, 429 Katlian St, Sitka, AK 99835
[8] Qawalangin Tribe of Unalaska, 1253 E Broadway Ave, Unalaska, AK 99685
[9] Alaska Veterinary Pathology Services, 23834 The Clearing Dr, Eagle River, AK 99577
[10] University of Alaska Fairbanks, 17101 Point Lena Loop Road, Juneau, AK 99801
[11] Knik Tribe of Alaska, 1744 North Prospect Palmer, AK 99645
[12] US Geological Survey Alaska Science Center, 4210 University Dr. Anchorage, AK 99508

Contact: farrugia@aoos.org
Last updated: October 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 Beaufort Lab
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*
USGS Alaska Science Center
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: `http://www.dhss.alaska.gov/News/Documents/press/2020/DHSS_PressRelease_PSPFatality_20200715.pdf`). Analyses of paralytic shellfish toxins are commonly reported as µg of toxin/100 g of tissue, where the FDA regulatory limit is 80 µg/100 g. Toxin levels between 80 µg - 1000 µg/100 g are considered to potentially cause non-fatal symptoms, whereas levels above 1000 µg/100 g ($\sim$ 12x regulatory limit) are considered potentially fatal.

Pseudo-nitzschia produces domoic acid which can cause amnesic shellfish poisoning and inflict permanent brain damage. Domoic acid has been detected in 13 marine mammal species and has the potential to impact the health of marine mammals and birds 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 harvests and researchers, and to reduce human health risk (Figure 93). 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 `https://aoos.org/alaska-hab-network/` or through the sampling partners listed above.

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 2020 and 2019, 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. A recent analysis found no positive results for okadaic acid in 20 historical marine mammal samples (collected from 2012–2020) (S. Fire, Florida International University, in collaboration with Alaska Veterinary Pathologists and University of Alaska). These 20 samples came from throughout Alaska (from Juneau to Unalaska to Pt. Hope) and included bearded and ring seals, Steller sea lions, harbor porpoise, and humpback, gray and beluga whales.

East GOA: *Southeast Alaska & Kodiak* – Southeast Alaska Tribal Ocean Research (SEATOR) partners sample shellfish and phytoplankton in 16 communities. As of early September 2021, the observed paralytic shellfish toxin peak concentrations and the number of toxic samples were lower than observed in 2020 (which were lower than 2019). The peak PST concentration for a single sample was 1300 µg/100 g in 2021 relative to 2500 µg/100 g in 2020. Shellfish samples exceeded the regulatory limit (80 µg/100 g) at 30 out of 40 sites in 2021, compared to 26 sites in 2020, and 135 samples exceeded the regulatory limit in 2021 compared to 160 in 2020 (Figure 94). The lower levels in 2020 compared to 2019 were likely influenced by a particularly rainy summer which resulted in cooler water temperatures.

Juneau – 2021 was the first year, since 2018, that *Alexandrium* counts at a Juneau oyster Farm were low and the farm did not experience any closures due to high PSP levels. These results are part of a new University of Alaska research program related to HABs and shellfish aquaculture farms around Juneau.

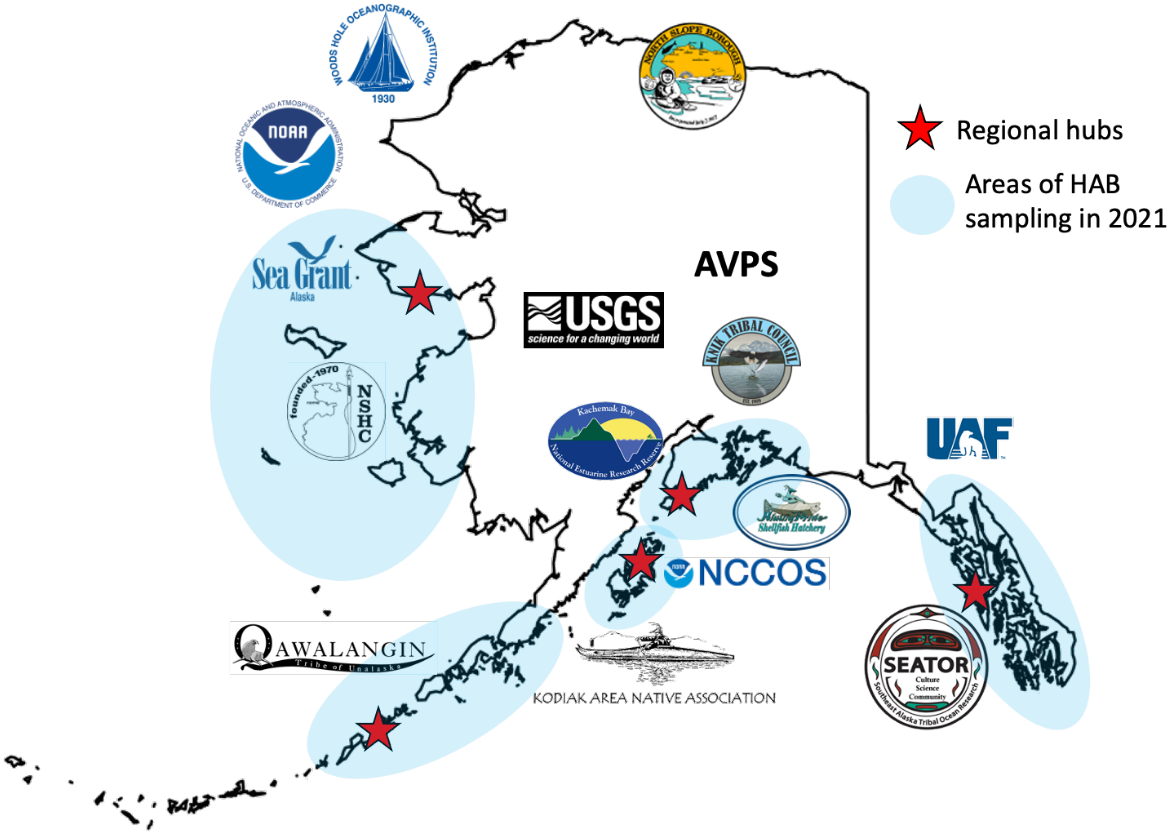


Figure 93: Map of 2021 sampling areas and partners conducted by partners of the Alaska Harmful Algal Bloom Network (AHAB). Opportunistic sampling of marine mammal tissue and other marine species occurs statewide and is not shown here.

West GOA:

Kachemak Bay — Numerous samples of phytoplankton, zooplankton, and fish were collected in Kachemak Bay and throughout SEAK by the Kachemak Bay National Estuarine Research Reserve's (NERR) Community Monitoring Program and NOAA National Centers for Coastal Science in 2021, most of which have not yet been analyzed. One shellfish sample from the west side beaches of Lower Cook Inlet was found to be below the regulatory limit for paralytic shellfish toxins. *Dinophysis* has been seen at abundant or bloom levels in inner Kachemak Bay during the Fall, over the past three years.

Kodiak Island – Shellfish and phytoplankton toxicity monitoring occurs at four locations on the road system (Mission Beach Northeast, Mission Beach Southwest, North Trident Basin and South Trident Basin). So far, paralytic shellfish toxin values in 2021 have, on average, shown a lower general trend than the previous monitoring years, 2019 and 2020. Of the 66 blue mussel samples submitted so far in 2021, 21% were above the FDA regulatory limit of (80 µg/100 g). In addition, 48% of the 56 butter clams submitted were above the regulatory limit. In June, Kodiak saw the

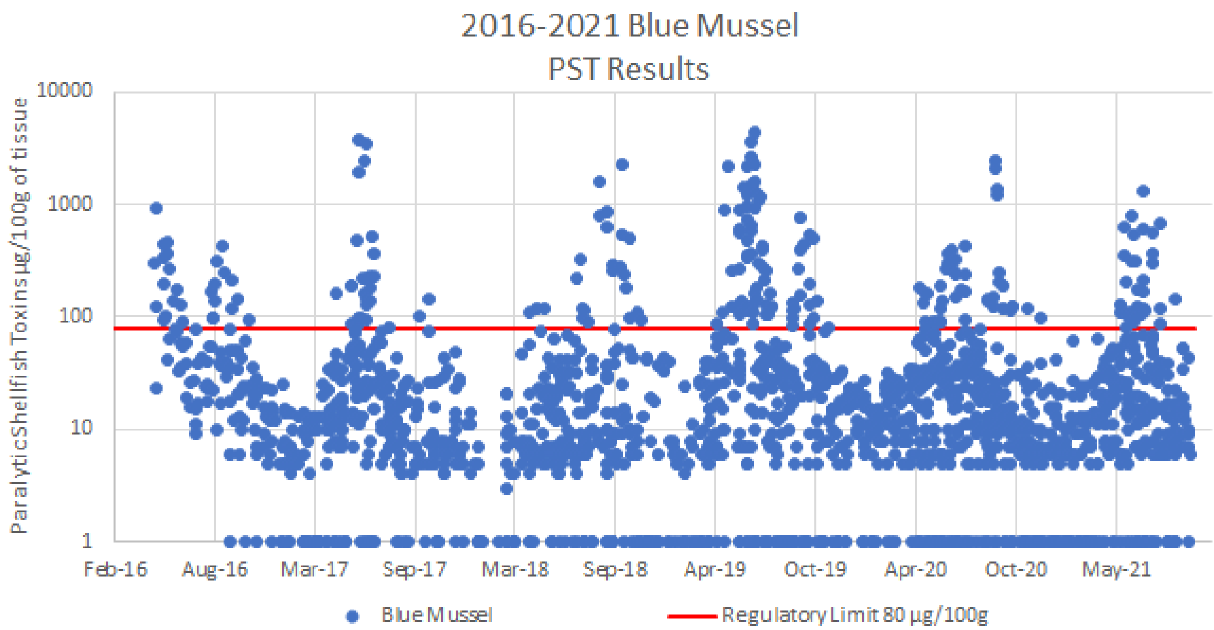


Figure 94: Paralytic shellfish toxicity (PST) results from blue mussel samples collected from 2016 through September 2021 in Southeast Alaska and Kodiak communities. The red line is the regulatory limit (80 µg of toxin/100 g of tissue. Data provided by SEATOR.

highest levels of shellfish toxicity in blue mussels since this monitoring program began in 2019. Blue mussels at South Trident Basin were recorded at 1,300 µg of toxicity. Additionally, 10 of the 13 samples (6 species from 5 locations), submitted by community harvesters in 2021 through the Harvest and Hold program, came back above the regulatory limit.

Resurrection Bay and Prince William Sound – Alutiiq Pride Marine Institute conducted phytoplankton and shellfish monitoring at 8 locations (multiple locations in Resurrection Bay, Pigot Bay, Derickson Bay, Tatitlek, and Chenega). The phytoplankton monitoring observed a sparse occurrence of *Pseudo-nitzschia* in Chenega in April and in Seward at the end of June. *Alexandrium* was not found at any of the phytoplankton monitoring locations.

Middleton Island – A seabird die-off on Middleton Island in July raised concerns of potential HABs involvement, but so far samples have been negative or low for paralytic shellfish toxins (PST). More tests for domoic acid and PST on other samples still need to be conducted, but HABs are not considered the cause of this die-off at this time (see Seabird mortality event in this report, p.24)

GOA: Preliminary analysis of fish samples collected from 2014-2020 from multiple locations across the GOA (at different times of year and during different *Alexandrium* concentrations) show the following trends: 1) toxins were found across all species, generally but not always at low levels, 2) some levels exceeded regulatory limits, 3) there were differences between different fish tissues, and 4) differences between species (Figure 95). Additional, preliminary analysis of saxitoxin accumulation across tissue types in piscivorous fish found at least one sample above the regulatory limit in liver (pink salmon and sockeye salmon) and kidney (Chinook salmon, chum salmon and coho salmon), relative to digestive organs, muscle, roe, and stomach contents (preliminary data provided by Steve Kibler, NOAA NOS Beaufort Lab).

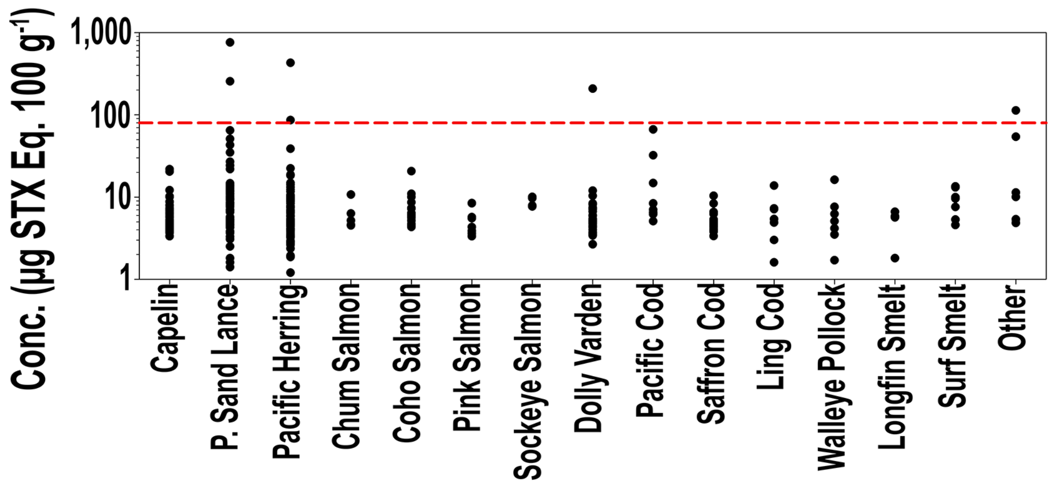


Figure 95: Preliminary saxitoxin concentrations (µgSTX Eq./100g; log scale) in fish samples across GOA (2014-2020). Samples were collected at different times of year and during different *Alexandrium* concentrations. The red dashed line shows the regulatory limit of saxitoxins for safe human consumption at 80µg/100g of shellfish tissue. Data are provided by Steve Kibler, NOAA NOS Beaufort Lab).

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* blooms occur at temperatures above 10°C and salinities above 20 (Vandersea et al., 2018; Tobin et al., 2019; Harley et al., 2020). As waters warm throughout Alaska, blooms may increase in frequency and geographic extent.

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). A multi-disciplinary statewide study funded by NOAA's ECOHAB program is underway and encompasses ship-based sediments samples, water samples, zooplankton samples, krill samples, copepod samples, multiple species of fish, bivalves, and the continuation of sampling subsistence-harvested and dead stranded marine mammals.

"Mushy" Halibut Syndrome Occurrence

Contributed by Stephani Zador
Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
Contact: stephani.zador@noaa.gov
Last updated: October 2021

Description of indicator: Mushy Halibut Syndrome was first detected in Gulf of Alaska halibut in 1998. Increased prevalence occurred in 2005, 2011, 2012, 2015, and 2016. It was apparently absent in 2013 and 2014, and there were relatively few occurrences in 2017 and 2018. It is most often observed in smaller halibut of 15–20 lbs in the Cook Inlet area, but has also been noted in Kodiak, Seward, and Yakutat. Alaska Department of Fish and Game (ADF&G) describes the typical condition consisting of fish having large areas of body muscle that are abnormally opaque and flaccid or jelly-like. The overall body condition of these fish is usually poor, and often they are released because of the potential inferior meat quality. Data are collected through searches of ADF&G fishing reports and queries to IPHC and ADF&G staff. Incidence of mushy halibut is reported opportunistically in recreational fishing reports and may not represent true trends. In particular, for these types of qualitative indicators, absence of reporting does not prove absence in the environment.

Status and trends: There were no reports of "mushy" halibut during the 2019–2021 sport fishing seasons in central Alaska (`http://www.adfg.alaska.gov/sf/fishingreports/`). However, there was one anecdotal report of "mushy" halibut in a tribal fishery off Washington in 2020 (pers. comm. Josep Planas, IPHC).

Factors influencing observed trends: The condition is considered a result of nutritional myopathy/deficiency, and thus may be indicative of poor prey conditions for halibut. According to ADF&G, the Cook Inlet and Homer/Seward areas are nursery grounds for large numbers of young halibut that feed primarily on forage fish that have recently declined in numbers. Stomach contents of smaller halibut now contain mostly small crab species. Whether this forage is deficient, either in quantity or in essential nutrients is not known. However, mushy halibut syndrome is similar to that described for other animals with nutritional deficiencies in vitamin E and selenium. This muscle atrophy would further limit the ability of halibut to capture prey possibly leading to further malnutrition and increased severity of the primary nutritional deficiency. Also, as the reporting for this indicator is opportunistic and subject to observation error, it may not reflect true prevalence in the ecosystem.

Implications: The relatively few reports of "mushy" halibut since the end of the 2014–2016 marine heatwave in the GOA may indicate that foraging conditions for young halibut have been more favorable in recent years. However, the absence of "mushy" halibut reports during the 2019 heatwave year suggests that there is not a simple link between environmental conditions and the prevalence of this condition.

Prince William Sound

Sea surface temperature shows an increasing trend in central Prince William Sound (PWS) for the last four decades, at approximately 0.09°C per decade. There have been primarily positive anomalies with consecutive heatwaves since 2014, but in 2021 temperatures finally returned to near long-term mean levels. Similarly for nearshore intertidal zones in 2021, water temperatures were at long-term means in western PWS during winter and spring, followed by cooling and negative anomalies into summer. Despite returning to long-term mean temperature levels, however, biological metrics in PWS have still not returned to pre-heatwave levels, though some show promising signs. Pacific herring abundance (miles-day milt during spring spawning) continued to increase after the lowest abundance in the nearly 50-year time series following recent heatwaves, but remains below pre-heatwave levels. With herring as a key prey item, humpback whale abundance (encounter rate during fall surveys) also remains low 7 years after recent heatwaves. Likewise, intertidal food webs in 2021 remain in a similar post-heatwave state, where primary producers (*Fucus*) and predators (sea stars) remain in relatively low abundance, whereas secondary consumers (mussels) remain positive or near the long-term mean.

Temperature trends in the near surface waters of Prince William Sound

Contributed by Rob Campbell and Caitlin McKinstry, Prince William Sound Science Center, Box 705 Cordova, AK, 99574
Contact: rcampbell@pwssc.org
Last updated: September 2021

Description of indicator: A 46-year time series of sea surface temperature (SST) was compiled in Prince William Sound (PWS), western Gulf of Alaska region, 1974–2020. Sea surface temperature anomalies were calculated as the residual of the 2nd order cosine fit to daily temperature data, to remove seasonality. Data were collected from the World Ocean Database (NOAA), and an unpublished database of casts done by the University of Alaska Fairbanks (UAF). The data represent an exhaustive collation of historical data from prior projects, and the data were collected with a variety of instruments from numerous platforms. Recent data (>2010) is from ongoing Gulf Watch Alaska (`gulfwatchalaska.org`) projects conducted by the PWS Science Center, UAF, and NOAA.

Status and trends: In 2021 near surface temperature anomalies appear to have returned to a state near to the climatological average. SST has been increasing in central PWS for the last four decades, at approximately 0.09°C per decade (Figure 96), although there is substantial year-to-year variability. In 2013, anomalies shifted towards strongly positive, and have for the most part stayed that way into 2020 except for a brief dip in 2018, which reflects basin scale marine heatwaves that have been noted throughout the Gulf of Alaska in 2013–2015 (Bond et al., 2015) and 2019 (Amaya et al., 2020). Temperature in PWS remained elevated for about 1 year longer than was observed offshore, which is typical–PWS generally lags the Gulf of Alaska by about 12 months (Campbell, 2018).

Factors influencing observed trends: Temperatures in PWS generally track those of the Gulf of Alaska with a lag of about 12 months, which is driven by circulation within the region (Campbell,

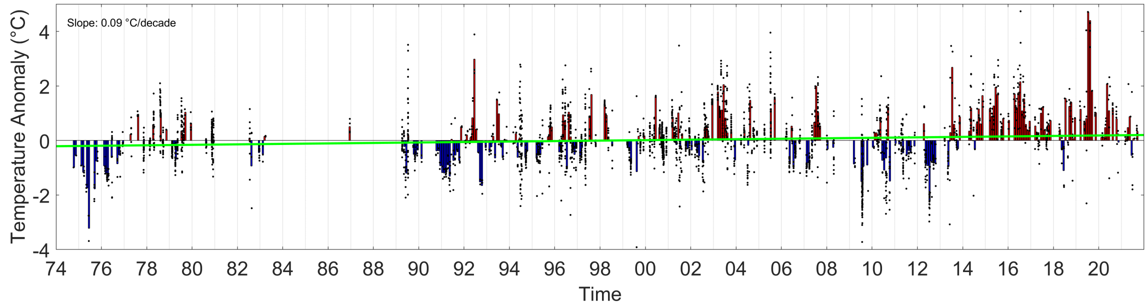


Figure 96: Near surface (2 m) temperature anomalies in central Prince William Sound, 1974–2021. Black dots indicate observations, and bars are monthly averages; the green line is the long-term trend. Anomalies were calculated as the residuals of a second order cosine curve fit to all years' data (to remove seasonality).

2018). The onset of the marine heatwaves in PWS was concurrent with the increase in temperatures basin-wide, because the driver of the onset of the heatwave was atmospheric. In 2013–2014 a prolonged period of calm winter weather occurred where heat was not mixed out of the surface layer in winter (Bond et al., 2015). In 2019 a period of calm weather allowed greater heat fluxes into the surface layer (Amaya et al., 2020). The long term trend towards warming also matches a long term warming trend observed in the Gulf of Alaska (Royer and Grosch, 2006; Janout et al., 2010).

The role of temperature in structuring the components of marine plankton ecosystems is less well understood. Warm-preferring species are generally more common within PWS than on the adjacent shelf and PWS may be a "refuge" of sorts for these species. The increase in their relative abundance during the marine heatwave years may have been in part because these species tend to be found in PWS and were already there, and thus able to grow and reproduce better during the marine heatwave years. Similarly, cool water species may have been at a competitive disadvantage during the marine heatwave years.

Implications: The changes in temperature in PWS in the last few decades mirror those observed basin-wide in the Gulf of Alaska and have been driven by a warming trend that is in turn driven by warming trends observed globally (Levitus et al., 2001), and because much of the increased heat flux has been taken up by the ocean. That warming trend is restructuring marine ecosystems in ways that are difficult to predict, much less to observe as they happen. Temperature is an important forcing function for the vital rates of most lower trophic level players (e.g., growth rates by cold-blooded organisms). Different species have different temperature preferences, and temperature also influences what species are present. Temperature thus influences the food environment of fish predators, as well as their growth rates.

Intertidal Ecosystem Indicators in the Northern Gulf of Alaska

Contributed by Heather Coletti[1], James Bodkin, Thomas Dean, Daniel Esler, Katrin Iken, Brenda Ballachey, Kim Kloecker, Brenda Konar, Mandy Lindeberg, Daniel Monson, Brian Robinson, Robert Suryan, Ben Weitzman
[1]National Park Service, 4175 Geist Rd., Fairbanks, AK, 99709
Contact: heather_coletti@nps.gov
Last updated: September 2021

Description of indicator: Nearshore monitoring in the Gulf of Alaska (GOA) provides ongoing evaluation of status and trends of more than 200 species associated with intertidal and shallow subtidal habitats. The spatial extent of sampling includes 21 sites distributed across the northern GOA from western Prince William Sound (WPWS), Kenai Fjords National Park (KEFJ), Kachemak Bay (KBAY), and Katmai National Park and Preserve (KATM). Due to the COVID-19 global pandemic, field sampling was significantly reduced in 2020. Most intertidal work was completed in KBAY, however, minimal sampling was conducted in KEFJ and WPWS, while none was completed in KATM. Due to the COVID-19 global pandemic, field sampling was significantly reduced in 2020, however all sampling was completed in 2021. Since 2018, we have reported one physical indicator (intertidal water temperature) and three biological indicators that represent key nearshore ecosystem components of primary production (algal cover), prey abundance (mussel density), and predator abundance (sea star density). Our algal cover indicator is percent cover of rockweed (*Fucus distichus*) sampled in quadrats at the mid intertidal level (1.5 m). Intertidal prey is represented by density estimates of large ($\geq$ 20 mm) Pacific blue mussels (*Mytilus trossulus*) sampled quantitatively within mussel beds. Nearshore predator abundance indicator is density of the most abundant sea stars, estimated along a 50 m x 4 m transect at each rocky intertidal site in the GOA. Indicators are presented as annual anomalies compared to the long-term mean of the data record by site.

Status and trends: Nearshore water temperature in all four intertidal zones from Prince William Sound to the Alaska Peninsula showed a warming trend beginning in 2014 and persisting across all regions through 2016 and into 2017 in WPWS and KEFJ (Figure 97). These results confirm that the 2014-2016 marine heatwave in the Gulf of Alaska affected intertidal zones. While temperatures had appeared to cool and return to normal across all regions later in 2017 and into 2018, 2019 indicated warmer than average water temperatures in the intertidal zone across all four study regions and a cooling during the early part of 2020, particularly in the western blocks of KBAY and KATM. Temperatures appeared to return to the long-term mean across all regions early in 2021, followed by cooling across all regions into the summer months of 2021.

For algal cover, despite considerable variability in percent cover among sites and generally positive anomalies through 2014, KATM and KEFJ sites showed consistently negative values during the recent marine heatwave and continuing through 2021 (Figure 98). KBAY continued to have roughly average *Fucus* cover without a noticeable response in percent cover of *Fucus* to the heatwave through 2021. Anomalies in WPWS had become slightly positive in 2019, possibly implying recovery from the heatwave. However, data from 2021 would indicate otherwise as WPWS continued to have a negative anomaly of *Fucus* % cover.

Large mussel densities ($\geq$ 20 mm) showed an overall strong positive trend across all sites consistent with timing of the marine heatwave through 2019, in this case switching from generally negative

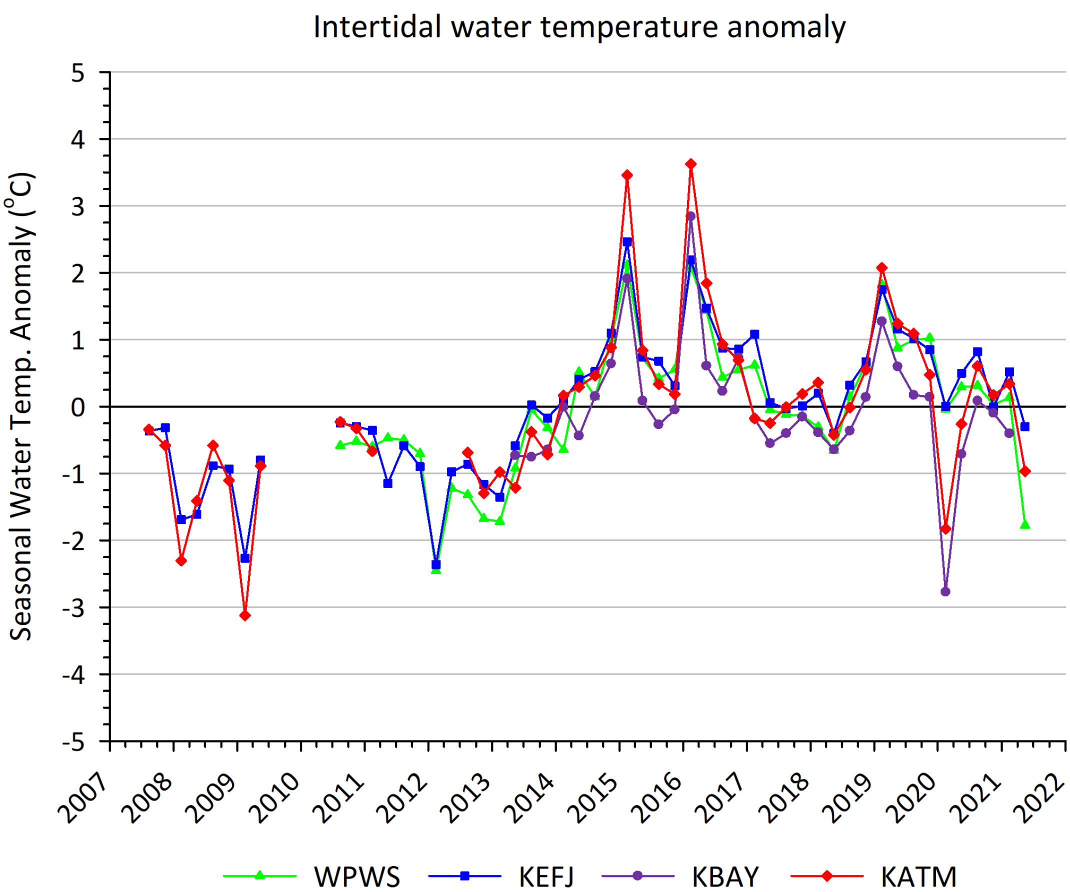


Figure 97: Seasonal intertidal water temperature anomalies at the 0.5 m tide level four regions of the western Gulf of Alaska, western Prince William Sound (WPWS; 2011-2021), Kenai Fjords National Park (KEFJ; 2008-2021), Kachemak Bay (KBAY; 2013-2021), and Katmai National Park adjacent to Shelikof Strait (KATM; 2006-2021). Long tick marks indicate the start of the calendar year (January) while short tick marks are quarterly divisions within the year (April, July, October).

to positive anomalies after 2014 — an opposite response compared to sea stars (Figures 99 and 100). In 2021, it appears that large mussel density has returned to the long-term mean across all regions. Also, in comparison to other indicators, there seems to be higher across-site variability in mussel density, indicating that other variables and local conditions are important drivers of mussel abundance (Bodkin et al., 2018).

For sea star abundance, variability in density, diversity and dominance of individual sea star species varied greatly among regions through 2015 (Figure 100). Between 2015 and 2017, abundance declined and remained strongly negative across all regions through 2018, likely due to sea star wasting (Konar et al., 2019). In 2019, there was some recruitment and recovery in WPWS, which persisted through 2020. However, the sea star species thought to be unaffected by sea star wasting in the northern Gulf of Alaska (primarily *Henricia* and *Dermasterias*) continued to be present and accounted for the positive anomalies. The positive anomaly in WPWS and KEFJ during 2020 surveys was driven by high numbers of *Dermasterias* (81% and 88% of observed sea stars, respectively). The previously dominant sea stars (primarily *Pycnopodia*, *Evasterias*, and *Pisaster*)

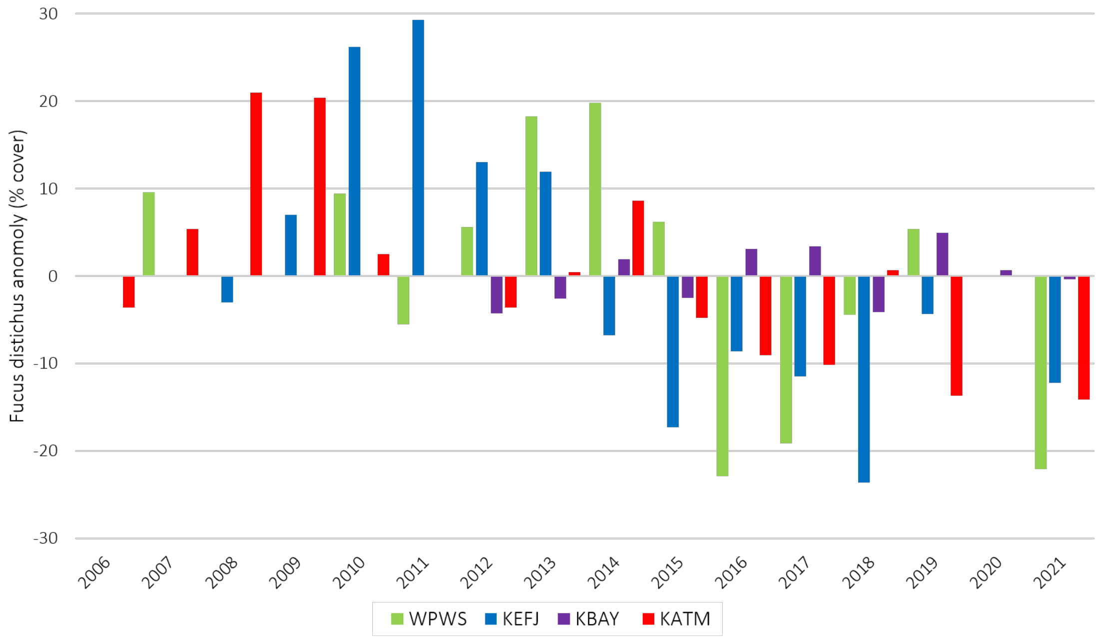


Figure 98: Percent cover anomalies for rockweed (*Fucus distichus*) in four regions of the western Gulf of Alaska, WPWS (2007, 2010-2019, 2021), KEFJ (2008-2019, 2021), KBAY (2012-2021), and KATM (2006-2010, 2012-2019, 2021). WPWS, KEFJ and KATM were not sampled in 2020 due to COVID-19. Note: KBAY anomaly in 2021 was close to 0 (-0.381), hence the lack of visible bar for KBAY 2021.

continued to be absent (or rare) in many of the Gulf Watch sites, although one site in WPWS in 2020 showed some recovery potential with many small *Pycnopodia*. But, by 2021 all regions except KATM again were negative (Figure 100). The star species documented in KATM that account for the positive anomaly were primarily *Evasterias* (53%), *Pisaster* (35%) and *Pycnopodia* (10%), indicating a potential return of sea stars along the KATM coast but not elsewhere across the Gulf. This may help explain the slightly negative anomaly of large mussel density observed in KATM (Figure 99) but fails to explain this pattern elsewhere in the GOA.

Factors influencing observed trends: The negative anomalies of rockweed in three of the four regions and sea stars across all regions were coincident with warm water temperatures in nearshore areas. The decline in sea star abundance across the Gulf was likely due to sea star wasting disease (Konar et al., 2019), first detected south of Alaska in 2014 and generally thought to be exacerbated by warm water temperature anomalies (Eisenlord et al., 2016).

Implications: Collectively, these indicators demonstrate consistent, broad-scale perturbations of nearshore ecosystems coincident with the Pacific marine heatwave throughout much of the western Gulf of Alaska, including areas both inside (WPWS, KBAY) and outside (KEFJ and KATM) of protected marine waters. Even though *Fucus* did not decline markedly in KBAY, a comprehensive analysis of rocky intertidal community structure was completed, indicating a loss of autotroph-macroalgal dominated communities to heterotroph-filter-feeder communities, ultimately resulting in a homogenization of community structure across all four regions (Weitzman et al., 2021). Concurrently, we suspected the loss of sea stars allowed for the increase in mussel density due to a decline in predation pressure. However, preliminary analyses indicate that the decline in sea stars

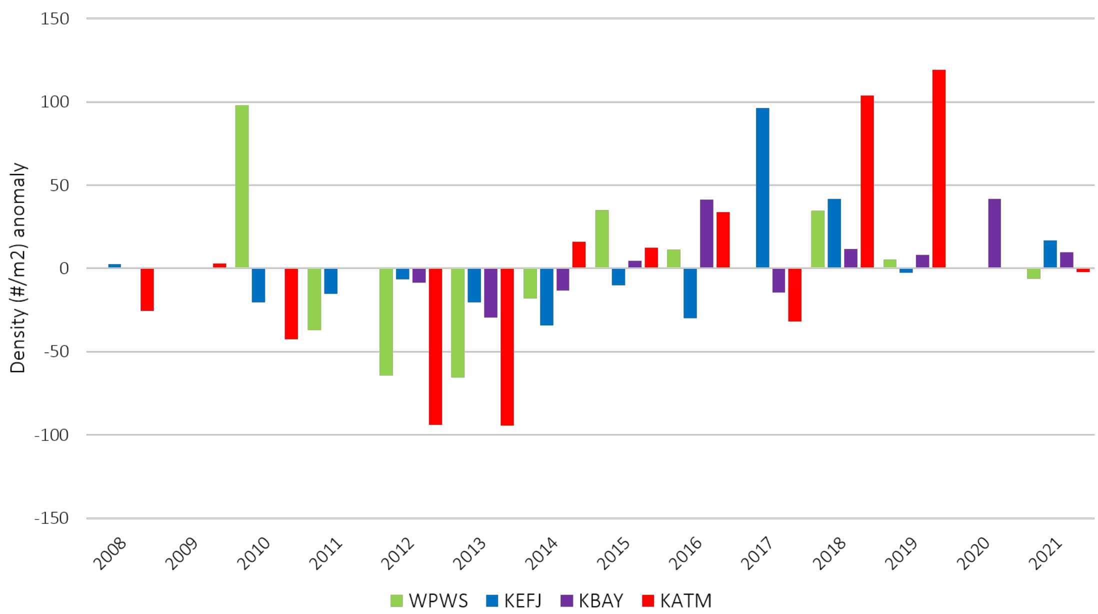


Figure 99: Density anomalies for large mussels (> 20 mm) in four study regions spanning the northern Gulf of Alaska. WPWS (2010–2019, 2021), KEFJ (2008–2019, 2021), KBAY (2012–2021), and KATM (2008–2010, 2012–2019, 2021).

and increased temperatures only explain 33% of the variation in large mussel density, suggesting that other factors such as predation pressure from nearshore vertebrates to shifts in primary productivity to changes in environmental variables (salinity) may also influence mussel density (Traiger et al., In Prep.).

Intertidal and nearshore ecosystems provide valuable habitat for early life stages of various commercially important species in the Gulf of Alaska, including Dungeness crab, Pacific cod, salmonids and several species of rockfish. Our indicators suggest that some nearshore biological responses to the heatwave appear to continue into 2021 and could possibly affect future recruitment and survival of species whose life stages rely on nearshore habitat. Further, we also hypothesize that we may see responses of nearshore-reliant, upper trophic level species (such as sea otters and sea ducks) to shifts in prey availability from changing ocean conditions across the Gulf of Alaska.

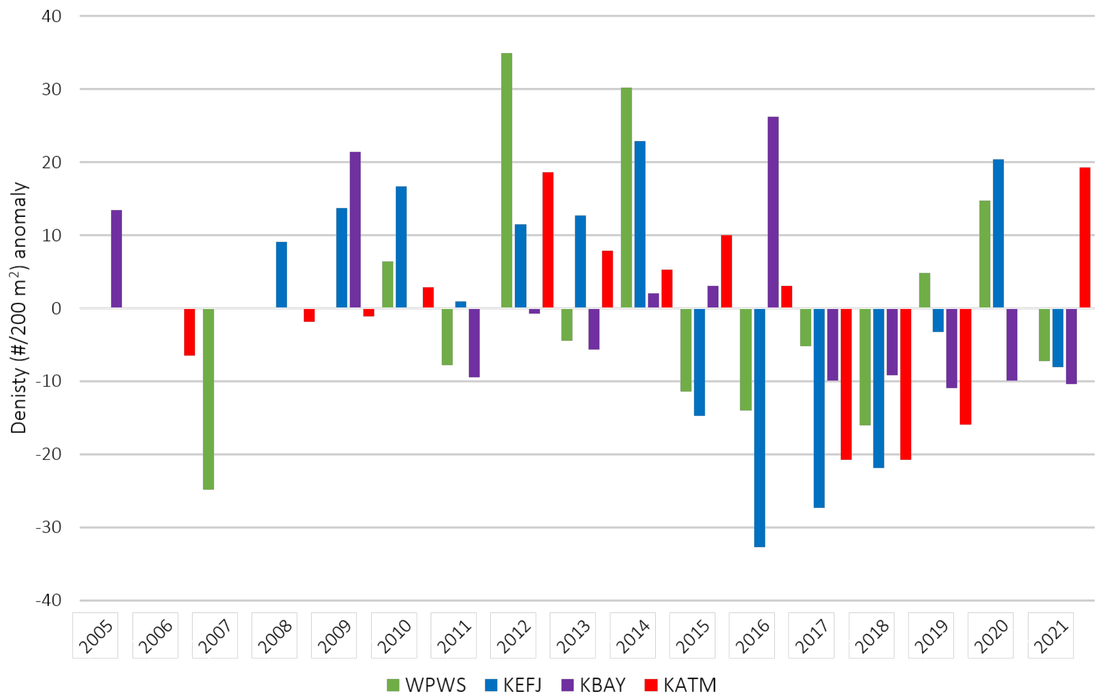


Figure 100: Density of sea stars (*Dermasterias imbricata*, *Evasterias troschelii*, *Pisaster ochraceus*, and *Pycnopodia helianthoides*) in four study areas spanning the northern Gulf of Alaska. WPWS (2007, 2010–2021), KEFJ (2008–2021), KBAY (2005, 2009, 2011–2021), and KATM (2006, 2008–2010, 2012–2019, 2021).

Prince William Sound Herring

Contributed by W. Scott Pegau[1], John Trochta[2], Stormy Haught[3]
[1]Prince William Sound Science Center, Box 705, Cordova, AK 99574
[2]School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195
[3]ADF&G, Division of Commercial Fisheries, Box 669, Cordova, AK 99574
Contact: wspegau@pwssc.org
Last updated: September 2021

Description of indicator: Prince William Sound (PWS) Pacific herring (*Clupea pallasii*) population estimates are generated annually by *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) researchers with an age-structure-assessment (ASA) model using data collected by EVOSTC researchers and Alaska Department of Fish and Game (ADF&G). The original catch-age analysis for PWS herring, developed by Funk and Sandone (1990) for ADF&G stock assessment and management, was later adapted for research and described by Hulson et al. (2007). The results presented here are from a Bayesian version of the ASA model described by Muradian et al. (2017) (hereafter referred to as BASA) that was developed and run by the University of Washington as part of the *Exxon Valdez* Oil Spill Trustee Council sponsored Herring Research and Monitoring program. The model inputs include aerial surveys of mile-days of spawn, acoustic surveys of spawning biomass, age-sex-size, historical egg deposition, and disease prevalence data. An output of the model is the annual median estimate of the pre-fishery biomass. The PWS surveys used by the model are conducted in the spring. The survey area covers traditional spawning regions within Prince William Sound and occasional surveys in the Kayak Island area, although Kayak Island is not included in the inputs to the ASA model.

The mile-days of milt surveys collected by ADF&G extend back to the early 1970s, but the approach used became more consistent beginning in 1980. While the mile-days of milt survey is a relative index of abundance, it is the longest abundance time series used in the model. Acoustic surveys collected by the Prince William Sound Science Center started in the mid-1990s. It is the sum of miles of spawn observed each day during the spawning season. ADF&G has also collected herring age, sex, and size data from PWS commercial fisheries and fishery-independent research projects since 1973. Egg deposition scuba surveys were conducted by ADF&G in 1983, 1984, and 1988–1997. Recently, we began an annual survey of the number of age-1 herring schools in PWS. The entire coastline of PWS is flown and the schools and school size identified by an observer. The number of schools is then weighted by the school size to provide an index of abundance.

Status and trends: A rapid rise in the estimated pre-fishery biomass of herring occurred in the 1980s and a subsequent decline in the 1990s (Figure 101). There is not agreement about the cause of the decline in the early 1990s, but an outbreak of viral hemorrhagic septicemia (VHS) is one mechanism thought to be possibly responsible for the decline. After that decline, the population remained fairly steady. In recent years the BASA model estimated a declining trend in herring biomass, with a rapid increase beginning in 2019 (Figure 101). The decline in the observed mile-days of milt is more rapid than the model decline (Figure 102) but also shows a rapid increase starting in 2019. The rapid increase is associated with the recruitment of the large 2016 year-class to the spawning biomass. The observed mile-days of milt in 2021 continued to increase as the 2016 year-class continues to recruit into the spawning biomass.

The time series of the age-1 herring school observations has now reached ten years and the index

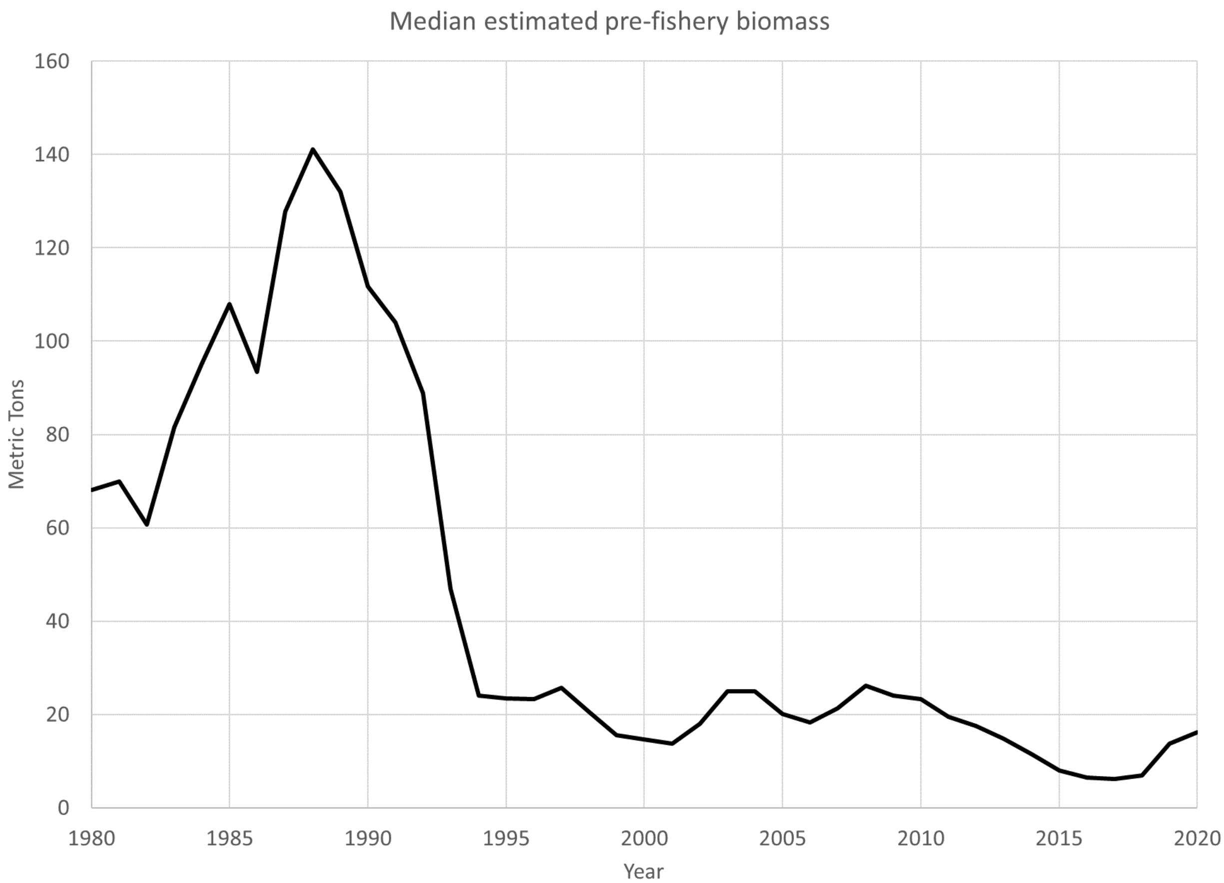


Figure 101: The Bayesian age-structured assessment model median estimate of the pre-fishery biomass.

is shown in Figure 103. The 2016 year-class appears in the 2017 survey of age-1 herring. While the 2012 herring year-class was strong at other locations, it was not a strong year class in PWS. The 2021 survey results showed nearly as many schools as was observed in 2017, which suggests the potential for another large year class.

Factors influencing observed trends: The building trend in herring biomass has been associated with the recruitment of the 2016 year-class. The 2016 year-class may have been a successful year class for herring throughout the Gulf of Alaska with recruit to spawner metrics across the region being nearly four times greater than the next most successful year class since 1980. The mile-days-milt leveled off in 2021 as the 2016 year-class has fully recruited to the spawning biomass.

Implications: The herring population is beginning to increase but will need additional large year classes to join the spawning biomass to reach the levels observed as recently as 2010. It is possible that lower abundance of herring may have negative impacts on predators that rely on them.

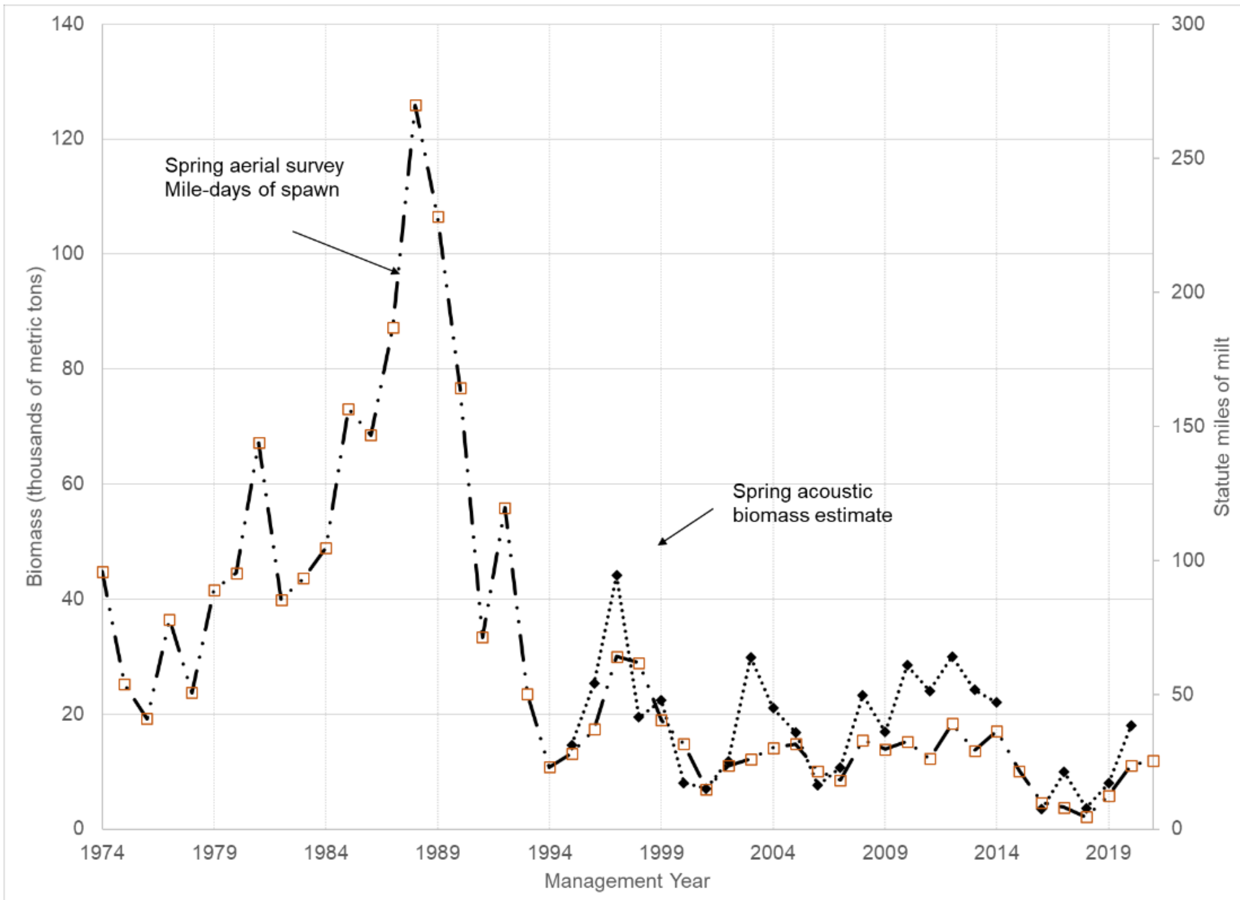


Figure 102: Mile-days of milt in Prince William Sound based on aerial surveys and biomass estimates from acoustic surveys. Includes preliminary results of the 2021 survey from Alaska Department of Fish and Game.

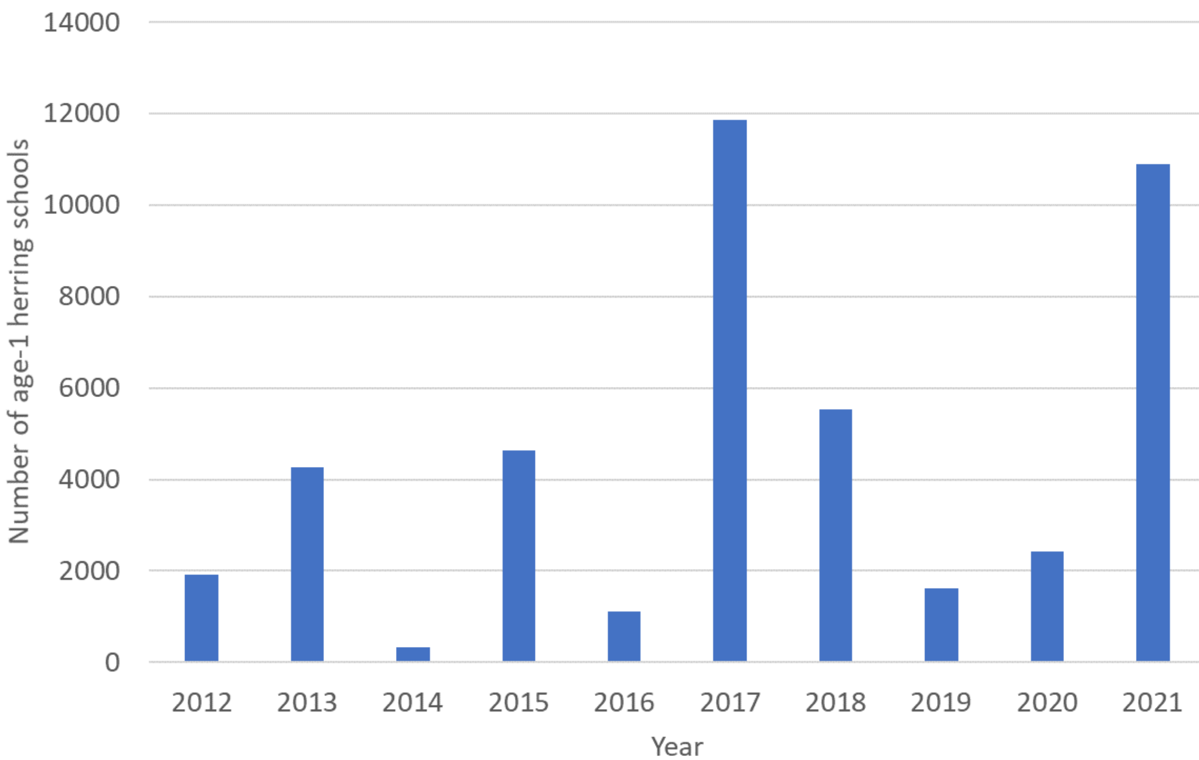


Figure 103: The school-size weighted number of age-1 herring schools in Prince William Sound.

Fall Surveys of Humpback Whales in Prince William Sound

Contributed by John Moran[1] and Janice Straley[2]
[1]Auke Bay Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA
[2]University of Alaska Southeast, 1332 Seward Ave, Sitka, AK 99835
Contact: john.moran@noaa.gov
Last updated: September 2021

Description of indicator: The humpback whale population in the North Pacific has rebounded from near extinction in the late 1960s to over 22,000 individuals (Barlow et al., 2011). This rapid recovery has coincided with major natural and anthropogenic perturbations in the marine ecosystem. Over much of the same period, in Prince William Sound, the abundance of the dominant forage fish, Pacific herring, shifted from an abundant state to a diminished state. The lack of a commercial fishery has not restored the herring population to its former abundance. Humpback whale abundance and calf production within Prince William Sound often tracks herring abundance and indicates the ability of the ecosystem to support populations of large vertebrate predators.

Status and trends: Foraging observations seen prior to the 2014–2016 marine heatwave, consisted of groups of whales (up to 80 individuals) typically targeting shoals of energy rich adult herring in predictable locations as they moved into the Sound. Our September 2021 survey, completed with fair to excellent conditions, yielded similar results to our 2017–2020 effort. No calves were seen in 2021 during our April or September surveys. The 2021 encounter rate for humpback whales (number of whales/nm traveled) was similar to 2020 (Table 6). Acoustic surveys for prey in 2021 have yet to be quantified, however, we were able to identify juvenile and adult herring as the primary prey for humpback whales. We did not locate any large aggregations of humpback whales feeding on large shoals of adult herring.

Table 6: Index of PWS humpback whale abundance and counts of calves in PWS.

Month/year	Whale counts	Calves counts	Nautical miles surveyed	Encounter rate whale/nm
Sep-08	71	17	412	0.17
Oct-11	62	2	441	0.14
Sep-12	81	5	444	0.18
Sep-13	113	6	355	0.32
Sep-14	181	1	427	0.42
Sep-17	12	0	543	0.02
Sep-18	17	1	541	0.03
Sep-19	35	0	573	0.06
Sep-20	14	2	331	0.04
Sep-21	23	0	525	0.04

Factors influencing observed trends: The abundance of herring in Prince William Sound has yet to return to pre-2014 levels. The 2021 spawn surveys indicated a slight increase in herring biomass from 2020, however, it does not appear that whale numbers followed suit. The fate of the whales who typically forage in Prince William Sound remains uncertain. We are comparing sighting data from Prince William Sound to other feeding and breeding grounds to locate the missing whales.

Implications: The trend in whale numbers and calf production within Prince William Sound differs with observations from Southeast Alaska and Hawaii where both the sightings of adults and calves are showing signs of recovery towards pre-2014–2016 Pacific marine heatwave levels. This implies that forage species in PWS may be diminished and are not following the same trajectory as other regions in the Gulf of Alaska.

Fishing and Human Dimensions Indicators

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 104 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.*

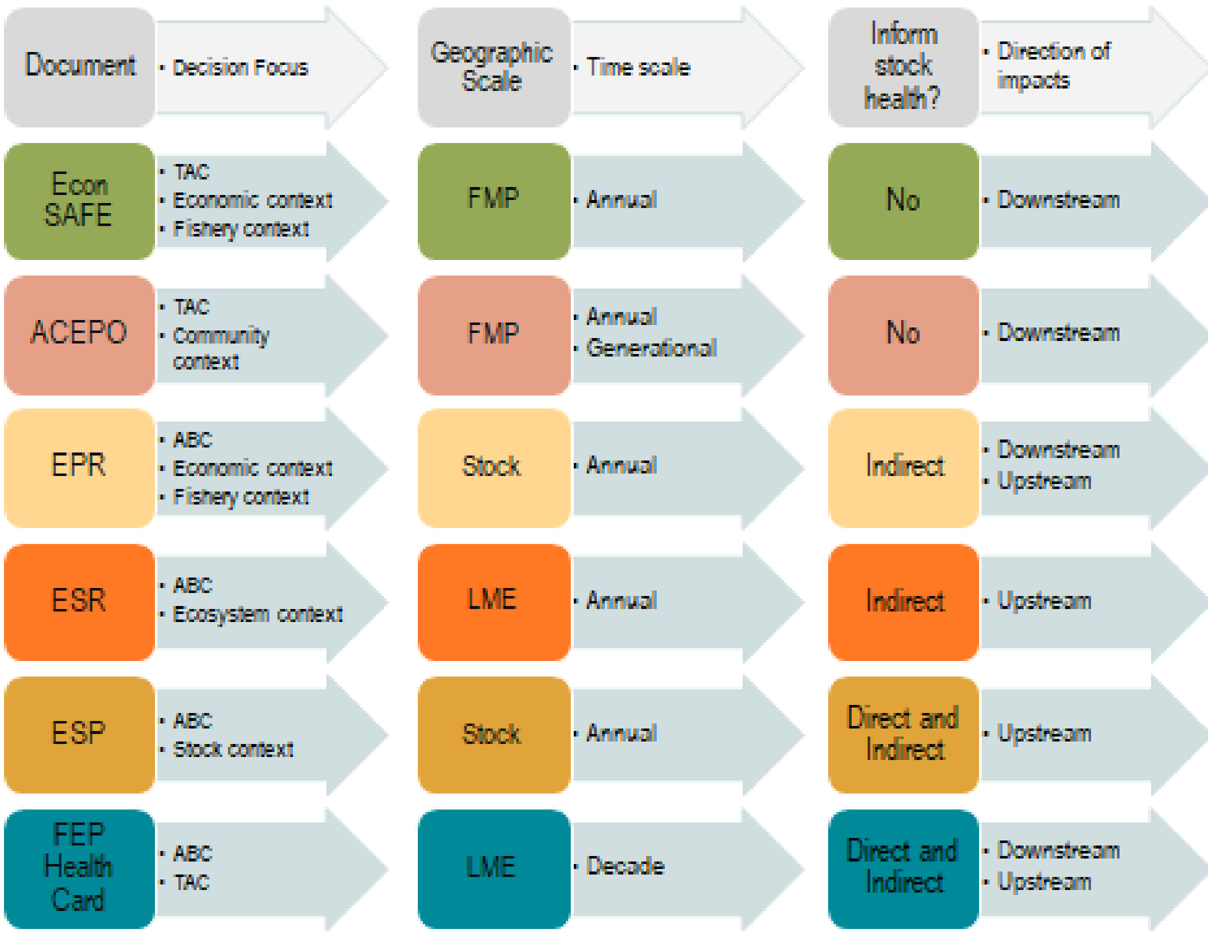


Figure 104: NOAA Alaska Fisheries Science Center's human dimensions indicators mapping

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:

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

Maintaining Diversity: Discards and Non-Target Catch

Time Trends in Groundfish Discards

Contributed by Jean Lee, Resource Ecology and Fisheries Management Division, AFSC, NMFS, NOAA, and 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 105, 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 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.

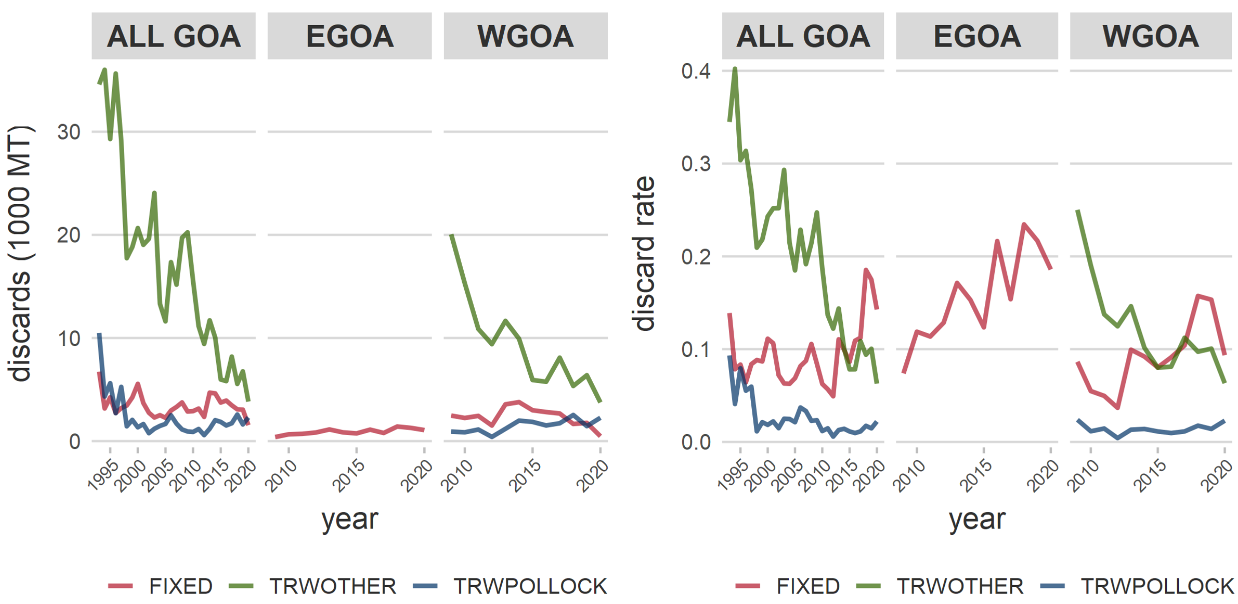


Figure 105: Total biomass and percent of total catch biomass of FMP groundfish discarded in the fixed gear (FIXED), pollock trawl (TRWPOLLOCK), and non-pollock trawl sectors (TRWOTHER) for the Gulf of Alaska (ALL GOA) region, 1993–2020; and for and eastern and western GOA subregions, 2009–2020. Discard 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: Discard biomass in the fixed gear and non-pollock trawl sectors, in 2021, is trending lower relative to the previous 5 years through week 33, whereas trawl pollock discard biomass is trending in line with previous years (Figure 106). Since 1993 discard rates of groundfish species in federally-managed Alaskan groundfish fisheries have generally declined in both pollock and non-pollock trawl fisheries in the Gulf of Alaska (GOA) (Figure 105). In the non-pollock trawl sector, discard rates dropped from 40% in 1994 to 21% in 1998, trended upwards from 1998 to 2003, and generally declined to a low of 8% in 2015 and 2016 before increasing slightly to 11% in 2017. Discard rates in the GOA pollock trawl sectors declined from over 10% in 1993 to about 1% in 1998 and have since fluctuated between 1% and 3%. Discard biomass in the fixed gear (hook-and-line and pot) sector has generally declined from 2013 onward, though discard rates for fixed gear across the GOA as a whole increased to over 17% in 2018 and 2019 after remaining at 11% or lower from 2013 to 2017.

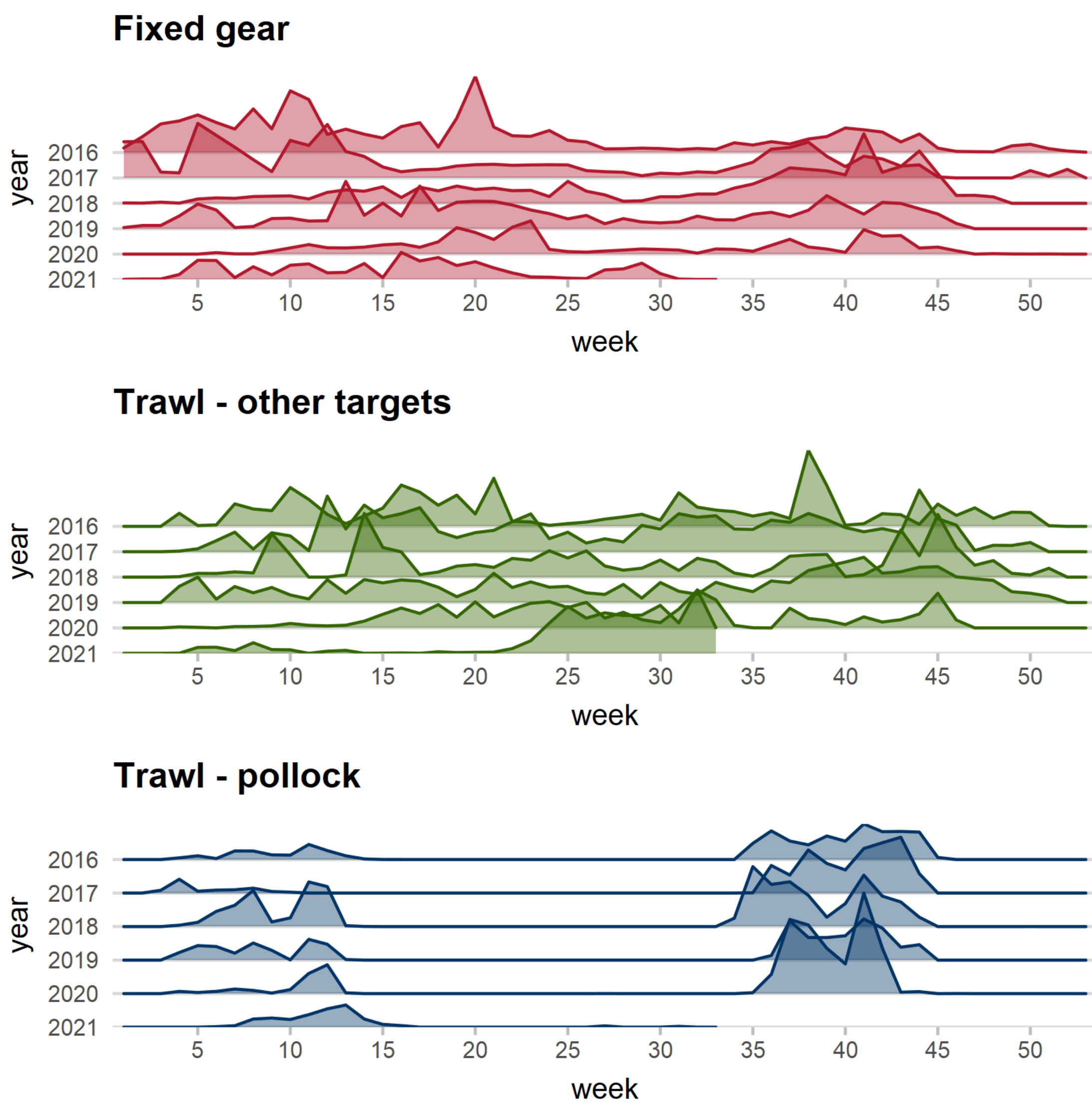


Figure 106: Total biomass of FMP groundfish discarded in the Gulf of Alaska by sector and week of the fishing season, 2014–2021 (data for 2021 is shown through week 36). Plotted heights are not comparable across fisheries.

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—for example, 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; National Marine Fisheries Service, 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; and maximum retainable amounts (MRAs), which allow for limited retention of species harvested incidentally in directed fisheries.

In the Gulf of Alaska LME, management and conservation measures aimed at reducing bycatch have contributed to an overall decline in groundfish discards since the early 1990s (NPFMC, 2016). Pollock roe stripping, wherein harvesters discard all but the the highest value pollock product, was prohibited in 1991 (56 Federal Register 492). In 1997 arrowtooth flounder was added as a basis species for retention of pollock and Pacific cod (62 Federal Register 11109), and in 1998 full retention requirements for pollock and cod were implemented for federally-permitted vessels fishing for groundish, leading to overall declines in pollock and cod discards in the GOA (62 Federal Register 65379). Additional retention requirements went into effect in 2003 for shallow-water flatfish species across the entire GOA (62 Federal Register 65379) and in 2004 for demersal shelf rockfish in the Southeast Outside district of the Eastern Gulf (69 Federal Register 68095). In 2009, NMFS revised the MRA for groundfish caught in the Gulf of Alaska arrowtooth flounder fishery, including an increase from 0 to 20 percent for flatfish species (74 Federal Register 13348). Under the GOA groundfish FMP, fisheries with discard rates over 5% for shallow-water flatfish are subject to annual review by the North Pacific Council. Reductions in flatfish discards account for most of the general decline in discards and discard rates for the non-pollock trawl sector.

Measures for reducing discards are included in the Pacific halibut and Sablefish Individual Fishing Quota (IFQ) Program, implemented in 1995, and the Central Gulf of Alaska (CGOA) Rockfish Program, piloted in 2007 and fully implemented in 2012. In the IFQ program, retention of sablefish and halibut is required as long as the harvester has catch quota available, which restricts the practice of high grading. Additionally, all Pacific cod and rockfish must be retained when IFQ halibut or sablefish are on board, subject to other regulations. Vessels participating in cooperatives with CGOA Rockfish Program catch quota are prohibited from discarding catch of allocated target species (Pacific ocean perch and northern, dusky, and thornyhead rockfish) and bycatch species (Pacific cod, sablefish, and rougheye and shortraker rockfish).

In recent years the species historically comprising the "other groundfish" assemblage (skate, sculpin, shark, squid, and octopus) have overtaken flatfish as the largest source of discards in the GOA. Most discards of these species currently occur in the longline fishery, although expanded observer coverage of smaller hook and line vessels beginning in 2013 may account for some of the recent increase in fixed gear sector discards. Retention rates for skate and octopus have fluctuated over time, in part due to changing market conditions for these species (Conners and Conrath, 2017; Ormseth, 2017). Interest in retention of skates and directed fishing for skates, despite management under bycatch-only status beginning in 2005, resulted in annual overages of longnose and big skate TACs from 2007 to 2013. Discards and discard rates of skate increased between 2013 and 2016 as

NMFS took action to prevent such overages, including regulatory discard requirements for big skate in the Central GOA, imposed at progressively earlier dates during the year from 2013 to 2015, and, in 2016, a reduction in the MRA for GOA skates from 20% to 5% (Ormseth, 2017).

Implications: Fishery discards 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). Discards 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; National Marine Fisheries Service, 2011; Clucas, 1997). 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]
[1]Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES), University of Washington, Seattle WA,
[2]Ecosystem Assessment Program, Northeast Fisheries Science Center, National Marine Fisheries Service, NOAA, Woods Hole MA,
Contact: andy.whitehouse@noaa.gov
Last updated: July 2021

Description of indicator: We monitor the catch of non-target species in groundfish fisheries in the Gulf of Alaska (GOA). 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 (see AFSC stock assessment website at `https://www.fisheries.noaa.gov/alaska/population-assessments/north-pacific-groundfish-stock-assessments-and-fishery-evaluation`). 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 Considerations Report, the three categories of non-target species we continue to track here are:

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 Fishery Management Plan 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.

The catch of non-target species/groups from the GOA includes the reporting areas 610, 620, 630, 640, 649, 650, and 659 (`https://www.fisheries.noaa.gov/alaska/sustainable-fisheries/alaska-fisheries-figures-maps-boundaries-regulatory-areas-and-zones`). Within reporting area 610, the GOA and Aleutian Islands (AI) Large Marine Ecosystems (LME) are divided at 164°W. Non-target species caught east of 164°W are within the GOA LME and the catch west of 164°W is within the AI LME.

Status and trends: The catch of Scyphozoan jellies in the GOA has been variable from 2011-2020, with peaks in 2012, 2015, 2016, and 2019 (Figure 107). The catch of jellies in 2020 was the third lowest over 2011–2020. Scyphozoan jellies are primarily caught in the pollock fishery. The catch of structural epifauna gradually increased from 2011 to 2016, and has since trended downward to 2020 where it reached its lowest level over 2011–2020. Sea anemones comprised the majority of the structural epifauna catch from 2011–2019 and they are primarily caught in the flatfish, Pacific cod, and sablefish fisheries. The catch of assorted invertebrates in the GOA has been variable since 2011. The catch increased from 2012 to a peak in 2015 then decreased each year since to a low in 2020. Sea stars dominate the assorted invertebrate catch, accounting for more than 86% of the total assorted invertebrate catch in each year. Sea stars are caught primarily in the Pacific cod and halibut fisheries.

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. The reductions in Pacific cod TAC since 2018 may have contributed to declines in the catch of structural epifauna and assorted invertebrates.

Jellyfish poulation dynamics are influenced by a suite of biophysical factors affecting the survival, reproduction, and growth of jellies including temperature, wind-mixing, ocean currents, and prey abundance (Purcell, 2005; Brodeur et al., 2008). The lack of a clear trend in the catch of scyphozoan jellies may reflect interannual variation in jellyfish biomass or changes in the overlap with fisheries.

Implications: The catch of structural epifauna and assorted invertebrates is very low compared with the catch of target species. Abundant jellyfish may have a negative impact on fishes as they compete with planktivorous fishes for prey resources (Purcell and Sturdevant, 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).

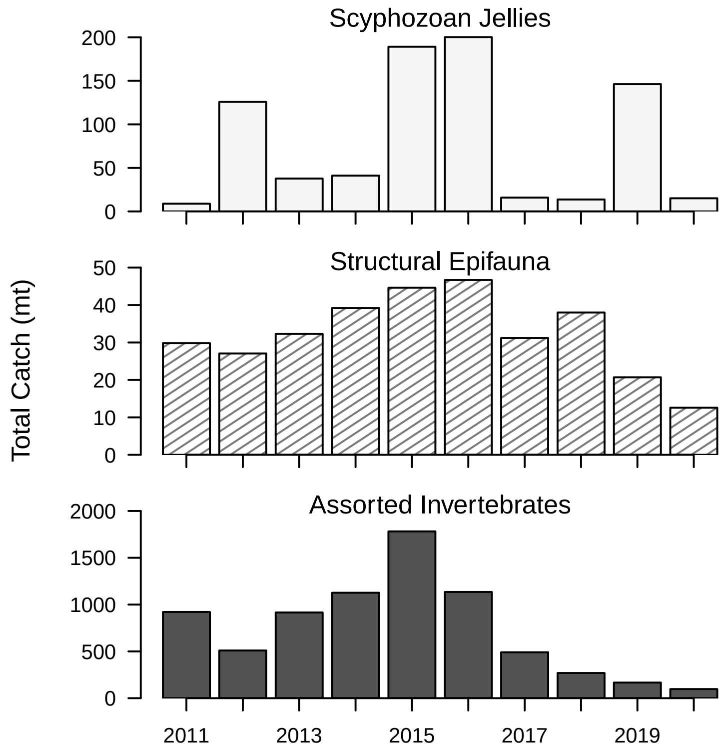


Figure 107: Total catch of non-target species (tons) in the GOA groundfish fisheries (2011–2020). Note the different y-axis scales between species groups.

Seabird Bycatch Estimates for Groundfish Fisheries in the Gulf of Alaska

Contributed by Joseph Krieger and Anne Marie Eich, Sustainable Fisheries Division, Alaska Regional Office, National Marine Fisheries Service, NOAA
Contact: josephkrieger@noaa.gov
Last updated: August 2021

Description of indicator: This Report provides estimates of the numbers of seabirds caught as bycatch in commercial groundfish fisheries operating in federal waters of the U.S. Exclusive Economic Zone of the Gulf of Alaska 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 (Alaska Fisheries Science Center (AFSC), 2011), and (2) industry reports of catch and production. Observer deployment plans are reviewed and updated annually in the Annual Deployment Plan (the 2021 plan is available at: `https://www.fisheries.noaa.gov/resource/document/2021-annual-deployment-plan-observers-and-electronic-monitoring-groundfish-and`). The NMFS Alaska Regional Office Catch Accounting System (CAS) produces the estimates (Cahalan et al., 2014, 2010). 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.

This Report delineates and separately discusses estimates of seabird bycatch in the eastern Gulf of Alaska and the western Gulf of Alaska (divided at 147°W). Estimates of seabird bycatch from the eastern Gulf of Alaska include reporting areas 650, 659, and 640. Estimates from the western Gulf of Alaska include reporting areas 649, 630, 620, and 610 (east of 164°W) (https://www.fisheries.noaa.gov/alaska/commercial-fishing/alaska-fisheries-figures-maps-boundaries-regulatory-areas-and-zones).

Status and trends: The number of seabirds estimated to be caught incidentally in eastern Gulf of Alaska fisheries in 2020 (128 birds) was nearly 50% less than in 2019 (216 birds), and was below the 2011–2019 average of 269 birds by 52% (Table 7, Figure 108). Black-footed albatross and gulls were the most common species caught incidentally. In 2020, the number of black-footed albatross (74 birds) was 29% less than that in 2019 (104 birds), and 33% below the 2011–2019 average of 110 birds. In 2020, the number of gulls was 32% less than in 2019 and was below the 2011–2019 average of 95 birds by 80%.

Table 7: Estimated seabird bycatch in the eastern Gulf of Alaska 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	26	0	0	0	0	42	1	0
Laysan Albatross	39	4	9	3	6	4	2	3	37	13
Black-footed Albatross	62	19	39	76	221	93	225	96	99	74
Northern Fulmars	131	0	13	4	19	6	31	18	41	2
Shearwaters	16	0	0	0	1	2	23	2	2	6
Gulls	208	5	47	77	116	66	220	31	16	19
Auklets	0	0	0	0	1	0	0	0	0	0
Cormorants	0	0	0	0	24	0	0	0	0	0
Unidentified Birds	3	1	0	0	17	2	1	0	0	14
Grand Total	459	29	134	160	405	174	501	192	196	128

The number of seabirds estimated to be caught incidentally in western GOA fisheries in 2020 decreased from that in 2019 by 88%, and was below the 2011–2019 average of 612 birds by 89% (Table 8, Figure 108). In all, only 32 seabirds were estimated to have been taken as bycatch in the western GOA in 2020. The 2020 estimate of seabird bycatch is the lowest in the 10 year time series and is 85% lower than the next lowest year's seabird bycatch (2012) of 211 birds.

Focusing solely on the bycatch of albatross (unidentified, short-tailed, Laysan, and black-footed) in the GOA, an average of 332 albatross per year were taken from 2011 through 2020 (Krieger and Eich, 2021), (Figure 109).

The sablefish IFQ fishery using demersal longline is responsible for the majority of seabird bycatch in the Gulf of Alaska—the average annual seabird bycatch for 2011 through 2020 is 557 birds per year (Table 13 in Krieger and Eich, 2021). In 2020, the estimated seabird bycatch was greater

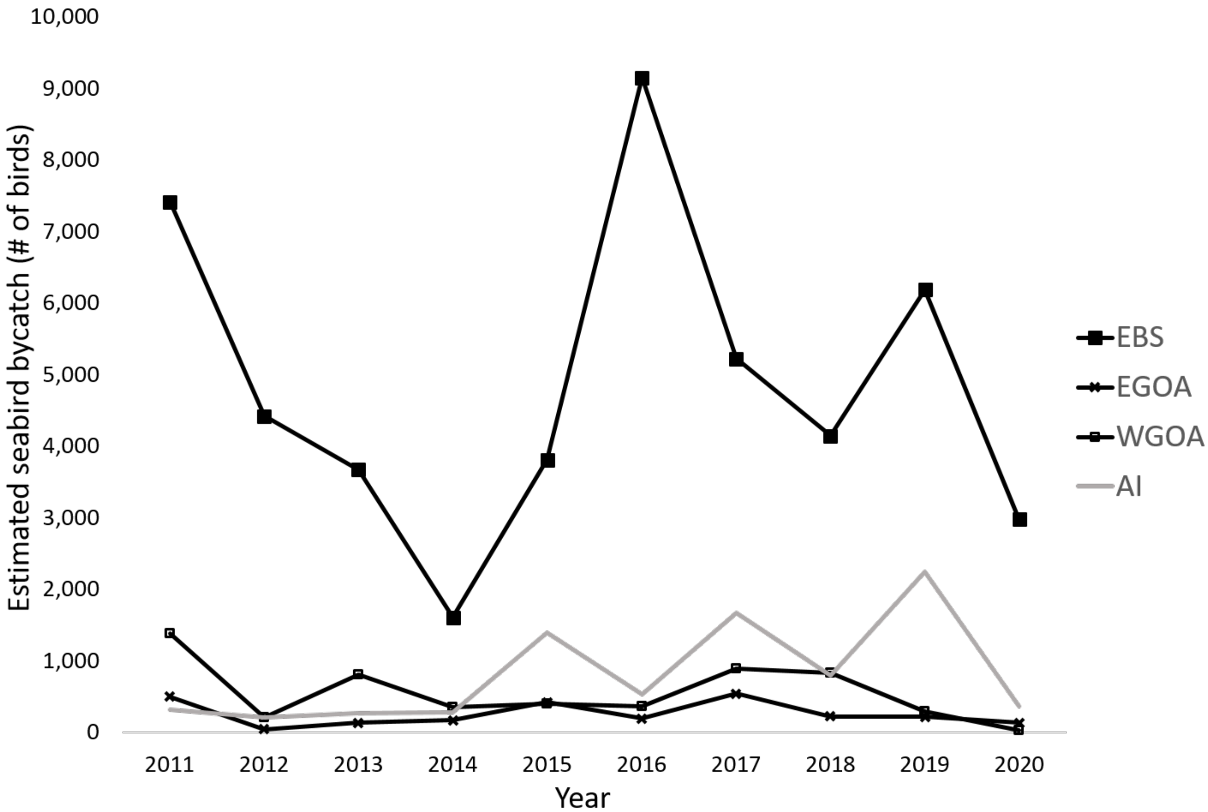


Figure 108: Total estimated seabird bycatch in eastern Bering Sea (EBS), eastern Gulf of Alaska (EGOA), western Gulf of Alaska (WGOA), and Aleutian Islands (AI), groundfish fisheries, all gear types combined, 2011 through 2020.

Table 8: Estimated seabird bycatch in the western Gulf of Alaska 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	9	0	3	0	0	0	0	10	18	0
Laysan Albatross	99	6	57	25	30	39	23	21	2	10
Black-footed Albatross	152	120	389	186	119	82	471	221	113	8
Northern Fulmars	748	18	239	47	64	175	238	231	95	6
Shearwaters	29	0	51	0	4	17	13	39	30	2
Gulls	375	46	91	77	156	74	258	212	41	3
Auklets	0	0	0	2	45	0	0	0	0	0
Other Alcids	0	0	0	37	0	0	0	0	0	0
Cormorants	0	0	0	0	3	0	0	0	0	0
Unidentified Birds	6	32	7	0	17	16	13	140	0	3
Grand Total	1418	223	838	375	438	403	1016	872	300	32

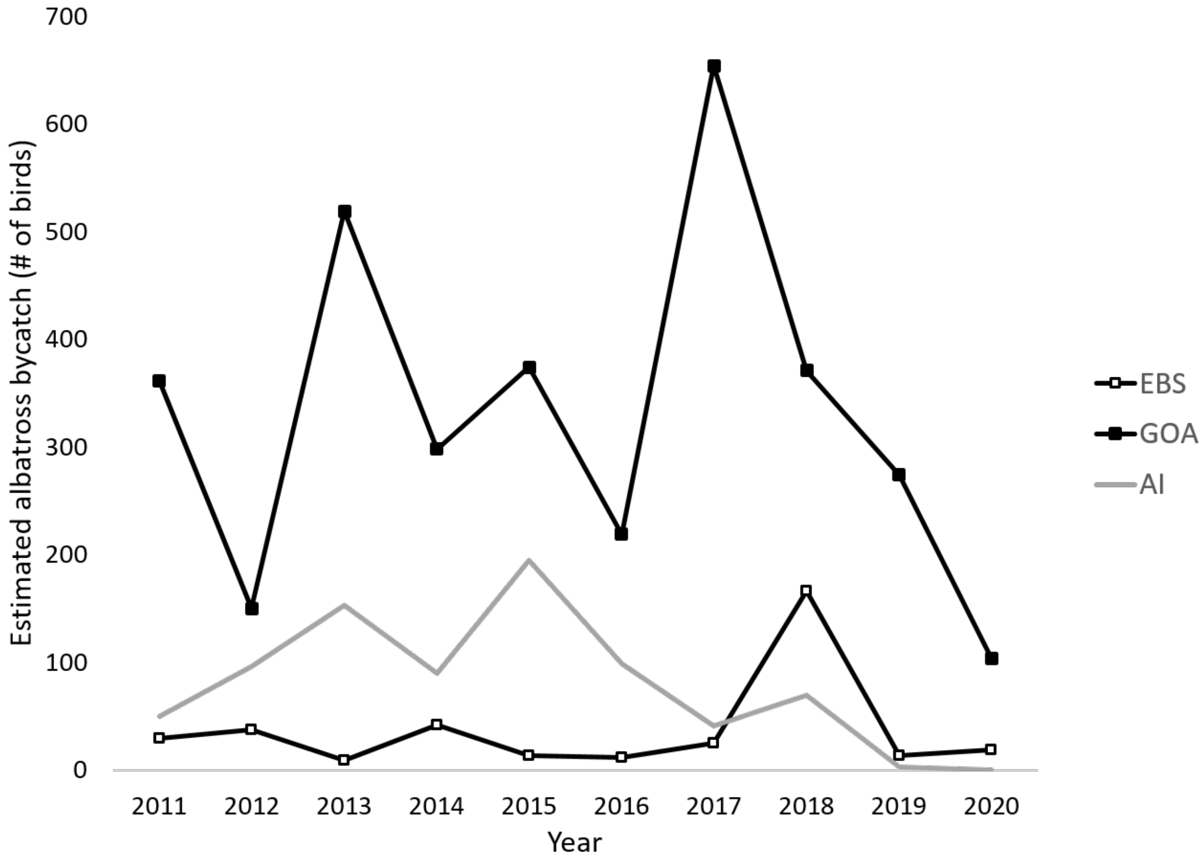


Figure 109: Total estimated albatross bycatch in eastern Bering Sea (EBS), Aleutian Islands (AI), and Gulf of Alaska (GOA) groundfish fisheries, all gear types combined, 2011 through 2020.

than 4 times lower compared to the 2011–2019 average (116 birds; Table 13 in Krieger and Eich, 2020). Figure 110 shows the spatial distribution of observed seabird bycatch from 2015–2020 from the sablefish IFQ fishery from vessels fishing with hook and line overlaid onto heat maps depicting fishing effort for the fishery.

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.

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 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 less seabird bycatch. Aside from disruptions associated with the COVID-19 pandemic, there was also a

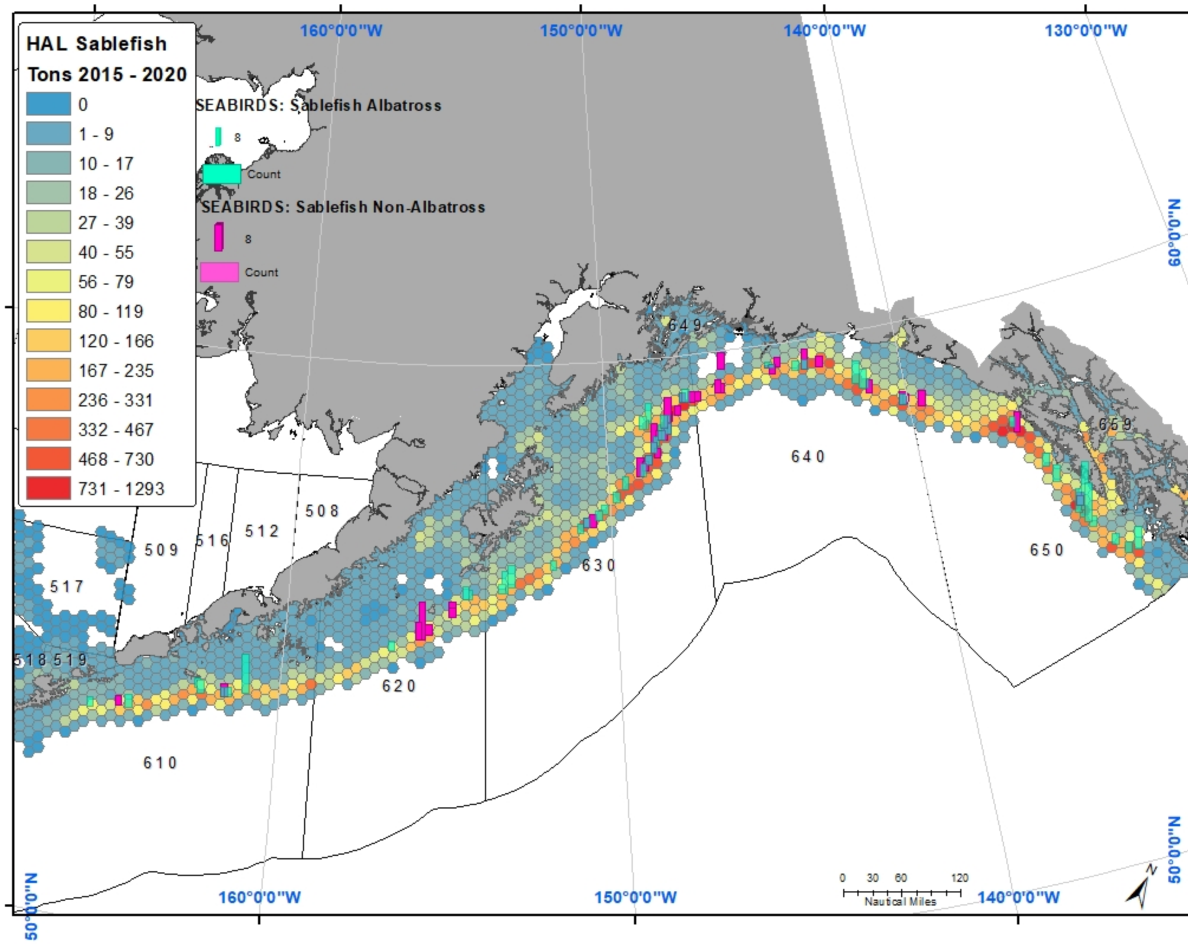


Figure 110: Spatial distribution of observed seabird bycatch from 2015 – 2020 from the sablefish IFQ fishery from vessels using hook and line gear. Colored vertical bars indicate the sum of incidental takes at a location grouped within 1/10 of a degree of latitude and longitude. Incidental takes are separated between takes of albatross and takes of non-albatross seabirds. Incidental takes of seabirds are overlaid on to heat maps depicting fishing effort for the sablefish IFQ fishery.

major shift in gear usage in the sablefish IFQ fishery that could partially explain the relatively low seabird bycatch estimates in 2020. 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 seabird 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 continue to expect to see reduced take of seabirds in this fishery.

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.

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 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 effected seabird bycatch, they themselves likely do not fully explain the reason for the observed trend.

It is difficult to determine how seabird bycatch estimates and trends 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

Areas Closed to Bottom Trawling in the BSAI and GOA

Contributed by John V. Olson, Habitat Conservation Division, Alaska Regional Office, National Marine Fisheries Service, NOAA
Contact: john.v.olson@noaa.gov
Last updated: September 2021

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 111, Table 9). 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 Fishery Management Council in February 2009 which closed all waters north of the Bering Strait to commercial fishing as part of the development of an Arctic Fishery Management Plan (FMP). 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 here at the website `https://www.fisheries.noaa.gov/alaska/sustainable-fisheries/alaska-fisheries-figures-maps-boundaries-regulatory-areas-and-zones`

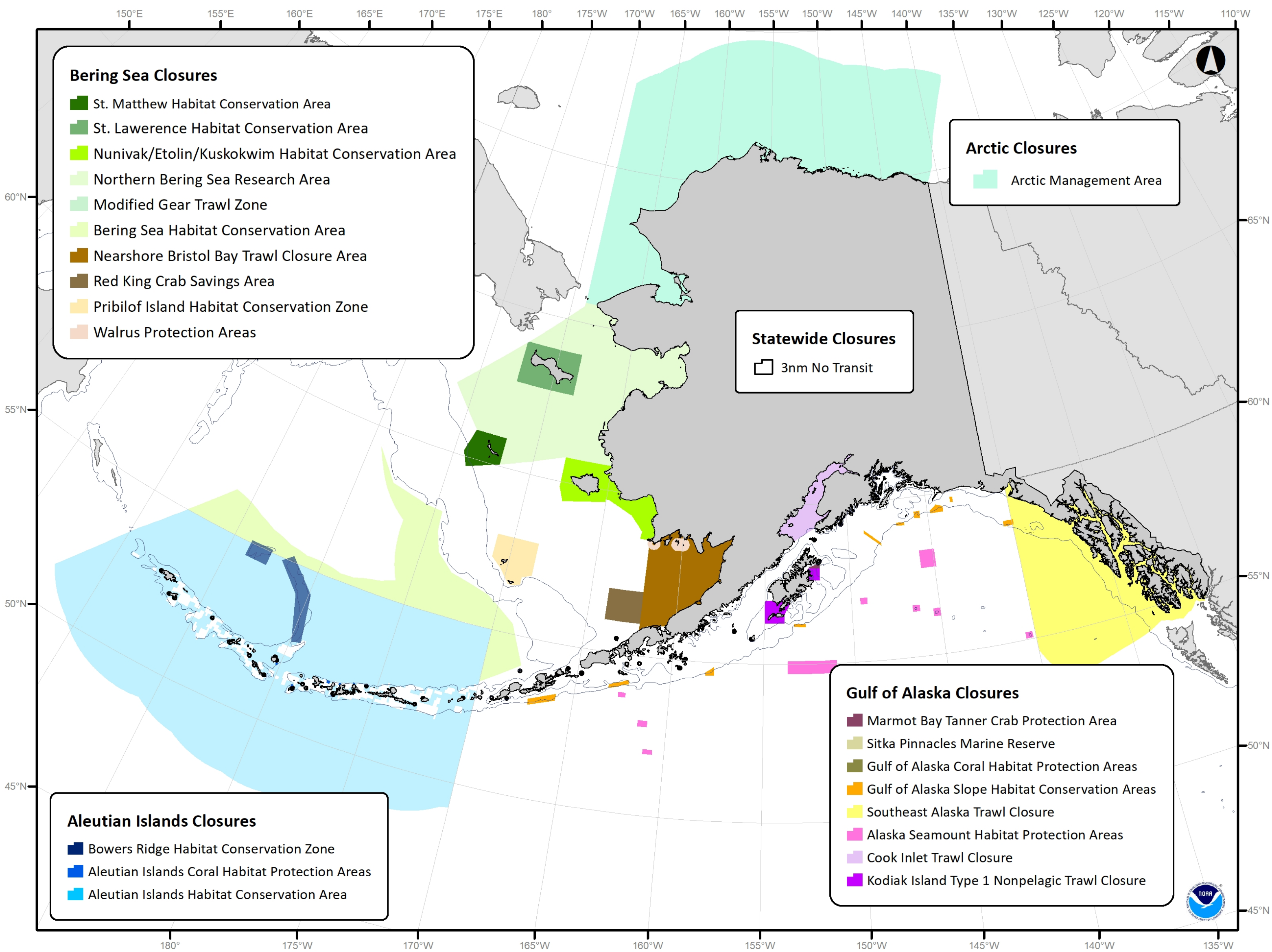


Figure 111: Year-round groundfish closures in the U.S. Exclusive Economic Zone (EEZ) off Alaska, excluding most SSL closures.

Table 9: 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–June)*	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–June)	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	

Area Disturbed by Trawl Fishing Gear in Alaska

Contributed by John V. Olson, Habitat Conservation Division, Alaska Regional Office, National Marine Fisheries Service, NOAA
Contact: john.v.olson@noaa.gov
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 in the Gulf of Alaska, 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. Additionally, fishing effort located in Cook Inlet, Prince William Sound, and the inside waters of Southeast Alaska are not included in this indicator as of 2021.

Status and trends: The percent of area disturbed due to commercial fishing interactions (pelagic and non-pelagic trawl, longline, and pot) has declined below 2% in the Western GOA, and under 0.2% in the Eastern GOA (Figure 112).

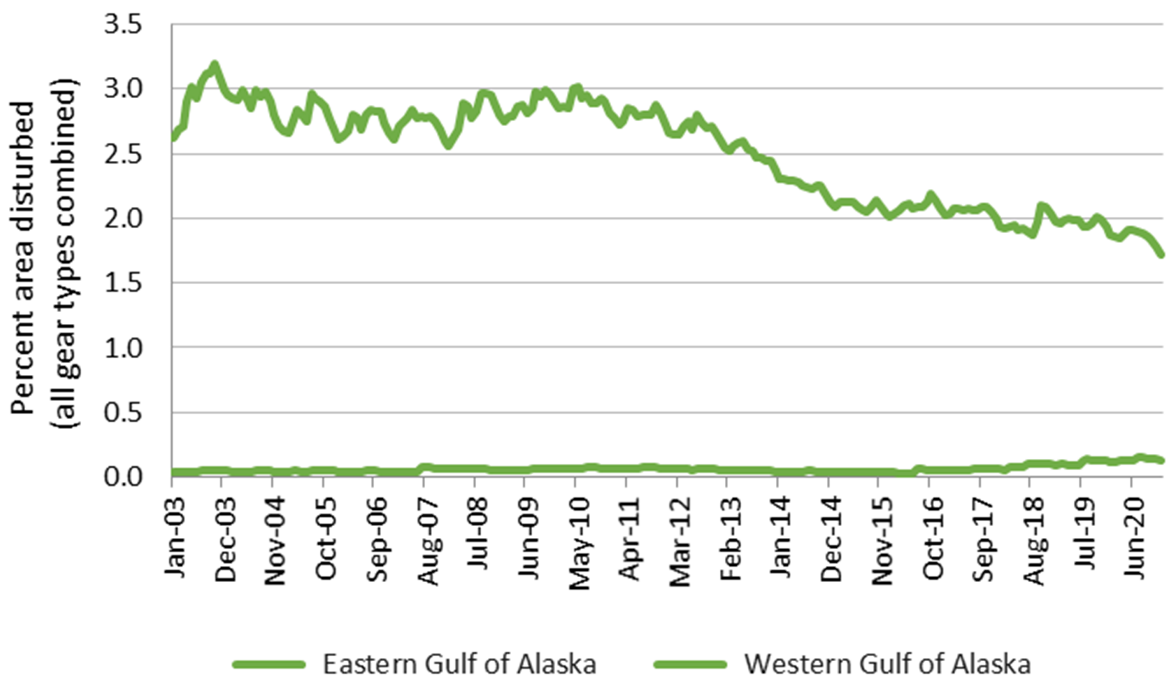


Figure 112: Percent habitat disturbance, all gear types combined, from 2003 through 2020 for the western and eastern GOA (divided at 147°W).

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. Bottom trawling is not permitted in the Eastern Gulf of Alaska; hook-and-line longline is the predominant gear type in the eastern GOA (Figure 113).

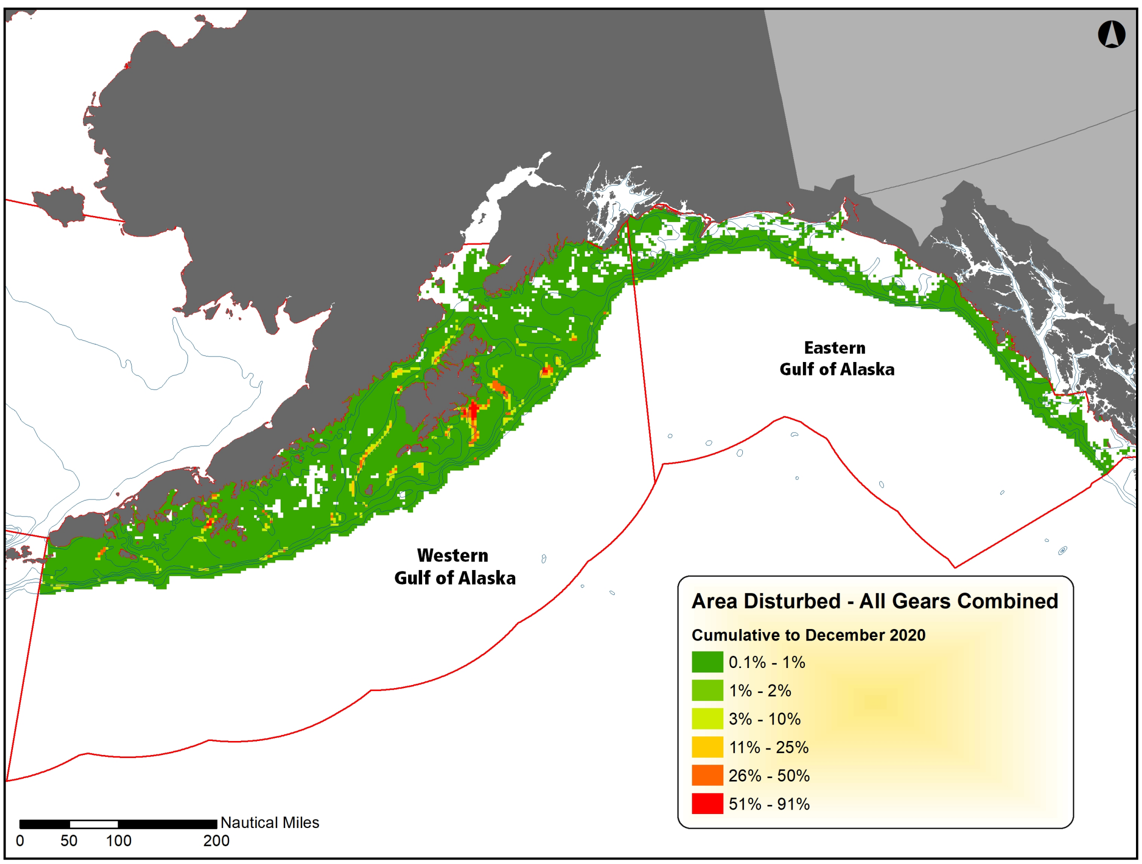


Figure 113: Map of percentage area disturbed per grid cell for all gear types. Effects are cumulative and consider impacts and recovery of features from 2003 to 2020.

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 (`ftp://ftp.library.noaa.gov/noaa_documents.`

lib/NMFS/TM_NMFS_AFKR/TM_NMFS_FAKR_15.pdf). 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.

Sustainability (for consumptive and non-consumptive uses)

Fish Stock Sustainability Index—Gulf of Alaska

Contributed by George A. Whitehouse, Cooperative Institute for Climate Ocean and Ecosystem Studies (CICOES), University of Washington, Seattle, WA
Contact: andy.whitehouse@noaa.gov
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 (`https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`). 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. In the GOA, this meant that the deepwater flatfish complex was removed from the FSSI and Shortraker rockfish were added. In the GOA region there are 14 FSSI stocks including sablefish. The assessment for sablefish is based on aggregated data from the GOA and BSAI regions. (`https://www.fisheries.noaa.gov/national/population-assessments/status-us-fisheries#fish-stock-sustainability-index`)

Additionally, in Alaska there are 28 non-FSSI stocks, two ecosystem component species complexes, and Pacific halibut which are managed under an international agreement. Two of the non–FSSI crab stocks in the BSAI region are overfished but are not subject to overfishing. 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`.

Table 10: Status summary for GOA FSSI stocks managed under federal fishery management plans, updated through June 2021.

GOA FSSI (14 stocks)	Yes	No	Unk	Undef	N/A
Overfishing	0	14	0	0	0
Overfished	0	11	3	0	0
Approaching Overfished Condition	0	11	3	0	0

Status and trends: As of June 30, 2021, none of the GOA groundfish stocks or stock complexes are subject to overfishing, are known to be overfished, or known to be approaching an overfished condition (Table 10). The GOA FSSI is up to 84.8% in 2021 from 83.0% in 2020 (Figure 114). The increased in GOA FSSI from 2020 is due to the biomass of sablefish increasing above 80% of their B_{MSY}. The FSSI for all other stocks are unchanged from last year.

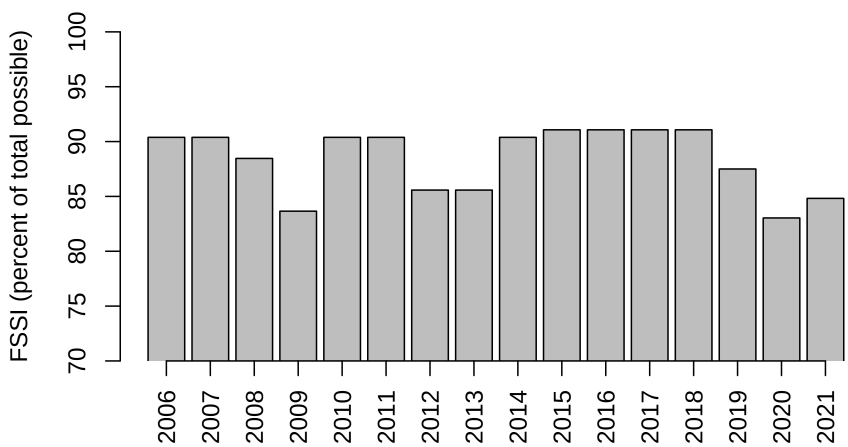


Figure 114: The trend in FSSI from 2006 through 2021 for the GOA region as a percentage of the maximum possible FSSI. All scores are reported through the second quarter (June) of each year, and are retrieved from the Status of U.S. Fisheries website: `https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`.

Ongoing reasons that the GOA FSSI is below the maximum value include GOA Pacific cod losing a point for having biomass below 80% of B_{MSY} (Table 11). Two and a half points were deducted from the shortraker rockfish stock, the demersal shelf rockfish complex, and the thornyhead rockfish complex for unknown status determinations and not estimating B/B_{MSY}.

Table 11: GOA FSSI stocks under NPFMC jurisdiction updated June 2021 adapted from the Status of U.S. Fisheries website: `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
GOA Arrowtooth flounder	No	No	No	N/A	N/A	2.85	4
GOA Flathead sole	No	No	No	N/A	N/A	2.60	4
GOA Shallow Water Flatfish Complex[a]	No	No	No	N/A	N/A	2.32	4
GOA Rex sole	No	No	No	N/A	N/A	2.36	4
GOA Blackspotted and Rougheye Rockfish complex[b]	No	No	No	N/A	N/A	1.96	4
GOA Shortraker rockfish	No	Unknown	Unknown	N/A	N/A	Not estimated	1.5
GOA Demersal Shelf Rockfish Complex[c]	No	Unknown	Unknown	N/A	N/A	Not estimated	1.5
GOA Dusky Rockfish	No	No	No	N/A	N/A	1.31	4
GOA Thornyhead Rockfish Complex[d]	No	Unknown	Unknown	N/A	N/A	Not estimated	1.5
Northern rockfish-Western / Central GOA	No	No	No	N/A	N/A	1.49	4
GOA Pacific Ocean perch	No	No	No	N/A	N/A	1.75	4
GOA Pacific cod	No	No	No	N/A	N/A	0.66	3
Walleye pollock-Western / Central GOA	No	No	No	N/A	N/A	1.68	4
GOA BSAI Sablefish[e]	No	No	No	N/A	N/A	0.93	4

The overall Alaska FSSI generally trended upwards from 80% in 2006 to a high of 94% in 2018 (Figure 115). The FSSI decreased in 2019 and 2020 to 88.9% but increased in 2021 to 89.6%.

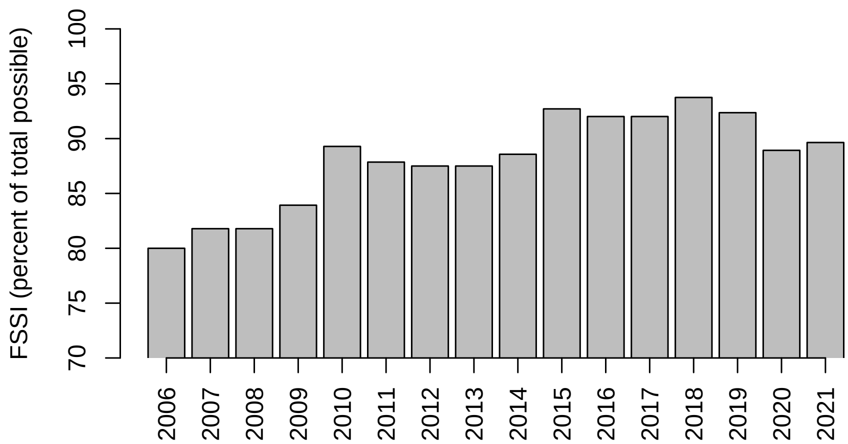


Figure 115: The trend in Alaska FSSI, as a percentage of the maximum possible FSSI from 2006 through 2021. The maximum possible FSSI is 140 for 2006 to 2014, 144 from 2015 to 2019, and 140 in 2020 and 2021. All scores are reported through the second quarter (June) of each year, and are retrieved from the Status of U.S. Fisheries website `https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates`.

Factors influencing observed trends: Since 2006 the GOA FSSI has been generally steady, fluctuating between a low of 83% in 2020 to a high of 91% from 2015–2018 (Figure 114). There were minor drops in the FSSI in 2008–2009, in 2012–2013, and 2019–2020. In 2008 and 2009 a point was lost each year for B/B_{MSY} walleye pollock in the western/central GOA dropping below 0.8. In 2009 an additional 2.5 points were lost for the Rex sole stock having unknown status determinations and for not estimating B/B_{MSY}. In 2012 and 2013 2.5 points were lost for having unknown status determinations and not estimating B/BMSY for the deepwater flatfish complex. The drop in 2019 was due biomass dropping below 80% B_{MSY} for Pacific cod and sablefish.

Implications: The majority of Alaska groundfish fisheries appear to be sustainably managed, including GOA groundfish fisheries. Until the overfished status determinations are defined for the Demersal Shelf Rockfish complex, the Thornyhead Rockfish complex, and shortraker rockfish, it will be unknown whether these stocks are overfished or approaching an overfished condition.

Total Annual Surplus Production and Overall Exploitation Rate of Groundfish, Gulf of Alaska

Contributed by Franz Mueter, University of Alaska Fairbanks, 17101 Point Lena Road, Juneau, AK 99801
Contact: fmueter@alaska.edu
Last updated: August 2021

Description of indices: Total annual surplus production (ASP) of the groundfish complex in the GOA from 1978–2017 was estimated by summing annual production across six major commercial groundfish stocks for which Tier 3 assessments are available (Table 12. Fewer stocks were included in the index this year because many biomass and catch time series have not been updated since 2018. Annual surplus production in year t was estimated as the change in total adult (mature) groundfish biomass across species from year t (B_t) to year t+1 (B_{t+1}), plus total catches in year t (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 recently available stock assessments. An index of total exploitation rate was obtained by dividing the total groundfish catch across the major commercial species by the estimated combined biomass at the beginning of the year:

$$u_t = C_t / B_t$$

Table 12: Species included in computing annual surplus production in the GOA management area.

Stocks
Walleye Pollock (*Gadus chalcogrammus*)
Pacific Cod (*Gadus macrocephalus*)
Arrowtooth Flounder (*Atheresthes stomias*)
Pacific Ocean Perch (*Sebastes alutus*)
Dover sole (*Microstomus pacificus*)
sablefish (*Anoplopoma fimbria*)

Status and trends: The resulting indices suggest high interannual variability in groundfish production in the Gulf of Alaska (Figure 116), with very high ASP in 1981/1982 associated with a number of strong recruitment events for multiple groundfish species after the 1976/77 oceanographic regime shift. ASP was relatively low in the late-1990s through early 2000s and was lowest in 2013/2014. ASP increased after 2014 to relatively high values during the marine heatwave from 2015–2017. Because of large fluctuations in pollock biomass, ASP was also computed without pollock included, which increased in the early 1980s due to strong increases in groundfish biomass, fluctuated around a stable mean over much of the time period, and decreased substantially at the beginning of the marine heatwave in 2014 and remained low through 2017 due to a substantial decrease in non-pollock biomass (Figure 117). Total exploitation rates for the groundfish complex ranged from 2.5–7.2% in the GOA (Figure 116). Overall exploitation rates were below 7% of adult (mature) biomass and relatively stable, but increased to about 9% during the marine heatwave as catch rates remained relatively high until 2017 but biomass decreased considerably.

Factors causing 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 typically highest during periods of increasing total biomass and lowest during periods of decreasing biomass. In the absence of a long-term trend in total biomass, ASP is equal to the long-term mean 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 GOA management area. Exploitation rates are primarily determined by management and reflect a relatively precautionary management regime with rates that have mostly averaged less than 7% for the groundfish complex. Overall exploitation rates are low in part because arrowtooth flounder dominate biomass in the GOA and have had very low exploitation rates.

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,

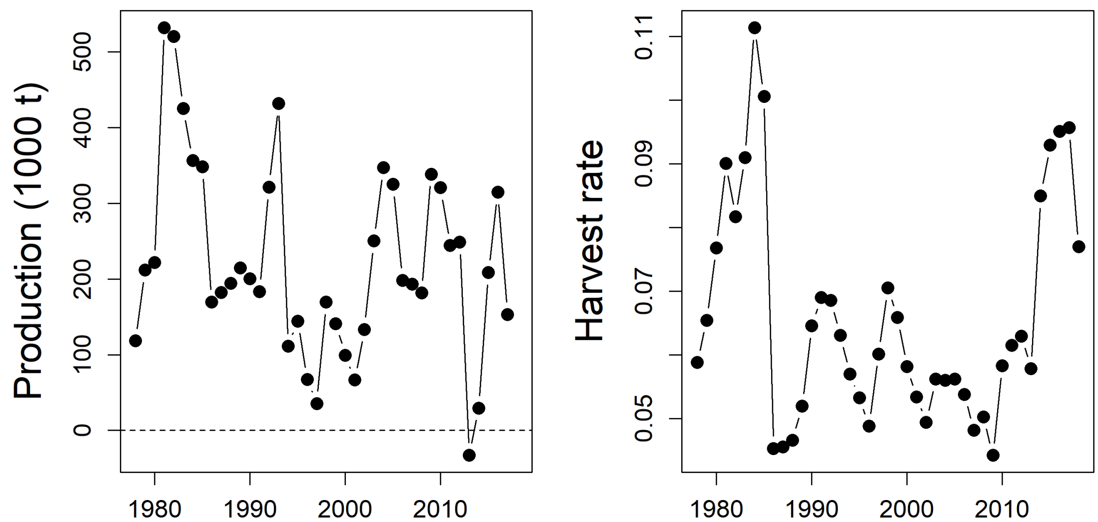


Figure 116: Total annual surplus production (change in biomass plus catch) across all major groundfish species in the Gulf of Alaska and total harvest rate (total catch / beginning-of-year biomass, each summed across all major groundfish species).

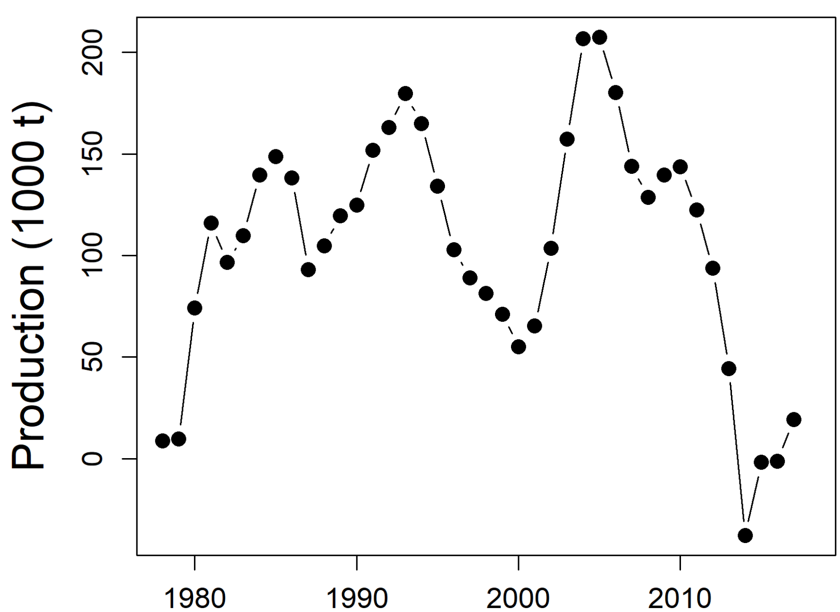


Figure 117: Total annual surplus production (change in biomass plus catch) across all major groundfish species in the Gulf of Alaska and total harvest rate (total catch / beginning-of-year biomass, each summed across all major groundfish species, **excluding walleye pollock).**

2006, Figure 118). However, there was relatively little contrast in total biomass over time in the GOA and there is only weak evidence of production peaking at an intermediate level of biomass. The estimated maximum sustainable yield for the complex of 6 groundfish species was 223,575 t.

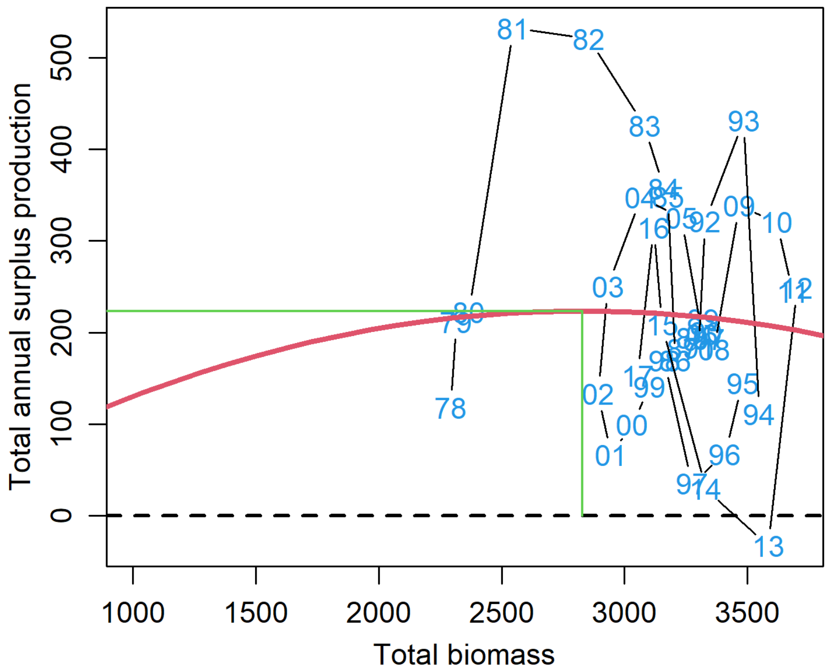


Figure 118: Estimated annual aggregated surplus production against total biomass of major commercial species with fitted Graham-Schaefer curve. Units on both axes are in 1000 t.

References

Alaska Fisheries Science Center (AFSC). 2011. Observer Sampling Manual for 2012. Fisheries Monitoring and Analysis Division, North Pacific Groundfish Observer Program. AFSC, 7600 Sand Point Way N.E., Seattle, Washington, 98115.

Alverson, D., M. Freeberg, J. Pope, and S. Murawski. 1994. A global assessment of fisheries bycatch and discards.FAO Fisheries Technical Paper. No. 339. Rome, FAO. 1994. 233p.

Amaya, D., A. Miller, S. Xie, and Y. Kosaka. 2020. Physical drivers of the summer 2019 North Pacific marine heatwave. Nature Communications **11**:1903.

Anderson, P., and J. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series **189**:117–123.

Anderson, P. J. 2003. Gulf of Alaska small mesh trawl survey trends, In: J.L.Boldt (Ed.), Ecosystem Considerations for 2004. Appendix C of the BSAI/GOA Stock Assessment and Fishery Evaluation Reports. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Andrews, A., W. Strasburger, E. Farley, J. Murphy, and K. Coyle. 2016. Effects of warm and cold climate conditions on capelin (*Mallotus villosus*) and Pacific herring (*Clupea pallasii*) in the eastern Bering Sea. Deep-Sea Research Part II **134**:235–246.

Arimitsu, M., J. Piatt, H. S., R. Suryan, S. Batten, M. Bishop, R. Campbell, H. Coletti, D. Cushing, K. Gorman, and R. Hopcroft. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology **27**:1859–1878.

Atwood, E., J. K. Duffy-Anderson, J. K. Horne, and C. Ladd. 2010. Influence of mesoscale eddies on ichthyoplankton assemblages in the Gulf of Alaska. Fisheries Oceanography **19**:493–507.

Aydin, K. 2000. Trophic feedback and carrying capacity of Pacific salmon (*Oncorhynchus spp.*) on the high seas of the Gulf of Alaska. Ph.D. thesis, Univ. Washington, Seattle. 397 pp.

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

Banas, N. S., E. F. Møller, T. G. Nielsen, and L. B. Eisner. 2016. Copepod life strategy and population viability in response to prey timing and temperature: Testing a new model across latitude, time, and the size spectrum. Frontiers in Marine Science **3**:225.

Barbeaux, S., K. Aydin, B. Fissel, K. Holsman, B. Laurel, and W. Palsson. 2018. Assessment of Pacific Cod Stock in the Gulf of Alaska [In] Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage.

Barbeaux, S., B. Ferriss, W. Palsson, K. Shotwell, I. Spies, M. Wang, and S. Zador. 2020*a*. Assessment of Pacific Cod Stock in the Gulf of Alaska [In] Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage.

Barbeaux, S., K. Holsman, and S. Zador. 2020*b*. Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. Frontiers in Marine Science **703**:1–21.

Barlow, J., J. Calambokidis, E. Falcone, C. Baker, A. Burdin, P. Clapham, J. K. B. Ford, C. M. Gabriele, R. LeDuc, D. K. Mattila, T. I. Quinn, L. RojasBracho, J. Straley, B. L. Taylor, U. Jorge, P. Wade, D. Weller, B. H. Witteveen, and M. Yamaguchi. 2011. Humpback whale abundance in the North Pacific estimated by photographic capture-recapture with bias correction from simulation studies. Publications, Agencies and Staff of the U.S. Department of Commerce. 239. `https://digitalcommons.unl.edu/usdeptcommercepub/239`.

Batten, S. D., G. T. Ruggerone, and I. Ortiz. 2018. Pink salmon induce a trophic cascade in plankton populations in the southern Bering Sea and around the Aleutian Islands. Fisheries Oceanography **27**:548–559.

Batten, S. D., and D. W. Welch. 2004. Changes in oceanic zooplankton populations in the northeast Pacific associated with the possible climatic regime shift of 1998/1999. Deep Sea Research Part II: Topical Studies in Oceanography **51**:863–873.

Beamish, R. J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Progress in Oceanography **49**:423–437.

Berkeley, S. A., M. A. Hixon, R. J. Larson, and M. S. Love. 2004. Fisheries sustainability via protection of age structure and spatial distribution of fish populations. Fisheries **29**:23–32.

Blackburn, J. E. 1977. Demersal fish and shellfish assessment in selected estuary systems of Kodiak Island. Annual Report, OCSEAP Research Unit 512, ADF&G, Kodiak, Alaska.

Blanchard, F., and J. Boucher. 2001. Temporal variability of total biomass in harvested communities of demersal fishes. Fisheries Research **49**:283–293.

Bodkin, J. L., H. A. Coletti, B. E. Ballachey, D. H. Monson, D. Esler, and T. A. Dean. 2018. Variation in abundance of Pacific blue mussel (*Mytilus trossulus*) in the northern Gulf of Alaska, 2006–2015. Deep Sea Research Part II: Topical Studies in Oceanography **147**:87–97.

Boeing, W. J., and J. T. Duffy-Anderson. 2008. Ichthyoplankton dynamics and biodiversity in the Gulf of Alaska: responses to environmental change. Ecological Indicators **8**:292–302.

Boldt, J. 2007. Ecosystem Considerations for 2008. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands and Gulf of Alaska. North Pacific Fishery Management Council, 605 W. 4th Ave, Suite 306, Anchorage, AK 99501, https://apps-afsc.fisheries.noaa.gov/refm/docs/2007/ecosystem.pdf.

Boldt, J., C. Rooper, and J. Hoff. 2017. Gulf of Alaska Groundfish Condition. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Boldt, J. L., and L. J. Haldorson. 2004. Size and condition of wild and hatchery pink salmon juveniles in Prince William Sound, Alaska. Transactions of the American Fisheries Society **133**:173–184.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters **42**:3414–3420.

Borchers, D. L., W. Zucchini, and R. M. Fewster. 1998. Mark-recapture models for line transect surveys. Biometrics **54**:1207–1220.

Brenner, R., S. Larsen, A. Munro, and A. Carroll. 2020. Run forecasts and harvest projections for 2021 Alaska salmon fisheries and review of the 2020 season. Alasks Department of Fish and Game, Special Publications No. 21-07. Anchorage, AK.

Brickley, P. J., and A. C. Thomas. 2004. Satellite-measured seasonal and inter-annual chlorophyll variability in the Northeast Pacific and coastal Gulf of Alaska. Deep-Sea Research Part II-Topical Studies in Oceanography **51**:229–245.

Briscoe, R., M. Adkison, A. Wertheimer, and S. Taylor. 2005. Biophysical factors associated with the marine survival of Auke Creek, Alaska, coho salmon. Transactions of the American Fisheries Society **134**:817–828.

Brodeur, R., and D. M. Ware. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fisheries Oceanography **1**:32–37.

Brodeur, R. D., M. B. Decker, L. Ciannelli, J. E. Purcell, N. A. Bond, P. J. Stabeno, E. Acuna, and G. L. Hunt. 2008. Rise and fall of jellyfish in the eastern Bering Sea in relation to climate regime shifts. Progress in Oceanography **77**:103–111.

Brodeur, R. D., R. L. Emmett, J. P. Fisher, E. Casillas, D. J. Teel, and T. W. Miller. 2004. Juvenile salmonid distribution, growth, condition, origin, and environmental and species associations in the Northern California Current. Fishery Bulletin **102**:25–46.

Brosset, P., J. Fromentin, E. Van Beveren, J. Lloret, V. Marques, G. Basilone, A. Bonanno, and et al. 2017. Spatio-temporal patterns and environmental controls of small pelagic fish body condition from contrasted Mediterranean areas. Progress in Oceanography **151**:149–162.

Buchheister, A., M. T. Wilson, R. J. Foy, and D. A. Beauchamp. 2006. Seasonal and geographic variation in condition of juvenile walleye pollock in the Western Gulf of Alaska. Transactions of the American Fisheries Society **135**:897–907.

Cahalan, J., J. Mondragon, and J. Gasper. 2010. Catch sampling and estimation in the federal groundfish fisheries off Alaska. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-205, 42 p.

Cahalan, J. A., J. R. Gasper, and J. Mondragon. 2014. Catch sampling and estimation in the federal groundfish fisheries off Alaska, 2015 edition. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-286, 46 p.

Campbell, R. W. 2018. Hydrographic trends in Prince William Sound, Alaska, 1960–2016. Deep Sea Research Part II: Topical Studies in Oceanography **147**:43–57.

Catchpole, T., C. Frid, and T. Gray. 2006. Importance of discards from the English Nephrops norvegicus fishery in the North Sea to marine scavengers. Marine Ecology Progress Series **313**:215–226.

Clucas, I. 1997. A study of the options for utilization of bycatch and discards from marine capture fisheries. FAO Fisheries Circular. No. 928. Food and Agriculture Organization, Rome. 59pp.

Combes, V., and E. Di Lorenzo. 2007. Intrinsic and forced interannual variability of the Gulf of Alaska mesoscale circulation. Progress in Oceanography **75**:266–286.

Conners, M. E., and C. L. Conrath. 2017. Assessment of the Octopus Stock Complex in the Gulf of Alaska. In: Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W 4th Ave Suite 306, Anchorage, Alaska 99501. 36 pp.

Cooney, R. T., and T. Willette. 1997. Factors influencing the marine survival of pink salmon in Prince William Sound, Alaska, page 313 . U.S. Dep. Commer., NOAA Tech. Memo. NMFS-NWFSC-29.

Crance, J. L., C. L. Berchok, and J. L. Keating. 2017. Gunshot call production by the North Pacific right whale *Eubalaena japonica* in the southeastern Bering Sea. Endangered Species Research **34**:251–267.

Crusius, J., A. W. Schroth, J. A. Resing, J. Cullen, and R. W. Campbell. 2017. Seasonal and spatial variabilities in northern Gulf of Alaska surface water iron concentrations driven by shelf sediment resuspension, glacial meltwater, a Yakutat eddy, and dust. Global Biogeochemical Cycles **31**:942–960.

Davis, N. 2003. Feeding ecology of Pacific salmon (*Oncorhynchus spp.*) in the central North Pacific and central Bering Sea 1991–2000. Ph.D. thesis, Hokkaido University. 190 pp.

Davis, N., K. Myers, and Y. Ishida. 1998. Caloric values of high-seas salmon prey organisms and simulated salmon ocean growth and prey consumption. N. Pac. Anadr. Fish Comm. Bull. **1**:146–162.

Di Lorenzo, E., and N. Mantua. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change **6**:1042–1047.

Di Lorenzo, E., D. Mountain, H. Batchelder, N. Bond, and E. Hofmann. 2013. Advances in marine ecosystem dynamics from US GLOBEC: The horizontal-advection bottom-up forcing paradigm. Oceanography **26**:22–33.

Dietrich, K. S., and S. Fitzgerald. 2010. Analysis of 2004-2007 vessel-specific seabird bycatch data in Alaska demersal longline fisheries. AFSC Processed Rep. 2010-04, 52 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

Dorn, M., and S. Zador. 2020. A risk table to address concerns external to stock assessments when developing fisheries harvest recommendations. Ecosystem Health and Sustainability **6**:1813634.

Dorn, M. W., K. Y. Aydin, B. Fissel, W. Palsson, K. Spalinger, S. Stienessen, K. Williams, and S. Zador. 2018. Stock assessment of the walleye pollock stock in the Gulf of Alaska. North Pacific Fisheries Management Council, 605 West 4th, Suite 306, Anchorage, AK 99501.

Doyle, M. J., and K. L. Mier. 2012. A new conceptual framework for evaluating the early ontogeny phase of recruitment processes among marine fish species. Canadian Journal of Fisheries and Aquatic Sciences **69**:2112–2129.

Doyle, M. J., S. J. Picquelle, K. L. Mier, M. Spillane, and N. Bond. 2009. Larval fish abundance and physical forcing in the Gulf of Alaska, 1981-2003. Progress in Oceanography **80**:163–187.

Ducet, N., P. Y. Le Traon, and G. Reverdin. 2000. Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and-2. Journal of Geophysical Research-Oceans **105**:19477–19498.

Duffy-Anderson, J., S. Barbeaux, E. Farley, R. Heintz, J. Horne, S. Parker-Stetter, C. Petrik, E. Siddon, and T. Smart. 2016. The critical first year of life of walleye pollock (*Gadus chalcogrammus*) in the eastern Bering Sea: Implications for recruitment and future research. Deep-sea Research Part II-topical Studies in Oceanography **134**:283–301.

Echave, K., C. Rodgveller, and S. Shotwell. 2013. Calculation of the geographic area sizes used to create population indices for the Alaska Fisheries Science Center longline survey. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-253, 93 p.

Eisenlord, M. E., M. L. Groner, R. M. Yoshioka, J. Elliott, J. Maynard, S. Fradkin, M. Turner, K. Pyne, N. Rivlin, R. van Hooidonk, and C. D. Harvell. 2016. Ochre star mortality during the 2014 wasting disease epizootic: role of population size structure and temperature. Philosophical Transactions of the Royal Society B: Biological Sciences **371**:20150212.

FAO. 1995. Code of Conduct for Responsible Fisheries. Rome, Food and Agriculture Organization 41 p.

Ferguson, M. C., C. Curtice, and J. Harrison. 2018. Biologically Important Areas for cetaceans within US waters-Gulf of Alaska region. Aquatic Mammals **41**:65–78.

Fergusson, E., A. Gray, and J. Murphy. 2020*a*. Annual survey of juvenile salmon, ecologically-related species, and biophysical factors in the marine waters of southeastern Alaska, May–August 2018. NPAFC Doc. 43 pp. National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center, Auke Bay Laboratories, Ted Stevens Marine Research Institute (Available at http://www.npafc.org).

Fergusson, E., T. Miller, M. McPhee, C. Fugate, and H. Schultz. 2020*b*. Trophic responses of juvenile Pacific salmon to warm and cool periods within inside marine waters of Southeast Alaska. Progress in Oceanography **186**:102378.

Fergusson, E., J. Murphy, and A. Gray. 2021. Southeast Alaska Coastal Monitoring Survey: salmon trophic ecology and bioenergetics, 2019. NPAFC Doc. 41 pp. National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center, Auke Bay Laboratories, Ted Stevens Marine Research Institute. http://www.npafc.org.

Fergusson, E. A., M. V. Sturdevant, and J. A. Orsi. 2013. Trophic relationships among juvenile salmon during a 16-year time series of climate variability in Southeast Alaska. N. Pac. Anadr. Fish Comm. Tech. Rep. 9: 112-117. (Available at www.npafc.org).

Friday, N. A., J. M. Waite, A. N. Zerbini, and S. E. Moore. 2012. Cetacean distribution and abundance in relation to oceanographic domains on the eastern Bering Sea shelf: 1999–2004. Deep Sea Research Part II: Topical Studies in Oceanography **65**:260–272.

Fritz, L. W., K. Sweeney, R. G. Towell, and T. W. Gelatt. 2016. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) conducted in Alaska in June-July 2013 through 2015, and an update on the status and trend of the western distinct population segment in Alaska. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-321, 72 p.

Funk, F., and G. J. Sandone. 1990. Catch-age analysis of Prince William Sound, Alaska, herring, 1973-1988. Alaska Department of Fish and Game, Division of Commercial Fisheries. Fishery Research Bulletin No. 90-01.

Gabriele, C., C. Amundson, J. Neilson, J. Straley, C. Baker, and S. Danielson. 2021. Sharp decline in humpback whale (*Megaptera novaeangliae*) survival and reproductive success in southeastern Alaska during and after the 2014-2016 Northeast Pacific marine heatwave. Mammalian Biology. In press .

Gabriele, C., and J. Nielson. 2018. Trends in Humpback Whale Calving in Glacier Bay and Icy Strait In: S. Zador and E. Yasumiishi (Ed.), Ecosystem Status Report for the Gulf of Alaska, Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Gabriele, C., and J. Nielson. 2019. Trends in Humpback Whale Calving in Glacier Bay and Icy Strait In: S. Zador, E. Yasumiishi, and G. A. Whitehouse (Ed.), Ecosystem Status Report for the Gulf of Alaska, Stock Assessment and Fishery Evaluation Report. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501.

Gabriele, C., J. Straley, and J. Nielson. 2007. Age at first calving of female humpback whales in southeastern Alaska. Marine Mammal Science **23**:226–239.

Gabriele, C. M., J. L. Neilson, J. M. Straley, C. S. Baker, J. A. Cedarleaf, and J. F. Saracco. 2017. Natural history, population dynamics, and habitat use of humpback whales over 30 years on an Alaska feeding ground. Ecosphere **8**:e01641.

Geiger, H., W. Smoker, L. Zhivotovsky, and A. Gharrett. 1997. Variability of family size and marine survival in pink salmon (*Oncorhynchus gorbuscha*) has implications for conservation biology and human use. Canadian Journal of Fisheries and Aquatic Sciences **54**:2684–2690.

Gentemann, C. L., M. Fewing, and M. Garcia-Reyes. 2017. Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. Arctic **44**:312–319.

Goethel, D., D. Hanselman, C. Rodgveller, K. Fenske, K. Shotwell, K. Echave, P. Malecha, K. Siwicke, and C. Lunsford. 2021. Assessment of the Sablefish Stock in Alaska [In] Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage.

Goldstein, E. D., J. L. Pirtle, J. T. Duffy-Anderson, W. T. Stockhausen, M. Zimmermann, M. T. Wilson, and C. W. Mordy. 2020. Eddy retention and seafloor terrain facilitate cross-shelf transport and delivery of fish larvae to suitable nursery habitats. Limnology and Oceanography https://doi.org/10.1002/lno.11553 .

Good, S., M. Martin, and N. Rayner. 2013. EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. Journal of Geophysical Research: Oceans **118**:6704–6716.

Graham, C. J., T. M. Sutton, M. D. Adkison, M. V. McPhee, and P. J. Richards. 2019. Evaluation of growth, survival, and recruitment of Chinook Salmon in Southeast Alaska rivers. Transactions of the American Fisheries Society **148**:243–259.

Greene, K. 2002. Coastal cool-down. Science **295**:1823–1823.

Guttormsen, M., and P. Yasenak. 2007. Results of the 2003 and 2005 echo integration-trawl surveys in the Gulf of Alaska during summer, Cruises MF2003–09 and OD2005–01. AFSC Processed Rep. 2007–04. Alaska Fisheries Science Center, NOAA, National Marine Fisheries Service, Seattle, WA.

Hard, J., M. Gross, M. Heino, R. Hilborn, R. Kope, R. Law, and J. Reynolds. 2008. Evolutionary consequences of fishing and their implications for salmon. Evolutionary Applications **1**:388–408.

Harley, J. R., K. Lanphier, E. Kennedy, T. Leighfield, A. Bidlack, M. O. Gribble, and C. Whitehead. 2020. The Southeast Alaska Tribal Ocean Research (SEATOR) Partnership: Addressing data gaps in harmful algal bloom monitoring and shellfish safety in Southeast Alaska. Toxins **12**:407.

Harris, R., P. Wiebe, L. J., S. H.R., and H. M. 2000. ICES Zooplankton Methodology Manual. Elsevier Academic Press, Amsterdam.

Hatch, S. A. 2013. Kittiwake diets and chick production signal a 2008 regime shift in the Northeast Pacific. Marine Ecology Progress Series **477**:271–284.

Hebert, K. P. 2017. Southeast Alaska 2016 herring stock assessment surveys. Alaska Department of Fish and Game, Fishery Data Series No. 17-01.

Hedd, A., D. Bertram, J. Ryder, and I. Jones. 2006. Effects of interdecadal climate variability on marine trophic interactions: Rhinoceros auklets and their fish prey. Marine Ecology-progress Series **309**:263–278.

Hobday, A. J., L. V. Alexander, S. E. Perkins, D. A. Smale, S. C. Straub, E. C. Oliver, J. A. Benthuysen, M. T. Burrows, M. G. Donat, and M. Feng. 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography **141**:227–238.

Hobday, A. J., E. C. J. Oliver, A. S. Gupta, J. A. Benthuysen, M. T. Burrows, M. G. Donat, N. Holbrook, P. Moore, M. Thomsen, T. Wernberg, and D. Smale. 2018. Categorizing and naming marine heatwaves. Oceanography **31**:162–173.

Holbrook, N. J., H. A. Scannell, A. Sen Gupta, J. A. Benthuysen, M. Feng, E. C. J. Oliver, L. Alexander, M. Burrows, M. Donat, A. Hobday, P. Moore, S. Perkins-Kirkpatrick, D. Smale, S. Straub, and T. Wernberg. 2019. A global assessment of marine heatwaves and their drivers. Nature Communications. Nature Communications **10**:1–13.

Holsman, K., A. Haynie, A. Hollowed, and et al. 2020. Ecosystem-based fisheries management forestalls climate-driven collapse. Nature Communications **11**:4579.

Holsman, K. K., and K. Aydin. 2015. Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Marine Ecology Progress Series **521**:217–235.

Holsman, K. K., K. Aydin, J. Sullivan, T. Hurst, and G. H. Kruse. 2019. Climate effects and bottom-up controls on growth and size-at-age of Pacific halibut (Hippoglossus stenolepis) in Alaska (USA). Fisheries Oceanography **28**:345–358.

Hsieh, C.-h., C. S. Reiss, J. R. Hunter, J. R. Beddington, R. M. May, and G. Sugihara. 2006. Fishing elevates variability in the abundance of exploited species. Nature **443**:859.

Hu, Z., A. Kumar, B. Jha, J. Zhu, and B. Huang. 2017. Persistence and predictions of the remarkable warm anomaly in the northeastern Pacific Ocean during 2014–16. Journal of Climate **30**:689–702.

Hubálek, Z. 2021. Pathogenic microorganisms associated with gulls and terms (*Laridae*). Journal of Vertebrate Biology **70**:21009.1–98.

Hulson, P.-J. F., S. E. Miller, T. J. Quinn, G. D. Marty, S. D. Moffitt, and F. Funk. 2007. Data conflicts in fishery models: incorporating hydroacoustic data into the Prince William Sound Pacific herring assessment model. ICES Journal of Marine Science **65**:25–43.

Hunt, G. L., P. H. Ressler, G. A. Gibson, A. De Robertis, K. Aydin, M. F. Sigler, I. Ortiz, E. J. Lessard, B. C. Williams, and A. Pinchuk. 2016. Euphausiids in the eastern Bering Sea: A synthesis of recent studies of euphausiid production, consumption and population control. Deep Sea Research Part II: Topical Studies in Oceanography **134**:204–222.

Ito, J. 1964. Food and feeding habits of Pacific salmon (genus *Oncorhynchus*) in their oceanic life. Bull. Hokkaido Reg. Fish. Res. Lab. **29**:85–97.

Jacox, M. 2019. Marine heatwaves in a changing climate. Nature **571**:485–487.

Janout, M. A., T. J. Weingartner, T. C. Royer, and S. L. Danielson. 2010. On the nature of winter cooling and the recent temperature shift on the northern Gulf of Alaska shelf. Journal of Geophysical Research: Oceans **115**:C05023.

Jones, D., N. Lauffenberger, K. Williams, and A. De Robertis. 2011. Ecology of cephalopod early life history in the Gulf of Alaska and Bering Sea. Ph.D. thesis, Univ. Washington, Seattle. 193pp.

Jones, D., N. Lauffenberger, K. Williams, and A. De Robertis. 2019. Results of the acoustic-trawl survey of walleye pollock (*Gadus chalcogrammus*) in the Gulf of Alaska, June-August 2017 (DY2017–06). AFSC Processed Rep. No. 2019–08. Alaska Fisheries Science Center, NOAA, National Marine Fisheries Service, Seattle, WA.

Jones, D., S. Stienessen, K. Simonsen, and M. Guttormsen. 2015. Results of the acoustic-trawl survey of walleye pollock (*Gadus chalcogrammus*) in the Western/Central Gulf of Alaska, June-August 2011 (DY2011–03). AFSC Processed Rep. No. 2015–04. Alaska Fisheries Science Center, NOAA, National Marine Fisheries Service, Seattle, WA.

Kaeriyama, M., M. Nakamura, R. Edpalina, J. Bower, H. Yamaguchi, R. Walker, and K. Myers. 2004. Change in feeding ecology and trophic dynamics of Pacific salmon (*Oncorhynchus spp.*) in the central Gulf of Alaska in relation to climate events. Fisheries Oceanography **13**:197–207.

Kaga, T., S. Sato, T. Azumaya, N. D. Davis, and M. Fukuwaka. 2013. Lipid content of chum salmon *Oncorhynchus keta* affected by pink salmon *O. gorbuscha* abundance in the central Bering Sea. Marine Ecology Progress Series **478**:211–221.

Kalnay, E., M. Kananitcu, R. Kistler, W. Collins, and D. Deaven. 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society **77**:437–471.

Kelleher, K. 2005. Discards in the world's marine fisheries: an update. FAO Fisheries Technical Paper. No. 470. Rome, FAO. 2005. 131p.

Kimmel, D., and J. Duffy-Anderson. 2020. Zooplankton abundance trends and patterns in Shelikof Strait, western Gulf of Alaska, USA, 1990–2017. Journal of Plankton Research **42**:334–354.

King, J. 2005. Report of the Study Group on Fisheries and Ecosystem Responses to recent regime shifts. PICES Scientific Report No. 28.

Kiörboe, T., and M. Sabatini. 1995. Scaling of fecundity, growth and development in marine planktonic copepods. Marine Ecology progress Series **120**:285–298.

Kline, J., T. C. 2010. Stable carbon and nitrogen isotope variation in the northern lampfish and Neocalanus, marine survival rates of pink salmon, and meso-scale eddies in the Gulf of Alaska. Progress in Oceanography **87**:49–60.

Kline, T. C., J. Boldt, E. Farley, L. J. Haldorson, and J. H. Helle. 2008. Pink salmon (*Oncorhynchus gorbuscha*) marine survival rates reflect early marine carbon source dependency. Progress in Oceanography **77**:194–202.

Koehn, L., M. Siple, and T. Essington. 2021. A structured seabird population model reveals how alternative forage fish control rules benefit seabirds and fisheries. Ecological Application **31**:e02401.

Konar, B., T. J. Mitchell, K. Iken, H. Coletti, T. Dean, D. Esler, M. Lindeberg, B. Pister, and B. Weitzman. 2019. Wasting disease and static environmental variables drive sea star assemblages in the Northern Gulf of Alaska. Journal of Experimental Marine Biology and Ecology **520**:151209.

Kovach, R., A. Gharrett, and D. Tallmon. 2013*a*. Temporal patterns of genetic variation in a salmon population undergoing rapid change in migration timing. Evolutionary Applications **6**:795–807.

Kovach, R. P., J. Joyce, S. Vulstek, E. Barrientos, and D. Tallmon. 2014. Earlier migration timing, decreasing phenotypic variation, and biocomplexity in multiple salmonid species. Canadian Journal of Fisheries and Aquatic Sciences **71**:799–807.

Kovach, R. P., J. E. Joyce, J. D. Echave, M. S. Lindberg, and D. A. Tallmon. 2013*b*. Earlier migration timing, decreasing phenotypic variation, and biocomplexity in multiple salmonid species. PLoS ONE **8**:e53807.

Krieger, J., and A. Eich. 2020. Seabird bycatch estimates for Alaska Groundfish Fisheries: 2019. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/AKR-24, 40 p.doi:10.25923/jtgr-1595.

Krieger, J., and A. Eich. 2021. Seabird bycatch estimates for Alaska Groundfish Fisheries: 2020. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/AKR-25, 40 p. doi:10.25923/a0fb-nt02.

Kristensen, K., A. Nielsen, C. W. Berg, H. Skaug, and B. Bell. 2015. TMB: Automatic differentiation and laplace approximation. ArXiv **70**:1–21.

Kuletz, K., E. Labunski, and S. Speckman. 2008. Abundance, distribution, and decadal trends of Kittlitz's and marbled murrelets and other marine species in Kachemak Bay, Alaska. Final Report (Project No. 14) by U.S. Fish and Wildlife Service for Alaska Department of Fish and Game, State Nongame Wildlife Grant, Anchorage, Alaska.

Ladd, C. 2007. Interannual variability of the Gulf of Alaska eddy field. Geophysical Research Letters **34**:L11605.

Ladd, C., and W. Cheng. 2016. Gap winds and their effects on regional oceanography Part I: Cross Sound, Alaska. Deep Sea Research II **132**:41–53.

Ladd, C., W. R. Crawford, C. Harpold, W. Johnson, N. B. Kachel, P. Stabeno, and F. Whitney. 2009. A synoptic survey of young mesoscale eddies in the Eastern Gulf of Alaska. Deep-Sea Research Part II **56**:2460–2473.

Ladd, C., N. B. Kachel, C. W. Mordy, and P. J. Stabeno. 2005. Observations from a Yakutat eddy in the northern Gulf of Alaska. Journal of Geophysical Research-Oceans **110**:C03003.

Ladd, C., C. W. Mordy, N. B. Kachel, and P. J. Stabeno. 2007. Northern Gulf of Alaska eddies and associated anomalies. Deep-Sea Research Part I-Oceanographic Research Papers **54**:487–509.

Lamb, J. F., and D. G. Kimmel. 2021. The contribution of diet to the dramatic reduction of the 2013 year class of Gulf of Alaska walleye pollock (*Gadus chalcogrammus*). Fisheries Oceanography doi 10.1111/fog.12557 .

Landingham, J. H., M. V. Sturdevant, and R. D. Brodeur. 1998. Feeding habits of juvenile Pacific salmon in marine waters of southeastern Alaska and northern British Columbia. Fishery Bulletin **96**:285–302.

Laurel, B., M. Hunsicker, L. Ciannelli, T. Hurst, J. Duffy-Anderson, R. O'Malley, and M. Behrenfeld. 2021. Regional warming exacerbates match/mismatch vulnerability for cod larvae in Alaska. Progress in Oceanography **193**:102555.

Laurel, B. J., and L. A. Rogers. 2020. Loss of spawning habitat and prerecruits of Pacific cod during a Gulf of Alaska heatwave. Canadian Journal of Fisheries and Aquatic Sciences **77**:644–650.

Lefebvre, K. A., L. Quakenbush, E. Frame, K. B. Huntington, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J. A. Snyder, T. Gelatt, F. Gulland, B. Dickerson, and V. Gill. 2016. Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae **55**:13–24.

Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli. 2001. Anthropogenic warming of Earth's climate system. Science **292**:267–270.

Link, J. S., J. K. T. Brodziak, S. F. Edwards, W. J. Overholtz, D. Mountain, J. W. Jossi, T. D. Smith, and M. J. Fogarty. 2002. Marine ecosystem assessment in a fisheries management context. Canadian Journal of Fisheries and Aquatic Sciences **59**:1429–1440.

Locarnini, R., A. Mishonov, O. Baranova, T. Boyer, M. Zweng, H. Garcia, J. J.R. Reagan, D. Seidov, K. Weathers, C. Paver, and I. Smolyar. 2019. World Ocean Atlas 2018, Volume 1: Temperature. A. Mishonov, Technical Editor. NOAA Atlas NESDIS 81, 52pp.

Mackas, D. L., W. Greve, M. Edwards, S. Chiba, K. Tadokoro, D. Eloire, M. G. Mazzocchi, S. Batten, A. J. Richardson, C. Johnson, E. Head, A. Conversi, and T. Peluso. 2012. Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology. Progress in Oceanography **97–100**:31–62.

Magurran, A. E. 1988. Ecological diversity and its measurement. Princeton University Press, Princeton, N.J.

Malick, M. J., M. Adkison, and A. Wertheimer. 2009. Variable effects of biological and environmental processes on coho salmon marine survival in southeast Alaska. Transactions of the American Fisheries Society **138**:846–860.

Matarese, A. C., D. M. Blood, S. J. Picquelle, and J. L. Benson. 2003. Atlas of abundance and distribution patterns of ichthyoplankton from the northeast Pacific Ocean and Bering Sea ecosystems based on research conducted by the Alaska Fisheries Science Center (1972-1996).

McCann, K. S. 2000. The diversity–stability debate. Nature **405**:228–233.

McGowan, D., E. Goldstein, M. Arimitsu, A. Deary, O. Ormseth, A. De Robertis, J. Horne, L. Rogers, M. Wilson, K. Coyle, K. Holderied, J. Piatt, W. Stockhausen, and S. Zador. 2020. Spatial and temporal dynamics of Pacific capelin *Mallotus catervarius* in the Gulf of Alaska: implications for ecosystem-based fisheries management. Marine Ecology Progress Series **637**:117–140.

McGregor, A. J., S. Lane, and M. Thomason. 1998. Migration timing , a life history trait important in the genetic structure of pink salmon. North Pacific Anadromous Fish Commission **1**:262–273.

Mellinger, D., K. Stafford, S. Moore, L. Munger, and C. Fox. 2004. Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. Marine Mammal Science **20**:872–879.

Mortensen, D., A. Wertheimer, C. Taylor, and J. Landingham. 2000. The relation between early marine growth of pink salmon, *Oncorhynchus gorbuscha*, and marine water temperature, secondary production, and survival to adulthood. Fishery Bulletin .

Moss, J. H., D. A. Beauchamp, A. D. Cross, K. W. Myers, E. V. Farley Jr, J. M. Murphy, and J. H. Helle. 2005. Evidence for size-selective mortality after the first summer of ocean growth by pink salmon. Transactions of the American Fisheries Society **134**:1313–1322.

Mueter, F. J., and B. A. Megrey. 2006. Maximum productivity estimates for the groundfish complexes of the Gulf of Alaska and Eastern Bering Sea / Aleutian Islands. Fisheries Research **81**:189–201.

Mueter, F. J., and B. L. Norcross. 2002. Spatial and temporal patterns in the demersal fish community on the shelf and upper slope regions of the Gulf of Alaska. Fishery Bulletin **100**:559–581.

Muradian, M. L., T. A. Branch, S. D. Moffitt, and P.-J. F. Hulson. 2017. Bayesian stock assessment of Pacific herring in Prince William Sound, Alaska. PloS ONE **12**:e0172153.

Murphy, J., E. Fergusson, A. Piston, S. Heinl, and A. Gray. 2020. Southeast Alaska coastal monitoring survey cruise report, 2018. NPAFC Doc. 1894. 23 pp. National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Alaska Fisheries

Science Center, Auke Bay Laboratories, and Alaska Department of Fish and Game (Available at https://npafc.org).

Murphy, J., E. Fergusson, A. Piston, S. Heinl, A. Gray, and E. Farley. 2019. Southeast Alaska pink salmon growth and harvest forecast models. NPAFC Tech. Rept. 15:75-81. National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center, Auke Bay Laboratories, and Alaska Department of Fish and Game (Available at https://npafc.org).

Murphy, J. M., A. Piston, J. Moss, S. Heinl, E. Fergusson, W. Strasburger, and A. Gray. 2021. Southeast Alaska coastal monitoring survey: salmon distribution, abundance, size, and origin, 2019. NPAFC Doc. 1970. 23 pp. Alaska Fisheries Science Center, and Alaska Department of Fish and Game. (Available at `https://npafc.org`).

Muto, M., V. Helker, R. Angliss, B. Allen, P. Boveng, J. Breiwick, M. Cameron, P. Clapham, S. Dahle, M. Dahlheim, B. S. Fadely, M. C. Ferguson, L. W. Fritz, R. C. Hobbs, Y. V. Ivashchenko, A. S. Kennedy, J. M. London, S. A. Mizroch, R. R. Ream, E. L. Richmond, K. E. W. Shelden, R. G. Towell, P. R. Wade, J. N. Waite, and A. N. Zerbini. 2016. Alaska Marine Mammal Stock Assessments, 2016. National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center.

Myers, K., K. Aydin, R. Walker, S. Fowler, and M. Dahlberg. 1996. Known ocean ranges of stocks of Pacific salmon and steelhead as shown by tagging experiments, 1956–1995. FRI-UW-9614. Fish. Res. Inst., Univ. Washington, Seattle. 137 pp.

Napp, J., L. Incze, P. Ortner, D. Siefert, and L. Britt. 1996. The plankton of Shelikof Strait, Alaska: Standing stock, production, mesoscale variability and their relevance to larval fish survival. Fisheries Oceanography **5**:19–38.

National Marine Fisheries Service. 2011. U.S. National Bycatch Report [W. A. Karp, L. L. Desfosse, S. G. Brooke, Editors].U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-117E, 508 pp.

Neilson, J. L., and C. M. Gabriele. 2021. Glacier Bay & Icy Strait Humpback Whale Population Monitoring: 2020 Update. Glacier Bay National Park and Preserve . 6pp. https://irma.nps.gov/DataStore/Reference/Profile/2286991.

Neilson, J. L., C. M. Gabriele, and L. F. Taylor-Thomas. 2017. Humpback whale monitoring in Glacier Bay and adjacent waters 2016: Annual progress report. Natural Resource Report NPS/GLBA/NRR—2017/1503. National Park Service, Fort Collins, Colorado.

Nielsen, J., L. Rogers, R. Brodeur, A. Thompson, T. Auth, A. Deary, J. Duffy-Anderson, M. Galbraith, J. Koslow, and R. Perry. 2021. Responses of ichthyoplankton communities to the recent marine heatwave and previous climate fluctuations in Northeast Pacific marine ecosystems. Global Change Biology doi:10.1111/gcb.15415 **27**:506–520.

NOAA. 2021*a*. Central Gulf of Alaska Marine Heatwave Watch — NOAA Fisheries. NOAA. https://www.fisheries.noaa.gov/feature-story/central-gulf-alaska-marine-heatwave-watch (accessed 10.12.21).

NOAA. 2021*b*. NOAA High Resolution SST data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at https://www.fisheries.noaa.gov/feature-story/central-gulf-alaska-marine-heatwave-watch.

NPFMC. 2016. Fishery Management Plan for Groundfish of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W 4th Ave Suite 306, Anchorage, Alaska 99501. 150 pp.

Ogura, M., Y. Ishida, and S. Ito. 1991. Growth variation of coho salmon *Oncorhynchus kisutch* in the western North Pacific. Nippon Suisan Gakk. **57**:1089–1093.

Okkonen, S. R., G. A. Jacobs, E. J. Metzger, H. E. Hurlburt, and J. F. Shriver. 2001. Mesoscale variability in the boundary currents of the Alaska Gyre. Continental Shelf Research **21**:1219–1236.

Okkonen, S. R., T. J. Weingartner, S. L. Danielson, D. L. Musgrave, and G. M. Schmidt. 2003. Satellite and hydrographic observations of eddy-induced shelf-slope exchange in the northwestern Gulf of Alaska. Journal of Geophysical Research-Oceans **108**:10.1029/2002JC001342.

Ormseth, O. 2017. Assessment of the skate stock complex in the Gulf of Alaska. North Pacific Fishery Management Council, 605 W 4th Ave Suite 306, Anchorage, Alaska 99501. 58 pp.

Orsi, J., A. Wertheimer, M. Sturdevant, E. Fergusson, D. Mortensen, and B. Wing. 2004. Juvenile chum salmon consumption of zooplankton in marine waters of southeastern Alaska: a bioenergetics approach to implications of hatchery stock interactions. Reviews in Fish Biology and Fisheries **14**:335–359.

Orsi, J. A., E. A. Fergusson, A. Wertheimer, and E. Farley. 2016. Chinook salmon first-year production indicators from ocean monitoring in Southeast Alaska. North Pacific Anadromous Fish Commission Bulletin 6:169–179.

Orsi, J. A., E. A. Fergusson, E. M. Yasumiishi, E. V. Farley, and R. A. Heintz. 2015. Southeast Alaska Coastal Monitoring (SCEM) survey plan for 2015. Auke Bay Lab., Alaska Fisheries Science Center, NOAA, NMFS. `http://www.npafc.org`

Orsi, J. A., M. Sturdevant, and E. Fergusson. 2013. Connecting the “dots” among coastal ocean metrics and Pacific salmon production in Southeast Alaska, 1997–2012. North Pacifc Anadromous Fish Commission Technical Report No. 9: 260-266.

Park, W., M. Sturdevant, J. Orsi, A. Wertheimer, E. Fergusson, W. Heard, and T. Shirley. 2004. Interannual abundance patterns of copepods during an ENSO event in Icy Strait, southeastern Alaska. ICES Journal of Marine Science: Journal du Conseil **61**:464–477.

Parker, R. R. 1971. Size selective predation among juvenile salmonid fishes in a British-Columbia inlet. Journal of the Fisheries Research Board of Canada **28**:1503–1510.

Paul, A., and J. Paul. 1999. Interannual and regional variations in body length, weight and energy content of age-0 Pacific herring from Prince William Sound, Alaska. J. Fish Biol. **54**:996–1001.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres. 1998. Fishing down marine food webs. Science **279**:860–863.

Peterson, G. D., S. R. Carpenter, and W. A. Brock. 2003. Uncertainty and the management of multistate ecosystems: an apparently rational route to collapse. Ecology **84**:1403–1411.

Piatt, J., M. Arimitsu, W. Sydeman, S. Thompson, H. Renner, S. Zador, D. Douglas, S. Hatch, A. Kettle, and J. Williams. 2018. Biogeography of pelagic food webs in the North Pacific. Fisheries Oceanography **27**:366–380.

Piatt, J., J. Parrish, H. Renner, S. Schoen, T. Jones, M. Arimitsu, K. Kuletz, B. Bodenstein, M. García-Reyes, R. Duerr, and R. Corcoran. 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. PloS ONE **15**:e0226087.

Piatt, J. F., and P. J. Anderson. 1996. Response of Common Murres to the Exxon Valdez oil spill and long-term changes in the Gulf of Alaska marine ecosystem. American Fisheries Society Symposium **18**:720–737.

Piatt, J. F., and T. Van Pelt. 1997. Mass-mortality of Guillemots (*Uria aalge*) in the Gulf of Alaska in 1993. Marine Pollution Bulletin **34**:656–662.

Piston, A., and S. Heinl. 2020. Pink salmon stock status and escapement goals in Southeast Alaska through 2019. Alaska Department of Fish and Game, Special Publication No. 20-09, Anchorage.

Porter, S. M., L. Ciannelli, N. Hillgruber, K. M. Bailey, K.-S. Chan, M. F. Canino, and L. J. Haldorson. 2005. Environmental factors influencing larval walleye pollock Theragra chalcogramma feeding in Alaskan waters. Marine Ecology Progress Series **302**:207–217.

Purcell, J. E. 2005. Climate effects on formation of jellyfish and ctenophore blooms: a review. Journal of the Marine Biological Association of the United Kingdom **85**:461–476.

Purcell, J. E., and M. N. Arai. 2001. Interactions of pelagic cnidarians and ctenophores with fish: a review. Hydrobiologia **451**:27–44.

Purcell, J. E., and M. V. Sturdevant. 2001. Prey selection and dietary overlap among zooplanktivorous jellyfish and juvenile fishes in Prince William Sound, Alaska. Marine Ecology Progress Series **210**:67–83.

Queirolo, L. E., L. Fritz, P. Livingston, M. Loefflad, D. Colpo, and Y. DeReynier. 1995. Bycatch, utilization, and discards in the commercial groundfish fisheries of the Gulf of Alaska, easternBering Sea, and Aleutian Islands. U.S. Dep. Commer., NOAA Tech.Memo. NMFS-AFSC-58, 148 p.

Ream, R. R., J. T. Sterling, and T. R. Loughlin. 2005. Oceanographic features related to northern fur seal migratory movements. Deep-Sea Research Part II-Topical Studies in Oceanography **52**:823–843.

Reiniger, R., and C. Ross. 1968. A method of interpolation with application to oceanographic data. Deep Sea Research **15**:185–193.

Rice, A., A. Širović, J. S. Trickey, A. J. Debich, R. S. Gottlieb, S. M. Wiggins, J. Hildebrand, and S. Baumann-Pickering. 2021. Cetacean occurrence in the Gulf of Alaska from long-term passive acoustic monitoring. Marine Biology **168**:1–29.

Richardson, A. J., A. W. Walne, A. G. J. John, T. D. Jonas, J. A. Lindley, D. W. Sims, D. Stevens, and M. Witt. 2006. Using continuous plankton recorder data. Progress in Oceanography **68**:27–74.

Robins, J. B. 2006. Biophysical factors associated with the marine growth and survival of Auke Creek, Alaska Coho Salmon. Masters thesis, University of Alaska Fairbanks.

Robinson, K. L., J. J. Ruzicka, M. B. Decker, R. D. Brodeur, R. J. Hernandez, J. Quinones, E. M. Acha, S.-i. Uye, H. Mianzan, and W. M. Graham. 2014. Jellyfish, Forage Fish, and the World's Major Fisheries. Oceanography **27**:104–115.

Rogers, L. A., and A. B. Dougherty. 2019. Effects of climate and demography on reproductive phenology of a harvested marine fish population. Global Change biology **25**:708–720.

Rogers, L. A., and K. L. Mier. 2017. Gulf of Alaska Euphausiid ("krill") Acoustic Survey. In: S. Zador and E. Yasumiishi (Ed.), Ecosystem Considerations for 2017, Stock Assessment and Fishery Evaluation Report. Technical report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Rogers, L. A., M. Wilson, J. Duffy-Anderson, D. Kimmel, and J. Lamb. 2020. Pollock and "the Blob": Impacts of a marine heatwave on walleye pollock early life stages. Fisheries Oceanography **30**:142–158.

Rogers, L. A., M. T. Wilson, J. T. Duffy-Anderson, D. G. Kimmel, and J. F. Lamb. 2010. Pollock and "the Blob": Impacts of a marine heatwave on walleye pollock early life stages. Fisheries Oceanography **30**:142–158.

Rone, B. K., A. N. Zerbini, A. B. Douglas, D. W. Weller, and P. J. Clapham. 2017. Abundance and distribution of cetaceans in the Gulf of Alaska. Marine Biology **164**:1–23.

Rooper, C. N. 2008. An ecological analysis of rockfish (Sebastes spp.) assemblages in the North Pacific Ocean along broad-scale environmental gradients. Fishery Bulletin **106**:1–11.

Root, R. 1967. The niche exploitation pattern of the blue-gray gnatcatcher. Ecological Monographs **37**:317–350.

Royer, T. C., and C. E. Grosch. 2006. Ocean warming and freshening in the northern Gulf of Alaska. Geophysical Research Letters **33**:L16605.

Ruggerone, G., E. Farley, J. Nielsen, and P. Hagen. 2005. Seasonal marine growth of Bristol Bay sockeye salmon (*Oncorhynchus nerka*) in relation to competition with Asian pink salmon (*O. gorbuscha*) and the 1977 ocean regime shift. Fish. Bull. NOAA **103**:355–370.

Ruggerone, G. T., and J. Irvine. 2018. Numbers and biomass of natural- and hatchery-origin pink salmon, chum salmon, and sockeye salmon in the North Pacific Ocean. Mar. Coast. Fish. Dyn. Manag. Ecosyst. Sci. **10**:152–168.

Ruggerone, G. T., M. Zimmermann, K. W. Myers, J. L. Nielsen, and D. E. Rogers. 2003. Competition between Asian pink salmon (*Oncorhynchus gorbuscha*) and Alaskan sockeye salmon (*O-nerka*) in the North Pacific Ocean. Fisheries Oceanography **12**:209–219.

Schlegel, R., E. Oliver, A. Hobday, and A. Smit. 2019. Detecting marine heatwaves with sub-optimal data. Frontiers in Marine Science **6**:737.

Shanley, C. S., S. Pyare, M. I. Goldstein, P. B. Alaback, D. M. Albert, C. M. Beier, T. J. Brinkman, R. T. Edwards, E. Hood, and A. MacKinnon. 2015. Climate change implications in the northern coastal temperate rainforest of North America. Climatic Change **130**:155–170.

Shaul, L. D., and H. Geiger. 2016. Effects of climate and competition for offshore prey on growth, survival, and reproductive potential of coho salmon in Southeast Alaska. North Pacific Anadromous Fish Commission Bulletin **6**:329–347.

Shaul, L. K., E. Crabtree, S. McCurdy, and B. Elliott. 2011. Coho salmon stock status and escapement goals in Southeast Alaska. Alaska Department of Fish and Game, Special Publication No. 11-21 3.

Shin, Y., M. Rochet, S. Jennings, J. Field, and H. Gislason. 2005. Using size-based indicators to evaluate the ecosystem effects of fishing. ICES Journal of Mainer Science **62**:384–396.

Shin, Y.-J., L. J. Shannon, A. Bundy, M. Coll, K. Aydin, N. Bez, J. L. Blanchard, M. d. F. Borges, I. Diallo, E. Diaz, J. J. Heymans, L. Hill, E. Johannesen, D. Jouffre, S. Kifani, P. Labrosse, J. S. Link, S. Mackinson, H. Masski, C. Möllmann, S. Neira, H. Ojaveer, K. ould Mohammed Abdallahi, I. Perry, D. Thiao, D. Yemane, and P. M. Cury. 2010. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2. Setting the scene. ICES Journal of Marine Science **67**:692–716.

Siddon, E. C., R. A. Heintz, and F. J. Mueter. 2013. Conceptual model of energy allocation in walleye pollock (Theragra chalcogramma) from age-0 to age-1 in the southeastern Bering Sea. Deep Sea Research Part II: Topical Studies in Oceanography **94**:140–149.

Siwicke, K. A., J. Moss, B. Beckman, and C. Ladd. 2019. Effects of the Sitka Eddy on juvenile pink salmon in the eastern Gulf of Alaska. Deep-Sea Res. II **165**:348–363.

Sogard, S. M., and B. L. Olla. 2000. Endurance of simulated winter conditions by age-0 walleye pollock: Effects of body size, water temperature and energy stores. Journal of Fish Biology **56**:1–21.

Soos, C., and G. Wobeser. 2010. Identification of primary substrate in the initiation of avian botulism outbreaks. Journal of Wildlife Management **70**:45–53.

Sousa, L., K. O. Coyle, R. P. Barry, T. J. Weingartner, and R. R. Hopcroft. 2016. Climate-related variability in abundance of mesozooplankton in the northern Gulf of Alaska 1998–2009. Deep Sea Research Part II: Topical Studies in Oceanography **132**:122–135.

Spalinger, K. 2020. Large-mesh bottom trawl survey of crab and groundfish: Kodiak, Chignik, South Peninsula, and Eastern Aleutian Management Districts, 2019. Alaska Department of Fish and Game, Fishery Management Report No. 20-16, Anchorage.

Spies, I., and W. Palsson. 2018. Stock assessment of the Arrowtooth Flounder Stock in the Gulf of Alaska. North Pacific Fisheries Management Council, 605 West 4th, Suite 306, Anchorage, AK 99501.

Springer, A. M., and G. B. van Vliet. 2014. Climate change, pink salmon, and the nexus between bottom-up and top-down forcing in the subarctic Pacific Ocean and Bering Sea. Proceedings of the National Academy of Sciences **111**:E1880–E1888.

Stabeno, P., and S. Bell. 2019. Extreme conditions in the Bering Sea (2017–2018): record-breaking low sea-ice extent. Geophysical Research Letters **46**:8952–8959.

Stabeno, P. J., N. A. Bond, A. J. Hermann, N. B. Kachel, C. W. Mordy, and J. E. Overland. 2004. Meteorology and oceanography of the Northern Gulf of Alaska. Continental Shelf Research **24**:859–897.

Stabeno, P. J., J. D. Schumacher, K. M. Bailey, R. D. Brodeur, and E. D. Cokelet. 1996. Observed patches of walleye pollock eggs and larvae in Shelikof Strait, Alaska: Their characteristics, formation and persistence. Fisheries Oceanography **5(Suppl. 1)**:81–91.

Stewart, I., and A. Hicks. 2019. Assessment of the Pacific halibut (Hippoglossus stenolepis) stock at the end of 2018. Seattle, Wa. Retrieved from `https://iphc.int/data/projection-tool`.

Stone, R., H. Lehnert, and H. Reiswig. 2011. A guide to the deepwater sponges of the Aleutian Island Archipelago. NOAA Professional Paper NMFS 12, 187 p.

Sturdevant, M., M. Sigler, and J. Orsi. 2009. Sablefish predation on juvenile Pacific salmon in the coastal marine waters of Southeast Alaska in 1999. Transactions of the American Fisheries Society **138**:675–691.

Suryan, R., M. Arimitsu, H. Coletti, R. Hopcroft, M. Lindeberg, S. Barbeaux, S. Batten, W. Burt, M. Bishop, J. Bodkin, R. Brenner, R. Campbell, D. Cushing, S. Danielson, M. Dorn, B. Drummond, D. Esler, T. Gelatt, D. Hanselman, S. Hatch, S. Haught., K. Holderied, K. Iken, D. Irons, A. Kettle, D. Kimmel, B. Konar, K. Kuletz, B. Laurel, J. Maniscalco, C. Matkin, C. McKinstry, D. Monson, J. Moran, D. Olsen, W. Palsson, S. Pegau, J. Piatt, L. Rogers, N. Rojek, A. Schaefer, I. Spies, J. Straley, S. Strom, K. Sweeney, M. Szymkowiak, B. Weitzman, E. Yasumiishi, and S. Zador. 2021. Ecosystem response persists after a prolonged marine heatwave. Scientific Reports **11**:6235.

Sydeman, W., J. Piatt, S. Thompson, M. García-Reyes, S. Hatch, M. Arimitsu, L. Slater, J. Williams, N. Rojek, S. Zador, and H. Renner. 2017. Puffins reveal contrasting relationships between forage fish and ocean climate in the North Pacific. Fisheries Oceanography **26**:379–395.

Tadokoro, K., Y. Ishida, N. Davis, N. Davis, S. Ueyanagi, and T. Sugimoto. 1996. Change in chum salmon (*Oncorhynchus keta*) stomach contents associated with fluctuation of pink salmon (*O. gorbuscha*) abundance in the central subarctic Pacific and Bering Sea. Fisheries Oceanography **5**:89–99.

Tobin, E. D., C. Wallace, C. Crumpton, G. Johnson, and G. Eckert. 2019. Environmental drivers of paralytic shellfish toxin producing *Alexandrium catenella* blooms in a fjord system of northern Southeast Alaska. Harmful Algae **88**:101659.

Toge, K., R. Yamashita, K. Kazama, M. Fukuwaka, O. Yamamura, and Y. Watanuki. 2011. The relationship between pink salmon biomass and the body condition of short-tailed shearwaters in the Bering Sea: can fish compete with seabirds? Proceedings of the Royal Society B-Biological Sciences **278**:2584–2590.

Toresen, R. 2001. Spawning stock fluctuations and recruitment variablity related to temperature for selected herring (*Clupea harengus*) stocks in the North Atlantic. In Herring: Expectations for a New Millennium, Alaska Sea Grant College Program, volume AK-SG-01-04, pg 315-334.

Traiger, S., J. Bodkin, H. Coletti, B. Ballachey, T. Dean, D. Esler, K. Iken, B. Konar, M. Lindeberg, D. Monson, B. Robinson, and B. Suryan, R.M. amd Weitzman. In Prep. Indirect effects of sea star wasting syndrome on mussel abundance in the northern Gulf of Alaska during a period of unprecedented warming. Marine Ecology Progress Series .

Vandersea, M., S. Kibler, P. Tester, K. Holderied, D. Hondolero, K. Powell, S. Baird, A. Doroff, D. Dugan, and R. Litaker. 2018. Environmental factors influencing the distribution and abundance of Alexandrium catenella in Kachemak Bay and lower Cook Inlet, Alaska. Harmful Algae **77**:81–92.

von Szalay P.G., and N. Raring. 2018. Data Report: 2017 Gulf of Alaska bottom trawl survey. US Dep Commer, NOAA Tech Memo NMFS-AFSC-374:260.

Waite, J. N., and F. Mueter. 2013. Spatial and temporal variability of chlorophyll-a concentrations in the coastal Gulf of Alaska, 1998–2011, using cloud-free reconstructions of SeaWiFS and MODIS-Aqua data. Progress in Oceanography **116**:179–192.

Ward, E., S. Anderson, and L. Damiano. 2019. bayesdfa: Bayesian Dynamic Factor Analysis (DFA) with 'Stan'. R package version 0.1.3. https://CRAN.R-project.org/package=bayesdfa.

Warzybok, P., J. Santora, D. Ainley, R. Bradley, J. Field, C. P.J., C. R.D., E. M., J. Beck, G. McChesney, M. Hester, and J. Jahncke. 2018. Prey switching and consumption by seabirds in the central California Current upwelling ecosystem: Implications for forage fish management. Journal of Marine Systems **185**:25–39.

Weitkamp, L. A., J. A. Orsi, K. Myers, and R. Francis. 2011. Contrasting early marine ecology of Chinook salmon and coho salmon in Southeast Alaska: insight into factors affecting marine survival. Marine and Coastal Fisheries **3**:233–249.

Weitzman, B., B. Konar, K. Iken, H. Coletti, D. Monson, R. Suryan, T. Dean, D. Hondolero, and M. Lindeberg. 2021. Changes in rocky intertidal community structure during a marine heatwave in the northern Gulf of Alaska. Frontiers in Marine Science **8**:1–18.

Wertheimer, D., A., J. A. Orsi, E. A. Fergusson, and M. V. Sturdevant. 2010. Calibration of Juvenile Salmon Catches using Paired Comparisons between Two Research Vessels Fishing Nordic 264 Surface Trawls in Southeast Alaska, July 2009.(NPAFC Doc. 1277). Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service (Available at https://npafc.org).

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

Wilderbuer, T. K., A. B. Hollowed, W. J. Ingraham, P. D. Spencer, M. E. Conners, N. A. Bond, and G. E. Walters. 2002. Flatfish recruitment response to decadal climatic variability and ocean conditions in the eastern Bering Sea. Progress in Oceanography **55**:235–247.

Wilson, M. T., A. Dougherty, M. E. Matta, K. L. Mier, and J. A. Miller. 2018. Otolith chemistry of juvenile walleye pollock *Gadus chalcogrammus* in relation to regional hydrography: evidence of spatially split cohorts. Marine Ecology Progress Series **588**:163–178.

Wilson, M. T., and N. Laman. 2021. Interannual variation in the coastal distribution of a juvenile gadid in the northeast Pacific Ocean: The relevance of wind and effect on recruitment. Fisheries Oceanography **30**:3–22.

Wilson, M. T., K. L. Mier, and C. M. Jump. 2013. Effect of region on the food-related benefits to age-0 walleye pollock (*Theragra chalcogramma*) in association with midwater habitat characteristics in the Gulf of Alaska. Marine Ecology Progress Series **70**:1396–1407.

Winemiller, K. 2005. Life history strategies, population regulation, and implications for fisheries management. Canadian Journal of Fisheries and Aquactic Sciences **62**:872–885.

Witherell, D., and D. Woodby. 2005. Application of marine protected areas for sustainable production and marine biodiversity off Alaska. Marine Fisheries Review **67**:1–28.

Work, T., J. Klavitter, M. Reynolds, and D. Blehert. 2010. Avian botulism: A case study in translocated endangered laysan ducks (*Anas laysanensis*) on Midway Atoll. Wildlife Diseases **46**:499–506.

Yang, Q., E. D. Cokelet, P. J. Stabeno, L. Li, A. B. Hollowed, W. A. Palsson, N. A. Bond, and S. J. Barbeaux. 2019. How "The Blob" affected groundfish distributions in the Gulf of Alaska. Fisheries Oceanography **28**:434–453.

Yasumiishi, E., E. Farley, G. Ruggerone, B. Agler, and L. Wilson. 2016. Trends and factors influencing the length, compensatory growth, and size-selective mortality of juvenile Bristol Bay, Alaska, sockeye salmon at sea. Marine and Coastal Fisheries **8**:315–333.

Zador, S., G. L. Hunt, T. TenBrink, and K. Aydin. 2013. Combined seabird indices show lagged relationships between environmental conditions and breeding activity. Marine Ecology Progress Series **485**:245–258.

Zador, S. G., and S. Fitzgerald. 2008. Seabird Attraction to Trawler Discards. AFSC Processed Rep. 2008-06, 26 p. Alaska Fisheries Science Center, NOAA, National Marine Fisheries Service, 7600 Sand Point Way NE, Seattle WA 98115.

Zebdi, A., and J. Collie. 1995. Effect of climate on herring (*Clupea pallasi*) population dynamics in the Northeast Pacific Ocean: Climate change and northern fish populations., 1995, pp. 277-290, Canadian special publication of fisheries and aquatic sciences /Publication speciale canadienne des sciences halieutiques et aquatiques Ottawa ON [Can. Spec. Publ. Fish. Aquat. Sci./Publ. Spec. Can. Sci. Halieut. Aquat.], no. 121.

Zerbini, A. N., M. F. Baumgartner, A. S. Kennedy, B. K. Rone, P. R. Wade, and P. J. Clapham. 2015. Space use patterns of the endangered North Pacific right whale *Eubalaena japonica* in the Bering Sea. Marine Ecology Progress Series **532**:269–281.

Appendices

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 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 reports, one for the Gulf of Alaska, Aleutian Islands, eastern Bering Sea, and the Arctic[3].

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 they are 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 the Ecosystem Status Reports. In the past, concerns used to justify an ABC below the maximum calculated by the assessment model were doc-

[3]The Arctic report is under development

umented in an ad hoc manner in the stock assessment report 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 EBS, 2019 for GOA, and 2020 for AI. 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 119). 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.

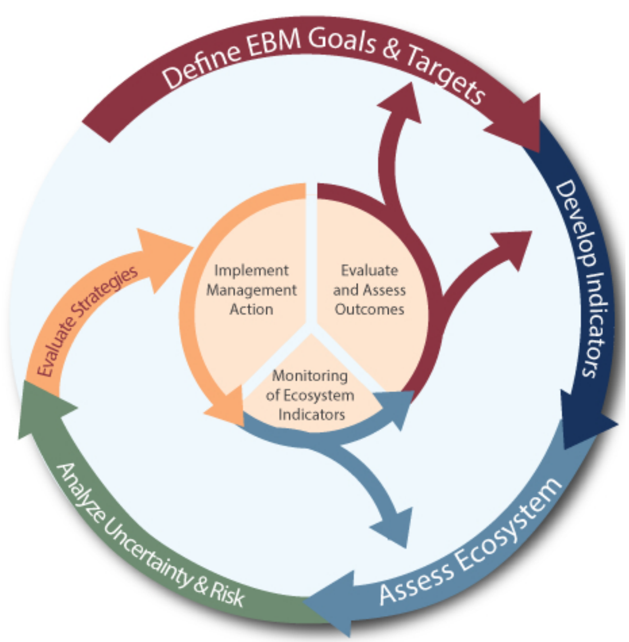


Figure 119: The IEA (integrated ecosystem assessment) process.

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/index.php`. 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 Comments from the Scientific and Statistical Committee (SSC)

December 2020 SSC Comments

General comments for all Ecosystem Status Report sections.

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.

We have updated the format of the AI ESR this year to have a more cohesive format across all ESRs. Some formatting differences between ESRs will remain as we try to portray the information in a way that it highlights particular features of an ecosystem (e.g. regional report cards in the AI). With regards to standardized methodologies, contributors follow the same methodology (and text) for indicators sent to all three ESRs. However, sometimes using the same methodology is not possible or suitable- even when using the same kind of data. For example, satellite chla coverage has more gaps in the AI as opposed to the EBS, and hence the methodologies and indicators differ between both ESRs, despite the similarity in data sources. 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.

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 sections of the ESRs are likely to be of greatest use to the SSC in this regard. The assessments are based on a synthesis of the 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 here, 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.

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 ESR authors 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.

Response from AFSC Economic and Social Science Research Program: 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.

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 Briefs" 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 focussed on specific ecosystem stories, and no additional videos at this time.

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.

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 occuring, 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's 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 SD in 2017 and thus the low indicator value.

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.

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.

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.

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.

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.

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.

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.

Gulf of Alaska Chapter

The commercial harvest of salmon was low across most of the GOA, and was the lowest in SEAK since 1976. The poor catches of salmon resulted in numerous requests for the State of Alaska to declare salmon fishery disasters. The poor catches are of social and economic concern. The low returns in SEAK were primarily driven by low chum and sockeye returns. Low adult returns were likely the result of high juvenile mortality in 2017 (and years since then for certain species), but the mechanism driving that trend (e.g., environment, predation) is still uncertain. Juvenile abundance since 2017 has been increasing, suggesting harvests will increase in coming years ***The SSC supports additional research on the survival and growth of salmon during the first marine year and on survival during their later marine stages.***

The ESR editors are excited to monitor the research produced by the International Year of the Salmon collaborative program, which is continuing this year. Along with other ongoing salmon research programs, this unique opportunity has the potential to add to our understanding of early marine survival of salmon in the Gulf of Alaska.

There was a consistent presence of HABs in Kachemak Bay and around Kodiak Island in the WGOA in 2020. Bivalves in Kachemak Bay had levels of paralytic shellfish poisoning toxins (PSP, saxitoxins) approaching but remaining under the regulatory limit for human consumption. Around Kodiak, several high toxicity samples were collected that exceeded the regulatory limit. In the EGOA, HABs were above the regulatory limit at over half of the monitored sites. This was slightly lower than in 2019, likely due to the rainy summer. The SSC commends the highly collaborative efforts to provide data to the HAB network from tribal organizations (Southeast Alaska Tribal Ocean Research, communities (Kachemak Bay National Estuarine Research Reserve's Community Monitoring Program), and NOAA researchers, and supports continued efforts to monitor these toxins across all ecoregions, as it poses a considerable concern for human health. ***The SSC suggests exploring if data exist on HABs in planktivorous forage fish or upper trophic level animals for inclusion in future ESRs.***

There is ongoing research to quantify these toxins throughout the food web in the GOA. Data are still preliminary, but some are reported in the HABs section of this report. In general, some saxitoxin levels above the regulatory limit have been observed in sand lance and herring, and the liver and kidny of certain salmon species. Additional sampling opportunities were lost in 2021 due to the cancellation of the AFSC summer EcoFOCI cruise. The ESR editor is in communication with PIs in these research projects and monitoring their progress.

The desertion of two additional kittiwake colonies in 2020 in the Kodiak region is a matter of concern. It may be an indication that forage fish have become scarce in that area.

We agree the abandonment of kittiwake colonies is a concern, although there are multiple reasons why this might occur (e.g., prey availability, predation). Forage fish data in 2021 show potentially improvide forage conditions, including general reproductive success among piscivorous seabirds in the region. Kittiwakes had poor reproductive success on Middelton Island in 2021, indicating poor forage conditions. This could also be related to less favorable zooplankton abundance in general in the GOA this year.

The presence of chub mackerel in the diets of seabirds at Middleton Island is of considerable interest. ***The SSC encourages the authors to evaluate whether the consumption of chub mackerel has increased over time and whether there are other indicators that suggest they are becoming more numerous. In addition, it would be useful to evaluate the role of the small pelagic species in the GOA ecosystem, and whether they are projected to be an important prey species under a warming climate.***

Response contributed by Scott Hatch regarding Chub mackerel in Middleton Island seabirds: There were no chub mackerel in the diets of black-legged kittiwakes (BLKI) this year (2021), perhaps owing to an ocean cooling trend (Jun-Aug PDO -1.39 in 2021). It will be an interesting species to watch if it proves to be a good indicator of warming conditions. It is definitely a newcomer as of 2019—4 occurrences in 61 BLKI food samples in August 2019 (7%), 15 occurrences in 146 BLKI food samples in August 2020 (10

A caveat on this, however, is that the BLKI diet was poorly sampled in August 2021, because of the 2021 Middleton Island seabird mortality event. Field personnel were advised to be hands-off with the kittiwakes for several weeks after July 17, 2021. Only 15 samples were obtained in August, and only 5 samples were from 6 Aug. 6 or later. The earliest date for chub mackerel was Aug. 6 in both 2019 and 2020.

New methods for assessing body condition of groundfish show that trends in body condition vary across species. For example the body condition of large walleye pollock, arrowtooth flounder, and dusky rockfish has been below average since 2015. The body condition of northern rockfish and possibly Pacific ocean perch has been above average but trending downward since 2015. Whereas, the residual body condition of Pacific cod and southern rock sole have been trending upward over the same time. Prior to 2011, condition indexes of these GOA species varied from survey to survey, cycling between negative and positive residuals with no clear temporal trend.

Response contributed by the lead author: Due to programmatic constraints, we are using the same method to calculate 2021 condition indicators as was used in 2020. We intend to pursue a transition to VAST-based condition indicators for the 2022 ESR. These trends of lower body condition since 2015 do still persist in certain species.

No new data were provided on Steller sea lion populations in 2020. In 2019, non-pups in the central and WGOA had declined from the 2017 counts, but following COVID-19 cancellations, SSL surveys have been postponed in the GOA until 2022 to focus on the Aleutian Islands in 2021. ***The SSC suggests exploring other long-term datasets on sea lion reproduction from the WGOA that might be able to provide information on non-pup and pup numbers during this gap (e.g., pup production and attendance at Chiswell Island from 1998-present, Alaska SeaLife Center)****.*

The ESR editor discussed incorporation of additional Steller sea lion data with researchers at the Alaska SeaLife Center. We mutually concluded that their work, while scientifically valuable, is very localized and might not necessarily represent what is happening in broader areas of the Gulf of Alaska. We will note be including these data in the ESR at this time.

There were no updates for Fisheries or Human Dimensions indicators in 2020; ***the SSC looks forward to seeing these indicators updated in 2021.***

Response provided by the Economic and Social Science Research Program: Existing 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) were all updated and included in the 2020 report, however these are always lagged by one year so they were updated to 2019 values. These contributions 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 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). The Alaska Fisheries Science Center will be reexamining these contirbutions to the Council in the context of all relevant products (ESR, Ecosystem and Socioeconomic Profile, Risk Table, Economic SAFE, ACEPO report).

Report Card Indicator Descriptions & Methods

We present separate Western and Eastern Gulf of Alaska Report Cards to highlight inherent differences in ecosystem structure and function between the eastern and western ecoregions. Top-ranked indicators were selected for each category: physical, plankton, benthic, forage fish, non-forage fish, seabirds, marine mammals, and humans. We include two physical and plankton indicators and one from each of the other categories where available. The indicators are defined below.

Western Gulf of Alaska

Winter Pacific Decadal Oscillation The leading mode of monthly sea surface temperature anomalies in the North Pacific Ocean, poleward of 20°N. The monthly mean global average SST anomalies are removed to separate this pattern of variability from any "global warming" signal that may be present in the data. The winter index is the average monthly values from December–February. Data from `https://oceanview.pfeg.noaa.gov/erddap/tabledap/cciea_OC_PDO.htmlTable?time,PDO`. (See Bond, p.31)

Contact: nicholas.bond@noaa.gov

Summer Sea Surface Temperature The NOAA Coral Reef Watch Program provides a gap-free daily SST dataset (`https://coralreefwatch.noaa.gov/product/5km/`) that was accessed via the NOAA Coast WatchWest Coast Node ERDDAP server (`https://coastwatch.pfeg.noaa.gov/erddap/griddap/NOAA_DHW.html`). Daily summer temperatures (June-August) were averaged for the western GOA (147°W–163°W). (See Watson, p.39)

Contact: jordan.watson@noaa.gov

Mesozooplankton biomass Mesozooplankton biomass is estimated from taxon-specific abundance data collect from Continuous Plankton Recorders (CPRs). These have been deployed in the North Pacific routinely since 2000. The transect for the region known as the Alaska Shelf is sampled monthly (∼Apr–Sept) and presented here. Anomaly time series of each index are calculated as follows: a monthly mean value (geometric mean) was first calculated. Each sampled month was then compared to the mean of that month and an anomaly calculated (Log_{10}). The mean anomaly of all sampled months in each year was calculated to give an annual anomaly. (See Ostle, p.68)

Contact: claost@mba.ac.uk

Copepod community size Mean copepod community size (Richardson et al., 2006) as sampled by Continuous Plankton Recorders is presented as an indicator of community composition. The methods used to calculate this indicator is listed above for mesozooplankton biomass. (See Ostle, p.68)

Contact: claost@mba.ac.uk

Motile epifauna biomass The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 2000. The motile epifauna foraging guild is calculated from the survey data modified by an ecopath-estimated catchability. This guild includes: eelpouts, octopi, crab, sea stars, brittle stars, sea urchins, sand dollars, sea cucumbers, snails, and hermit crabs. This indicator is presented to reflect the trends in the benthic community of the western GOA. In the 2016 report, this indicator included the entire survey area. (See Whitehouse, p.174)

Contact: andy.whitehouse@noaa.gov

Capelin Previously we used the common trend identified by Dynamic Factor Analysis of capelin in prey composition time series from various piscivorous seabird and groundfish species, considered to be "samplers" of the forage fish community. In 2019, data were not available in time for this indicator to be updated and we use the time series that loaded most strongly on the DFA trend: the percent biomass of capelin from rhinocerous auklets (*Cerorhinca monocerata*) chick diets at Middleton Island (ISRC). This alternative metric was used again in 2020 as the full suite of data were not available in 2020 due to COVID-19 related seabird survey cancellations. (See Hatch, p.94)

Contact: stephani.zador@noaa.gov; shatch.isrc@gmail.com

Apex predator biomass The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 2000. The apex predator foraging guild is calculated from the survey data modified by an ecopath-estimated catchability. Fish in this guild include: Pacific cod, arrowtooth flounder, halibut, sablefish, large sculpins, and skates. Marine mammals, seabirds, and some other fishes such as sharks are included as constant ecopath-estimated biomasses. (See Whitehouse contribution, p.174)

Contact: andy.whitehouse@noaa.gov

Black-legged kittiwake reproductive success Black-legged kittiwakes are common surface-foraging, piscivorous seabirds that nest in the GOA. Reproductive success is defined as the proportion of nest sites with fledged chicks from the total nest sites that were built. Reproductive success of this species is considered to be more sensitive to foraging conditions than that of common murres, another common seabird that has less variable reproductive success due to behaviors that can buffer the effects of poor food supply. Data are collected by the Alaska Maritime National Wildlife Refuge staff, U.S. Fish and Wildlife Service. These data were not updated in 2020 due to COVID-19 related survey cancellations. (See AMNWR data in Seabird Synthesis, p 152)

Contact: heather_renner@fws.gov

Steller sea lion non-pup estimates The R package agTrend model was used to produce abundance estimates of Steller sea lions within the bounds of the GOA. This region includes the GOA portion of the western Distinct Population Segment (known as the west, central and east GOA).

Contact: kathryn.sweeney@noaa.gov

Eastern Gulf of Alaska

Multivariate ENSO Index (MEI) The bi-monthly Multivariate El Niño/Southern Oscillation (ENSO) index (MEI.v2) is the time series of the leading combined Empirical Orthogonal Function (EOF) of five different variables (sea level pressure (SLP), sea surface temperature (SST), zonal and meridional components of the surface wind, and outgoing longwave radiation (OLR) over the tropical Pacific basin (30°S-30°N and 100°E-70°W). The EOFs are calculated for 12 overlapping bi-monthly "seasons" (Dec-Jan, Jan-Feb, Feb-Mar,..., Nov-Dec) in order to take into account ENSO's seasonality, and reduce effects of higher frequency intraseasonal variability. We include the Dec-Jan value in the East Gulf of Alaska Report Card, with the year corresponding to January.

Key features of composite positive MEI events (warm, El Niño) include (1) anomalously warm SSTs across the east-central equatorial Pacific, (2) anomalously high SLP over Indonesia and the western tropical Pacific and low SLP over the eastern tropical Pacific, (3) reduction or reversal of tropical Pacific easterly winds (trade winds), (4) suppressed tropical convection (positive OLR) over Indonesia and Western Pacific and enhanced convection (negative OLR) over the central Pacific. Key features of composite negative MEI events (cold, La Niña) are of mostly opposite phase. For any single El Niño or La Niña situation, the atmospheric articulations may depart from this canonical view. Data are from `http://www.esrl.noaa.gov/psd/enso/mei/table.html`. (See Bond, p.31)

Contact: nicholas.bond@noaa.gov

Summer Sea Surface Temperature The NOAA Coral Reef Watch Program provides a gap-free daily SST dataset (`https://coralreefwatch.noaa.gov/product/5km/`) that was accessed via the NOAA Coast WatchWest Coast Node ERDDAP server (`https://coastwatch.pfeg.noaa.gov/erddap/griddap/NOAA_DHW.html`). Daily summer temperatures (June-August) were averaged for the eastern GOA (133°W–147°W). (See Watson, p.39)

Contact: jordan.watson@noaa.gov

Mesozooplankton biomass Zooplankton biomass is represented by zooplankton density (number per m^3) as captured by 333-μm bongo net samples during summer months in Icy Strait. (See Fergusson, p.78)

Contact: emily.fergusson@noaa.gov

Copepod Community size The ratio of large calanoid copepods to total large and small calanoid copepods as sampled in Icy Strait is used to represent copepod community size. (See Fergusson, p.78)

Contact: emily.fergusson@noaa.gov

Motile epifauna biomass The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 2000 (in the odd years). The motile epifauna foraging guild is calculated from the survey data modified by an ecopath-estimated catchability. This guild includes: eelpouts, octopi, crab, sea stars, brittle stars, sea urchins, sand dollars, sea cucumbers, snails, and hermit crabs. This indicator is presented to reflect the trends in the benthic community of the GOA. These values are summarized for the eastern region, where survey efforts vary among years. (See Whitehouse, p.174)

Contact: andy.whitehouse@noaa.gov

Sitka mature herring biomass The stock assessment estimates of the Sitka herring stock is used to represent forage fish trends in the eastern GOA region. Previously, total mature herring biomass was estimated from nine primary sites for which regular assessments are conducted and probably account for the majority of the spawning biomass in southeastern Alaska in any given year. The Sitka stock has the longest time series of assessed biomass. (See Hebert, p.102)

Contact: kyle.hebert@alaska.gov

Apex predator biomass The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 2000 (in the odd years). The apex predator foraging guild is calculated from the survey data modified by an ecopath-estimated catchability. Fish in this guild include: Pacific cod, arrowtooth flounder, halibut, sablefish, large sculpins, and skates. Marine mammals, seabirds, and some other fishes such as sharks are included as constant ecopath-estimated biomasses. These values are summarized for the eastern region, where survey efforts vary among years. (See Whitehouse, p.174)

Contact: andy.whitehouse@noaa.gov

Rhinoceros auklet chick growth rate Mean growth rates of rhinoceros auklet chicks at St. Lazaria Island. Reproductive success is difficult to determine for these burrow-nesting seabirds because they are sensitive to disturbance. Data are only included for chicks that were measured at least three times during the linear phase of growth; chicks that did not exhibit linear growth were excluded. Data are collected by the Alaska Maritime National Wildlife Refuge staff, U.S. Fish and Wildlife Service. The colony was not monitored in 2017. These data were not updated in 2020 due to COVID-19 related seabird survey cancellations. (See AMNWR data in Seabird Synthesis, p.152)

Contact: heather_renner@fws.gov

Steller sea lion non-pup estimates The R package agTrend model was used to produce abundance estimates of Steller sea lions within the bounds of the GOA. This region includes the eastern Distinct Population Segment known as southeast Alaska.

Contact: kathryn.sweeney@noaa.gov

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 "2017–2021 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 "2017–2021 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 figures 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.