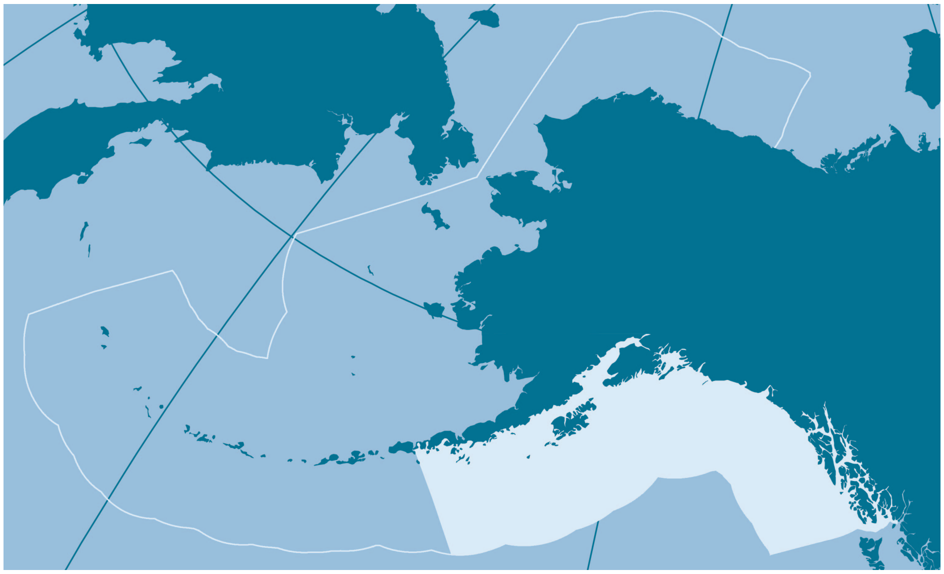
Ecosystem Status Report 2023

GULF OF ALASKA



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QR code for NOAA Alaska Fisheries Science Center's Ecosystem Status Reports webpage[1].Time series from the report cards are also available[2].

[1] https://www.fisheries.noaa.gov/alaska/ecosystems/ecosystem-status-reports-gulf-alaska-bering-sea-and-aleutian-islands

[2] https://apps-afsc.fisheries.noaa.gov/refm/reem/ecoweb/index.php

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 (Figure 1).

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[3,4]. 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 as well as other Council decisions. Additional background can be found in the Appendix (p.241).

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

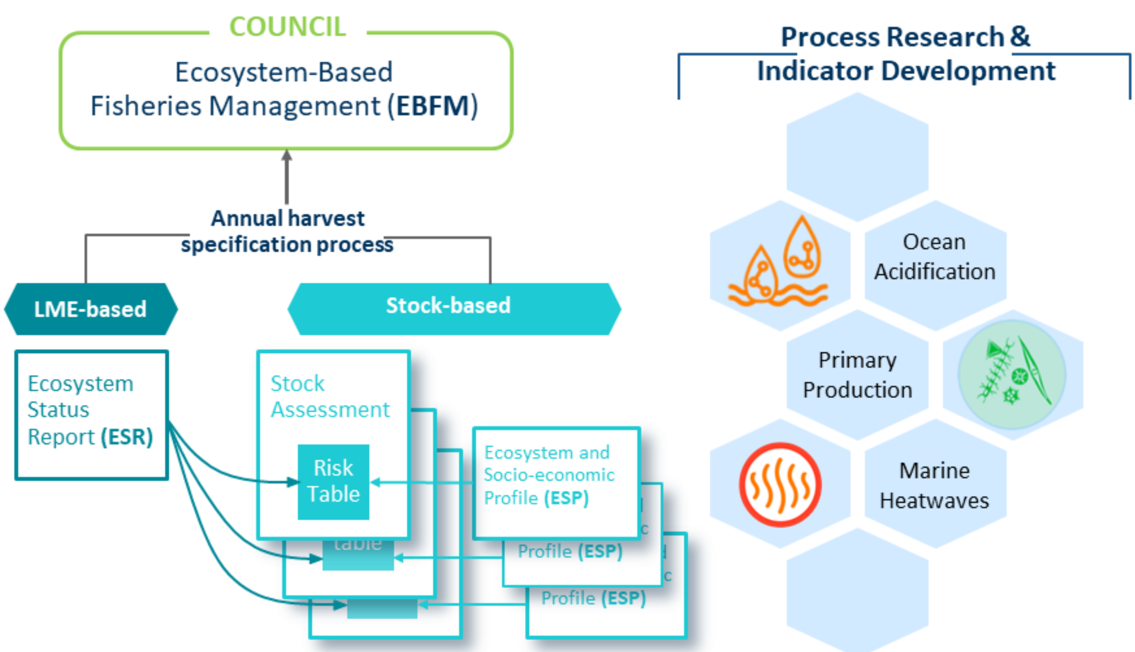

Figure 1: NOAA Fisheries' ecosystem information mapping to support ecosystem-based fisheries management through Alaska's annual harvest specification process. The 'honeycomb' on the right shows examples of ecosystem indicators that are provided to Ecosystem Status Reports (ESRs) at the large marine ecosystem scale and/or to Ecosystem and Socio-economic Profiles (ESPs) at the stock-based level.

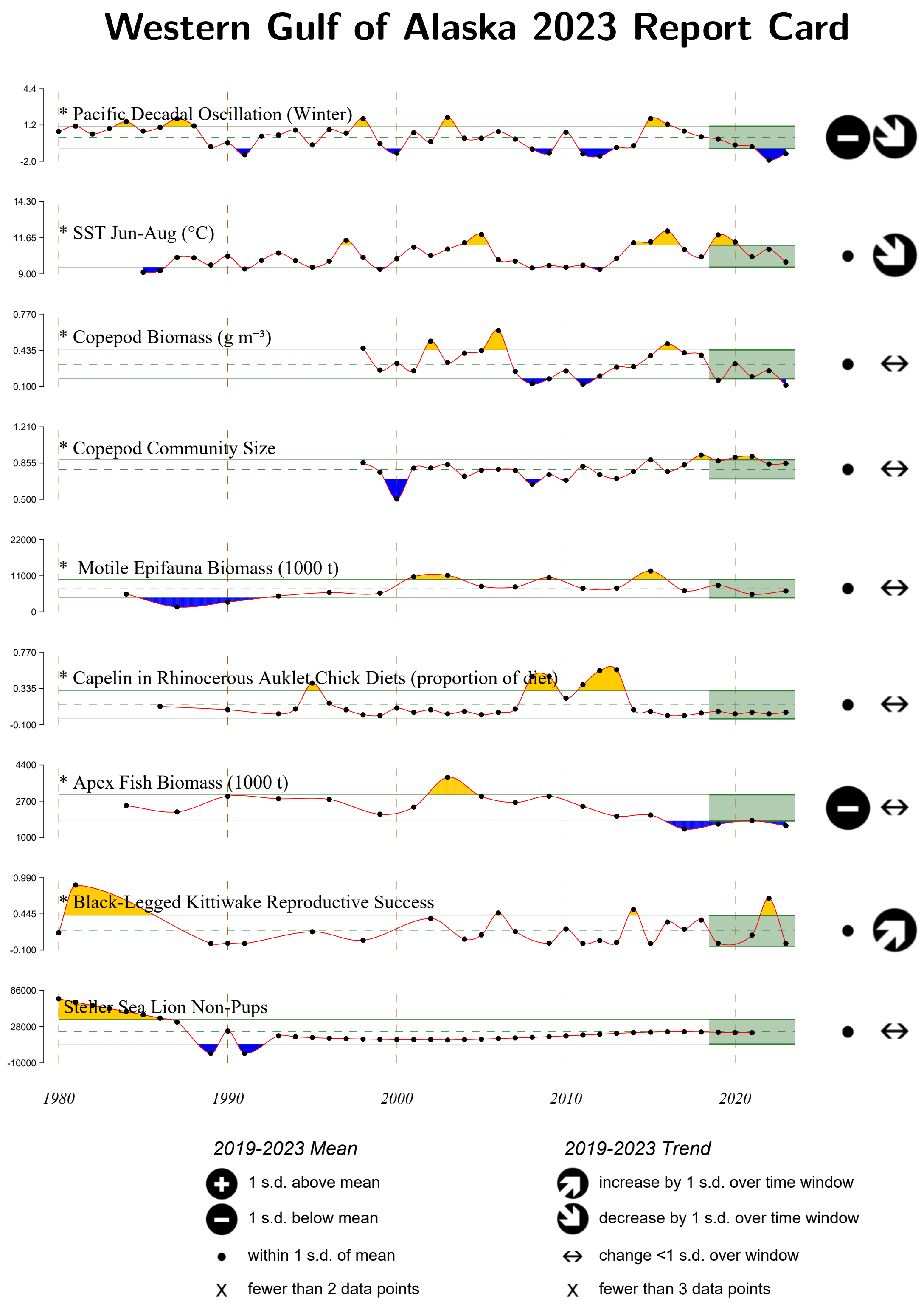

Figure 2: Western Gulf of Alaska report card indicators. For additional information on these indicators, refer to "Report Card indicator Description and Methods" in the Appendix of this Report (p.248) and relevant contributions in this Report. * Indicates time series updated with 2023 data.

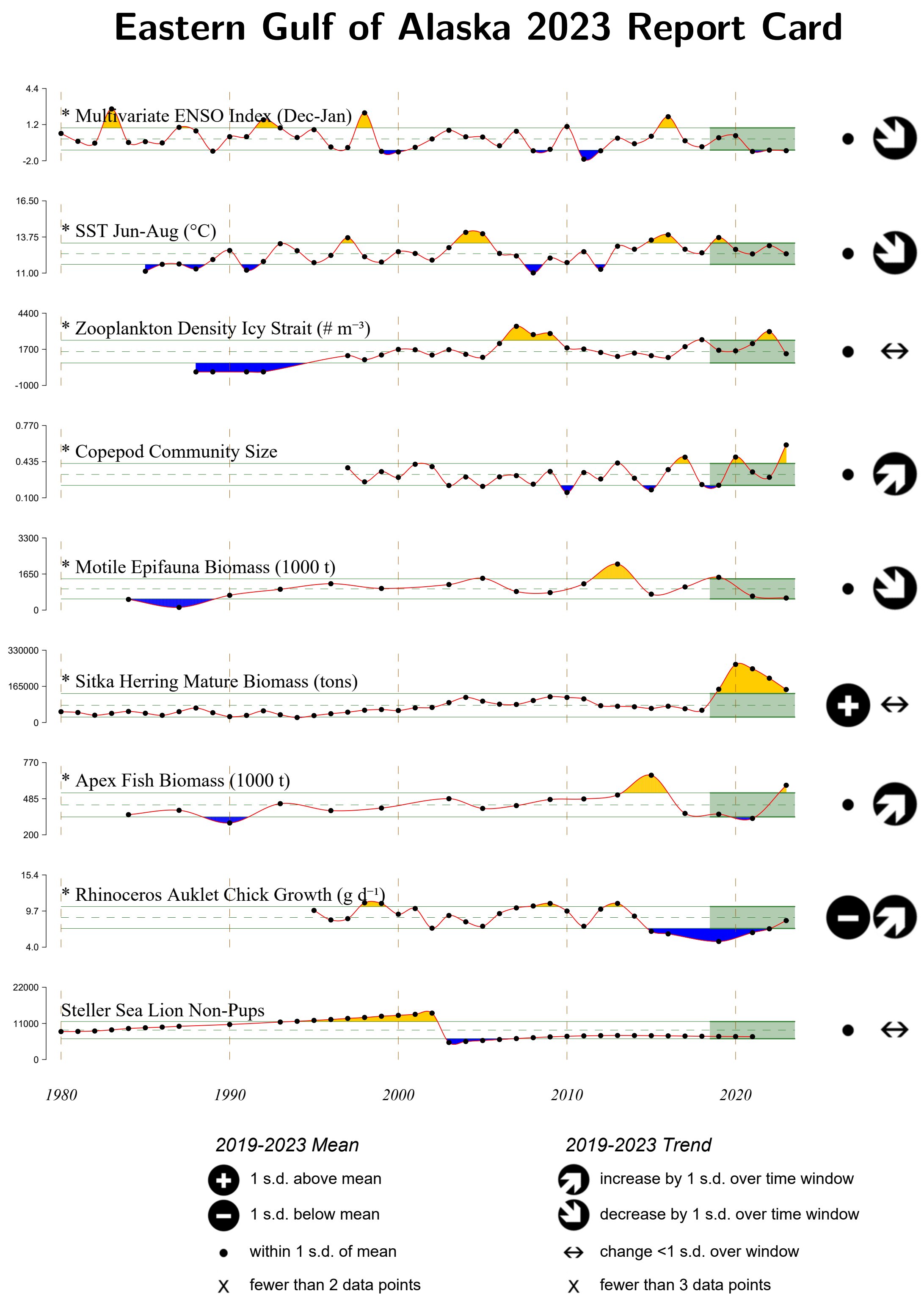

Figure 3: Eastern Gulf of Alaska report card indicators. For additional information on these indicators, refer to "Report Card indicator Description and Methods" in the Appendix of this Report (p.248) and relevant contributions in this Report. * Indicates time series updated with 2023 data.

Western Gulf of Alaska 2023 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.248).

- **Winter average PDO index** (Dec.-Feb., 1980–2023) continued its negative trend in 2023, reflecting cooling sea surface temperatures in the GOA.
- **Sea-surface temperatures in the summer (°C)** (Jun.-Aug., 1985–2023) in the western GOA were cooler than average, but remained within 1SD of the long-term mean.
- **Copepod biomass (g m^{-3})** was 1 standard deviation below average (1998–2023) in 2023, indicating below average foraging conditions for planktivorous predators. Total (large and small) calanoid copepods are surveyed south of Seward in May of each year. Euphausiid biomass was above average during the same time period.
- **Copepod community size** (ratio of large calanoid copepods to total calanoid copepods) remained elevated in 2023, close to 1 standard deviation above average (1998–2023), indicating increased large copepods in the community, relative to small copepods. Total (large and small) calanoid copepods are surveyed south of Seward in May of each year.
- **Motile epifauna biomass (1,000 t)** increased from 2021 to 2023 and is near the long term mean (1984 – 2023). The biomass of this guild is dominated by hermit crabs, brittle stars, other echinoderms, and octopus. In 2023, brittle star biomass has declined from 2021 while the biomass of hermit crabs, octopus, and other echinoderms have all increased.
- **Capelin abundance (proportion of diet by weight)**, as sampled by rhinoceros auklets at Middleton Island (Apr.-Aug., 1986–2023), continue to be minimalslightly increased in seabird chick diets in recent years, and remain within 1 standard deviation of the long-term mean.
- **Fish apex predator biomass (1,000 t)** decreased from 2021 to 2023 and is more than one standard deviation below the long term mean. The biomass trends for apex predators, as sampled by NOAA's bottom trawl survey, are primarily driven by arrowtooth flounder, Pacific cod, Pacific halibut, and sablefish. In 2023, arrowtooth flounder, Pacific halibut, and sablefish all declined from 2021 and are below their long-term means. Pacific cod biomass increased from 2021 to 2023 but remain below their long term mean.
- **Black-legged kittiwakes reproductive success** in 2023 (Jun.-Jul., 1980–2023) experienced reproductive failure (no reproduction) at the Semidi Islands, a sharp decrease from the production in 2022. This drop indicates below-average prey (sandlance and age-0 pollock) availability for these surface-feeding, piscivorous seabirds.
- **Western Gulf of Alaska Steller sea lion non-pup** model predicted counts continued a slightly decreasing trend from previous years, remaining within 1 standard deviation of the long-term mean (1980–2021). These data have not been updated since 2021 due to lack of GOA surveys.

Eastern Gulf of Alaska 2023 Report Card

- **Multivariate ENSO Index** was negative, La Niña conditions for the third consecutive winter of 2022/2023 (Dec./Jan., 1980-2023). The North Pacific transitioned to El Niño conditions (positive ENSO index) in the summer 2023, which are predicted to persist through 2024.
- **Sea-surface temperatures (°C)** in the summer of 2023 (Jun.-Aug.), were approximately average (1985–2023) in the eastern GOA.
- **Total zooplankton density (# m^{-3})** in southeastern Alaska inside waters (May-Aug., 1988–2023) deccreased from 1 standard deviation above long-term mean, to average, including a decrease in calanoid copepods. Euphausiid densities remained above average. This suggests below-average foraging conditions for planktivorous fish, seabirds, and mammals.
- **Copepod community size** (ratio of large calanoid copepods to total calanoid copepods) increased to 1 standard deviation above average in 2023 (May-Aug., 1997–2023). The copepod community is sampled in Icy Strait (southeast Alaska Inside waters). This suggests above-average quality zooplankton prey in SEAK inside waters (but at lower biomass).
- **Motile epifauna biomass (1,000 t)** has decreased from 2021 to 2023 and is below the long term mean. Eelpouts, hermit crabs, brittle stars, and other echinoderms are dominant components of this guild. Brittle stars have decreased from 2021 to 2023 and are 1 standard deviation below their long term mean, while eelpouts, hermit crabs, and other echinoderms have increased from 2021 to 2023.
- **Estimated total mature herring biomass (age 3+) of Sitka herring** in spring 2023 remains 1 standard deviation above average (1980–2023) continuing a 5 year trend of the largest value in the time series (since 1980). The population is declining due to the reduced abundance of the large 2016 year class. The two populations with ocean influence (Sitka Sound and Craig) were elevated while populations in southeastern AK inner waters and Prince William Sound increased but remained low.
- **Fish apex predator biomass (1,000 t)** has increased 79% from 2021 to 2023 and is more than one standard deviation above their long-term mean. Apex predator biomass in the eastern GOA is primarily driven by arrowtooth flounder and Pacific halibut, both of which increased in biomass by more than 100% from 2021 to 2023. Pacific cod biomass continued to increase in 2023 from their low in 2017 and are above their long-term mean.
- **Growth rates of piscivorous rhinoceros auklet chicks (g d^{-1})** remain 1 standard deviation below the long-term mean in 2023 (Jun.-Jul., 1995–2023), but continue a multi-year increasing trend.
- **Eastern Gulf of Alaska Steller sea lion non-pups** model predicted counts continue a decreasing trend, but remain above 1 standard deviation of the long-term mean (1980–2021) through 2021. However, counts suggest that non-pup have been lower than predicted in 2019 and 2017. These data have not been updated since 2021 due to lack of GOA surveys..

Ecosystem Assessment

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Last updated: November 2023

This assessment reflects the recognition that the western and eastern GOA ecosystems (divided at 147°W) have substantial differences (Waite and Mueter, 2013; Mueter et al., 2016). 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 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 Status of the Gulf of Alaska 2023

The Gulf of Alaska shelf marine ecosystem had an average year of productivity in 2023, with some declining trends from the highly productive previous year. Some highlights for 2023 include an increase in Pacific cod although still very low population levels) and capelin populations (both had not shown signs of recovery since declines related to the 2014–2016 marine heatwave), and a transition from three consecutive years of La Niña to El Niño conditions. Despite the generally productive year, some concerns persist around a decline in the zooplankton prey base. Total zooplankton biomass in 2023 was variable, but overall declined to below average, as indicated by multiple zooplankton surveys, low biomass of age-0 pollock and cod (WGOA), and low energy density of juvenile pink and sockeye salmon (eastern GOA; predators of zooplankton). Given the current El Niño status and the associated warming surface waters predicted in winter/spring of 2024, the reduction in zooplankton availability and quality may persist into the coming year. The last El Niño event occurred in 2016, with warming effects augmented by the ongoing 2014–2016 marine heatwave. If we do not experience another separate marine heatwave event, the upcoming El Niño is predicted to be of a strength similar to that in 1997/1998 (Bond in this report, p.27). Vulnerable groundfish in 2024 (due to warm surface waters and reduced zooplankton quality) potentially include the larval and age-0 juveniles of Pacific cod, walleye pollock, and northern rock sole. Warm surface waters can be favorable for larval rockfish and sablefish. Adult zooplanktivorous groundfish may have reduced prey availability (walleye pollock, Pacific ocean perch, dusky and northern rockfish) but the deeper adult habitat is not predicted to warm unless El Niño-related warming persists long enough to be mixed to depth.

Gulf of Alaska Shelf 2023

Ocean temperatures were approximately average to cooler than average in the winter and spring (surface and depth) extending to above average in the summer, ranging from 5.8°C (WGOA Bottom Trawl Survey, O'Leary, in this report, p.40) to 10.5°C (Icy Strait, SEAK, Fergusson in this report, p.40). The cool early spring surface temperatures were favorable for walleye pollock, Pacific cod, northern rock sole egg and larval survival. The warm late spring/early summer surface temperatures may have been favorable for rockfish larval feeding and survival. Winter across- and along-shelf transport was reduced but variable, characterized by anomalous winter winds from the west that resulted in relaxed downwelling conditions. Variable eddy kinetic energy (strength of eddies on the shelf edge), and strong spring gap winds around Kodiak may have reduced the ability for groundfish larvae to be retained in favorable nearshore habitat, such as Shelikof Strait for juvenile pollock. Reduced cross-shelf transport is less conducive to the movement of larval arrowtooth flounder, Pacific halibut, and rex sole (slope spawners) to more favorable shelf habitat.

The spring chlorophyll-a concentration (an indicator of primary production) continued a multiyear below average trend, and peak bloom timing was considerably late (western GOA) to average (eastern GOA) across the regions (Gann in this report, p.72). While late peak spring blooms can be driven by colder springs, this event may also be explained by a deeper mixed layer in the winter/spring. Weaker stratification of the water column and a deeper mixed layer depth can reduce the opportunity for wind mixing to bring plankton and nutrients to the surface to promote spring blooms. Stratification strengthened in early May, one of the factors contributing to the spring bloom along the Seward Line (Danielson in this report, p.76).

Prey availability for zooplankton-eating adult groundfish (e.g., walleye pollock, Pacific ocean perch, dusky and northern rockfish), and larval/juvenile groundfish, was below average to average across the GOA shelf. Total zooplankton biomass progressed from below average in the spring to indications of greater abundance in the summer, with variable copepod biomass but relatively high euphausiid biomass across the GOA (Shelikof St., Kimmel in this report, p.81, Seward Line, Hopcroft in this report, p.89, Icy Strait, Fergusson in this report, p.91). Larval pollock biomass was low in 2023 (as surveyed in the spring and summer, Rogers in this report, p.102), another common prey item when abundant. Planktivorous seabird reproductive success, an indicator of zooplankton availability and nutritional quality, was approximately average in the western (Chowiet Island) and the central GOA (Middleton Island) (Drummond in this report, p.161, Whelan in this report, p.161).

The reduced total zooplankton biomass could be explained by lower production, potentially connected to the late and reduced spring phytoplankton bloom, or by increased top down grazing pressure. Predators of zooplankton increased in 2023, relative to 2022, driven by large returns of pink salmon (Whitehouse in this report, p.124, Vulstek in this report, p.134), relatively large and increasing populations of Pacific ocean perch (Hulson et al., 2023) and walleye pollock (Monnahan et al., 2023), and continued production of large year classes of juvenile sablefish in recent years (Goethel et al., 2023). Regardless of the mechanism, there appears to have been adequate, but not abundant, zooplankton available to support predators in 2023. Signs of a restricted prey base include a decline from above average to average zooplanktivorous seabird reproductive success, lower body condition (weight at length) of adult pollock, below average energy density of juvenile salmon, and juvenile pink salmon diet dominated by gelatinous prey (less nutritious alternative to zooplankton) (Icy Strait, SE Alaska, Fergusson in this report, p.91). Predictions for 2024 returns of pink salmon seem less favorable based on juvenile CPUE, length, and energy density in 2023, bolstering the indication of a reduced zooplankton prey base in 2023 (Yasumiishi in this report, p.124).

Prey availability for fish-eating groundfish (e.g., Pacific cod, sablefish, arrowtooth flounder, yelloweye rockfish) was approximately average with signs of reduced abundance in 2023. Capelin populations are rebounding for the first year since their decline during the 2014–2016 marine heatwave (McGowan in this report, p.110, Whelan in this report, p.161). Herring population biomass remains elevated, but is decreasing due to a declining 2016 strong year class (as assessed in EGOA but assumed GOA-wide trends; Hebert in this report, p.115, Pegau in this report, p.202). Age-0 pollock, a common prey in western GOA, had very low abundance (Rogers in this report, p.102). The reproductive success of piscivorous, diving seabirds (e.g., common murres and tufted puffins), decreased from 2022 to below average to average across the GOA (Drummond in this report, p.161 Whelan in this report, p.161), indicating less than sufficient/adequate prey to meet reproductive needs. In particular, black-legged kittiwakes failed to produce chicks on Chowiet Isl. (AK Peninsula), potentially due to lack of available age-0 pollock and Pacific sandlance in that area.

The predominant GOA groundfish species, by biomass, continue to be characterized by reduced populations of Pacific cod, Pacific halibut, and arrowtooth flounder, and increased sablefish and Pacific ocean perch populations. While the ecological implications of the Pacific ocean perch population expansion (biomass and spatially) are not well understood, the biomass has grown large enough for the signal of this longer-lived, zooplankton-eating species to influence trends in various GOA groundfish community metrics (e.g., groundfish community stability and average groundfish lifespan, Whitehouse in this report, p.181 and p.185).

GOA Shelf/Upper Slope 2023

The GOA shelf edge (200 – 300m) and upper slope demersal/benthic habitat is habitat for numerous managed groundfish species, including sablefish, Pacific ocean perch, rockfish (thornyhead rockfish, rougheye/blackspotted rockfish, shortraker rockfish, and the slope subgroup of the Other Rockfish complex), and the deepwater flatfish complex (e.g., Dover sole). A number of these species migrate onto the shelf to spawn, and others are capable of changing depths in response to environmental conditions (Yang et al., 2019), increasing their ability to mitigate unfavorable habitat and forage conditions.

This deeper habitat is often buffered from variable environmental conditions occurring in the upper water column (e.g., the predicted surface warming of El Niño in 2024). However, this habitat can be exposed to warmer temperatures mixed from shallower depths over time, such as during the 2014–2016 marine heatwave. Decreased dissolved oxygen, pH, and aragonite saturation can also occur from deep water intrusions from the central GOA gyre (Hauri et al., In Press). Bottom temperatures in 2023 along the shelf edge (250m) cooled to average after being consistently above average since 2016 (Temperature Synthesis, p.40). In fall 2022 and winter 2023, the Gulf of Alaska experienced weaker downwelling conditions on the shelf, favoring intrusion of deeper, saltier, and more acidic water from the central GOA gyre onto the upper slope and shelf (Bond in this report, p.26, Pages in this report, p.62). Modeled and observed time series along the Seward Line show statistically significant long-term decreasing trends of bottom water pH, aragonite saturation, and dissolved oxygen, an indication of steady degradation of the habitat. Observed bottom pH at GAK 9 (an outer shelf station of the Seward Line) was particularly low in spring of 2023, reaching values potentially detrimental to Tanner crab (pH = 7.56; Pages in this report, p.62). However, these environmental characteristics are not currently within the known range of detrimental effects of groundfish species in the shelf edge/slope region.

Structural epifauna (primarily sponges), which are measured poorly and indirectly from various surveys, continue to show signs of a multi-year decline in the WGOA (bottom trawl survey CPUE Laman in this report, p.60, non-target catch, Whithouse in this report, p.210). These slow growing structures are important habitat for rockfish, but any mechanistic link to rockfish population survival and productivity is currently unknown, and worthy of further investigations.

Looking Ahead to 2024 (El Niño)

Surface temperatures are predicted to warm in late winter/early spring of 2024, in alignment with the current El Niño (Bond in this report, 35). The most recent El Niño events occurred in 2015/2016, 2002/2003, and 1997/1998. The warming impacts of the 2016 event were compounded by the ongoing multi-year marine heatwave. The mass of warm water (termed "the Blob') that moved from the central north Pacific onto the Alaskan shelf to initiate the 2014–2016 marine heatwave has persisted offshore since then. To-date it does not show signs of moving back onto the shelf (as of Oct 2023). The trajectory of that warm mass would determine if Alaska experiences strong, but more typical, El Niño warming conditions (perhaps similar to 1997/1998) or a more persistent and intense separate marine heatwave/El Niño combination (similar to 2016). Past El Niño's have been associated with a stronger Aleutian Low, driving stronger southerly winds, and an increase in eddy strength (Crawford et al., 2002; Whitney and Robert, 2002) (potentially resulting in increased cross-shelf transport of slope-spawned larvae ATF, halibut, rex sole, rockfish and sablefish (Bailey and Susan J. Picquelle, 2002). These climate-ecosystem relationships can be tenuous and their potential impacts remain to be seen for 2024 (Litzow et al., 2020).

Warm winter/spring surface temperatures in the GOA drive early spring phytoplankton bloom (Gann in this report, p.72), early hatch times of cod eggs (up to 19 days earlier) and potentially larger age-0 cod (Laurel et al., 2023). There is potential for the surface temperatures to exceed the optimal temperatures for larvae survival and feeding of the early spring shelf spawners (Pacific cod, walleye pollock, northern rock sole), negatively impacting the 2024 year classes of these species. Conversely, warm surface waters in spring and summer can be favorable for rockfish larval survival. As it takes time for warm surface waters to mix to depth, the extent of warming that might occur in the deeper habitat of adult groundfish is dependent on the intensity and persistence of the surface warming, but would be a delayed effect of the winter El Niño warming event.

Most groundfish populations have one or more recent strong year classes that could help the population persist through a challenging year (e.g., potentially 2024 for some stocks). The warm period driven by 2014–2016 and 2019 marine heatwaves followed by a multi-year cooling during the 3 consecutive La Niña events (2020/2021–2022/2023) have jointly produced some strong year classes for numerous groundfish species across the spectrum of temperature affiliations. The warmer late spring/summers favored rockfish larvae (Sebastes spp., including Pacific ocean perch). Sablefish have had multiple strong year classes since 2014, although fewer in recent years. The cooler and productive winter/springs favored larval walleye pollock (2017, 2018, 2020) and Pacific cod (2020, 2022). The Pacific cod population is still at very low abundance, though, so would be most vulnerable to any population fluctuations. Some important forage species have also benefited from strong year classes, including herring (2016, 2020), capelin (2023) and Tanner crab (2019). In summary, these stocks will be entering a year of greater environmental uncertainty and variability (2024) from a year of average productivity (2023) (with some signs of reduced lower level productivity. Some of the better surveyed stocks have a few known strong year classes to buffer potential population fluctuations. While Pacific cod appears to have a good recruitment year class entering the fishery in 2023, their low population would be most vulnerable to potential declines.

Contents

† indicates new contribution

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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, a one-time event, or a deeper discussion on a topic of interest.

Gulf of Alaska Pacific cod (2017–2023)

The Gulf of Alaska stock of Pacific cod *Gadus macrocephalus Tilesius* experienced a 70% decline in population abundance in 2017, and has remained at reduced levels through 2023 (although the population is showing signs of growth in 2023). The commercial fishery was dramatically reduced from 2017–2019, closed in 2020, and has been opened to a very small harvest since 2021 (Barbeaux et al., 2020*b*; Hulson et al., 2022). The initial decline in cod abundance was attributed to the marine heatwave (MHW) from 2014–2016. The ocean temperatures at depth on the shelf exceeded the optimal thermal window for Pacific cod egg survival (3–6°C; Laurel and Rogers 2020). During the same period, adult cod increased their metabolic rate when nutritional quality and availability were reduced (Barbeaux et al., 2020*b*; Arimitsu et al., 2021). Since the 2014–2016 heatwave, the GOA remained relatively warm and experienced another MHW event in 2019. The GOA Pacific cod stock has not returned to pre-2014 levels, raising questions as to its productive capacity with continued and future warming.

Fluctuations in early year class strength of GOA Pacific cod may offer clues to future recruitment potential. Coastal monitoring of age-0 and age-1 year classes in Kodiak since 2006 (and expanded across the central and western GOA since 2018) indicated very low abundance during 2013–2016 and 2019 (MHW years). Age-0 year classes from 2017 and 2018 were strong, but did not reappear as age-1's in the following year's survey. Strong year classes reappeared in 2020 and 2022, and were observed as age-1's the following year in the beach seine survey. The 2020 year class appears to be recruiting to the fishery this year (Hulson et al., 2023) and the success of the very strong 2022 year class remains to be seen.

Remarkable year class variation in the age-0 cohort has been coupled with equally remarkable changes in size-structure. Since 2006, there has been an $\sim$ 200% increase in average individual mass of age-0 juveniles observed in August (Laurel et al., 2023). While these changes adhere to the 'temperature size rule' for fish, the mechanisms contributing to these size shifts are not entirely growth-related. New daily increment analyses on larval and juvenile otoliths indicate a consistent shift in hatch phenology, with hatch dates occurring an average of 19 days earlier for both larvae and juveniles since recent MHWs began. At the larval stage, observed increases in body size-at-capture could be wholly explained by their earlier hatch dates, and hence older ages. However, the increased body size-at-capture for juveniles could only partially be explained by their older age and modestly faster growth rates (Almeida et al., In Press). Rather, size-selection was enhanced during MHWs, contributing to the observed increases in body size. Overall, warmer temperatures account for some, but not all, of the observed changes in phenology and growth. Factors such as parental effects, epigenetics, and selection have also likely contributed. Therefore, these new otolith analyses challenge assumptions about how warming influences growth during early life history, which can inform future forecasting efforts.

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Ecosystem Status Indicators

Physical Environment

Physical Environment Summary

Climate: The sea level pressure (SLP) over the mid-latitude North Pacific was generally greater than normal from autumn 2022 through summer 2023 (Bond in this Report, p.28). The magnitude and position of the high pressure anomaly center varied seasonally but in general, the SLP anomaly pattern supported westerly wind anomalies for Alaskan waters. The positive SLP anomalies over the North Pacific were accompanied by warmer than normal sea surface temperatures (SSTs) between 30 and 50°N across the western and central portion of the basin. This warmth extended eastward to near the coast of the Pacific Northwest, and moderated in its intensity in the western portion of the basin, during the summer of 2023. The relatively high SLP in an overall sense, i.e., weak Aleutian low, is consistent with co-occurring conditions in the tropical Pacific, which featured a long-lasting La Niña event ending in the late winter of 2023. The PDO was negative, in large part due to persistent positive SST anomalies in the western and central North Pacific (Bond in this Report, p.26). The climate models used for seasonal weather predictions indicate that El Niño is virtually certain to be present from late 2023 into 2024. In an ensemble sense, the models are also predicting that the first three months of 2024 will include near normal SSTs in the Bering Sea and Aleutian Island regions, and warmer than normal temperatures along the west coast of North America from northern California to the southeast GOA (Bond in this Report, p.35).

Ocean Temperature: Long-term surface temperatures (1900 – 2023) show a persistent warming across the GOA shelf, driven largely by increasing temperatures in the summer months (May - Oct.) (Thoman in this Report, p.33). Ocean temperatures were cooler than or at survey-specific averages at surface and depth in 2023 (Temperature Synthesis in this Report, p.40), aligning with conditions associated with a third La Niñ winter (Bond in this Report, p.27). Brief periods of summer warming occured in the eastern GOA in late summer and fall. There were very few days of marine heatwave conditions in 2023. Notably, the longline survey temperatures at ∼250m along the shelf edge cooled to average after a warmer than average trend since 2018 (Siwicke: Temperature Synthesis in this Report, p.44). These cool conditions are predicted to transition to warmer sea surface temperatures across the GOA shelf (National Multi-model Ensemble Model, Bond, p.35, and approximately 0.5textsuperscriptoC at GAK1 near Seward in the northern GOA (Sitka air temperature prediction, Hennon p.37), in alignment with a trantion to El Niño conditions.

Ocean Transport: The 2022/2023 GOA winter experienced relaxed downwelling on the shelf in the winter (anomalous winds from the west and approximately average northword surface drift from the Papa Trajectory Index) (Stockhausen in this Report, p.53). Typical counter-clockwise circulation resumed in the late spring/summer as the anomalous westerly winds relaxed. Eddy kinetic energy along the shelf edge varied from above (Haida, Seward) to below (Sitka, Kodiak) average in 2023 indicating variable transport of nutrients and ichthyoplankton across the shelf (Cheng in this Report, p.50).

Climate: North Pacific

Climate: North Pacific Overview

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Last updated: August 2023

Regional Highlights of Gulf of Alaska and Neighboring Regions:

Aleutian Islands. The near-surface waters of the Aleutian Islands were generally warmer than average (baseline 1991 – 2020) from late 2022 into spring 2023 before cooling to near average to slightly below temperatures during summer 2023. It was relatively stormy during the winter of 2022 – 2023 and summer of 2023. The cooler conditions during 2023 were accompanied by greater upper mixed layer depths than during 2022. Much of the past year included wind anomalies of the sense associated with suppressed northward flow through Unimak Pass.

Gulf of Alaska. As discussed in the Ocean Temperature: Gulf of Alaska Synthesis section (p.40), the GOA underwent changes of the opposite sense from temperatures near to slightly above average (baseline 1991 – 2020) in autumn 2022 to 0.5 – 1.0°C below average in summer 2023. This cooling can be attributed to relatively high SLP south of the GOA resulting in westerly wind anomalies and equatorward Ekman transports during the winter of 2022 – 2023 through spring 2023. The summer of 2023 included somewhat stormy conditions in the western GOA. The freshwater discharges from mainstem rivers, such as the Alsek and Copper River, into the GOA were elevated during the fall of 2022 and mostly near average during spring and summer 2023. The coastal waters in the vicinity of the Alaska Peninsula were cooler than average (baseline 1991 – 2020), based on averages for the period of 1991 – 2020, from autumn 2022 through summer 2023. These cool temperatures during the winter of 2022 – 2023 were associated to the relative lack of mild maritime air masses due to a westward displacement of the stormtrack; these conditions were maintained by wind anomalies from the northwest during early spring 2023.

British Columbia Coast. This region experienced upper ocean temperatures that transitioned from about 0.5°C cooler than average (baseline 1991 – 2020) in late 2022/early 2023 to considerably warmer than average during summer 2023. At the time of this writing in late summer, the SST anomalies here were on the order of 1.5°C, which reaches the threshold for a marine heat wave (MHW) in this region. Tentatively, this warming appears to have been due to a combination of the advection of warmer water from the west and quiet weather leading to reduced wind mixing and perhaps also reduced cloud cover.

Climate Indices

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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, PDO index (the leading mode of North Pacific SST variability), North Pacific Index (NPI), North Pacific Gyre Oscillation (NPGO) and Arctic Oscillation (AO). The time series of these indices, with the application of three-month running means, from 2013 into spring/summer 2023 are plotted in Figure 4.

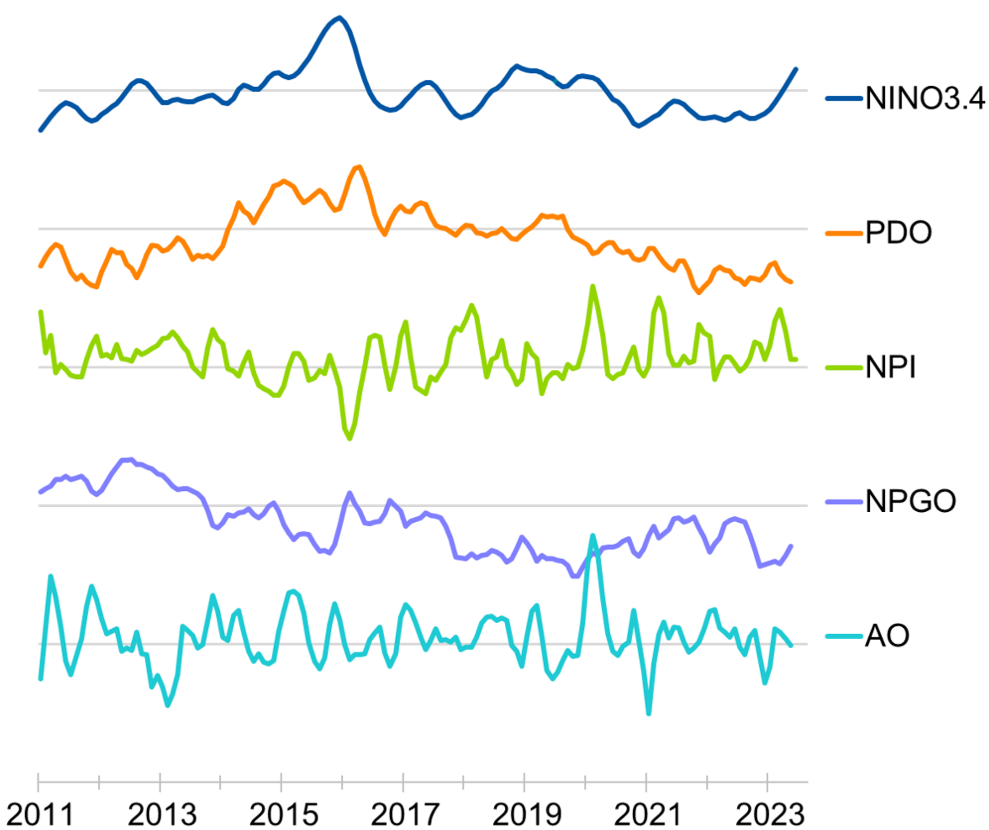

Figure 4: Time series of the NINO3.4 (blue), PDO (orange), NPI (green), NPGO (purple), and AO (turquoise) indices for 2013 – 2023 (through Aug. 2023). Each time series represents monthly values that are normalized using a climatology based on the years of 1991–2020, and then smoothed with the application of three-month running means. The distance between the horizontal grid lines represents 5 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 into early 2023, with values commensurate with La Niña of moderate intensity during the entirety of 2022. A return to more normal conditions in the tropical Pacific began in late 2022. Nevertheless, the winter of 2022 – 2023 represented the third La Niña winter in a row; that has occurred just twice before in the last 50 years.

The PDO was negative during 2022 as part of extended period of negative values beginning in the winter of 2019 – 2020 following its strongly positive state during the major Northeast Pacific marine heat wave of (MHW) of 2014 – 2016. The negative sense to the PDO over the previous 3 years is consistent with the concurrent state of ENSO; La Niña tends to be accompanied by atmospheric circulation patterns promoting relatively warm waters in the western and central North Pacific and cool temperatures along the west coast of North America. The former feature of the PDO's characteristic SST pattern was prominent in 2022.

The state of the Aleutian low is often summarized in terms of the NPI, with negative (positive) values signifying relatively low (high) SLP. The NPI was positive during most of 2022 with the strongest anomalies occurring in the boreal fall. The tendency for a mostly positive state to the NPI since 2020 can be ascribed, in part, to the atmospheric teleconnections associated with the extended La Niña. The systematically positive state of the NPI, i.e., weak Aleutian low, can also be linked to the overall decline in the PDO during the interval.

The NPGO has also been relatively persistent, with a long-term decline beginning in late 2012, resulting in consistently negative values since 2017. The negative phase of the NPGO is generally accompanied by warmer than normal upper ocean temperatures south of Alaska between 35 °N and 50 °N and is associated with high SLP over the GOA and low SLP in the vicinity and northeast of the Hawaiian Islands. There was some moderation in the NPGO during the late winter and spring of 2022, with the resumption of more negative values again late in the year.

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 transitioned from a positive state early in 2022 to a negative state by the end of the year. A negative state to the AO often is accompanied by enhanced outbreaks of arctic air to the middle latitudes of the Northern Hemisphere. That phenomenon was not prominent late in 2022, but that period did include relatively warm weather north of the Arctic circle, especially north of Alaska and the Canadian Archipelago.

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

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Last updated: August 2023

Description of indices: The state of the North Pacific climate from autumn 2022 through summer 2023 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 1991 – 2020. The SLP data are from the NCEP/NCAR Reanalysis project; the SST data are from NOAA's Extended SST V5 (ERSST) analysis. Both data sets are made available by NOAA's Physical

Sciences Laboratory[5].

Status and trends:
Autumn (Sep-Nov, 2022): The SST anomaly pattern featured a broad band of warmer than average (baseline 1991 – 2020) SST that extended across the entire North Pacific (Figure 5a), with anomalies exceeding 2.5°C near 40°N and the dateline. Cooler water relative to seasonal norms was present in the Sea of Okhotsk and the eastern Bering Sea shelf. The central and eastern tropical Pacific was cooler than normal in association with moderate La Niña conditions. The autumn SLP pattern featured a band of strongly positive anomalies extending across the entire North Pacific north of about 35°N, with a center of about +4 millibars (mb) located south of the Alaska Peninsula (Figure 6a). Negative SLP anomalies were present from eastern Siberia into the Chukchi Sea. This SLP distribution resulted in wind anomalies of $\sim$ 2 m s^{-1} from the west across the Bering Sea, and easterly wind anomalies of 2 – 3 m s^{-1} between 35°N and 45°N in the central and eastern North Pacific.

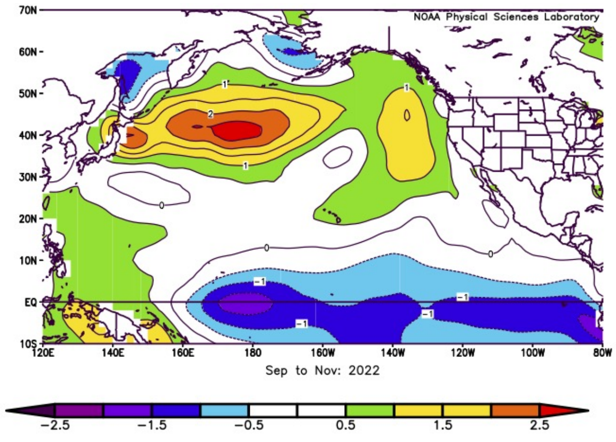
Winter (Dec-Feb, 2022 – 2023): The positive SST anomalies in the central North Pacific persisted through the winter (Figure 5b), with moderation in the warm temperatures in the western North Pacific. During this season, Alaskan waters were mostly within 0.5°C of average (baseline 1991 – 2020). La Niña weakened, with only a small region of water 1°C cooler than average near the dateline in the equatorial Pacific. Positive winter SLP anomalies were over the central North Pacific, with an anomaly center near 40°N, 150°W (Figure 6b). Lower than average (baseline 1991–2020) SLP occurred over eastern Siberia into the western Bering Sea. The associated winds included westerly anomalies of 2 – 3.5 m s^{-1} from the southern Sea of Okhotsk through the eastern Aleutian Islands, and a clockwise sense of the anomalies in the GOA. These winds were accompanied by anomalous upwelling in the coastal GOA, and downwelling in the central, deep water portion of the GOA. Anomalous winds from the north were present off the coast of western North America.

Spring (Mar-May, 2023): A band of warm water (baseline 1991 – 2020) centered along 40°N across all but the far eastern portion of the North Pacific was present during the spring (Figure 5c). Regions of cooler water reappeared in the Sea of Okhotsk and on the eastern Bering Sea shelf. The tropical Pacific had mostly near-average SSTs (baseline 1991 – 2020) with the exception of the immediate vicinity of the coast of South America, where positive anomalies began developing. Strongly positive SLP anomalies developed over the western and central North Pacific in the spring (Figure 6c), with magnitudes exceeding 7 mb south of the Aleutian Islands. This SLP distribution resulted in westerly wind anomalies of roughly 2 m s^{-1} across most of the Bering Sea, northwesterly wind anomalies of 2 – 3 m s^{-1} in the western and central GOA, and easterly wind anomalies of 3 – 4 m s^{-1} in the central portion of the North Pacific between 35°N and 45°N. Near average winds occurred along the west coast of North America.

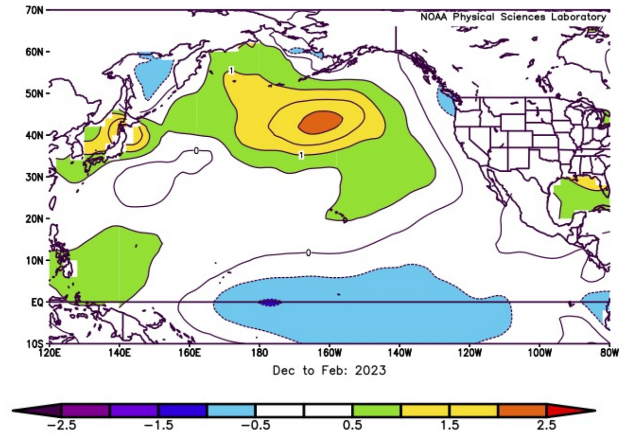
Summer (Jun-Aug, 2023): The summer brought marked moderation of the positive SST anomalies (baseline 1991 – 2020) in the western North Pacific between 30°N and 50°N but also an eastward extension of warm anomalies to the Pacific Northwest coast. This season also included a continuation of cool conditions in the eastern Bering Sea, the development of negative SST anomalies in the GOA, and cooling southwest of Baja California into the subtropical eastern North Pacific (Figure 5d). The tropical Pacific featured strong warming east of 140°W, with the SSTs meeting the threshold for El Niño in June 2023, according to NOAA's Climate Prediction Center (CPC). The summer reflected a transition from a prominent high SLP anomaly during the previous season to a dipole over the western North Pacific with lower than average (baseline 1991 – 2020) SLP extending from the Sea of Okhotsk

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

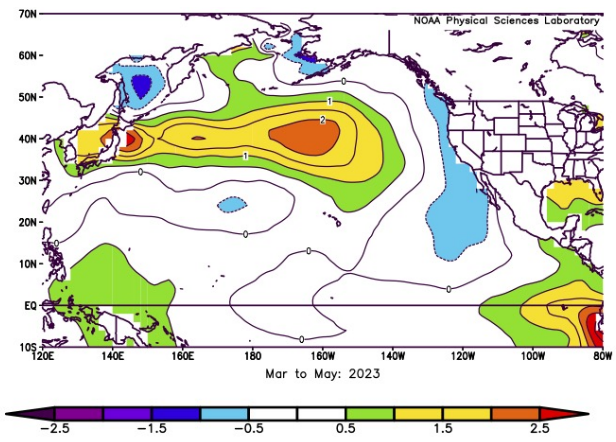
to the west coast of mainland Alaska, and higher than average SLP south of 40°N. The region between these two SLP anomaly centers experienced southwesterly wind anomalies of 2 – 3.5 m s^{-1}. The positive SLP anomalies over the eastern GOA extending southward were accompanied by lower than average precipitation for the coastal region from SE Alaska to the Pacific Northwest.



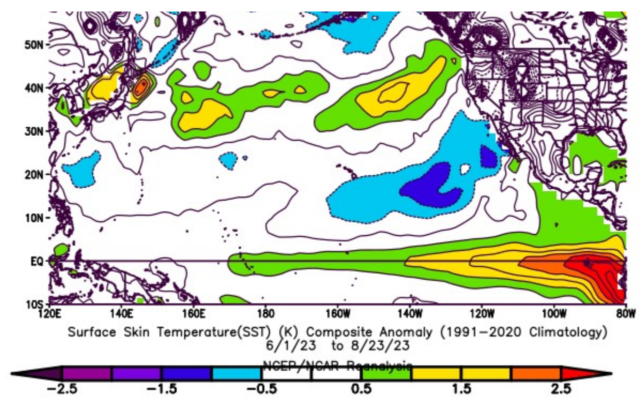
(a) Autumn



(b) Winter



(c) Spring



(d) Summer

Figure 5: SST anomalies for autumn (September–November 2022), winter (December 2022–February 2023), spring (March–May 2023), and summer (June–August 2023).

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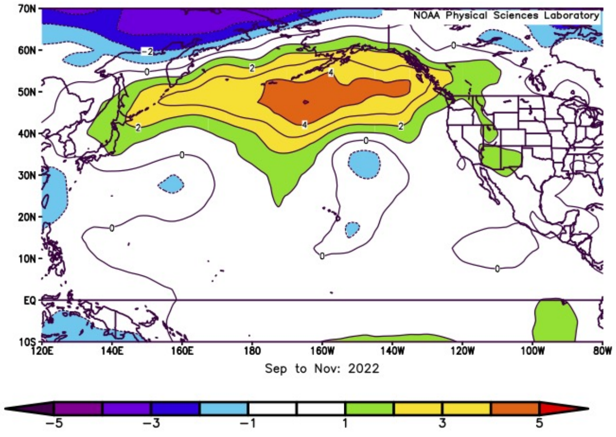
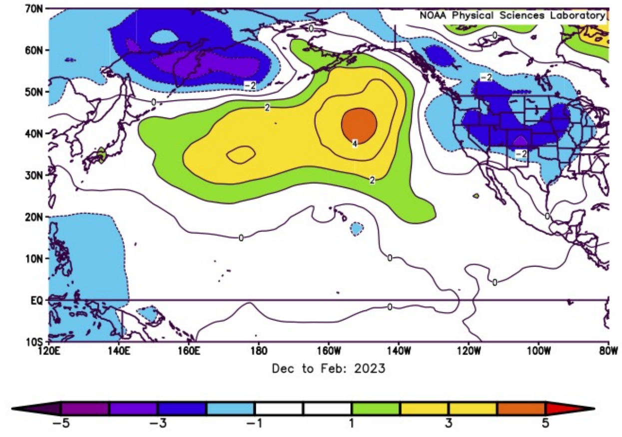
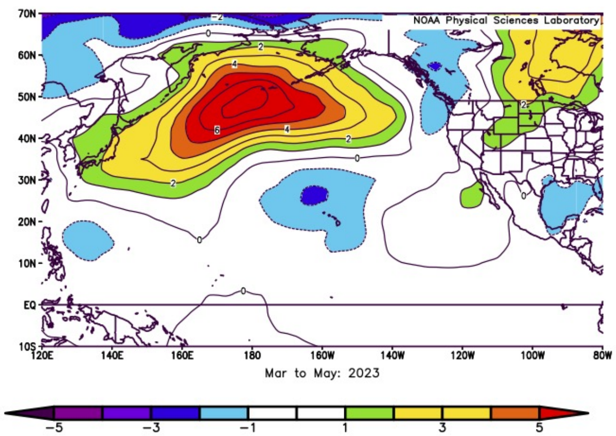


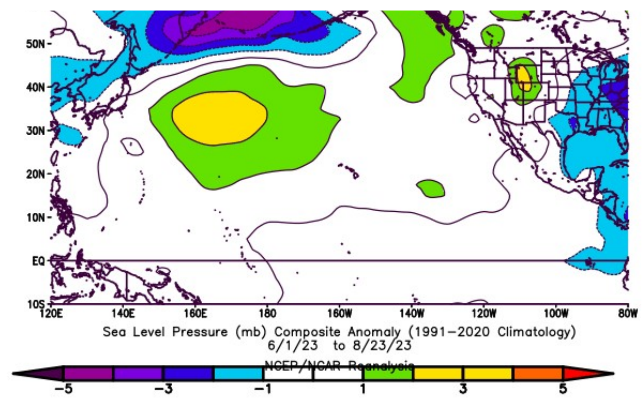
(a) Autumn



(b) Winter



(c) Spring



(d) Summer

Figure 6: Sea level pressure anomalies for autumn (September–November 2023), winter (December 2022–February 2023), spring (March–May 2023), and summer (June–August 2023).

Long-term Sea Surface Temperature in the Gulf of Alaska (1900-present)

Contributed by Rick Thoman[1] and Brian Brettschneider[2]
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[2]NOAA National Weather Service Alaska Region Headquarters
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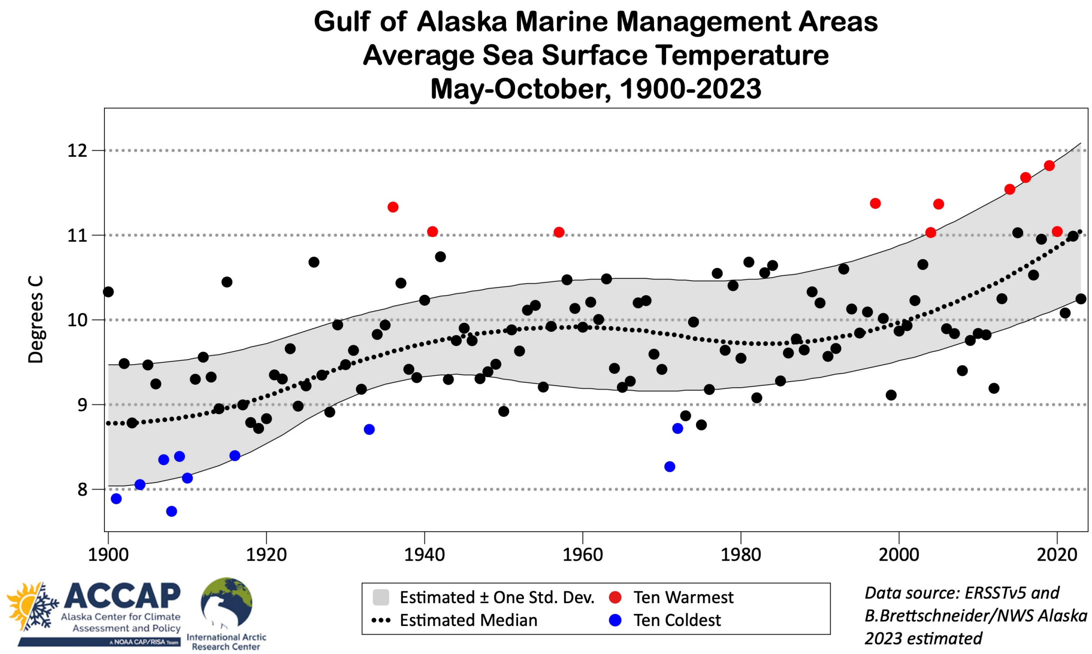
Last updated: August 2023

Description of indicator: Sea surface temperatures in the Gulf of Alaska can be calculated using NOAA's Extended Reconstructed SST V5 data[6]. ERSST is a global monthly sea surface temperature dataset produced at 2° x 2° resolution starting in 1854. Statistical processes are used to infill data sparse/missing areas and standardize the many ways that ocean surface temperatures have been collected and reported over the decades. However, known problems remain, especially pre-1900 and in the WW2 era and in general in Arctic and Southern Oceans. Constrained B-Spline regression used here is a form of nonparametric quantile regression using quadratic splines. This approach allows for conditional estimates of any quantile of interest. Initial analyses examined eastern and western GOA separately (divided 147°W) but the regions were combined due to reduced subregional sample sizes and similar trends across the western and eastern shelf.

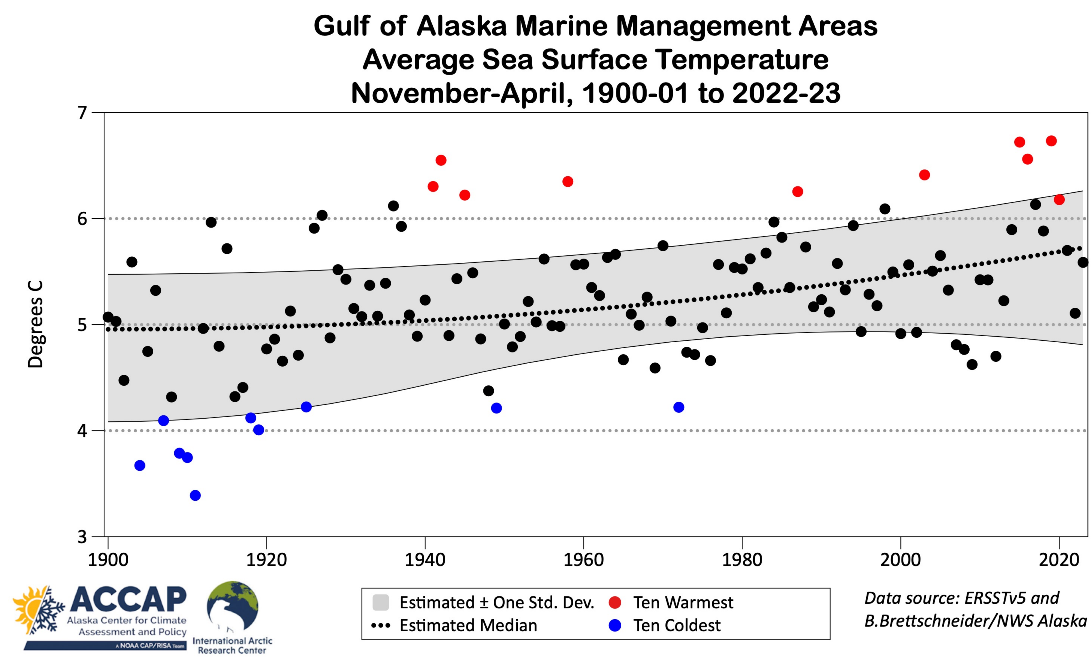
Status and trends: Summer (May - Oct.) sea surface temperatures (Figure 7) over the GOA shelf (10 m - 200 m) were cooler than most years in the past decade, though still above the pre-2000 median. It should be noted the May-Oct 2023 mean SST was estimated by using the observed May-August temps and then assuming Sept. and Oct. sea surface temperatures will be at the 1991–2020 mean. If Sept. and Oct. sea surface temperatures differ significantly from that 30-year mean, this result would change.This reduction in warm season temperatures may be lagged response to the multi-year La Niña event that ended in Spring 2023. The overall trend in summer temperatures show a warming during the first decades of the 20th century followed by an extended period of little long-term trend, with substantial warming resuming in the late 1990s. In contrast, Winter (Nov.- April) temperatures show much less warming over the past 123 years.

Factors influencing observed trends & Implications: The GOA shelf surface waters have been warming since 1900. Summer temperatures are primarily driving this warming trend. This analysis provides context for the short-term sea surface temperature time series presented elsewhere in this report (Temperature Synthesis, p. 40). The seasonal difference in warming trends are not determined but could be due to changes in stratification, precipitation and freshwater runoff, cloud cover, circulation or other oceanographic and atmospheric drivers. 'Above' or 'below' average surface temperatures, as reported in shorter-term time series in this report, may have different meaning if considered relative to the longer-term time series presented here. The thermal responses of species in the GOA marine ecosystem must be considered in terms of these longer-term shifts in temperature, to understand better their response to changing temperatures. Research on species-specific thermal ranges can also help interpret potential implications of continued warming of this marine system.

[6]https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html



(a) Summer (May - Oct.)



(b) Winter (Nov. - April)

Figure 7: Sea surface temperatures for the Gulf of Alaska from 1900–2023 for (a) summer (May-Oct.) and (b) winter (Nov.-April). Presented here are the quantiles representing $\pm$ 1 standard deviation of a Gaussian distribution and for completeness the median calculated using constrained B-Spline regression. The present year (2023) are preliminary data.

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

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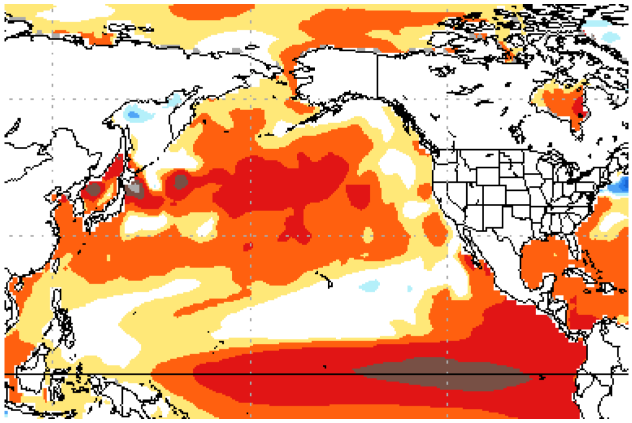
Last updated: August 2023

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 NCEP website[7].

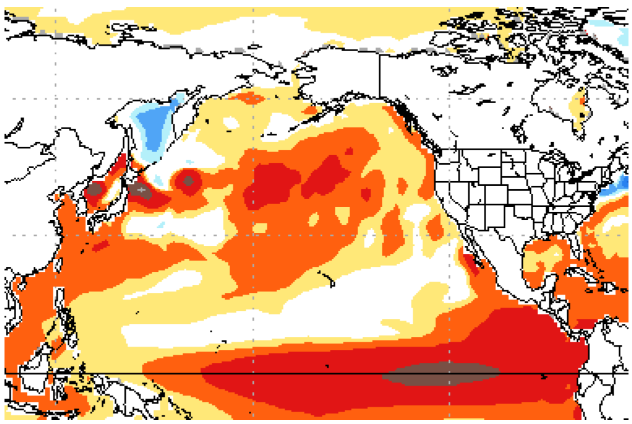
Status and trends: These NMME forecasts of three-month average SST anomalies indicate a continuation of El Niño in the tropical Pacific and a large region of relatively warm water in the central and western North Pacific between 30 and 50°N through the end of the calendar year (Nov 2023-Jan 2024; Figure 8a). The models also are indicating an atmospheric circulation pattern that would bring reduced storminess to the GOA (not shown). The ensemble of model predictions for January through March 2024 (Figure 8b) shows some moderation in tropical Pacific temperatures but still enough warmth to constitute El Niño. As is typical with these events; the projections show warming in the coastal zone of the eastern GOA. Moderation is indicated in the warm anomalies elsewhere in the coastal regions of Alaska. The projections for March through May of 2024 (Figure 8c) indicate continued decreases in tropical Pacific SST anomalies. On the other hand, substantial warming is forecast for the GOA and northern Bering Sea. Individual model predictions yield rather consistent outcomes for the GOA.

In a review of the projections from a year ago, the consensus of the model forecasts from September 2022 for the following fall and winter indicated a continuation of positive SST anomalies across the North Pacific south of 50°N and near to weakly cooler than normal temperatures on the southeast Bering Sea shelf. They also indicated negative anomalies of 0.5 – 1°C for the northern GOA. The extended range projections for spring 2023 showed essentially maintenance of the anomaly distributions established during the previous winter. The performance of the climate models as a group demonstrated mostly positive skill. For the first period considered of October through December 2022, they correctly forecast warmth in the central North Pacific and weakly negative anomalies in the Bering Sea. But the GOA was warmer than predicted. The overall SST anomaly pattern was forecast to remain similar for the following winter (Dec-Feb) with additional cooling for the southeast Bering Sea shelf and GOA. As with the previous forecast, the models captured the overall pattern for the North Pacific, but overpredicted the cool temperatures in the GOA. The consensus of the model forecasts for February-April 2022 included slight warming for the southeast Bering Sea shelf and modest cooling for the eastern GOA. The Bering shelf actually cooled (in association with a delay in ice retreat); the projection for the GOA was fairly accurate. In summary, the model predictions were quite good for the mid-latitude North Pacific, but were less skillful in terms of the details in season-to-season changes for Alaskan waters.

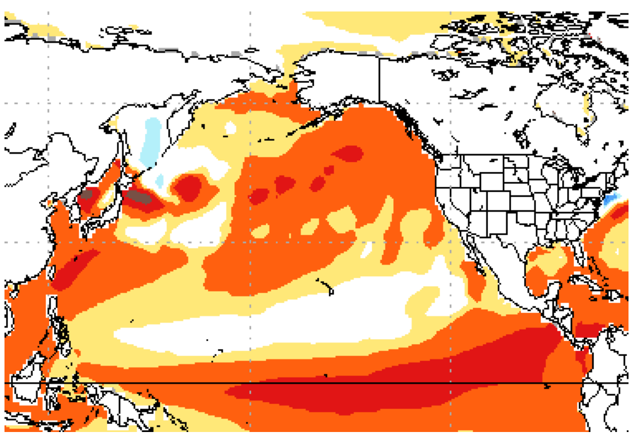
[7] http://www.cpc.ncep.noaa.gov/products/NMME/



(a) Months Nov–Dec–Jan



(b) Months Jan–Feb–Mar



(c) Months Mar–Apr–May

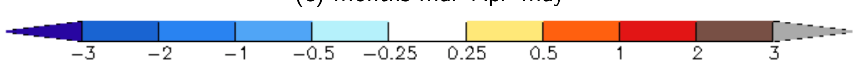


Figure 8: Predicted SST anomalies from the NMME model for Nov–Dec–Jan (1-month lead), Jan–Feb–Mar (3-month lead), and Mar–Apr–May (5-month lead) for the 2023–2024 season.

Predicted Ocean Temperatures in Northern Gulf of Alaska

Contributed by Tyler Hennon and Seth Danielson, College of Fisheries and Ocean Science, University of Alaska Fairbanks
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Last updated: October 2023

Description of indicator: Air temperatures in Sitka, AK are dominated by the marine climate. Danielson et al. (2022) found Sitka air temperatures had a weak but significant predictive power for integral coastal water column temperatures in the following year at the nearshore station (GAK1) of the Seward Line Transect, in northern GOA ($r^2 = 0.37$, $p < 0.05$). This predictive power can be explained by Sitka's 'upstream' location of GAK1 along the Alaska Coastal Current. Records of Sitka air temperatures exist since 1850 and GAK1 has recorded ocean temperatures since 1970. The temperature anomalies for both GAK1 and Sitka air temp are seasonally adjusted, and relative to the long-term average (1970-present for GAK1).

Status and Trends: The 2024 integrated water column temperatures for the nearshore GAK1 station of the Seward Line transect are likely to be warmer than average. The average Sitka air temperature through August 2023 was 1 to 1.5°C warmer than average (Figure 9). Based on these temperatures, GAK1 integrated ocean temperatures ($\pm$ 1SD) are predicted to range from 6.4 to 7.4°C (centered on 6.9°C) (Figure 10). The GAK1 long-term full water column depth averaged temperature is 6.24°C for the period of record, and there is a range of about -0.4 to 1.7 between $\pm$ 2 standard deviations ($\sim$ 95% CI) of our anomaly trend line. If the anomalies, so far in 2023, persist (i.e., Sitka air temperatures in Sep. to Dec. remain $\sim$1.5°C above seasonal average), we could expect whole water column GAK1 temperatures in 2024 to be $\sim$ 0.5°C above average (compared to the seasonal average).

Factors influencing observed trends: The north Pacific transitioned from La Niña to El Niño conditions in the summer of 2023. Warmer surface waters tend to move into the GOA by the Alaska Current and Coastal Current, passing Sitka to reach GAK1 and the Seward area in northern GOA. Ocean surface warming associated with an El Niño is predicted in winter/spring of 2024 (Bond in this report, p.35). It is likely that the warm surface temperatures will increased the integrated water column average temperatures, in line with the predictions based on Sitka air temperatures.

Implications: Warm surface waters in the GOA are generally associated with earlier peak spring phytoplankton blooms, earlier Pacific cod hatch timing (Laurel et al., 2023), and a change in the zooplankton community. The duration and intensity of warming can determing how the effects of warming permeates through the marine ecosystem.

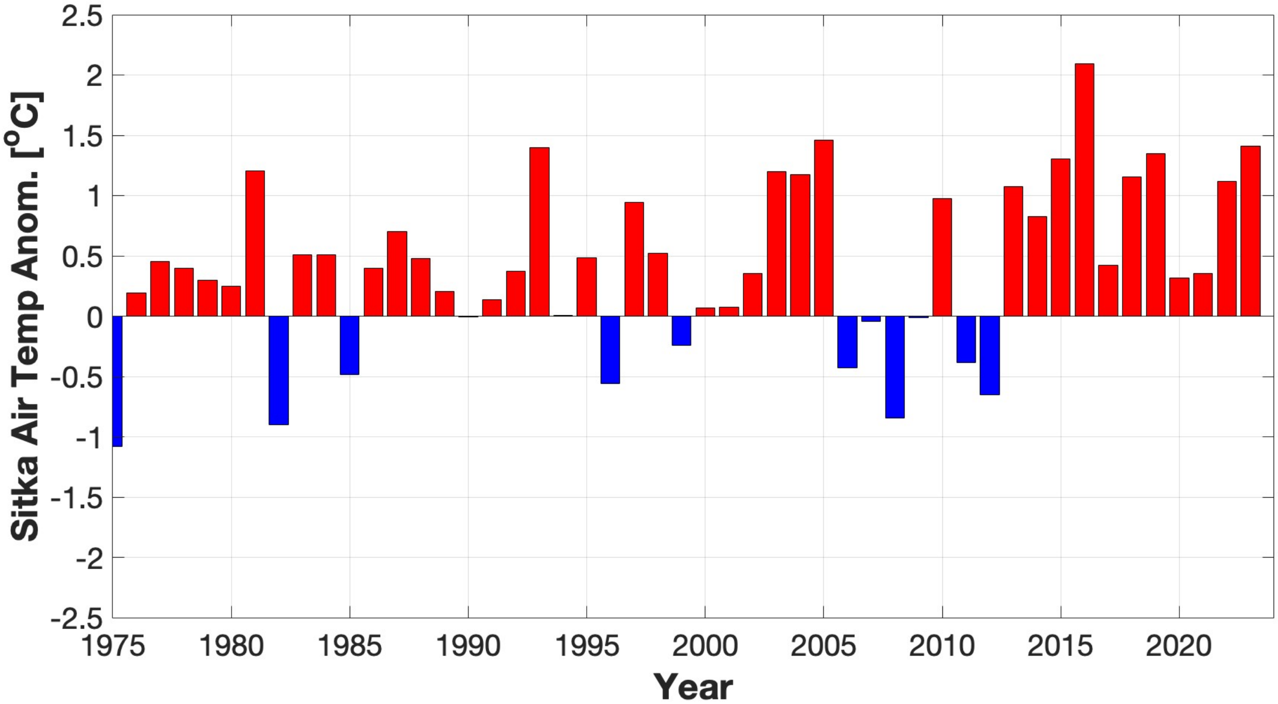

Figure 9: Annual averages of monthly temperature anomalies (seasonal climatology removed) Sitka, Alaska air temperature (entire record is 1828–2023; figure shows 1975 to present). Records are shown relative to a 50-year baseline computed over 1970–2023, updated from Danielson et al. (2022).

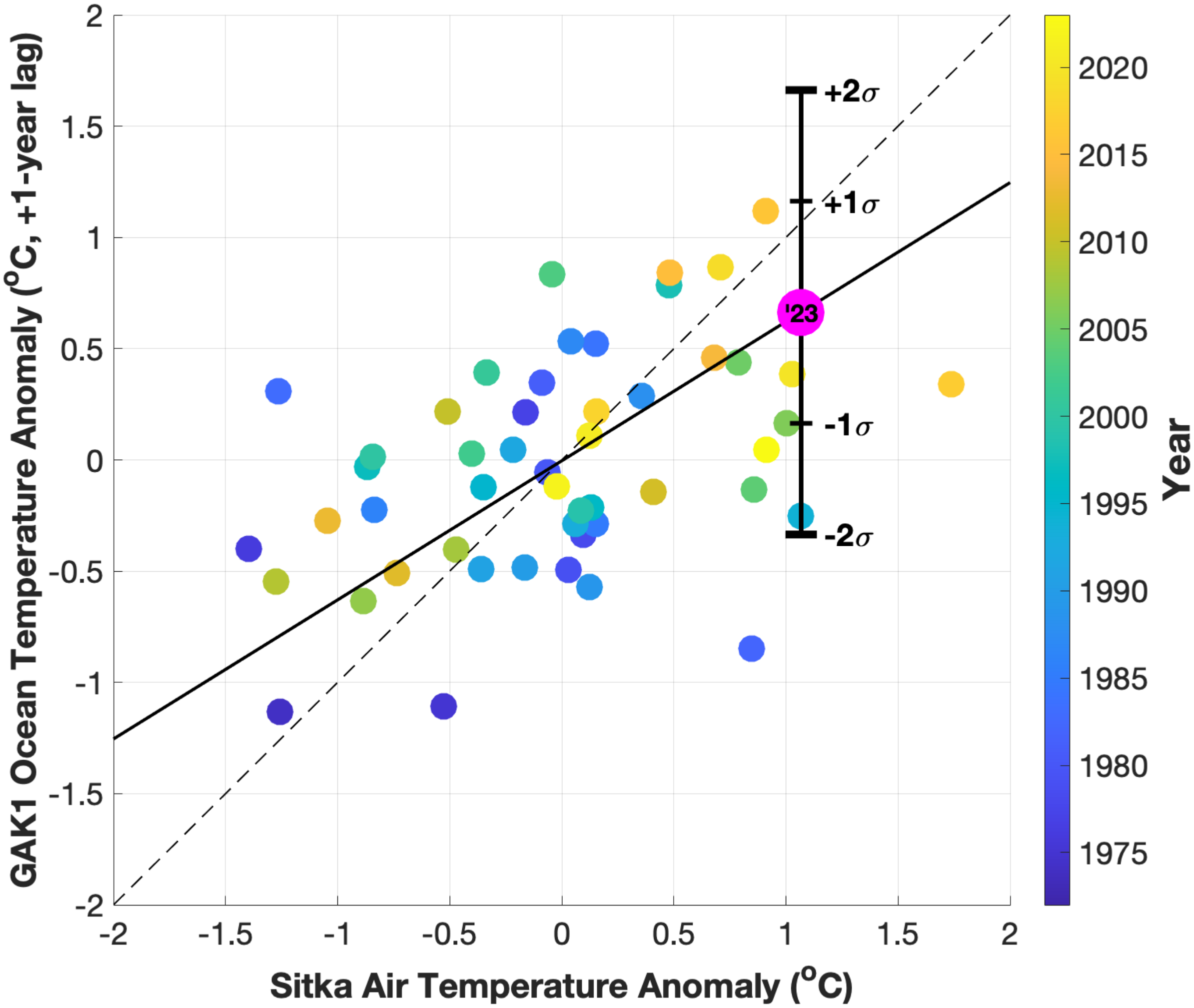

Figure 10: Relationship between the detrended annual Sitka air temperature anomaly (x axis) and the following-year whole water column ocean average temperature anomaly measured at station GAK1 (y axis), with a +1 year lag compared to Sitka. Thin black line shows a 1:1 slope and the thick black line is the least squares best fit line between the two records. Both anomalies are referenced to the average temperature from the early 1970s to present (1971 for GAK1, 1973 for Sitka air). The blue to yellow dots show each yearly comparison between Sitka air anomaly and the next year's GAK1 anomaly. The pink dot shows the 2023 air temperature anomaly (through August, 2023). The error bars show one and two standard deviations of variability from the trend line (which is the solid black line, the dashed line is 1:1).

Ocean Temperature: Gulf of Alaska Synthesis

Satellite Data: Emily Lemagie, NOAA's Pacific Marine Environmental Laboratory; Contact: emily.lemagie@noaa.gov and
Matt Callahan, Alaska Fisheries Information Network; Contact: matt.callahan@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 and Wesley Strasburger, Auke Bay Laboratories, Alaska Fisheries Science Center, NOAA Fisheries; Contact: emily.fergusson@noaa.gov
Bottom Trawl Survey: Cecilia O'Leary, Groundfish Assessment Program, Alaska Fisheries Science Center, NOAA Fisheries; Contact: cecilia.oleary@noaa.gov
AFSC Longline Survey: Kevin Siwicke, Marine Ecology and Stock Assessment Program, Alaska Fisheries Science Center, NOAA Fisheries; Contact: kevin.sewicki@noaa.gov
AFSC EcoFOCI Spring Larval Survey: Kelia Axler and Lauren Rogers, EcoFOCI, Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, NOAA Fisheries
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Last updated: October 2023

Description of indicator: Ocean temperature can vary sub-regionally, due to differences in circulation, freshwater runoff, wind-driven mixing, and other oceanographic drivers (Bograd et al., 2005). 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 90th 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 90th 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 2023 SST in context of long-term trends (1900-present) using NOAA's Extended Reconstructed SST V5 data[8]. We then present satellite data and reanalysis monthly data for 2023 ocean temperatures at surface and at depth, averaged across the western GOA and eastern GOA shelf. This

[8]https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html

is followed by a description of trends observed across multiple GOA sub-regional surveys conducted in the spring and summer of 2023. We then show observations related to marine heatwave conditions. Detailed methods are listed at the end of the contribution.

Status and trends: Ocean surface temperatures, averaged broadly across the eastern and western GOA shelf, were average to cooler than average during winter and spring (cooling from a warm 2022 fall), and warm in the eastern GOA during late summer, compared to the 1985–2014 baseline (Figure 11). All observed temperatures were at or cooler than the survey-specific average at the surface and at depth. Notably, the temperatures at depth along the shelf edge cooled to the long-term mean in the western and eastern GOA after a multi-year warm trend (longline survey; baseline 2005–2023). The satellite data show warmer than average summer surface temperatures in the eastern GOA that did not appear in survey data, presumably due to the survey timing and spatial/temporal averaging. Fall 2023 (as of Oct. 31) surface ocean surface temperatures have been average in the western GOA (baseline 1985-2014) and varying between average and warmer than average in the eastern GOA.

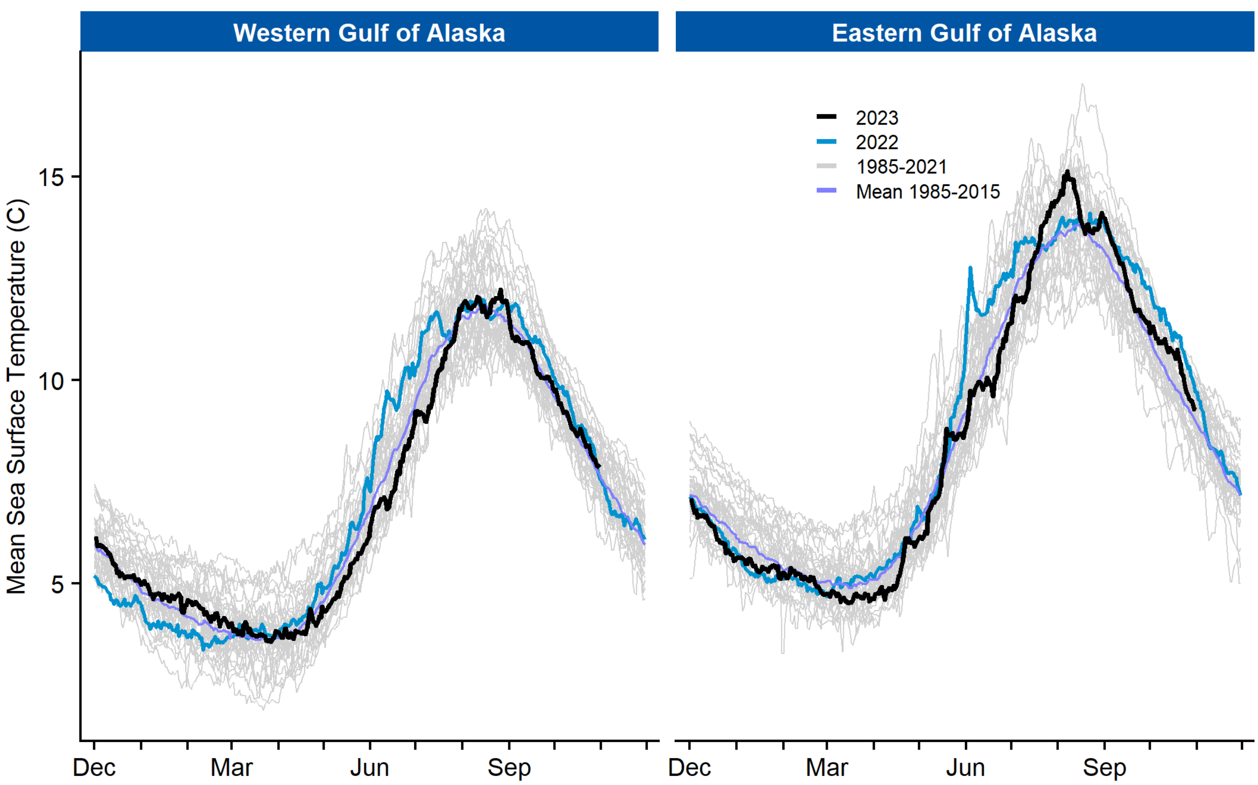

Figure 11: Daily sea surface temperatures (SST) for the western GOA and eastern GOA. Lines illustrate the daily SST for 2023 through October 31 (black), the daily SST for 2022 (blue), the 30-year (1985–2014) mean SST for each day (purple), and daily SST for each year of the time series (1985–2021; gray). Survey details are in the "Methods" section at the end of this contribution.

Spring western GOA: Western GOA and eastern GOA shelf averages of satellite-derived surface temperatures showed cooler/average (1985–2015) spring temperatures (Figure 11). Observed surface temperatures were all cooler than survey-specific averages, including 5.9°C along the Seward Line (May; 0.3°

below the long-term mean; baseline 1998–2022), 4.8°C in Shelikof Strait (May, top 5 m; baseline: 2013-2022) (Figure 12). Spring time temperatures at depth ranging from 5.8°C (May; 176–226m; Seward Line) to 4.4°C (May; 100–150 m; Shelikof Strait Survey) (Figure 12). Recent surveyed marine heatwave years (2015 and 2019) were $\sim$ 2–3° warmer at the surface and $\sim$ 0.5° warmer at depth, in Shelikof Strait.

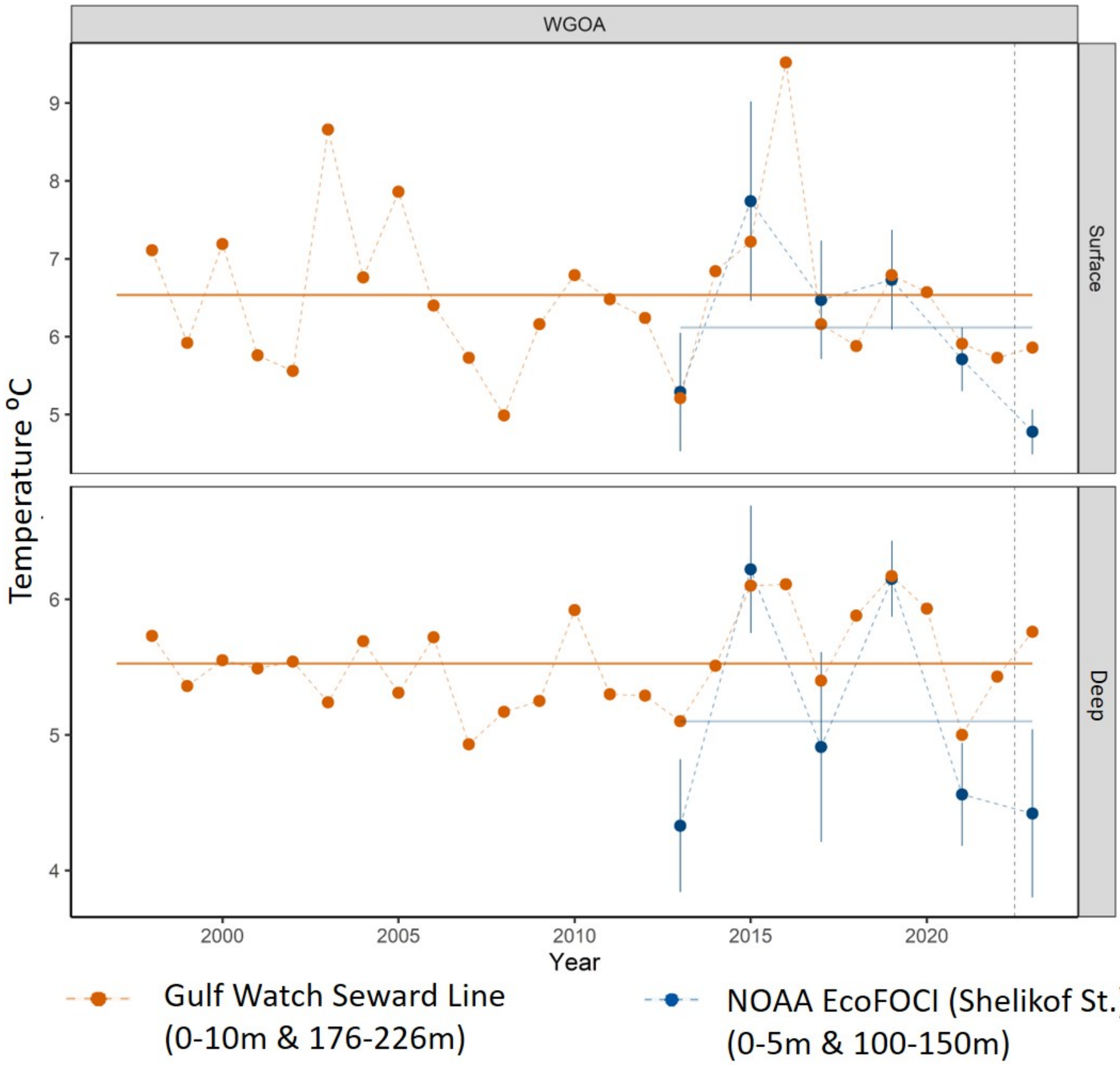

Figure 12: Observed temperatures at surface and depth from the AFSC EcoFOCI spring (May-June, alternating years) larval survey and the Gulfwatch Alaska spring (May) Seward Line survey. Data to the right of the vertical dashed line were collected in 2023. Multiple surveys are shown to reflect commonalities or differences in trends, primarily due to temporal and spatial coverage. Survey details are in the "Methods" section at the end of this contribution.

Summer western GOA: The relatively cooler spring trend in ocean temperatures persisted into the summer of 2023, with average surface temperatures either average or slightly cooler than the survey specific averages, including 8.8°C (top 5m; Bottom Trawl Survey), 10.7°C (top 5 m; Shelikof St Survey), and 10.6°C (July; Seward Line Survey) (Figure 13). These temperatures were ~2-3°C colder relative to late summer temperatures in 2015 and 2019 (marine heatwave years).

Temperatures at depth across the western GOA shelf were average to below average. Temperatures included 5.2°C (May-August: 195–205m, Bottom Trawl Survey), (5.8°C, ADF&G large mesh trawl survey), 5.6°C ($\sim$ 200 m; Seward Line) and 6.12°C (August: 100–150m, Shelikof St. Survey). Temperatures at depth on the shelf edge cooled to the long-term mean, 5.11°C (250m, shelf edge; Longline Survey; baseline 2005–2022), ending a warmer than average trend since 2017 (Figure 13).

Summer eastern GOA: The 2023 summer surface waters in eastern GOA included 13.5°C (top 5m, Bottom Trawl Survey), 8.92°C (top 20m; Icy Strait Survey). At depth, temperatures included 5.8°C (195-205m, Bottom Trawl Survey) and 5.5°C (August: 246–255m, Longline Survey). Along the shelf edge at $\sim$ 250 m depth, temperatures cooled to the long-term mean (5.5°) ending a warm trend since 2018 (Longline Survey; baseline 2005–2023).

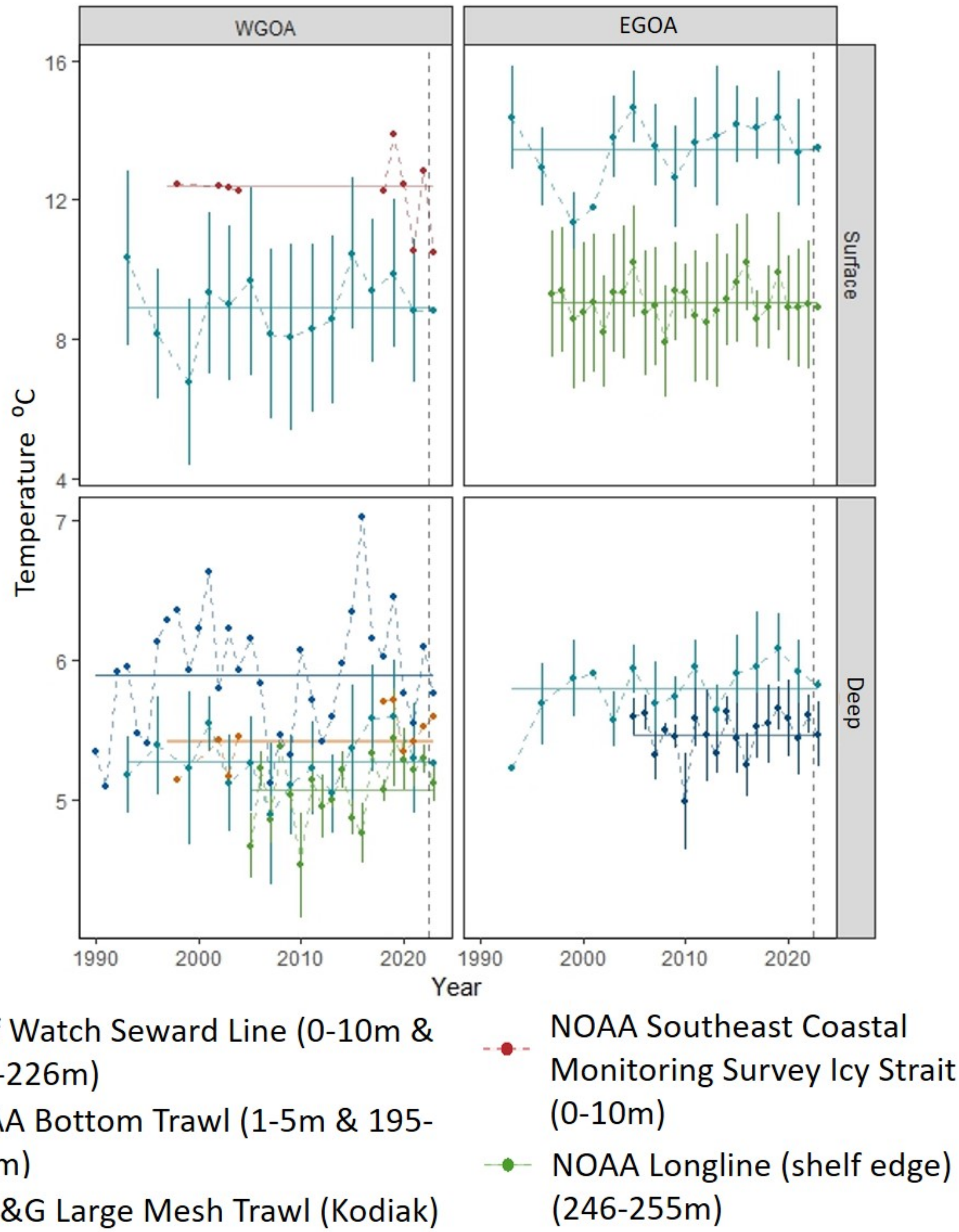

Figure 13: Observed temperatures at surface and depth from the AFSC Bottom Trawl Survey (alternating years, May-Sep.), AFSC Longline Survey (western GOA: June, eastern GOA: August), AFSC Southeast Alaska Coastal Monitoring (SECM Survey; May-Aug.), ADF&G Large Mesh Trawl Survey (Jun./Jul.), and the Gulfwatch Alaska spring (May) Seward Line survey. Multiple surveys are shown to reflect commonalities or differences in trends, primarily due to temporal and spatial coverage.Survey details are in the "Methods" section at the end of this contribution.

Marine Heat Waves: No marine heatwaves occurred in either the eastern of western GOA during Fall 2022, Winter 2023 or Spring 2023 (Figures 14 and 15). However, above-average temperatures in summer registered as a heatwave in the eastern GOA. Despite a warm summer in the eastern GOA, this year along with 2021 stands out from the previous half decade as having remarkably few days in marine heatwave status (Figure 15). 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. At the peak of the brief eastern GOA strong marine heatwave in August, $>$ 50% of the satellite pixels (5 km grid) analyzed experienced a marine heatwave that week. This contrasts with winter, when not a single pixel was in heatwave status Dec-Apr (Figure 16).

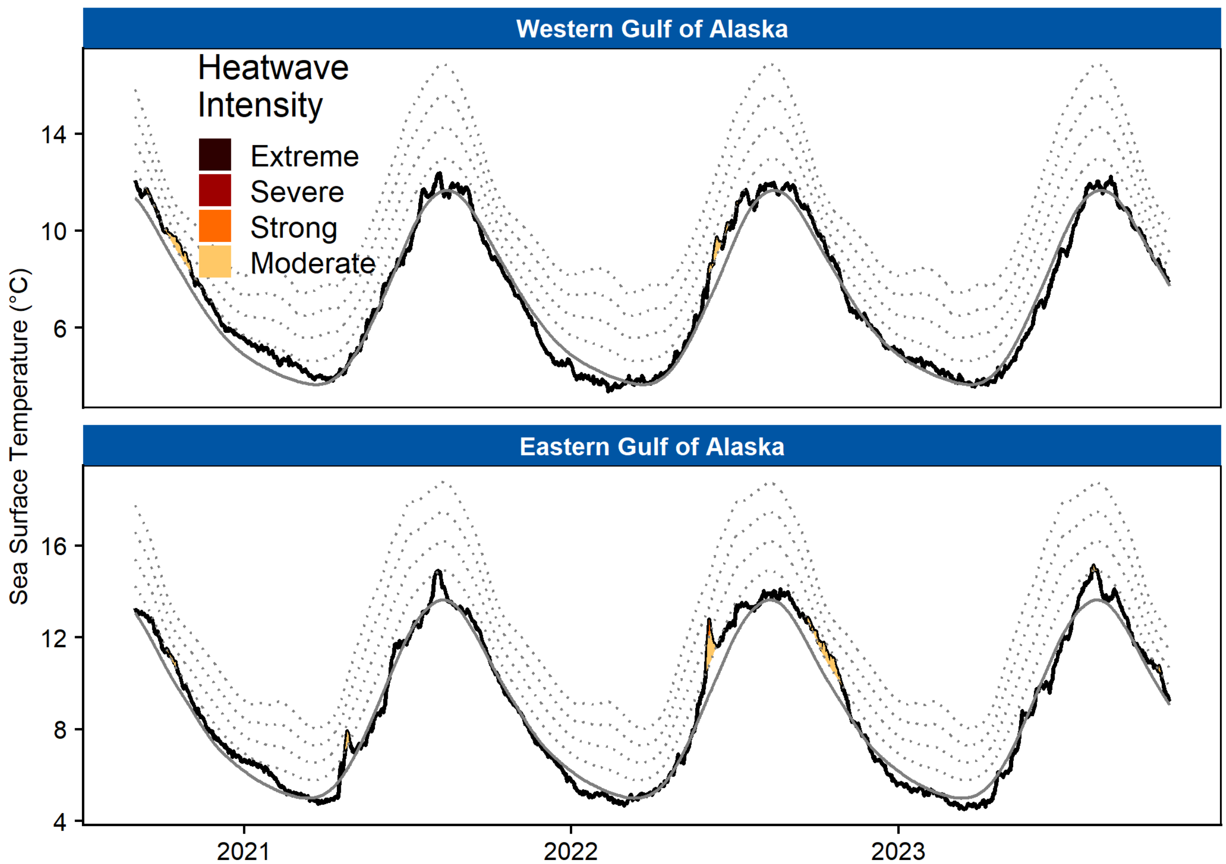

Figure 14: Marine heatwave (MHW) status from Sep. 2020 through Oct. 2023. Filled (yellow) areas depict MHW events. Black lines represent the 30-year baseline (smoothed line; 1985–2014.) and observed daily sea surface temperatures (jagged line). Faint gray dotted lines illustrate the MHW severity thresholds in increasing order (moderate and strong).

Factors influencing observed trends: Ocean temperatures in 2023 reflect a fourth 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*). 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). Icy Strait differs from the other shelf-oriented temperature datasets, reflecting conditions in the inside waters in southeastern Alaska.

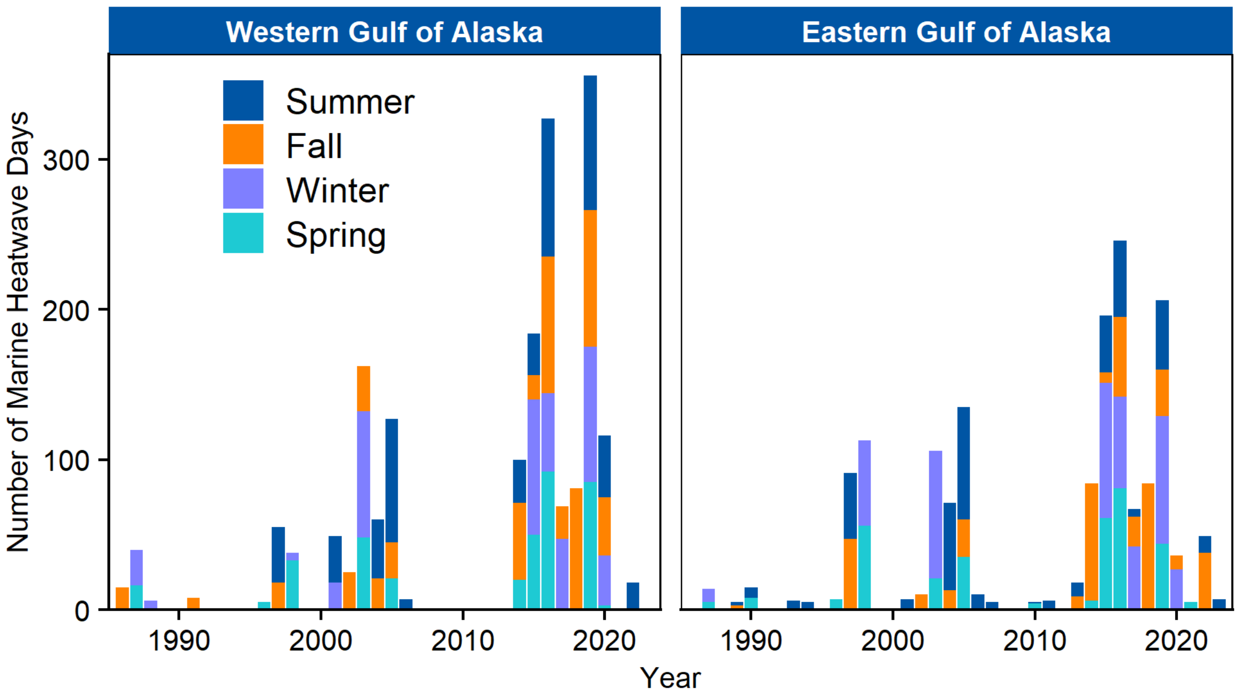

Figure 15: Number of days during which marine heatwave conditions persisted in a given year, through Oct 31, 2023. Seasons are summer (Jun-Aug), fall (Sept-Nov), winter (Dec-Feb), spring (Mar-Jun). Years are shifted to include complete seasons so December of a calendar year is grouped with the following year to aggregate winter data (e.g., Dec. 2021 occurs with winter of 2022).

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.

Implications: Persistently cooler winter and early spring surface temperatures generally correspond to higher productivity of lower trophic levels during the start to the year and thus the relatively average or even cooler ocean conditions observed in the western GOA in 2023 have important ecological implications for average to above-average forage conditions for planktivorous fishes, seabirds, and other upper trophic level organisms. 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 2023 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, 2021, and 2022) for spawning, zooplankton quality and quantity, and fish metabolic demands (Yang et al., 2019; Barbeaux et al., 2020*b*). Cool surface tem-

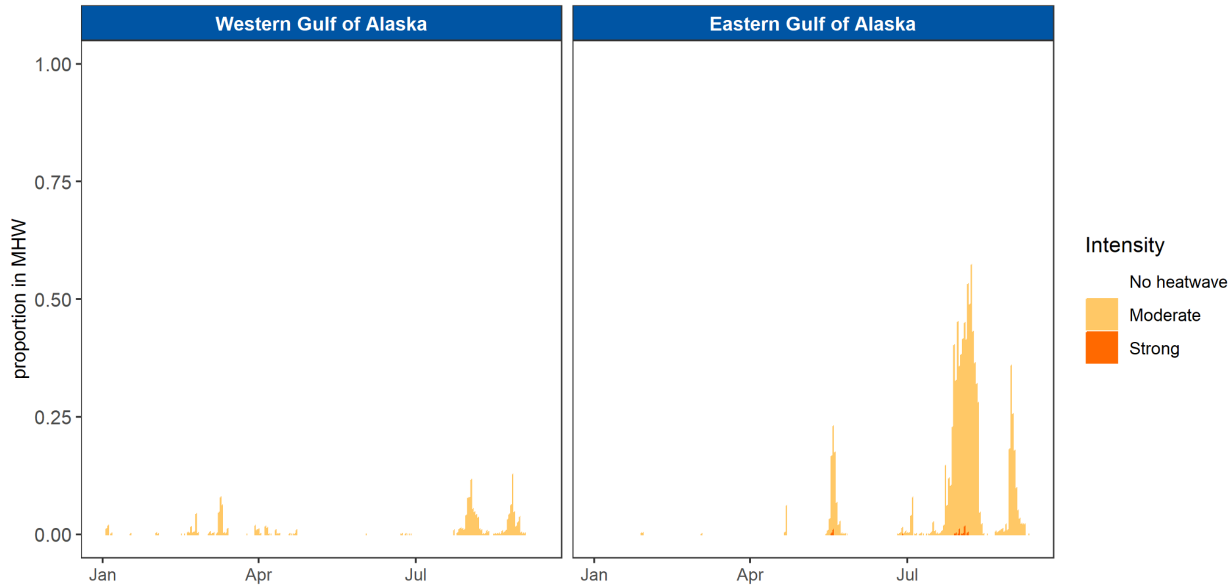

Figure 16: Proportion of region in heatwave status, through Oct. 31, 2023. Heatwave status calculations were performed on each 5 x 5 km grid cell within the Gulf of Alaska. This figure shows a five day rolling average of the proportion of cells within each region that are in heatwave status.

peratures may have contributed to the later spring phytoplankton blooms (Gann in this report, p.72). The average temperatures at surface and depth remain within the known thermal ranges of groundfish (including P. cod and walleye pollock; note thermal ranges for groundfish are not known). As of this report, surface temperatures are predicted to warm in the winter/spring 2024 (Bond in this report, p.35).

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 100 m (spring) or 200 m (late summer), or to 10 m 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 100–150 m depth using the custom R package FastrCAT[9]. While surveys have been ongoing for multiple decades, time-series are provided here for the most recent 6 surveys with similar survey extent. In 2023, the spring survey dates were May 16–21, 2023 and the summer survey dates were September 4–12, 2023. Due to crew staffing shortages and reduced ship time, the Shelikof Strait was not able to be sampled in 2023 and no summer survey was conducted in 2021.

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. 2023 temperatures were not standardized to account for the effect of collection date as in past years.

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 GOA. Data analyzed here are 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 GOA 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 and 5 km grid mhw status from the NOAA Coral Reef Watch Program were accessed via the Alaska Fisheries Information Network (AKFIN) for January 1985 - September 2023.

[9] https://github.com/Copepoda/FastrCAT

Daily SST data were averaged within the western (147°W– 164°W) and eastern (133°W–147°°W) Gulf of Alaska for depths from 10m – 200m (i.e., on the shelf). Detailed methods are online[10] and Watson and Callahan (2021) describes the automation of sst aggregation in depth.

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.

<u>AFSC Summer Longline Survey</u>: 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 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, 2022). 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).

<u>ADF&G Large Mesh Trawl Survey</u>: The Alaska Department of Fish and Game conducts an annual trawl survey for crab and groundfish in GOA targeting areas of crab habitat around Kodiak Island, the Alaska Peninsula, and the Eastern Aleutian Islands (Spalinger and Knutson 2022). Parts of these areas have been surveyed annually since 1984, but the most consistent time series begins in 1988. While the survey covers a large portion of the central and western GOA, results from Kiliuda and Ugak Bays (inshore) and

[10] `https://github.com/MattCallahan-NOAA/ESR/tree/main/SST`

the immediately contiguous Barnabas Gully (offshore) are generally representative of the survey results across the region. Temperature anomalies were calculated using average bottom temperatures recorded for each haul from 1990 to present.

Eddies in the Gulf of Alaska

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Last updated: September 2023

Description of indicator: Eddies in the northern GOA 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 GOA are generally formed in the eastern Gulf in autumn or early winter (Okkonen et al., 2001) and are sometimes 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 17; 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)[11].

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 GOA averaged over the altimetry record (updated from Ladd, 2007) shows four regions with local maxima (labeled a, b, c and d in Figure 17). 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 18).

Analysis updates — The most recent data were downloaded on September 07, 2023 providing daily time series covering 1/1/1993 to 9/07/2023 on a 0.25° longitude x 0.25° latitude grid. Original data set is global, but we subset it to 150°E-125°W and 40°N-72°N during the download. Data from 1993 to 2020 is the delayed/reprocessed product whereas data from 2021 onward is the “NRT” (near real time) products. Horizontal map of long-term mean EKE shown below (Figure 17) and monthly climatology (Figure 18) are averaged over 1993 to 2022 (period with full year coverage).

Status and trends: The seasonal cycle of EKE in the eastern and central GOA (Figure 17, box a-c) has similar phasing (high in winter/spring and low in summer/fall), suggesting their formation mechanisms are inter-related. As noted, EKE in region (d) (western GOA) has opposite seasonal cycle phasing to

[11] http://www.marine.copernicus.eu

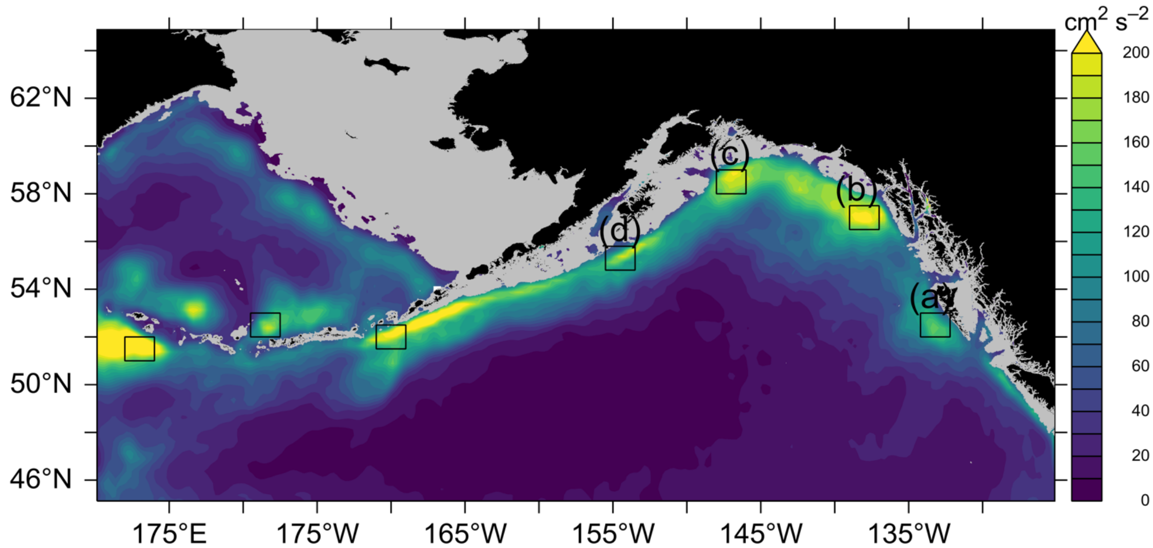

Figure 17: Eddy Kinetic Energy (cm^2 s^{-2}) averaged over January 1993–December 2022 calculated from satellite altimetry. EKE hot spots in the eastern GOA are associated with Haida (region a) and Sitka (region b) eddies. Regions (a)-(d) denote regions over which EKE was averaged for Figure 18.

the other regions (high in the autumn and low in the spring), suggesting different forcing mechanisms in the western GOA. In 2023, thus far, EKE in the GOA box regions is either below or close to the mean seasonal cycle (Figure 18). Region (a) (Haida eddies) historically has a well-defined mean seasonal cycle (high EKE in winter-spring and low EKE in summer-fall) that 2023 seasonal evolution does not closely follow. EKE in regions (b) and (d) are slightly below its long-term mean climatology, while EKE in region (a) and (c) rose above the long-term climatological mean in 2023. For box (b), this "slightly low to average" EKE state has maintained since the late 2010s, whereas boxes (a), (c) and (d) have had interannual variability, with high EKE in 2010, 2016, 2017 and 2019 for (a), 2016 and ∼2020 – 2021 for (c), and 2012 – 2013, 2015, 2017 – 2018, 2020 – 2021 for (d).

Temporal variability of EKE in a fixed relatively small box region (like the ones used in this document) is influenced by passing of meso-scale eddies (Figure 19). In addition to these regional EKE indices, we could average EKE over a larger "stripe" next to the shelf break all around the western, central, and eastern GOA, which provides complementary information to EKE averaged over the boxes. This can be discussed further.

To the extent SLA may be associated with ocean heat content anomalies, 2023 summer (June, July, August mean; Figure 19) does not have extremely strong anomalies.

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 Gulf of Alaska (Ladd and Cheng, 2016). In the western Gulf of Alaska, variability is related both to the propagation of eddies

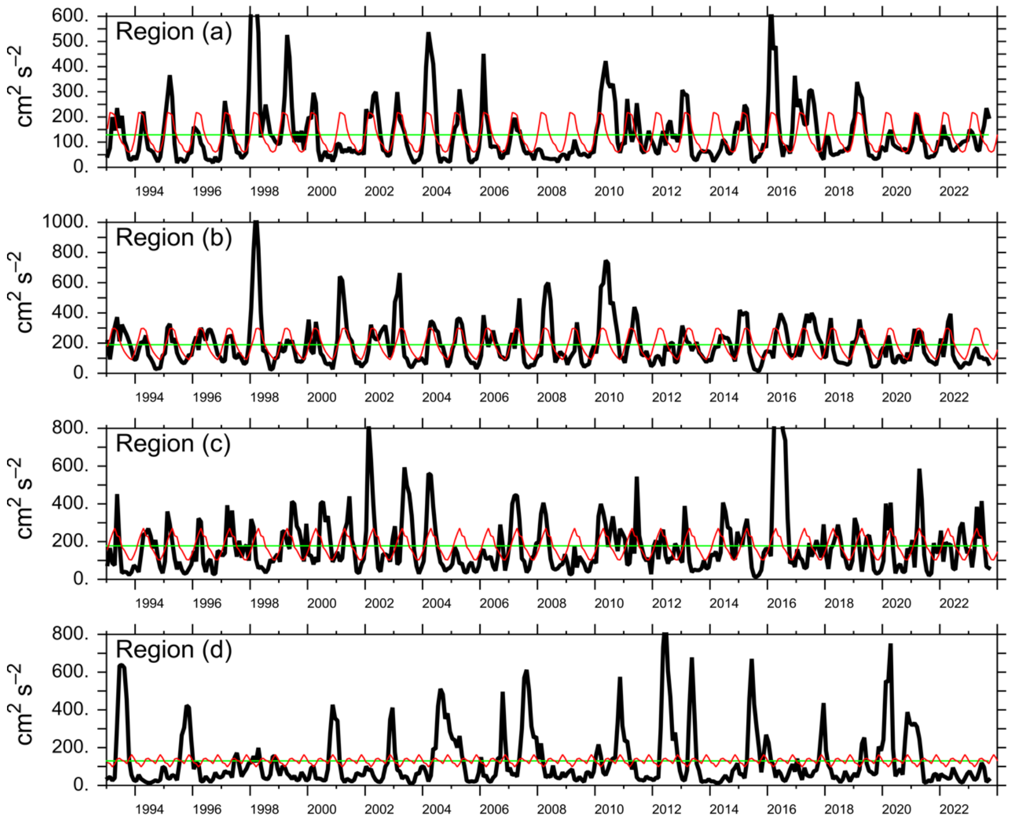

Figure 18: Eddy kinetic energy (cm^2 s^{-2}) averaged over regions shown in Figure 17. Black (line with highest variability): monthly EKE; Red: mean seasonal cycle; Green (straight line): mean over entire time series.

from their formation regions in the east and to intrinsic variability. Previous studies suggest that eastern GOA eddy activities (regions a and b) are related to large-scale forcing such that downwelling favorable wind anomalies along the Alaskan coast can generate positive SSH anomalies which promote formation of anticyclonic eddies. Downwelling favorable winds tend to happen during positive phases of PDO, but the correspondence between eddy activities and ENSO events is not always strong. ENSO associated forcing effects can be both local (via local wind anomalies) and remote (via coastal trapped waves arriving from lower latitudes and generate SSH anomalies along the Alaska coast). In comparison, interannual variability of eddies in the western GOA (region c and region d) tends to happen intrinsically and is not necessarily associated with large-scale forcing, although eddies from the eastern GoA could also arrive here.

Implications: 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). And eddies may result in enhanced settlement and recruitment for arrowtooth flounder (Goldstein et al., 2020).

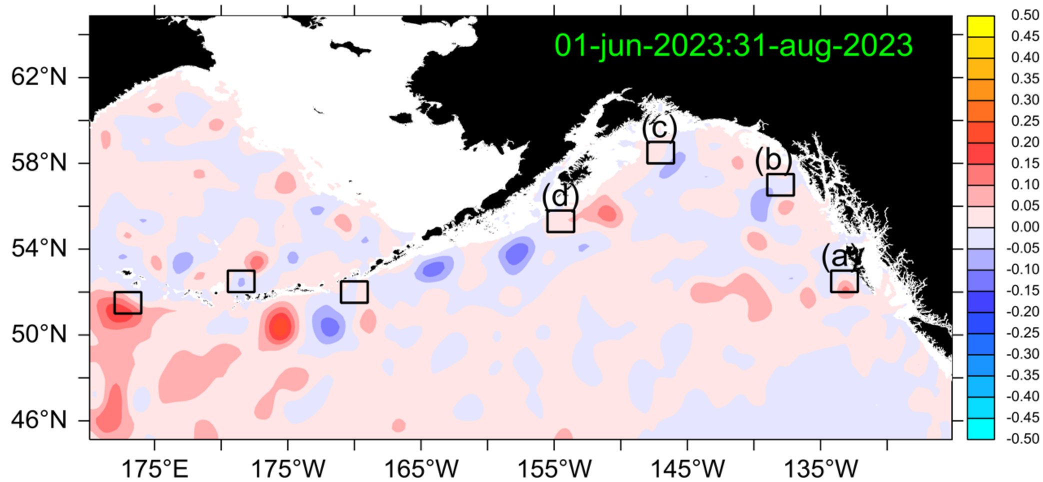

Figure 19: Sea level anomalies averaged in June, July, August, 2023, relative to its mean seasonal cycle. Expectedly, the closed circles match with high Eddy Kinetic Energy locations shown in Figure 17.

Ocean Surface Currents—Papa Trajectory Index

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Last updated: July 2023

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 20). The simulation for each year is conducted using the "Ocean Surface CURrent Simulator" (OSCURS[12]). 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 2022 (trajectory endpoints years 1902 – 2023).

Status and trends: In general, the trajectories fan out northeastward toward the North American continent (Figure 20); the 2021/22 is among the relatively few that initially moved strongly to the southeast and ended south of Ocean Station PAPA while the trajectory for 2022/23 was fairly typical

[12] http://oceanview.pfeg.noaa.gov/oscurs

among the time series (baseline 1968 – 2022). In this respect, the 2022/23 trajectory represented a return to more "average" (baseline 1968 – 2022) winter atmospheric conditions. The 2022/23 trajectory was influenced in December by high sea level pressure (SLP) anomalies centered over the Alaska mainland north of the central Gulf of Alaska that initially gave rise to weak southwesterly wind anomalies east of Ocean Station PAPA. The wind anomalies dropped in strength in January and shifted direction to the north, then increased again in February while shifting more directly eastward as a second high pressure system centered to the west of the California coast moved eastward. As a result, the ending latitude for the 2022/23 trajectory, and thus its PTI value, was closer to the longterm mean (baseline 1968 – 2022) than any year since 2017/18.

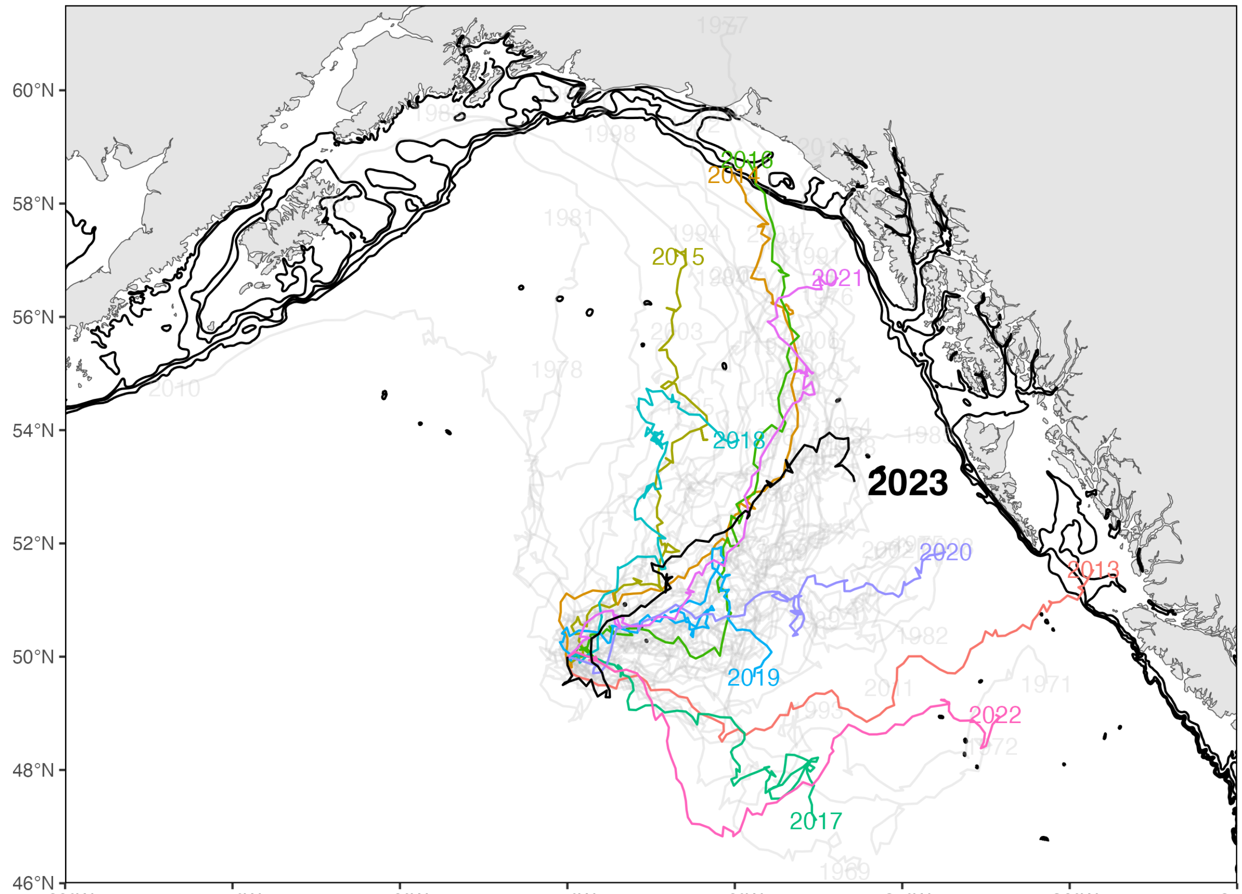

Figure 20: Simulated surface drifter trajectories for winters 2068–2023 (endpoint year). End points of 90-day trajectories for simulated surface drifters released on Dec. 1 of the previous year at Ocean Station Papa are labeled with the year of the endpoint (50°N, 145°W). The trajectory in black is 2022/2023, those in color end in 2013/2014-2021/2022, and those in gray end prior to 2012/2013.

The PTI time series (Figure 21) indicates high interannual variation in the north/south component of drifter trajectories, with an average between-year change of greater than 4° and a maximum change of greater than 13° (between 1968/69 – 1969/70). The change in the PTI between 2015/16 and 2016/17 was the largest since 1968/69 – 1969/70, while the changes between 2010/11 and 2011/12, and between 2020/21 and 2021/22, represent reversals with slightly less, but diminishing, magnitude. Such swings, however, were not uncommon over the entire time series. The 2021/22 value returned below the mean after an excursion above it in 2020/21; the 2022/23 value also remained below (although closer to) the long-term mean, with the result that the trajectories in six of the last seven years have ended below the mean (baseline 1968 – 2022).

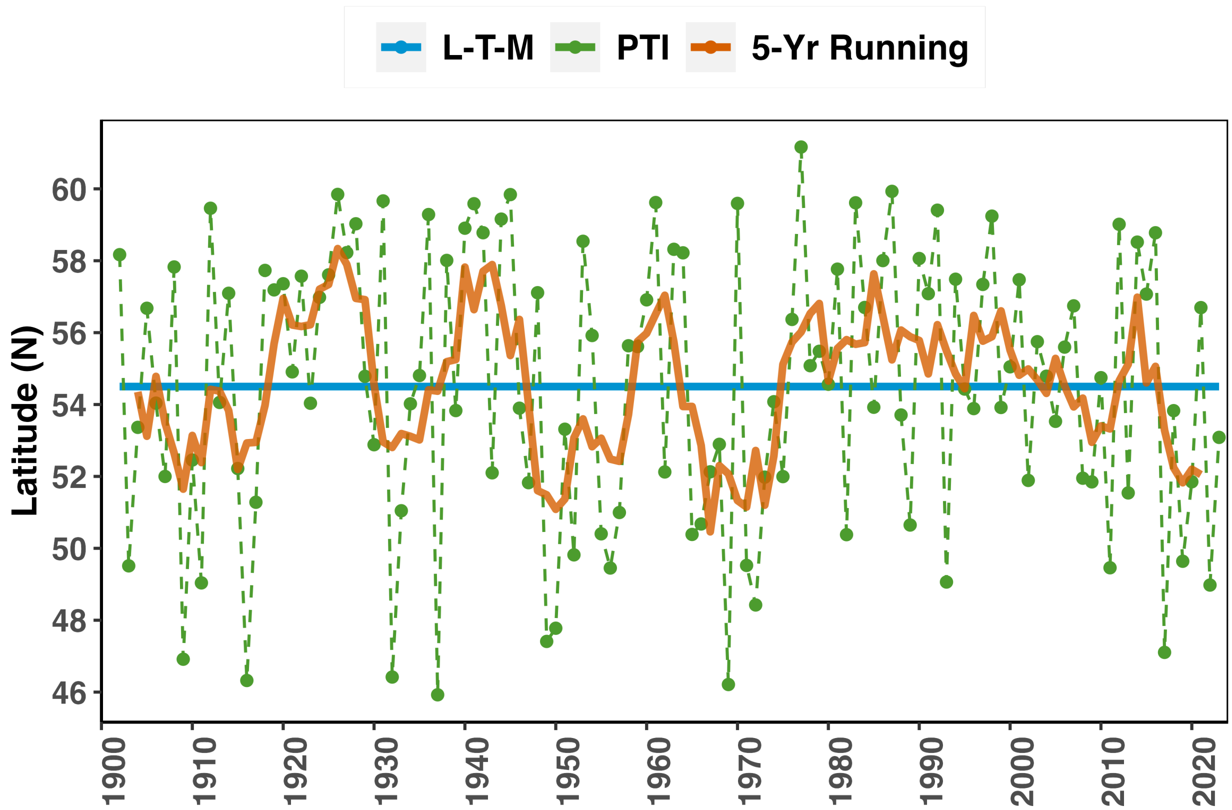

Figure 21: Annual, long-term mean (blue line), and 5-year running mean (orange line and squares) of the Papa Trajectory Index time series end-point latitudes (dotted green line and points) for 1902–2023 winters.

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). 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 an 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: Individual trajectories reflect interannual variability in regional (northeast Pacific) wind patterns which drive short-term changes in ocean surface currents, as well as longer term changes in atmospheric forcing that influence oceanic current patterns on decadal time scales.

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 GOA'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 Wind in the Coastal Western Gulf of Alaska

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Description of indicator: Surface wind is fundamental to the oceanography, 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. Its relevance to regional groundfish production in the Gulf is illustrated by studies of wind-driven turbulent mixing on walleye pollock larvae (e.g., Porter et al., 2005) and of wind-driven transport on juveniles and recruitment (Wilson and Laman, 2021).

Two complementary datasets were used to indicate springtime (April – May) surface wind in the coastal Gulf. This period coincides 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 (Ladd and Cheng, 2016). Springtime measurements at AMAA2 are currently available for 17 years: 2004 to 2023, except 2007, 2008, and 2018, with measurements recorded at 30 min intervals[13]. The second dataset consists of lower-resolution, reanalysis-based data from the National Centers for Environmental Prediction (NCEP) (Kalnay et al., 1996). The NCEP Reanalysis data averaged by month and year from 1948–2023 were provided by the

[13]https://www.ndbc.noaa.gov/

NOAA/OAR/ESRL PSL, Boulder, Colorado, USA[14]. We specified the geographic area to be 55–60oN latitude and 150–160oW 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 ($n = 17$) between the two datasets was $r = 0.62$ for the u component, and $r = 0.74$ 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 indicated winds blowing offshore through April, consistent with an extended period of gap winds, followed by more typical easterly or northeasterly winds through May (Figure 22). The April wind pattern is unusual with no comparable years in the AMAA2 record, however other data products (e.g., ERA5) do show years with similar overall wind patterns in April (not shown). In contrast, the trajectories for 2014, 2015 and 2016 were northwestward or westward.

The lower-resolution NCEP winds indicated mean April - May wind towards the south (Figure 23). NCEP winds in 2023 were most similar in direction and magnitude to winds in the early 2000s (2000, 2001, 2003), and in contrast to the period 2015 – 2019 when means indicated a relatively strong northward component in this region.

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. The Aleutian Low influences wintertime conditions and the El Niño-Southern Oscillation can affect conditions at multi-year intervals. Local terrain effects can intensify flow and lead to "gap" winds that affect oceanographic processes. Gap wind events in the AMAA2 region lead to diversion of the ACC to the outside of Kodiak and reduced transport down Shelikof Strait (Ladd and Cheng, 2016).

Implications: Wind speed and direction 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 drives upwelling and downwelling with consequent effects on vertical circulation and transport. At large scales, wind-driven transport influences the replenishment of adult fish and shellfish stocks by transporting larvae to favorable or unfavorable habitat. When the AMAA2 wind trajectories for this period (April - May) are toward the southwest (down Shelikof Strait), estimates of age-1 pollock abundance tend to increase, possibly 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). Historically, the number of gap wind events during spring (January - May) was positively correlated with Pacific cod recruitment and negatively correlated with arrowtooth flounder recruitment (Ladd and Cheng, 2016), and these relationships should be re-evaluated with more recent observations.

[14] https://www.esrl.noaa.gov/psd/cgi-bin/data/timeseries/timeseries1.pl

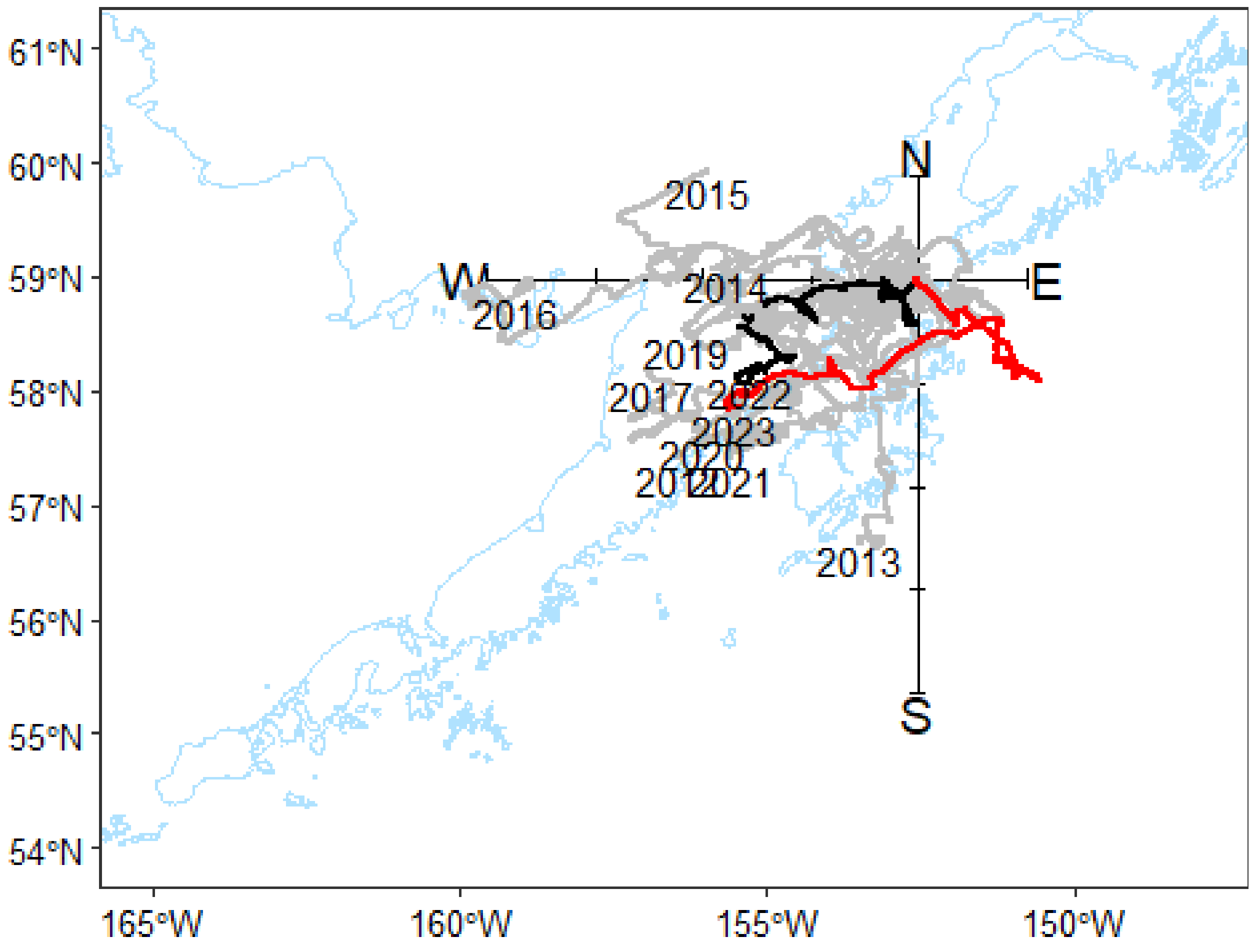

Figure 22: Progressive wind diagrams (PWD) from NDBC-AMAA2 for spring (April – May) 2004–2023 (except 2007, 2008, and 2018). Select trajectory endpoints are labeled by year, with the 2023 trajectory in red and the 2022 trajectory in black. The diagram is superimposed on the Alaska coastline with the origin centered on the location of the AMAA2 site. Note, the scale of distance differs between the trajectories and the coastline; PWD 1 tick mark ∼ 2700 nm.

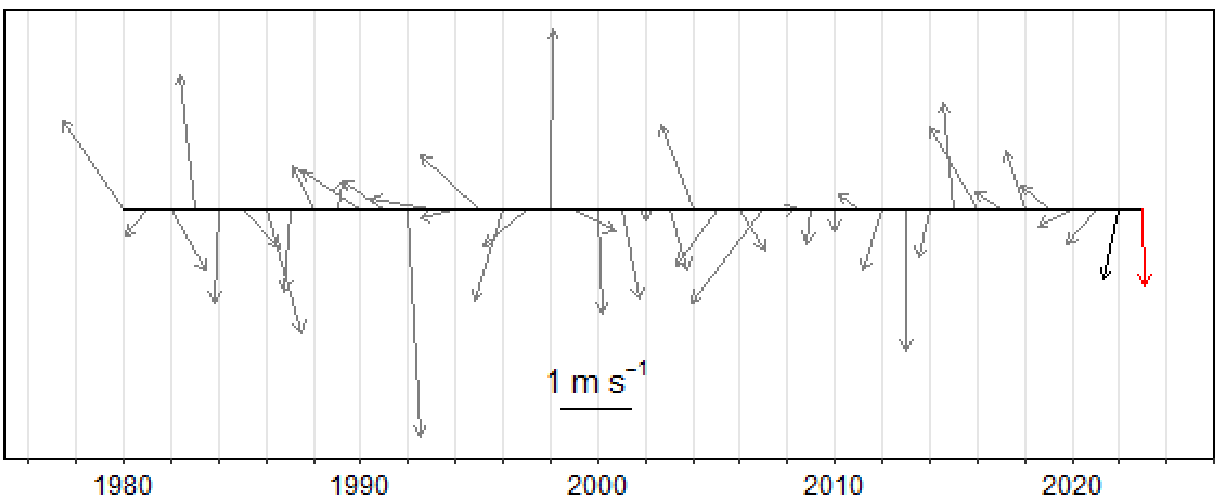

Figure 23: Mean wind from NCEP for spring (April – May) 1980 – 2021 (gray), 2022 (black), and 2023 (red). Each "stick " represents the magnitude (y-axis) and direction (e.g., northward is up, eastward is to the right) toward which the wind is blowing during each year.

Habitat

Structural Epifauna—Gulf of Alaska

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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 Alaska Fisheries' Resource Assessment and Conservation Engineering Division's Groundfish Assessment Program (RACE-GAP) fishery-independent summer bottom trawl surveys in the Gulf of Alaska (GOA) are designed to assess populations of commercially and ecologically important fishes and invertebrates. Since 1990, we have deployed the same standardized trawl gear (footrope and trawl net) as is presently in use in the GOA bottom trawl survey. Epifaunal groups like sponges, corals (both hard and soft), pennatulaceans, and anemones form benthic structure that can be part of the communities that make up Habitat Areas of Particular Concern (HAPC). A HAPC is a specific area designation for a type of habitat that plays an important role in a species' life cycle, or that is sensitive, rare, or vulnerable. For epifaunal groups collected in our bottom trawls, biomass estimates were scaled each year to the largest estimate in the time series for each group which was then arbitrarily scaled to a value of 100 and all other values were scaled in reference to that. The standard error ($\pm$ 1) was weighted proportionally to the biomass to yield a relative standard error. Prevalence in survey catches is also presented as the percentage of positive bottom trawl hauls for each group. **Status and Trends** A few general patterns are discernible among the epifaunal groups summarized here (Figure 24). Sponges are prevalent in bottom trawl survey hauls throughout the Gulf of Alaska (GOA), occurring in 40–50% of catches in all districts sampled, though their abundance appears to be declining in recent years in at least the Shumagin and Kodiak districts. Sea anemones appear to be more abundant in the western GOA though they are relatively common across the survey area, occurring in 40–50% of trawl catches much of the time. Gorgonian corals are most abundant in southeast Alaska, contrasting with the pattern of abundance observed with sponges and anemones, and are not common in our trawl catches, even where their abundance is higher. The sea pens and sea whips (Pennatulacea) are neither common nor abundant in GOA trawl catches though we have episodically caught them in high abundance in the Chirikof district. Hydrocorals are not abundant or common in the GOA either, though historically they have been caught in higher abundance in the Shumagin district of the western Gulf.

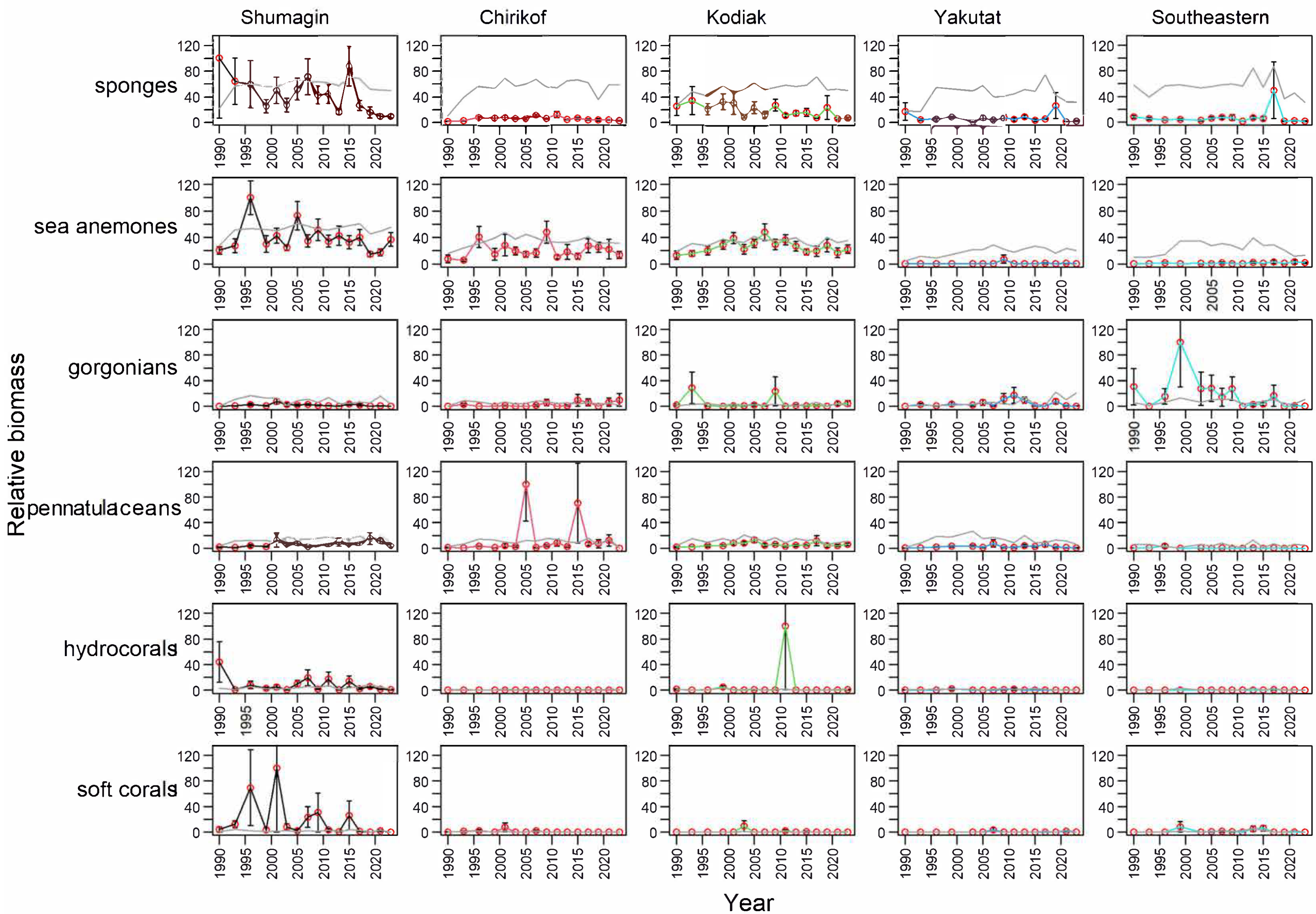

Figure 24: Estimated relative biomass of epifaunal species groups collected from International North Pacific Fisheries Commission (INPFC) statistical districts during fishery-independent summer bottom trawl surveys of the Gulf of Alaska (1990–2023). Error bars represent standard errors and the gray lines represent the prevalence (percentage) of non-zero catches for these taxa.

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: Population trends for these epifaunal groups across the GOA may reflect changes in their habitats or environment. Recent climatic events like the Warm Blob (Bond et al., 2015; Di Lorenzo and Mantua, 2016) have almost certainly impacted some of these sessile populations. Continued monitoring and further studies to better understand the mechanisms and implications of observed trends are key to a better understanding of the ecosystem.

Ocean Acidification in the Gulf of Alaska

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Description of indicator: Ocean acidification, caused by the oceanic uptake of anthropogenic CO2, has decreased the aragonite saturation state (Ωarag) and pH since the Industrial Revolution and may negatively impact Alaska's fisheries sector (Mathis et al., 2015) and the way of life of Indigenous communities. In addition to that long-term trend, recent studies found that local climate-driven oscillations can lead to ocean acidification extreme events and at times compound with heat and low oxygen extreme events, with potentially far-reaching consequences for marine ecosystems (Hauri et al., 2021*b*, In Press). A decrease in pH and/or Ωarag has a negative impact on the physiology of a variety of marine species.

In the following we use modeled and observed pH and Ωarag data to give an overview of the state of ocean acidification in the Gulf of Alaska. Model output was derived from a high-resolution (4.5 km horizontal grid and 50 vertical levels) 3D coupled physics and biogeochemistry hindcast simulation of the Gulf of Alaska, known as the Regional Ocean Modeling System-Carbon, Ocean Biogeochemistry and Lower Trophic (ROMS-COBALT-GOA) marine ecosystem model that covers the period 1993 to the end of 2022. This domain and simulation have been extensively evaluated in previous studies (Hauri et al., 2021*b*,*a*, In Press) and reproduce the main inorganic carbon patterns relatively well. We also present observed bottom pH and Ωarag at Seward Line stations GAK 5 and GAK 9 between 2018-2021 (Hauri et al., 2021*b*). Preliminary data from 2022 and 2023 are also shown. Water samples were analyzed for pH (4H-Jena HydroFIA pH), total alkalinity (4H-Jena HydroFIA TA), and dissolved inorganic carbon (Apollo DIC Analyzer AS-C6). Inorganic carbon parameters were calculated using CO2SYSv3 ; Lewis and Wallace, 1998 with dissociation constants for carbonic acid of Lueker et al. (2000), bisulfate of Dickson (1990), hydrofluoric acid of Perez and Fraga (1987), and the boron-to-chlorinity ratio of (Lee et al., 2010) with nutrients assumed to be zero.

Although there are a few species-specific ocean acidification thresholds available in the literature, it is important to note that these thresholds vary with other environmental factors such as temperature, dissolved oxygen, or food availability. To simplify our analysis, we will use ocean acidification indicator thresholds found for the southern Tanner crab *Chionoectes baridi*, pacific cod *Gadus macrocephalus*, coho salmon *Oncorhynchus kisutch*, and pteropods (Pteropoda). Tanner crab juveniles have reduced calcification and both juveniles and adults suffer increased mortality at pH < 7.8 (Long et al., 2013; Swiney et al., 2017). At pH ≤ 7.5 Tanner crab hatching success decreases dramatically (Swiney et al., 2017) and adult shells are severely impaired (Dickinson et al., 2021). Similarly, growth and lipid composition of pacific cod larvae and the olfactory-mediated neural and behavioral responses and gene expression of coho salmon were sensitive to pH < 7.5 (Hurst et al., 2019; Williams et al., 2019). Finally, the aragonitic shell of pteropods have shown signs of severe dissolution at Ωarag < 1.3 in the field and in experiments (Bednaršek and Ohman, 2015). Pteropods are an important part of the diet of Pacific salmon species, such as pink, sockeye, and chum salmon (Auburn and Ignell, 2000; Daly et al., 2019) and have been classified as ocean acidification indicator species (Bednaršek and Ohman, 2015).

Status and Trends: Ocean conditions at the seafloor had increased acidity near the shelf slope in fall 2022 and on the middle of the shelf in spring 2023. Modeled time series at Seward Line stations GAK 5 and 9 show statistically significant long-term decreasing trends of bottom water pH and Ωarag (not shown), an indication for a steady degradation of the habitat of organisms sensitive to the effects of ocean acidification. Observed bottom pH at GAK 9 was particularly low (pH $= 7.56$, (Figure 25C). In fall 2022, the Gulf of Alaska Downwelling Index was negative (Hauri et al., In Press), thereby favoring intrusion of deeper, saltier, and more acidic water onto the shelf (Figure 26). The model results suggest that in fall 2022 the bottom area with pH <7.8 was > 60 % of the shelf (Figure 27A). Data from Seward Line station GAK 5, which is in the middle of the shelf, suggest that pH and Ωarag are the lowest in spring 2023, compared to any other spring since 2019. A possible explanation could be that 2022 and 2023 were consecutive years of strong upwelling in the Alaska gyre (negative Northern Gulf of Alaska Oscillation Index, Figure 26) (Hauri et al., 2021*b*), which generally leads to lower pH, Ωarag, and oxygen concentration on the shelf. The model also indicates that the Western Gulf of Alaska bottom area with pH < 7.8 has progressively expanded, from an annual maximum area of ~ 45 % of the shelf in 1993 to ~ 80 % in 2022 (Figure 27). The depth below which pH < 7.8 has shoaled during the 1993-2022 period. The open ocean area of the western GoA generally exhibits the shallowest depth $\sim$ 100 m (Figure 28A) due to upwelling in the Alaska gyre.

Factors influencing observed trends: Bottom pH and Ωarag on the shelf are driven by the 1) long-term trend of ocean acidification (Figures 25C, 27, and 28, 2) winter mixing that increases pH, and late summer remineralization of organic matter that decreases pH, 3) intermittent acidic deep water intrusion at the continental shelf slope in fall that decreases pH and Ωarag (Hauri et al., In Press), and 4) strength of the Alaska gyre (Hauri et al., 2021*b*). Deep water intrusion occurs when the intensity of the coastal downwelling decreases and can be approximated through the downwelling index defined in Hauri et al. (In Press). This index (computed with sea surface height satellite data) was mostly positive in 2022 and 2023 (between January and September) indicating a strong downwelling activity and therefore a low probability for acidic deep water intrusion, except for in fall 2022, when the index became negative in fall, and bottom pH was exceptionally low at the shelf slope. The depth of water with pH < 7.8 in the offshore area of the western Gulf of Alaska is affected by ocean acidification and sub-decadal climate oscillations that drive the strength of the Alaska gyre. The intensity of the upwelling in this area can strongly influence the acidity in the upper water column offshore and on the shelf and can be estimated with satellite sea surface height through the Northern Gulf of Alaska index (Hauri et al., 2021*b*). In 2023 (as in 2022) this index is strongly negative, indicating a strong upwelling activity in the Alaska gyre and therefore more acidic conditions in the upper water column, including

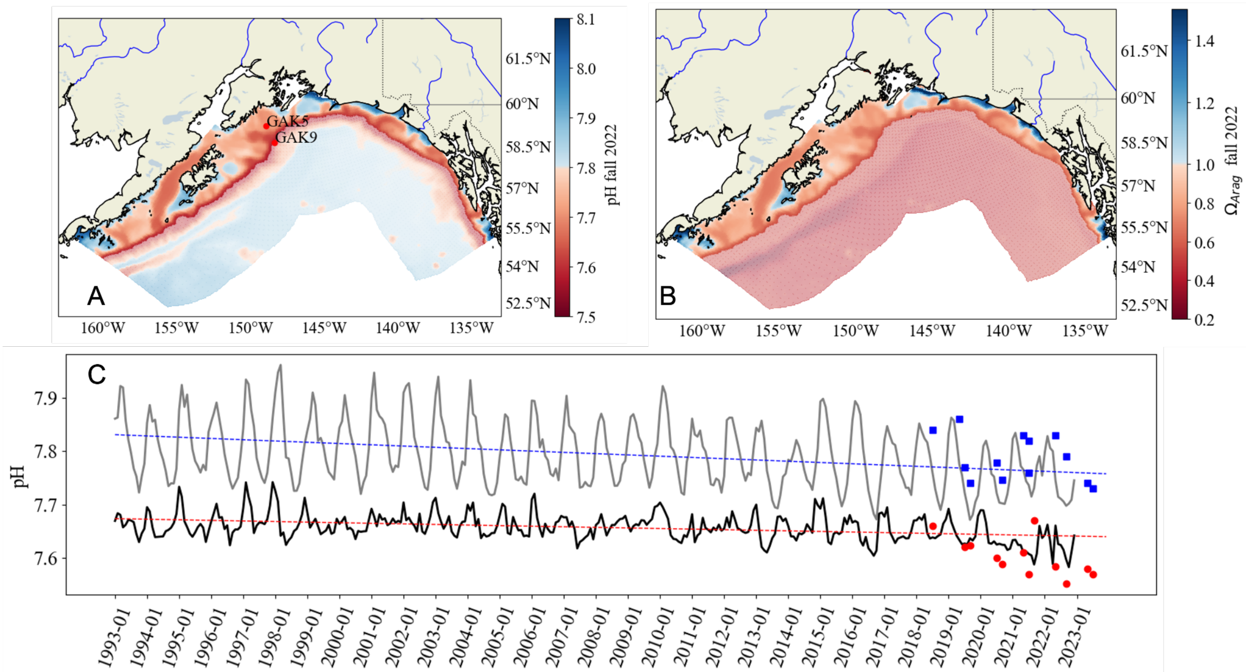

Figure 25: Maps of fall 2022 (Sept., Oct., and Nov.) of bottom pH (A) and aragonite saturation state (Ωarag, B). The faded area shows portions of the domain deeper than 500 m where the model vertical resolution decreases. The time series shows the modeled temporal evolution of pH (C) at the bottom of Seward Line stations GAK 5 (gray line) and GAK 9 (black line) between 1993 and 2022 (bottom depth of 170 m for GAK 5 and 280 m for GAK 9). The red circles show observations near the bottom of station GAK 9 and the blue squares show in situ observations at stationGAK 5 between 2018 and 2023. The dotted line shows the linear regression for each time series (GAK5, -0.0023 per year, R = -0.33, p-value < 0.01 and GAK 9, -0.001 per year, R = -0.37, p-value < 0.01).

the shelf, than in weak upwelling years, such as in 2019 and 2020.

Implications: Ocean acidification has the potential to adversely affect populations of sensitive species and the fisheries on which they depend; Tanner crab catch and profits, for example, are predicted to decline as pH levels drop below critical levels (Punt et al., 2016). OA thresholds for salmon have yet to be exceeded anywhere in the Gulf of Alaska other than in deeper waters in the southwest which are outside the range of those species. Although the vast majority of the benthic waters in the Gulf of Alaska are below critical thresholds for both Tanner crab juveniles and pteropods, there is not as yet significant intrusion of these waters into the habitats of these species. Tanner crab juveniles generally settle in shallow waters in the Gulf of Alaska (Ryer et al., 2015) where currently the pH levels are above pH 7.8, while pteropods are generally present in the plankton at relatively shallow depths. Currently there is no evidence to suggest that OA is significantly affecting any known species in the Gulf of Alaska (including Tanner crab and red king crab), in part due to this spatial refuge. However, given current trends it is likely that intrusion of low pH waters into the habitats of the species will become a more frequent occurrence with likely negative consequences (Bednaršek and Ohman, 2015). Additionally, other environmental stressors, such as increasing temperature or decreasing dissolved oxygen, can synergistically interact with OA effectively lowering thresholds and making organisms more vulnerable (e.g., Swiney et al., 2017).

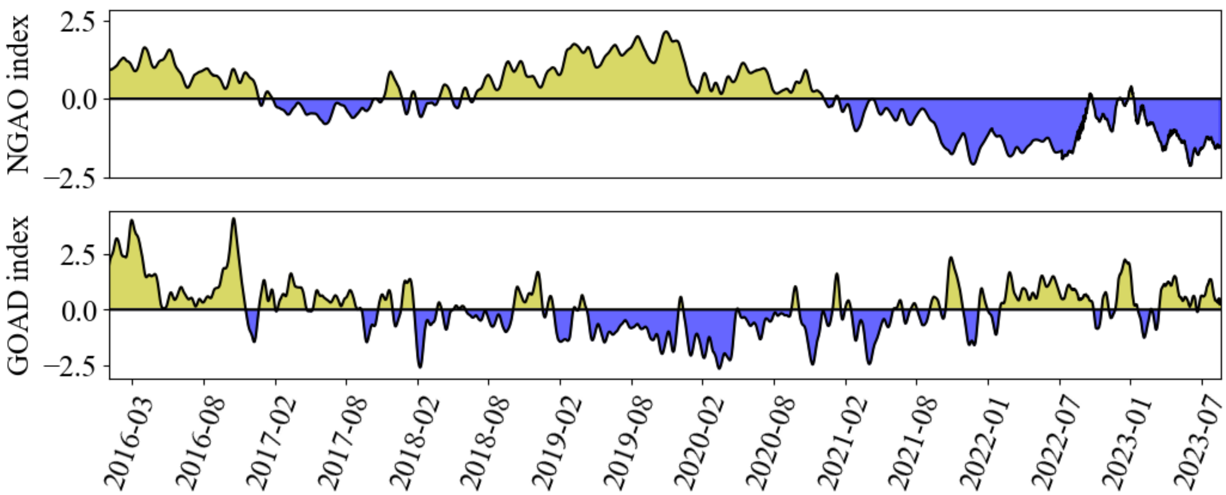

Figure 26: Northern Gulf of Alaska Oscillation index(NGAO) and Gulf of Alaska Downwelling Index (GOADI). Time series of the normalized principal component associated with the first (top) (Hauri et al., 2021*b*) and the second (bottom) (Hauri et al., In Press) Empirical Orthogonal Function mode of sea surface height obtain by satellite (`https://doi.org/10.48670/moi-00148`).

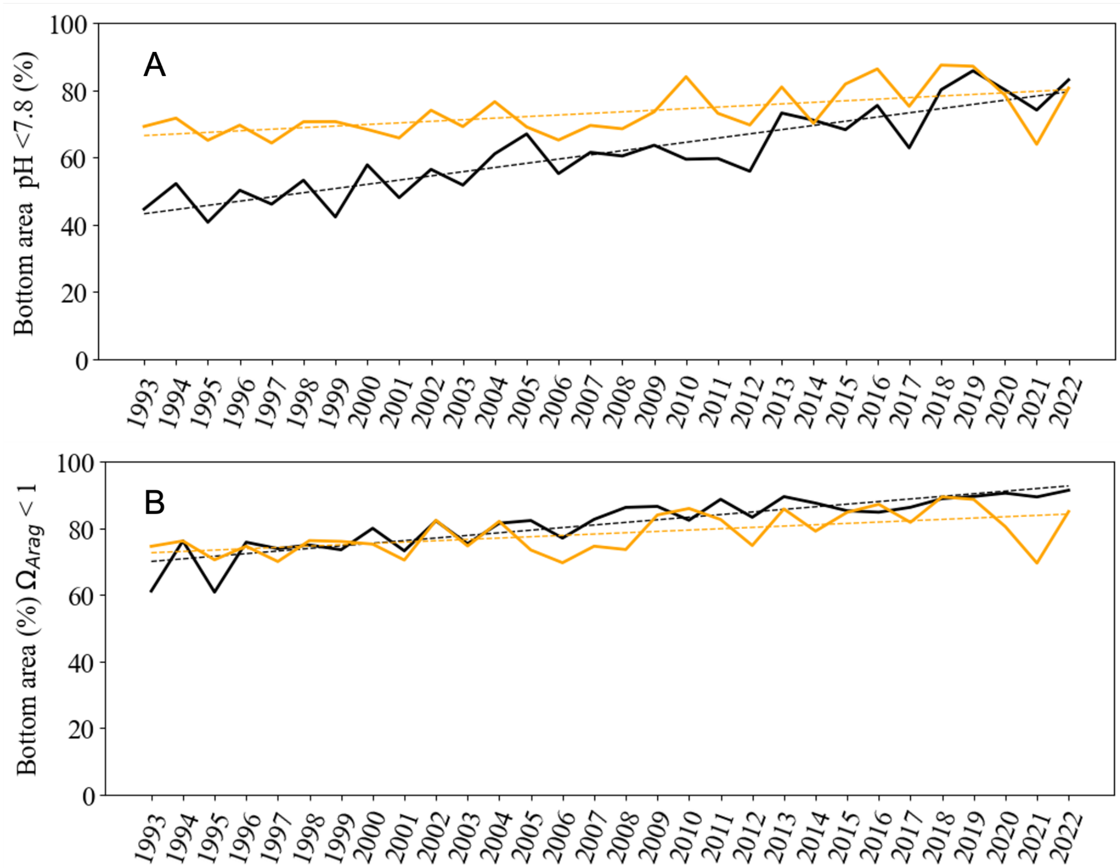

Figure 27: Time series of the annual averaged percent of seaflooor affected by low pH ($<$ 7.8) (A) an low aragonite ($<$ 1) (B) for the Western shelf (0–500 m, black line) and Eastern shelf (0–500 m, orange line) between 1993 and 2022 at the bottom. The dotted lines illustrate the trend for the Western area (1.25 % per year, R = 0.89, p-value $<$ 0.01 for pH and 0.78 % paer year, R = 0.87, p-value $<$ 0.01 for aragonite) and for the Eastern area (0.47 % year, R = 0.59, p-value $<$ 0.01 for pH and 0.4 % year, R = 0.57, p-value $<$ 0.01 for aragonite).

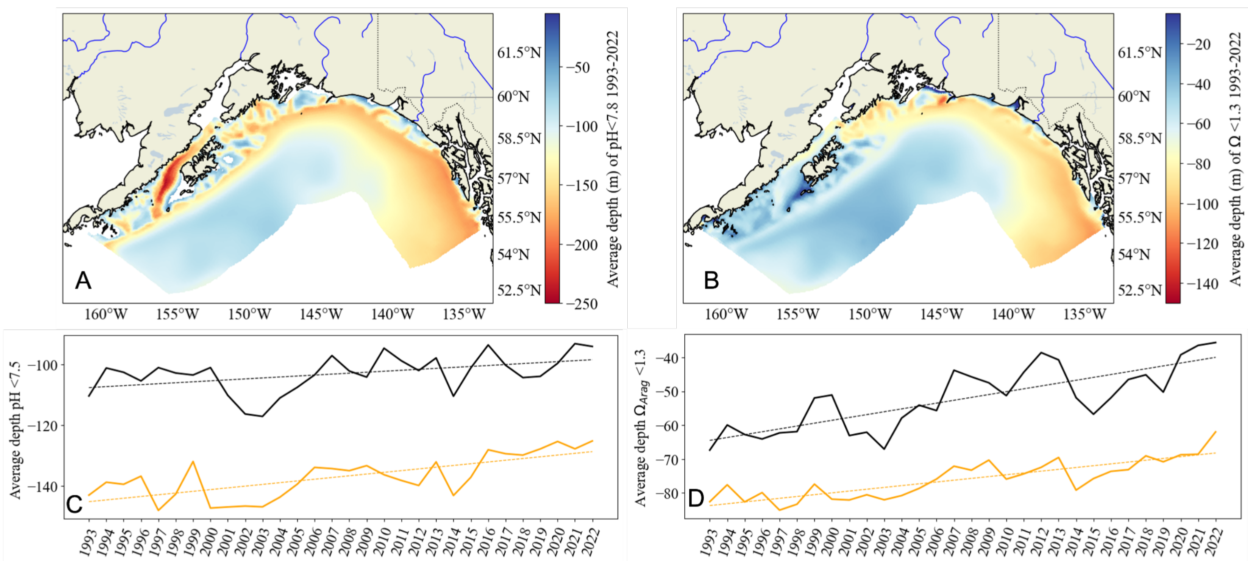

Figure 28: Water depth with pH < 7.8 and aragonite saturation state (Ωarag) < 1.3. Map of average (1993–2022) water depth with pH < 7.8 (A) andΩarag < 1.3 (B). Time series of annual averaged water depth with pH < 7.8 (C) and Ωarag < 1.3 (D) for the Western (black) and Eastern (orange) Gulf of Alaska. The dotted lines show the trend of the average water depth with pH < 7.8 (Eastern Gulf of Alaska: +0.56 m/year, R = 0.76, p-value < 0.01; Western Gulf of Alaska: +0.36 m per year, R = 0.45, p-value < 0.01) and Ωarag (Eastern Gulf of Alaska: +0.53 m per year, R = 0.83, p-value < 0.01; Western Gulf of Alaska: 0.84 m per year, R = 0.79, p-value < 0.01).

Dissolved oxygen in the Gulf of Alaska

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Last updated: October 2023

Description of indicator: Open and coastal ocean dissolved oxygen concentration has declined since the mid-20th century (Breitburg et al., 2018). Deoxygenation is known to be a major effect of climate change and anthropic activities, such as increased temperature that decreases oxygen solubility and winter mixing, and the eutrophication of the coastal area. The North Pacific is particularly affected by deoxygenation, with 15 % oxygen loss in the 0–3000 m water column since the 1960's, resulting in an expansion of the oxygen minimum zone (Ross et al., 2020). Low oxygen concentrations (hypoxic condition) are a major stressor for marine ecosystems and can directly endanger multiple species (Diaz, 2001). In the Gulf of Alaska, several important commercial and subsistence harvested species such as salmon, Dungeness crab *Metacarcinus magister*, Pacific cod eggs *Gadus macrocephalus* and bivalves (in the early life stage) are known to be sensitive to different thresholds of oxygen concentrations (Carter et al., 2008; Halley et al., 2017; Glober et al 2021; Berger et al., 2021; Alderdice and Forrester, 1971).

Here, we use modeled and observed oxygen concentrations to discuss patterns and trends of oxygen in the Gulf of Alaska. Modeled oxygen concentrations were extracted from a high-resolution (4.5 km horizontal grid and 50 vertical levels) 3D coupled physics and biogeochemistry simulation of the Gulf of Alaska, known as ROMS-COBALT-GOA that covers the period 1993 to the end of 2022. The model and simulation were extensively evaluated in previous studies (Hauri et al., 2021*b*,*b*, In Press) and reproduce the main patterns of oxygen relatively well. Oxygen profiles measured by Seabird's dissolved oxygen sensor SBE 43 (often dual), installed on a rosette, are shown for Seward Line stations GAK 5 and GAK 9 during the Northern Gulf of Alaska Long-Term Ecological Research cruises (spring, summer, and fall 2018–2023). Oxygen data was converted from native .hex format to ascii .btl files using a SeaBird Electronics application called SBE Data Processing. All cruises starting in 2022 have had in situ oxygen samples collected and analyzed shipboard (Winkler titration) in order to verify SBE 45 calibration (typical replicate precision < 1 μM and a sensor accuracy within 2%). Prior to 2022, a reduced number of samples were collected shipboard and then analyzed back on land resulting in great uncertainty.

Status and Trends: There are only a few studies looking at the impact of low oxygen on the Gulf of Alaska relevant species, and only a few cite species-specific thresholds. It is important to note that these thresholds strongly depend on time and place and can vary if other environmental conditions are extreme, such as during heat waves, harmful algal blooms, acidification events, and low food events. Nevertheless, we will use the threshold for hypoxia ($O2 < 60$), which is dangerous for most species (Diaz and Rosenberg, 2008) and induce acute mortality of salmon (Carter et al., 2008), increasing the mortality of small juvenile Dungeness crab by up to 80 %, and can lead to an increase of 30 % mortality of early life stage Bivalves. We will also use the threshold $O2 < 93$ Mm, which provokes severe production impairment in salmon (Carter et al., 2008) and affects the development of Pacific cod eggs (Alderdice and Forrester, 1971).

The model shows that the ocean conditions of the seafloor in fall (lowest annual oxygen concentration)

2022 were < 60 Mm over most of the shelf and only the deepest area of the shelf was > 93 Mm (Figure 29A). The modeled time series at Seward Line station (Figure 29C) GAK 5 (located in the middle of the shelf) shows statistically significant long-term decreasing trend of oxygen, indicating a steady degradation of the habitat of sensitive organisms. A comparison between the western and eastern shelf suggests that the deoxygenation of the western shelf progresses more rapidly than in the eastern part of the shelf (Figure 29B), however, modeled oxygen concentration has not been evaluated for the eastern shelf yet. This is corroborated by the modeled yearly averaged bottom shelf oxygen concentration which also shows a steady decrease (Figure 29B).

Observed bottom O2 at GAK 5 and 9 was close to the trend line in 2023 spring and summer (Figure 29C). Since the Gulf of Alaska Downwelling Index (Figure 30B) was positive in spring and summer 2023, the on-shelf intrusion of deeper, saltier, more acidic and deoxygenated water was inhibited (Hauri et al., In Press). However, upwelling in the Alaska gyre was strong in 2022 and 2023 (negative Northern Gulf of Alaska Oscillation Index, Hauri et al. (2021*b*), which generally leads to lower pH, temperature, and oxygen concentration on the shelf. But this effect has most likely been mitigated by the lower than usual upper water temperature (due to the strong upwelling) allowing more oxygen to be dissolved into the upper layer of the water column dragging up the oxygen concentration during the winter mixing.

Water masses with O2 < 60 Mm and 93 Mm in 2022 were shallower in the western than in the eastern Gulf of Alaska (Figure 31A and B), indicating that the favorable area for organisms is smaller in the western area. The model does not show any long-term trend in the depth of water with O2 < 60 Mm and 93 Mm (Figure 31C and D), likely because of the strong decadal variability induced by the intensity of the subpolar gyre upwelling (Northern Gulf of Alaska Oscillation Index) (Hauri et al., 2021*b*), which still masks out this long-term climate change driven trend.

Factors influencing observed trends: Bottom oxygen concentration on the shelf is driven by the 1) long-term trend of climate change (Figure 1 B), 2) seasonal winter mixing that increases oxygen, and late summer remineralization of organic matter that decreases oxygen, 3) intermittent low oxygen water intrusion at the continental shelf slope in fall also decreases oxygen (Hauri et al., In Press), and 4) strength of the Alaska gyre in the open ocean that sometimes also affects the shelf area (Hauri et al., 2021*b*). Deep water intrusion occurs when the intensity of the coastal downwelling decreases and can be approximated through the downwelling index (Figure 30B) defined in Hauri et al. (In Press).

This index (computed with sea surface height satellite data) was mostly positive in 2022 and 2023 (between January and September 2023) indicating a strong downwelling activity and therefore a low probability for deep water intrusion. However, the index became positive in fall 2022 and winter 2023, likely allowing intrusion of deeper and O2 poorer water onto the shelf. Modeled and observed bottom oxygen concentration was exceptionally low at the shelf slope (GAK 9).

The depth of water with O2 < 60 Mm and 93 Mm in the offshore area of the western Gulf of Alaska is affected by sub-decadal climate oscillations that drive the strength of the Alaska gyre. The intensity of the subpolar gyre upwelling in this area can strongly influence the oxygen concentration in the upper water column offshore and on the shelf and can be estimated with satellite sea surface height through the Northern Gulf of Alaska index (Figure 30A) (Hauri et al., 2021*b*). In a weak Alaska gyre upwelling year, such as 2019, the NGAO is positive, the subpolar gyre is weaker than usual leading to a more oxygenated upper water column. In 2023 (as in 2022) this index is strongly negative, indicating a strong upwelling activity in the Alaska gyre and therefore low oxygen conditions in the upper water column, including the shelf.

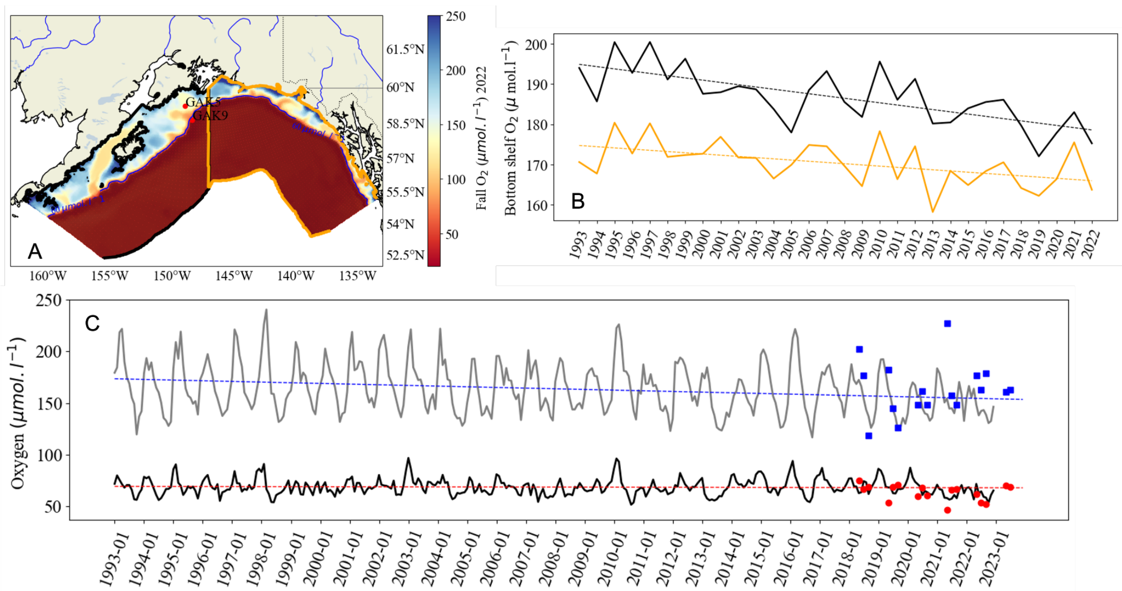

Figure 29: A map of fall 2022 (Sept. Oct., Nov.) bottom oxygen concentration (µmol/l) (A). Polygons show the western (black) and eastern (orange) Gulf of Alaska. The dark red area shows portions of the domain deeper than 500 m where the model vertical resolution decreases. The time series (B) of the modeled temporal evolution of oxygen concentration at the bottom of the western shelf (0–500 m, black line) and eastern shelf (0–500 m, orange line). The dotted lines illustrate the trend for the western area (-0.56 % per year, R = 0.7, p-value << 0.01) and for the eastern area (-0.3 % year, R = 0.49, p-value < 0.01). Modeled temporal evolution of oxygen concentration at the bottom of the Seward Line stations GAK 5 (gray line) and GAK 9 (black line) between 1993 and 2022 (bottom depth of 170 m for GAK 5 and 280 m for GAK 9) is shown in C. Observations (2018–2022) are illustrated as red circles at GAK 9 and blue squares at GAK 5. The dotted line shows the linear regression for each time series (GAK5, -0.64 micro mol/l/year, R = 0.23, p-value << 0.01 and GAK 9, not significant, p-value> 0.01).

Implications: DO conditions in 2022 were not of concern for GOA groundfish. DO, in combination with bottom temperature and pH, are oceanographic characteristics that can cumulatively impact groundfish habitat, affecting distribution and potentially survival (Hauri et al., In Press). Dissolved oxygen is projected to decrease in marine waters as temperatures increase with global warming. Decreased DO at depth may limit the availability of deeper waters as refuge from warmer temperatures. Some deeper-dwelling slope adult groundfish, including thornyhead (*Sebastolobus* spp.; 100–1,200m), rougheye (*S. aleutianus*), blackspotted (*S. melanostictus*; 300–500m), and shortraker rockfish (*S. borealis*; 300–400m), already live in reduced oxygen environments. A decrease in DO in those habitats may drive shifts in distribution to shallower waters (Thompson et al., 2023).

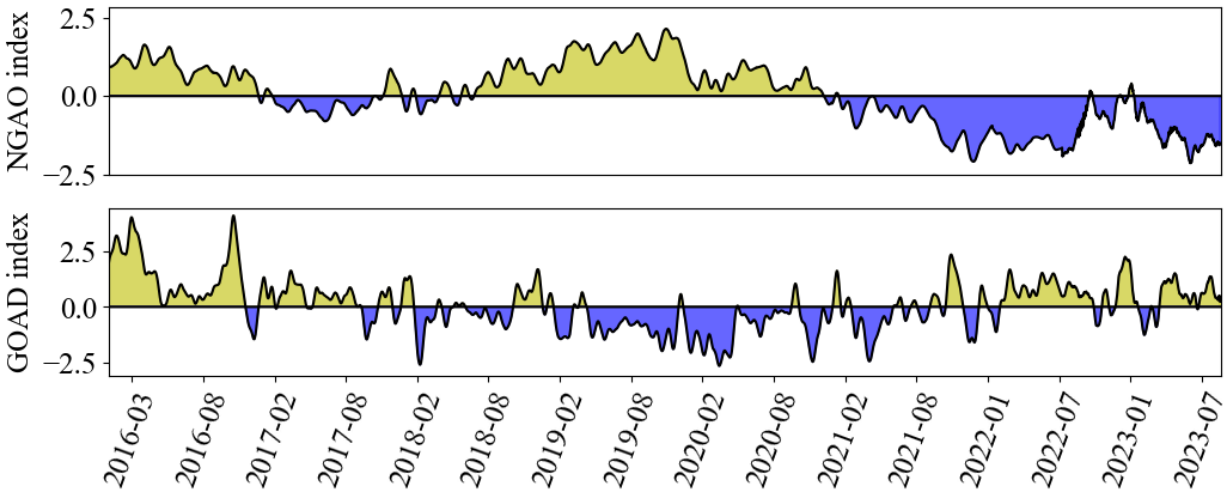

Figure 30: Northern Gulf of Alaska Oscillation index (NGAO) and Gulf of Alaska Downwelling Index (GOADI). Time series of the normalized principal component associated with the first (top, NGAO) (Hauri et al., 2021*b*) and the second (bottom, GOADI) (Hauri et al., In Press) Empirical Orthogonal Function (EOF) mode of sea surface height obtained by satellite `https://doi.org/10.48670/moi-00148`.

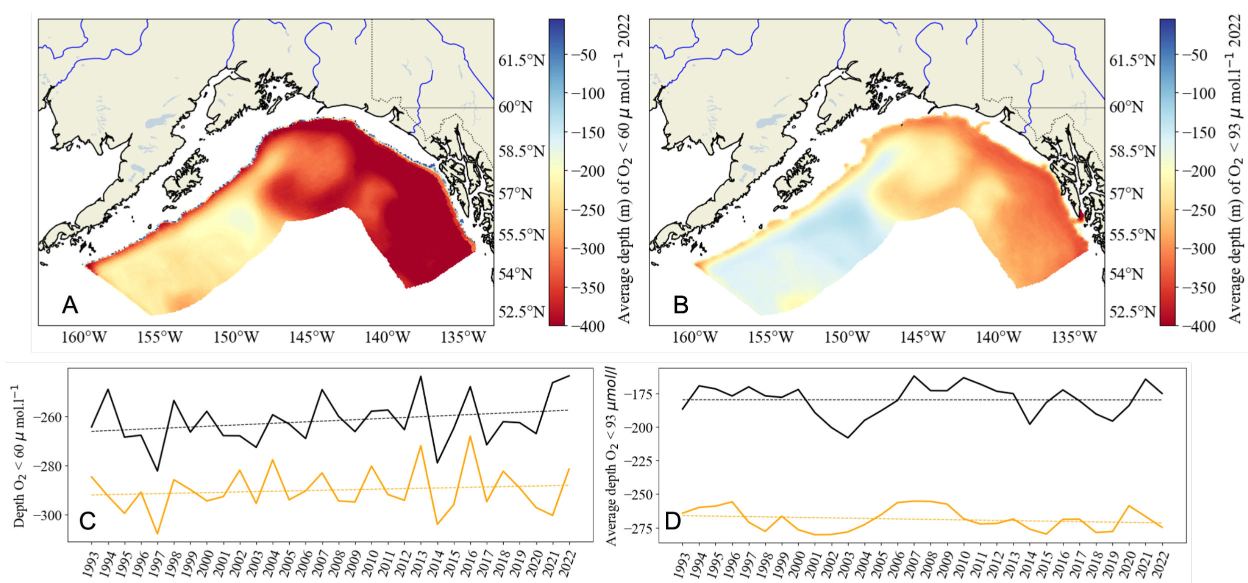

Figure 31: Map of annual average (2022) water depth with oxygen concentration < 60 μmol per l (A) and oxygen concentration < 93 μmol per l (B). Time series of annual averaged water depth with oxygen concentration < 60 (C) and oxygen concentration < 93 (D) for the western (black) and eastern (orange) Gulf of Alaska. The dotted lines show the trend however they are not statistically significant p-value > 0.01.

Primary Production

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

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Last updated: September 2023

Description of indicator: Phytoplankton provide 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 abundant 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 a phytoplankton bloom varies annually and may play an important role in the success of cohorts each year. We used 8-day composite satellite chla data average concentrations from April–June, across the eastern and western GOA (divided at 147^0W), to capture the spring bloom. The focus coastal areas (on the continental shelf; depths 10 – 200m) coincide with major fish and zooplankton feeding and spawning areas. We summarized the magnitude of the annual spring event (Figure 32) as well as a chronology of phytoplankton concentrations throughout the season to improve resolution of annual phenologies. 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, which adds uncertainty to our assessments. Detailed methods are available[15].

Status and trends: The spring bloom progresses from inshore to offshore for the eastern GOA, while the western GOA is more complex with high inter-annual variability for the whole time series (timeseries: 2002 – -2023, Figure33). For both the eastern and western GOA, there has been consistently lower than average chlorophyll-a spring bloom peaks since 2015 (except 2018 in the eastern GOA), with 2023 the lowest overall. Additionally, the peak bloom timing for both areas have been average-late for the low chlorophyll-a years with the exception of 2017 in the eastern GOA. The timing of the 2023 spring bloom was considerably late in western GOA (the WGOA 2003 – 2022 mean occurred on day 136; ~May 16), and about average for eastern GOA (the 2003 – 2022 mean occurred on day 131; ~May11) with a second increase in chlorophyll-a later in the season.

Factors influencing observed trends: Given the complexity of phytoplankton, a number of factors may be contributing to the low chlorophyll-a concentrations. Mesoscale eddies play a large role in the GOA

[15] `https://github.com/MattCallahanNOAA/ESR/tree/main/Chla`

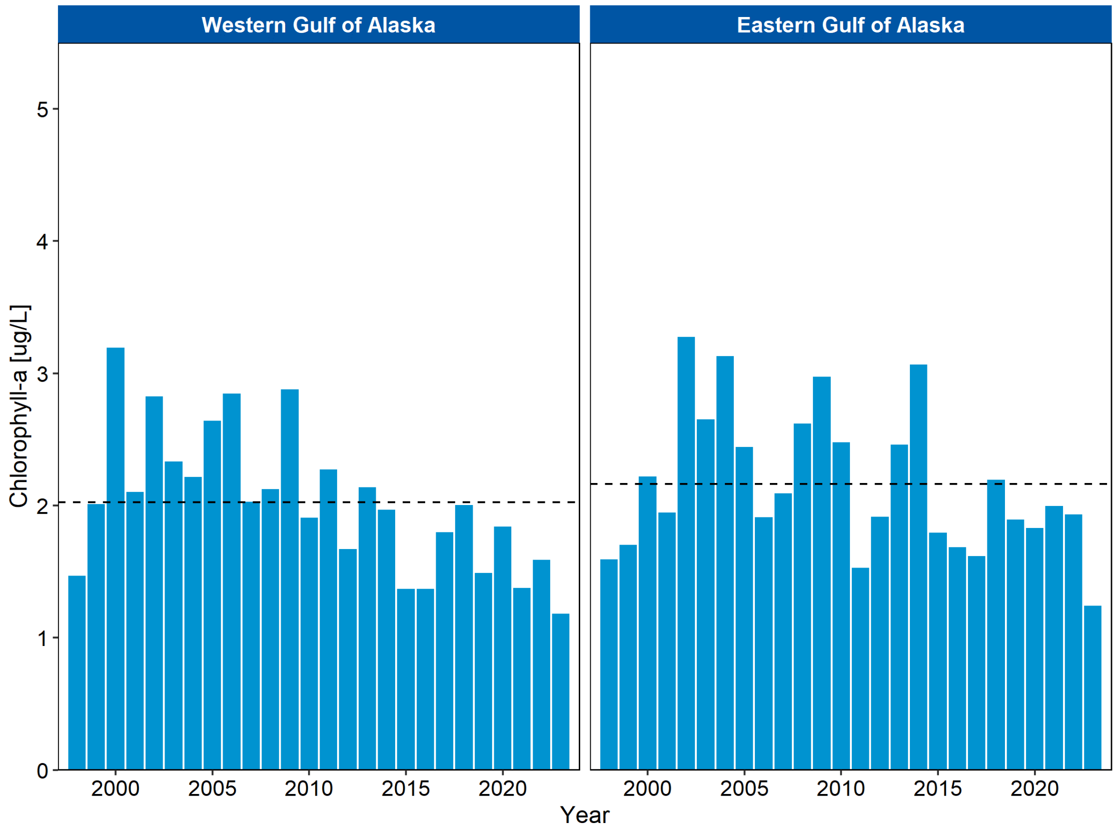

Figure 32: Average spring (April-June) chlorophyll-a concentrations based on MODIS satellite 8 day composites for the western and eastern GOA. The horizontal dashed line is the long-term mean (2003 – 2022).

chlorophyll patterns offshore of the continental shelf, with evidence of influence via eddy-moderated shelf-slope exchange creating phytoplankton 'hot spots' over the shelf (Okkonen et al., 2003). Additionally, spring runoff and ambient nutrient concentrations can affect timing of blooms over the shelf (Waite and Mueter, 2013). It is unclear why 2023 has such low chlorophyll-a or why the annual trend is down for recent years, but it's notable that satellite chlorophyll-a for the Aleutian Islands is showing a similar trend this year, with some lower concentrations found in areas of the EBS as well.

Implications: Timing and magnitude of peak chlorophyll concentrations are important for gauging general food availability for zooplankton and are thus also relevant for many of the planktivores that rely on zooplankton. In the eastern GOA, chlorophyll inter-annual variations are correlated with zooplankton biomass, which in turn are correlated with annual catch yields of resident fishes (Ware and Thomson, 2005). Factors affecting phytoplankton blooms can be complicated, and more extensive work is required to resolve any direct connections between groundfish recruitment and chlorophyll concentrations. Chlorophyll-a concentrations for the entire GOA have been consistently low in recent years, with 2023 marking the lowest over both time series. Both systems have also seen average to late bloom times, although the implications of these trends are unclear. The magnitude and timing of this years' chlorophyll-a spring bloom patterns in both the eastern GOA and western GOA seem to be unique when compared to previous years.

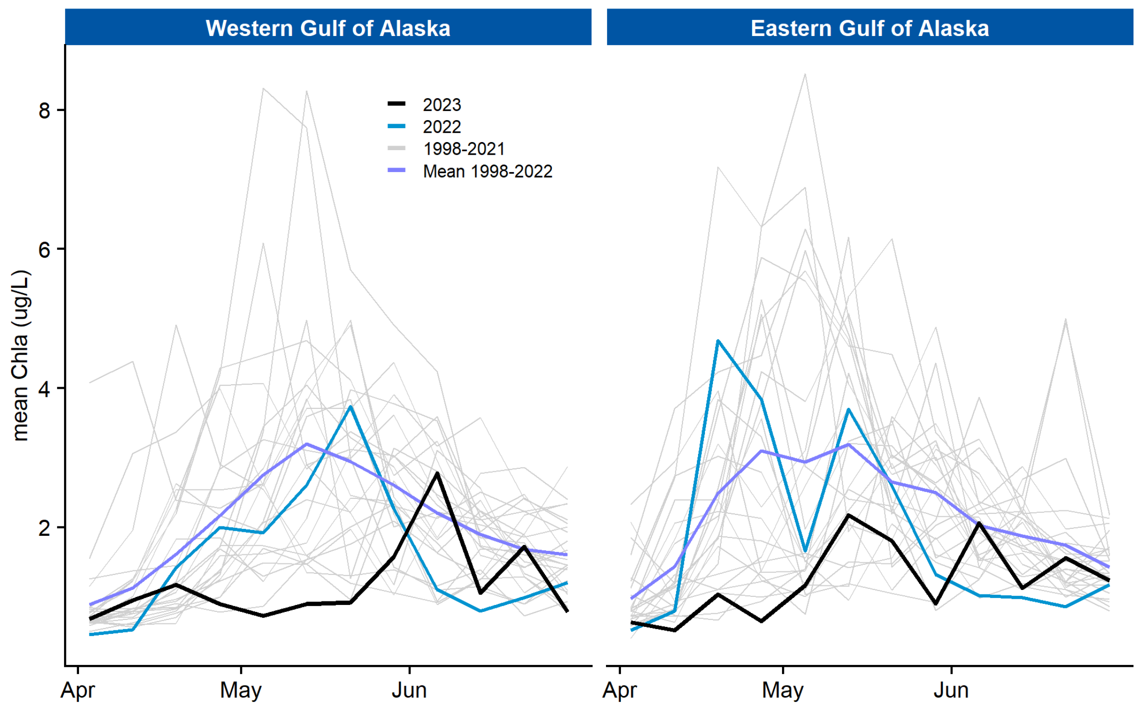

Figure 33: Average 8 day composite chlorophyll-a concentrations for the western and eastern GOA from April to July. The mean chlorophyll-a is represented by the black line in 2023, the blue line in 2022, and the gray line for all previous years. The purple line is the long-term mean (1998 – 2022). The average peak bloom occurs on day 136 (approximately May 16) in the western GOA and day 131 (approximately May 11) in the eastern GOA. For reference, days of year 100 and 180 fall around April 9 and June 30, depending on leap years.

Seward Line May Phytoplankton Size Index

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Last updated: August 2023

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 μm and > 20 μm) 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 shelf community. The index is computed from depth-integrated shelf station of chl-a values, for each early May cruise, and is equal to the fraction total chl-a found in the large (> 20 μm) size class (i.e., chl-a$_{>20}$ / chl-a$_{\text{total}}$). In most cases, 9 stations are averaged to generate the index. 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. Comparison with remote sensing-based estimates of spring bloom timing and magnitude shows that the size index is a predictor of two important aspects of the spring bloom. 1) When the index is (≤ 0.25, meaning that small cells strongly dominate), the spring bloom begins and peaks relatively late in the year. 2) When the index is ≥ 0.5, meaning that large cells comprise half or more of the total chl-a, the value of the index is strongly correlated ($r^2 = 0.65$) with the cumulative magnitude of the spring bloom (April – June) as measured by remote sensing.

Status and trends: The index for May 2023 was 0.69, predicting an average spring bloom magnitude relative to the time series (2001 – 2022, Figure 34). Data from later spring satellite imagery and late June at-sea observations show an extended spring bloom period for 2023. No long-term secular trend is evident in the phytoplankton size index, although there is a suggestion that variance has increased in recent years. 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. The past two years (May 2021 and 2022) had some of the highest index values in the time series (0.94 and 0.87, respectively), consistent with the intense diatom blooms that occurred relatively early in those years.

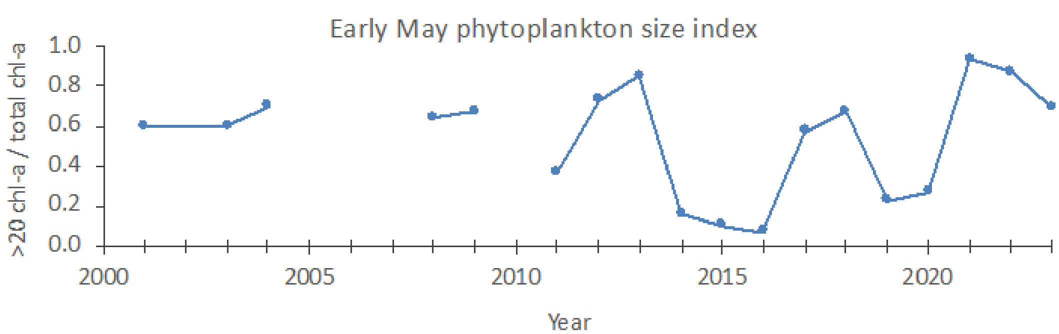

Figure 34: May 2001–2023 time series of phytoplankton size index (fraction of total chl-a present in cells $>$ 20 μm) for the Seward Line shelf stations.

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 probably has little direct influence, as the temperature 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., copepod, euphausiids). Low values of the size index correspond to phytoplankton communities dominated by small flagellates and cyanobacteria, which are less available to large zooplankton and may lead to less efficient transfer of primary production to higher trophic levels. A late spring bloom could 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, in the water column and the benthos.

Seward Line Spring Oceanography

Contributed by Seth Danielson[1], Hank Statscewich[1], Tyler Hennon[1], Tom Kelley[1], Ed Farley[2], Dave Kimmel[2], John Horne[3], and Calvin Mordy[3]
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Last updated: August 2023

Description of indicator: In the Gulf of Alaska and the Bering Sea, a number of commercially important species (e.g., walleye pollock and Pacific cod) have evolved a life history strategy that distributes eggs and larvae through the months preceding and surrounding the spring bloom (Doyle and Meier, 2016). Annually repeated glider transects provide cost-effective means to collect physical, chemical and biological data that can meaningfully characterize the spring bloom and other key facets of the marine ecosystem. Our deployments focus data collections that capture conditions from late winter through the onset of the spring bloom. Glider data are available for near-real-time viewing and download through the Alaska Ocean Observing System (AOOS) Ocean Data Explorer webpage. Trackline and data shown here are from the 2023 February-April Gulf of Alaska Seward Line transect (Figure 35).

Status and trends: The first glider was deployed in Resurrection Bay on February 15th, and it flew along the Seward Line to the mid-shelf region where it subsequently kept station between GAK6 and GAK7 (about 50 miles offshore) until recovery on the spring LTER cruise in early May. The data from this station-keeping glider showed that the spring bloom at this station was triggered by a combination of the seasonal increase in light conditions, a period of weak winds, and a shoaling of the mixed layer depth that coincided with a sharp increase of the near-surface stratification (Figure 36).

The second glider was deployed in Resurrection Bay on March 22, and this one flew across the whole Seward Line to beyond GAK15 and was then recovered on May 6th near GAK11. The second glider saw the spring phytoplankton bloom initiate about May 1st, but this also was a short-lived event and it was likely associated with a big anticyclonic eddy that was sitting at the end of the Seward Line.

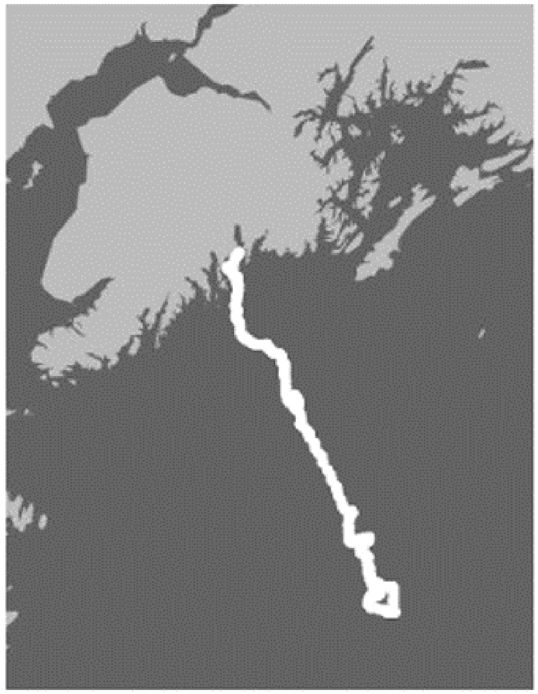

Figure 35: Trackline of spring glider from February-April, 2023, Gulf of Alaska Seward Line transect. The bloom onset is marked by the vertical dashed line.

Factors influencing observed trends: The bloom onset (Figure 36; dashed line) was the consequence of multiple environmental factors aligning, including increased stratification and decreased mixed layer depth. The two gliders helped show that the spring phytoplankton bloom was not fully synchronous across the Seward Line in 2023 and short-lived blooms can be influenced by regional eddies.

Implications: The characteristics of the spring phytoplankton bloom is influenced by varying physcial oceanographic characteristics. The timing and magnitude of this event can influence zooplankton productivity, groundfish larval survival, and upper trophic level feeding and reproductive success.

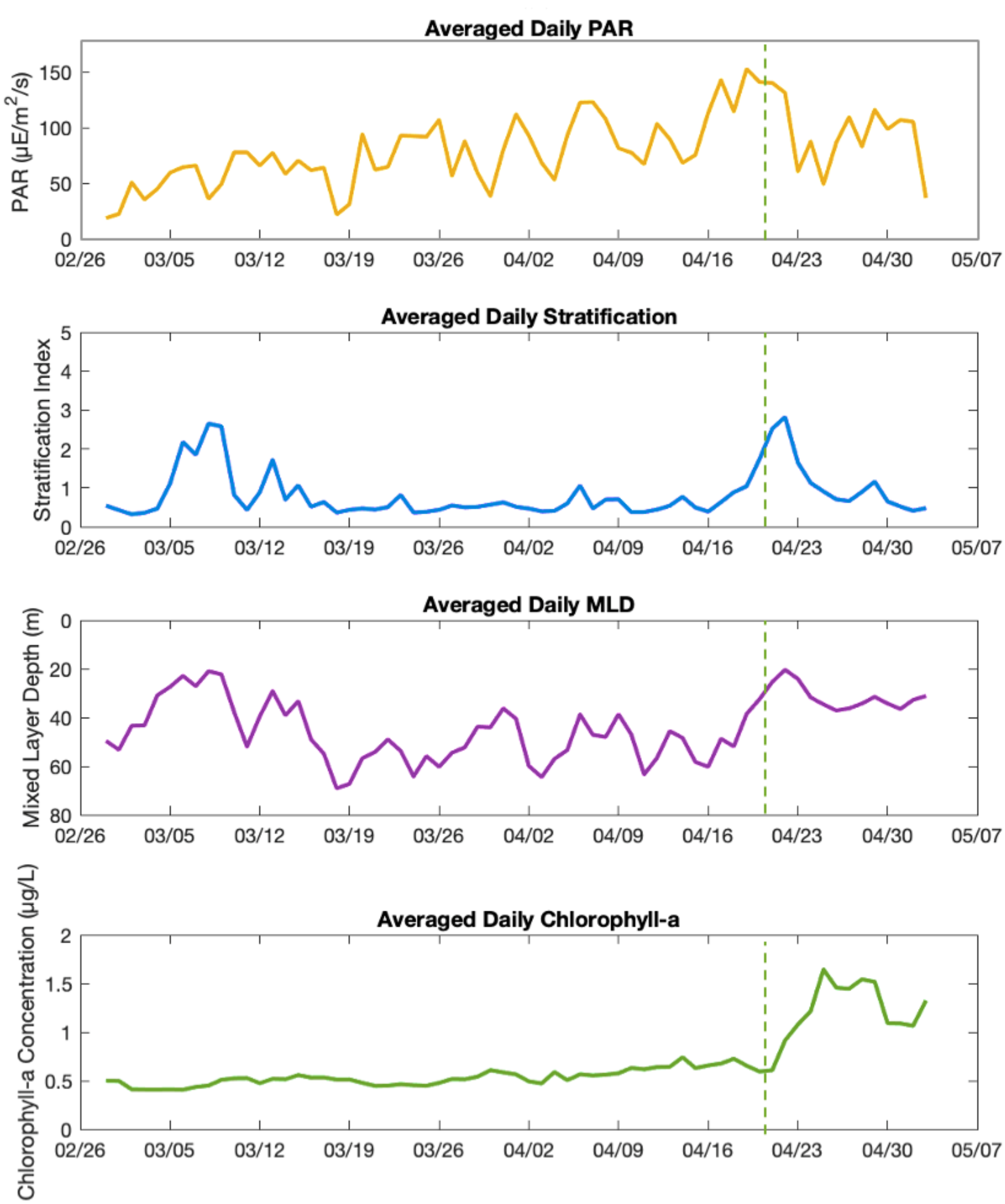

Figure 36: Daily average light, stratification, mixed layer depth and chlorophyll a concentration over the mid-shelf region as recorded by a Slocum glider (February-April, 2023).

Zooplankton

Continuous Plankton Recorder Data from the Northeast Pacific, 2002–2022

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Last updated: July 2023

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 37); 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), meso-zooplankton 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 (2002–2021 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 37). Only the red points within the shaded boxes in Figure 37 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 and the western GOA region is sampled 36 times per year, mostly by the east-west transect.

Status and trends: The diatom abundance anomaly for the shelf region was positive for 2022 and 2021 having been negative in 2020 (relative to a baseline of 2002-2021; Figure 38). On the western side of the oceanic Gulf of Alaska the diatom anomaly was also positive in 2021. On the eastern side of the oceanic Gulf of Alaska the diatom abundance anomaly was negative for the last three years, with the strongest negative anomaly of the time-series appearing in 2021. The copepod community size anomaly was mostly negative in all regions in the last 5 – 7 years, but it has oscillated in the Alaskan shelf to a positive anomaly in 2021 and 2022. Zooplankton biomass anomalies were positive in both the Shelf and eastern Gulf of Alaska regions in 2020, but have switched to negative in 2021, while the anomaly

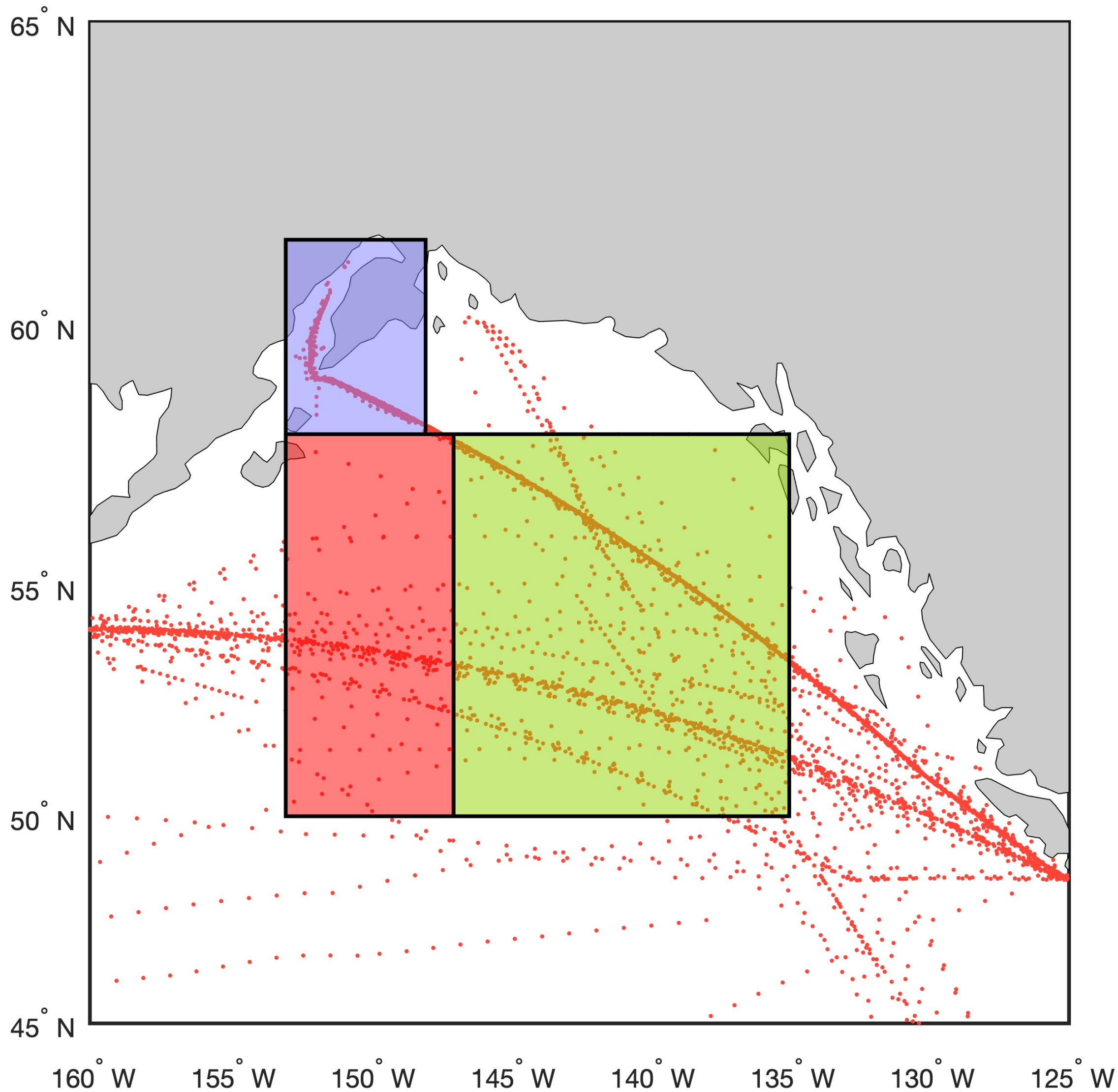

Figure 37: Location of the data used in this report, highlighted as Alaskan shelf (blue rectangle), eastern Gulf of Alaska (green rectangle), and western Gulf of Alaska (magenta rectangle). Red dots indicate actual sample positions (note that for the shelf region the multiple transects overlay each other almost entirely).

has remained negative in the western side of the Gulf of Alaska. The zooplankton biomass anomaly in 2021 in the eastern Gulf of Alaska is the most negative it has been for the timeseries presented.

Factors influencing observed trends: The Pacific Decadal Oscillation (PDO) monthly values were often negative in 2017 causing a lower annual mean value compared to the years of 2014 – 2016, which had experienced a marine heat wave (Di Lorenzo and Mantua, 2016). 2022 appears to be another warm year despite a negative PDO and Oceanic Niño Index (ONI). In warm conditions smaller species tend to be more abundant and the copepod community size index reflects this and was mostly negative throughout the marine heat wave periods of 2014 – 2016, and 2018 – 2020. The large diatom abundance was positive in 2022 in the shelf and western regions, however in the eastern GOA regions there is a lower than average diatom anomaly. It is unclear what has led to the decrease in diatom abundance in this region, but in the shelf and western Gulf of Alaska, it could be that the decreased meso-zooplankton

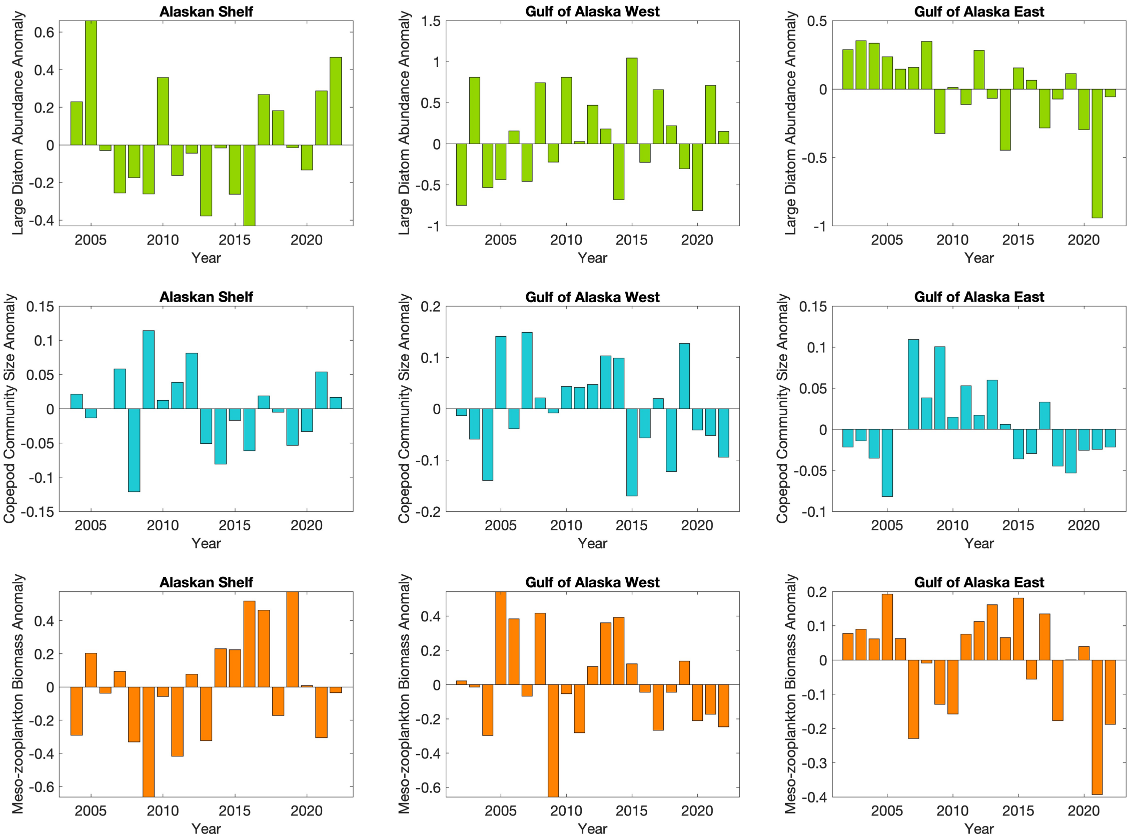

Figure 38: Annual anomalies of three indices of lower trophic levels (see text for description and derivation) for all three regions shown in Figure 37. Note that sampling of the shelf region did not begin until 2004.

biomass provided decreased grazing pressure and therefore an increase in the diatom abundance.

Implications: Each of these variables is important to the way that ocean climate variability is passed through 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.

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

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Last updated: August 2023

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. 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 ($>$ 2mm; example species: *Calanus marshallae* and *Neocalanus* spp.), and euphausiids ($>$ 15 mm; example species: *Thysanoessa* spp.). Small copepods were counted from the 153 μm mesh, 20 cm bongo net. Large copepods and euphausiids were counted from the 505 μm mesh, 60 cm bongo net. Other, rarer zooplankton taxa were present but were not sampled effectively with the on-board sampling method. RZA abundance estimates may not closely match historical estimates of abundance as methods differ between laboratory processing and ship-board RZA, particularly for euphausiids which are difficult to quantify accurately (Hunt et al., 2016). Rather, RZA abundances should be considered estimates of relative abundance trends 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. There were two surveys in 2023 and both were reduced in both spatial and temporal scope due to staffing shortages on the *Oscar Dyson*. The spring larval survey reports data from May 16 to May 21 and the summer age-0 survey from Sept. 4 to Sept. 11. Enough samples were collected within the core areas that both time-series were able to be updated. We also revised the time-series to correct error-bar miscalculations and standardize all gear types across the time-series. In addition to abundance estimates, the total lipid content for the zooplankton categories of large copepods and euphausiids was estimated. Zooplankton were collected separately in glass vials from each station, stored frozen, and analyzed at NOAA Auke Bay Laboratories following (Pinger et al., 2022). 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, a method which was proven to be highly accurate for analyzing zooplankton lipids in a recent inter-laboratory cross validation study (Pinger et al., 2022).

Status and trends: Large copepods were most abundant southwest of Kodiak Island and their distribution was patchy, with high variability in the core sampling area (Figure 39). Small copepods were moderately abundant, less patchy than the large copepods, and were abundant in the same sampling stations are large copepods (Figure 39). Euphausiid abundances were low in the core sampling area; however, large numbers were found in two locations southwest of the core sampling location (Figure 39).

Large copepods showed variability across years during spring (Figure 40). 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. Estimates for 2023 remain low and are similar to estimates since the occurrence of the marine heatwave of 2014–2016. Small copepods have had elevated abundances during recent sampling, particularly during the marine heatwave of 2014–2016 and in 2019, and abundances in 2023 are lower than those observed recently (Figure 40). Euphausiid abundances are typically low during the spring in the historical record; however, recent estimates have been higher, including 2023 (Figure 40). It is important to note the scale in the euphausiid time-series as the recent abundance increases are not large in magnitude, increasing by only 1–2 individuals m^{-3} (Figure 40).

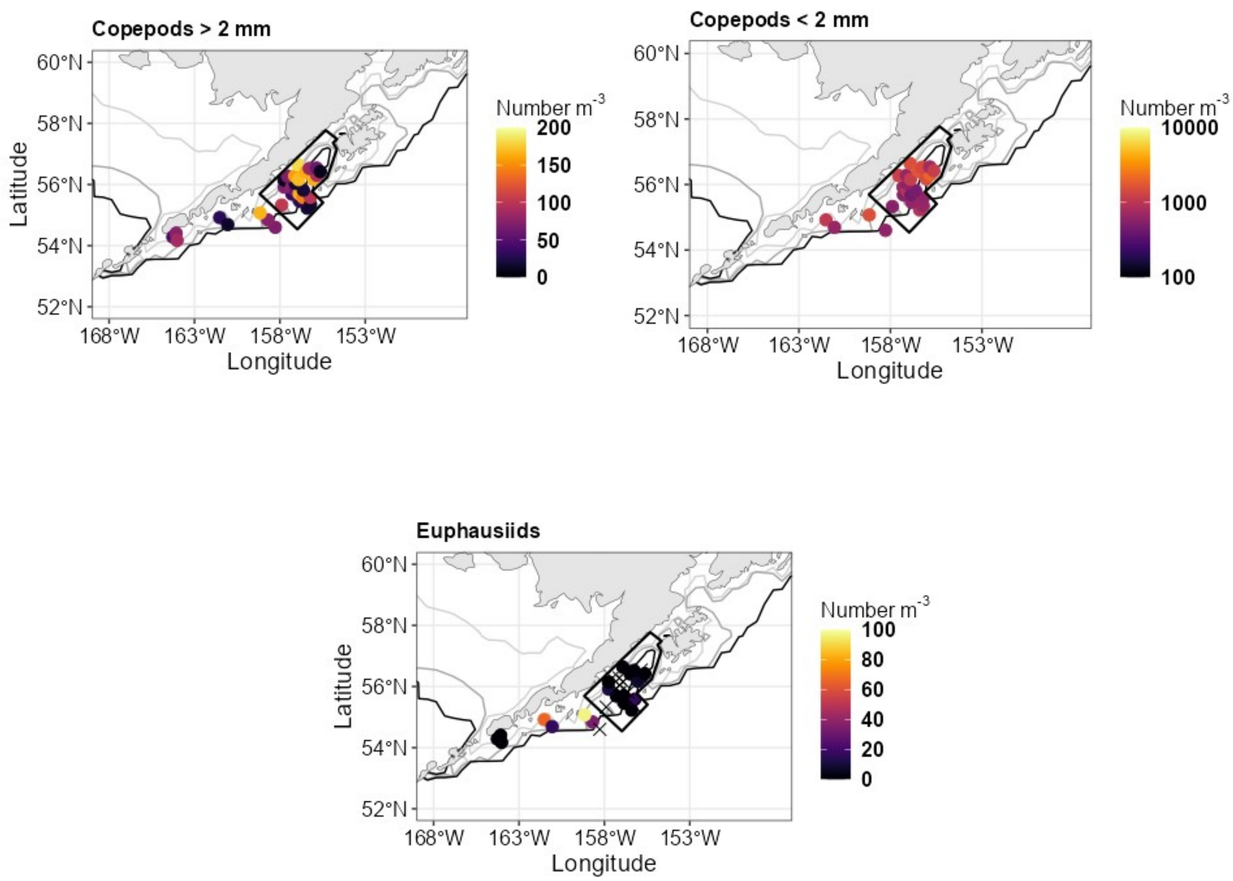

Figure 39: Maps show the spring abundance of large copepods, small copepods, and euphausiid larvae/juveniles estimated by the rapid zooplankton assessment. Note all maps have different abundance scales (number m^{-3}). X indicates a sample with abundance of zero individuals m^{-3}

A total of 9 and 15 samples of large copepods and euphausiids were analyzed, respectively, for percent lipid per wet weight. Large copepod lipid content was variable throughout the core sampling area (Figure 41) and lower on average (mean= 4.05, SD = 4.08) than euphausiids (mean = 6.26, SD = 3.92), with both taxa showing highest values nearshore and southwest of Kodiak Island (Figure 41) as has been observed in the past.

Large copepod numbers were similar throughout the core sampling area during the late summer age-0 survey, with only a few stations having high abundances (Figure 42). Small copepods were more abundant than spring and had similar abundances throughout the core sampling area (Figure 42). Euphausiid abundances were patchy within the core sampling area and overall abundances values were similar to spring (Figure 42).

Late summer, large copepod abundance declined from the early 2000s until the marine heatwave of 2014–2016 (Figure 43). Overall, large copepod numbers were similar to recent years and slightly higher than the marine heat wave years (Figure 43). Small copepod abundances show little variability during the summer and the 2023 RZA estimate was low both in relation to the entire data record and lower

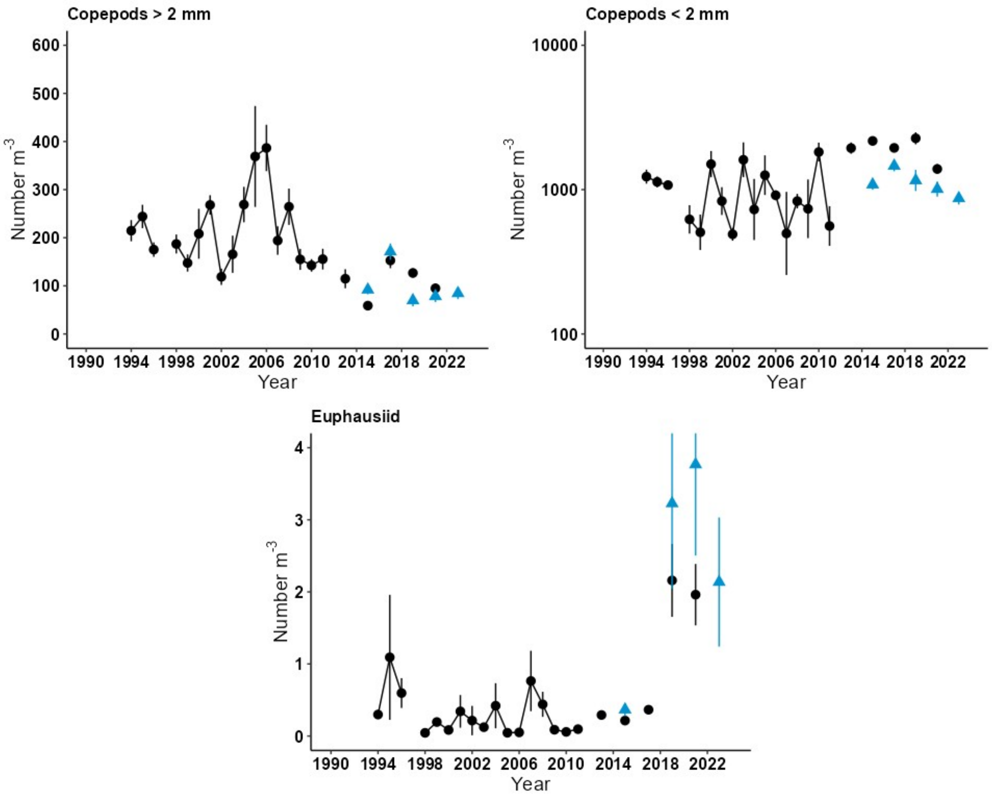

Figure 40: Mean abundance of large copepods (> 2 mm), small copepods (< 2 mm), and euphausiids (< 15 mm) in western Gulf of Alaska during spring (May-June). Black circles represent archived data, blue triangles represent RZA data. Note differences in scale.

than the marine heat wave years (Figure 43). Finally, average euphausiid abundances appear to have increased since the dip observed in 2015 and abundances in 2023 were higher than more recent years, with the exception of 2019 (Figure 43).

A total of 32 and 24 samples of large copepods and euphausiids were analyzed, respectively, for percent lipid per wet weight during the summer survey. Lipid content for both copepods and euphausiids was higher than values observed in spring (Figures. 41, 44). Large copepod lipid content was variable throughout the sampling area and lower on average (mean = 10.32, SD = 7.53) than euphausiids (mean = 13.8, SD = 8.07), with both taxa showing highest values nearshore and southwest of Kodiak Island (Figure 44).

Factors influencing observed trends: Cooler temperatures were observed relative to recent years in the western Gulf of Alaska during 2023. This resulted in average conditions during the spring where large copepods were low on average, but patchily distributed with high abundances in some locations (Figure 39). Large copepods were a mixture of *Neocalanus* spp. and *Calanus marshallae*. Increased abundances of large copepods are typically observed during warm springs, as in 2003–2005, likely due to increased abundances of *C. marshallae* (Kimmel and Duffy-Anderson, 2020) that are developing to later stages more quickly (Figure 40). Cooler temperatures likely reduced the development rate of *C. marshallae* into the summer when moderate abundances of these large copepods were observed (Figure 40). Small copepod abundances were reduced in spring (Figure 39) and this makes sense with respect to life history characteristics of small copepods, e.g., multiple generations per year, faster turnover times,

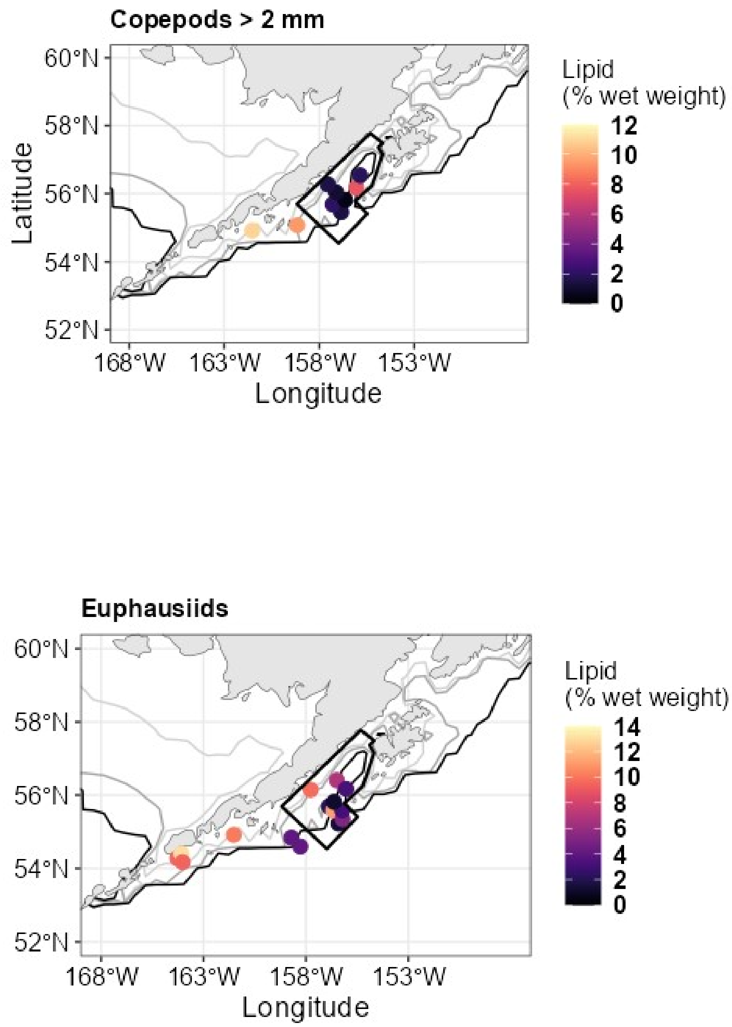

Figure 41: Lipid content (% wet weight) for large copepods (> 2mm) and euphausiids (> 15 mm) collected during the survey.

and metabolic rates that scale less dramatically with temperature (Kiörboe and Sabatini, 1995). Thus, cooler temperatures reduced the rate at which small copepod population increased. Recent warm years had high abundances of small copepods in spring and numbers in 2023 were lower than those peaks (Figure 40); summer abundance also showed this trend (Figure 43). As is typically the case, euphausiids were patchily distributed overall with low abundance in the core sampling area in both spring and summer (Figures 40, 43). This is expected due to the patchy nature of euphausiid distribution and the difficulty in accurately estimating euphausiid abundances (Hunt et al., 2016). Spring euphausiid numbers are typically low; however, numbers appear to have increased in the past three sampling years (Figure 40). It should be noted that this increase is still quite small overall, a difference of only 1–2 individuals m^{-3}. Euphausiid numbers in late summer were higher on average compared to the marine heatwave years (Figure 43). Euphausiid population dynamics remain difficult to explain in the absence of more accurate

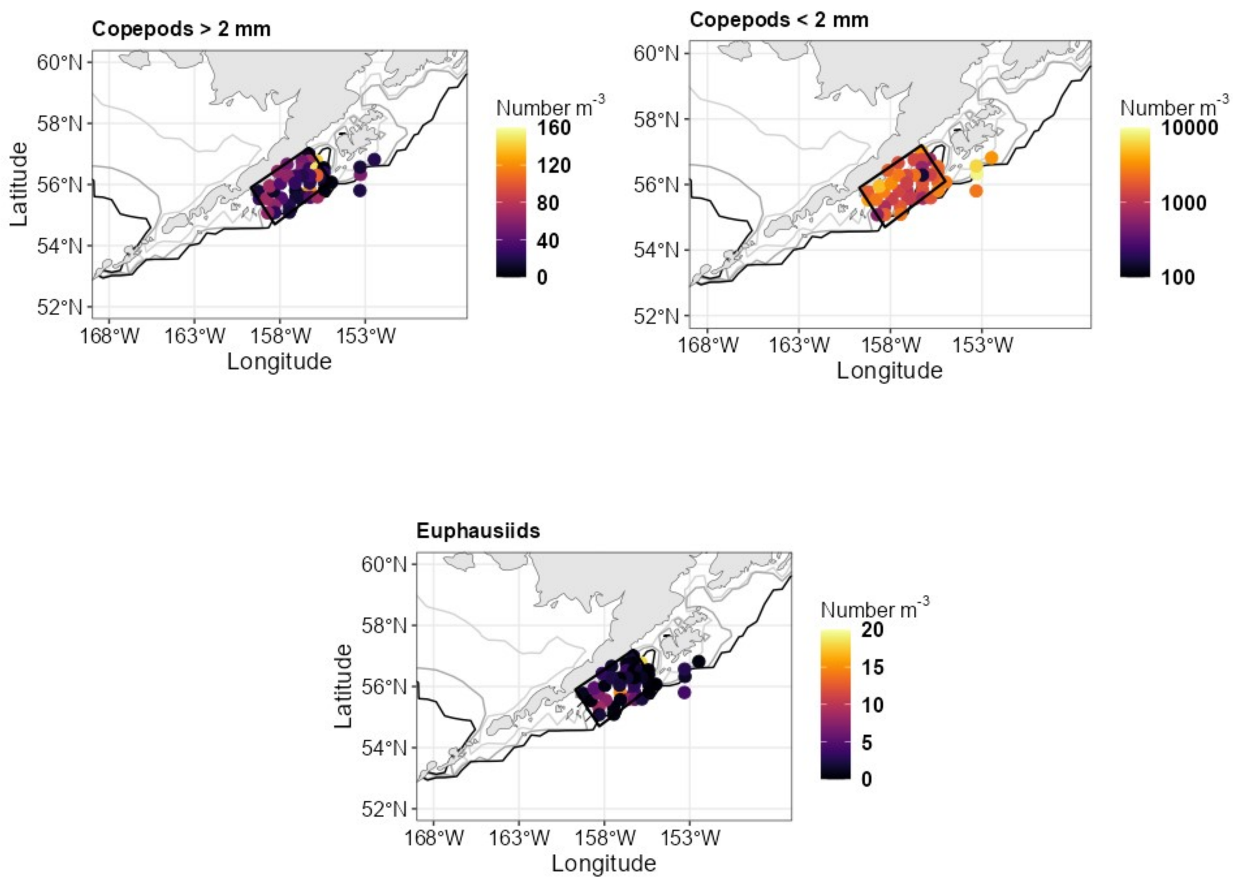

Figure 42: Maps show the abundance estimated by the RZA during the summer age-0 survey. Note all maps have different abundance scales (Number m^{-3}). X indicates a sample with abundance of zero individuals m^{-3}. Black polygon shows the core sampling area used to estimate the time-series.

temporal and spatial sampling. 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 southwest of Kodiak Island (Figure 41, 44). This was more pronounced for euphausiids, than large copepods (Figure 41, 44) 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, spring lipid content in some copepods reflected large Neocalanus spp. that were accumulating lipid prior to overwintering in the spring, resulting in large estimates at some stations (Figure 41), whereas C. marshallae copepods were generally lower in lipid during spring (Figure 41). Lipid values increased in both large copepods and euphausiids during the summer survey, reflecting an increase in lipid storage in both species prior to fall (Figure 44). Overall, euphausiids were highest in lipid content during both sampling periods and this is likely why they have been primary prey items in juvenile fish diets historically (Lamb and Kimmel, 2021).

Implications: Zooplankton are an important prey base for larval and juvenile fishes in spring and summer. While small copepod numbers were reduced relative to recent spring values, numbers remained high indicating that there is likely a significant number of nauplii and smaller copepods available as prey

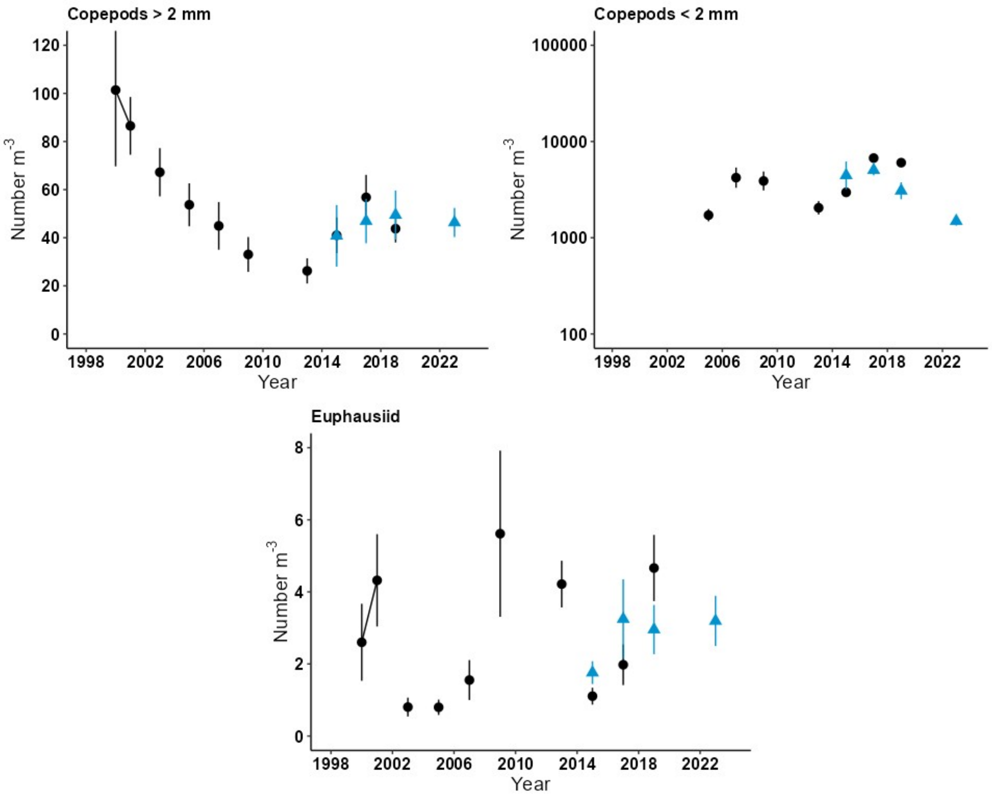

Figure 43: Mean abundance during the summer age-0 survey over time. Black circles represent laboratory processed data, blue triangles represent vessel-based RZA data. Line ranges are the standard error of the mean. Note differences in scale.

for larval fishes. Note the small copepod proportion does not include nauplii (the primary prey for early larval fishes) and recent work has suggested a decline in nauplii did occur during the recent marine heatwave (Rogers et al., 2020). Given the cooler temperatures in 2023, nauplii numbers should be adequate given the small copepod standing stock. Lipid values for both large copepods and euphausiids were lower in the spring (Figure 41) as is expected. More lipid-rich prey are more important for juveniles in the late-summer fall. The lack of large copepods is less relevant in spring when larval fishes predominate; however, it may indicate that the system timing for larger copepods is changing or may indicate shifts in overall productivity (Kimmel and Duffy-Anderson, 2020). Thus, phenological changes that have been detected for walleye pollock in the western GOA (Rogers et al., 2018) may also be occurring for copepods. Both large copepod numbers and euphausiid abundances were average during the late summer relative to long-term trends (Figure 43). Both are principal diet items for juvenile fish and these numbers appear to indicate adequate forage. A lack of large copepods and euphausiids leads to diet shifts where less energetically dense prey items are consumed (Lamb and Kimmel, 2021). Lipid estimates for the late summer indicated that large copepods and euphausiids had, on average, $> 10\%$ of their wet weight as lipid. Lipid values for large copepods would be expected to increase into fall as they prepare to overwinter. In conclusion, we suggest the zooplankton community in the western GOA in 2023 was average and likely to provide sufficient forage for the larval and juvenile fish community.

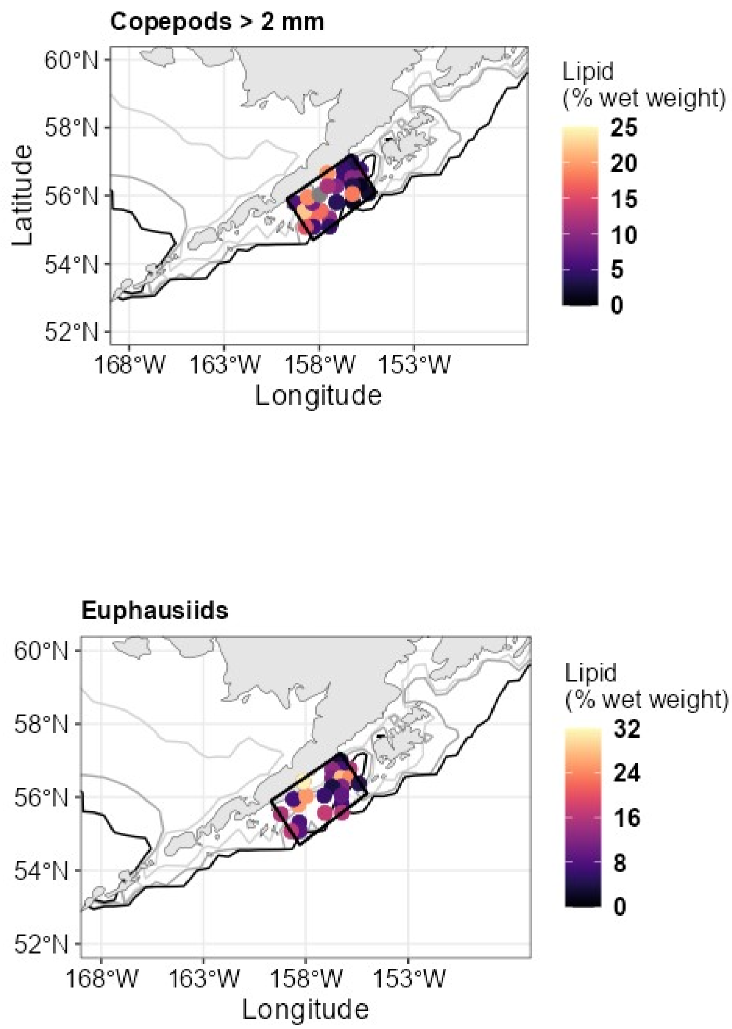

Figure 44: Lipid content (% wet weight) for large copepods (> 2 mm, Calanus spp.) and euphausiids (> 15 mm, Thysanoessa spp.) for the summer age-0 survey. Black polygon shows the core sampling area used to estimate the time-series, for reference.

Spring and Fall Large Copepod and Euphausiid Biomass: Seward Line

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Last updated: October 2023

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: Preliminary analysis suggests large calanoid biomass was lower than normal in May 2023 after a string of average years with small copepod biomass also below average (baseline 1998–2022, Figure 45). The biomass of small copepods in September has been average to below average for several years. Large copepod biomass during May often tends to track spring temperatures, because they grow faster and therefore individuals are larger when waters are warmer, however a strong spring bloom can also favor faster growth. By September most large calanoids have descended into offshore waters and their biomass is greatly reduced. Smaller-bodied copepods biomass shows less change between seasons. For both May and September 2022, and May 2023, biomass appear to be at or above average (baseline 1998–2022, Figure 45), although confidence intervals are broad with the means poorly constrained. May euphausiid biomass appears to be negatively impacted by warm springs, with peaks May often driven by high abundances of their larval stages when conditions are favorable. Continued growth and recruitment often lead to higher biomass by September.

Factors influencing observed trends: Temperatures during 2021-2023 were cooler than the 25-year thermal mean along the Seward Line during spring, but these spring phytoplankton blooms were productive (see Seward Line temperatures in this Report, p.40). September of 2021 and 2023 was also cool and this may have favored euphausiids, whereas September of 2022 was slightly warmer than normal. 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 roughly average during 2021 and 2022, their biomass during 2023 was low and may have been created challenges for some of their predators this year. The above-average biomass of euphausiids during fall 2021 and May 2022 suggests their predators may have more favorable feeding conditions compared to 2020 when fall biomass was low.

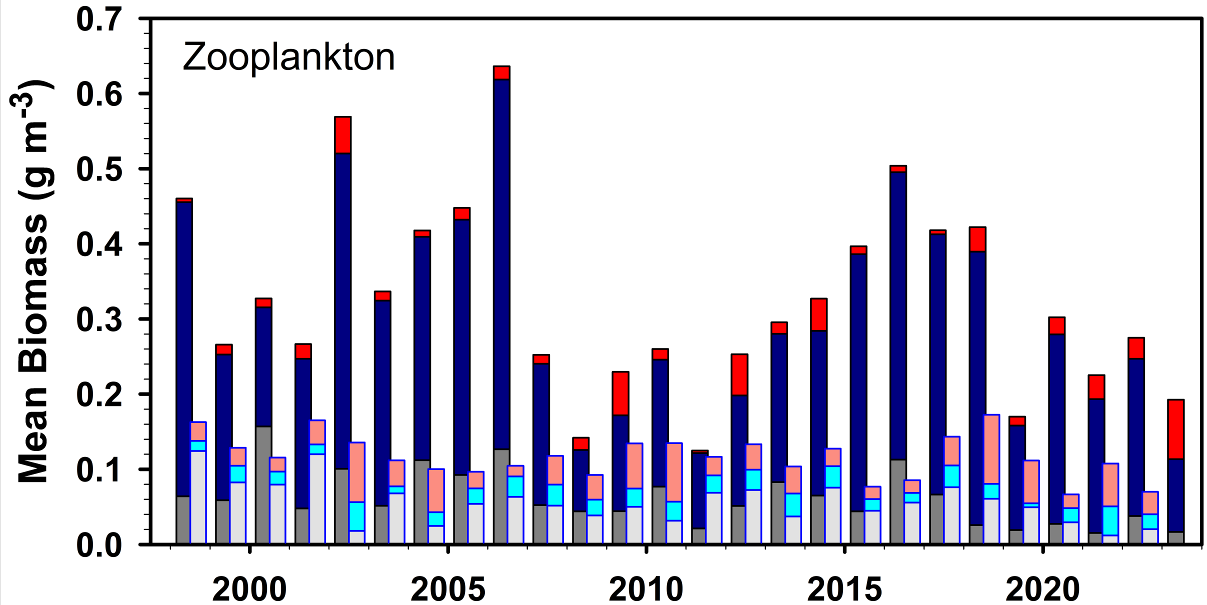

Figure 45: Biomass of calanoid copepods and euphausiids along the Seward Line sampled using a 0.5 mm mesh at night. Transect means and 95% confidence intervals are calculated on power-transformed data. Data for 2019–2023 are only available from a subset of stations and will change as more stations are completed.

Zooplankton Trends in Icy Strait, Southeast Alaska

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Last updated: September 2023

Description of indicator: The Southeast Coastal Monitoring project (SECM, 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 (Murphy et al., 2020; Fergusson et al., 2020). Annual zooplankton collections occur in Icy Strait during monthly (May to July) fisheries oceanography surveys.

This report presents the mean 2023 annual values of zooplankton density in relation to the long-term trends in taxonomic groups in Icy Strait. Zooplankton densities (number per m^3) for each group were 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 mean values.

Status and trends: Zooplankton density trends over time represent prey availability to higher trophic levels and the zooplankton community response to climate and ocean conditions. Total zooplankton density ranged from 922 to 3,420 organisms per m^3 from 1997 to 2023. Recent trends had shown increases in most taxa since 2017 however, the 2023 total density showed a stark decrease to well below the long-term average (Figure 46). During 2023, densities of large and small calanoid copepods, hyperiid amphipods, and gastropods all decreased from densities in 2022, and all were below the long-term average with the exception of large calanoid copepods. The decrease in densities to below average for most taxa indicates negative availability of selected prey utilized by larval and juvenile fish in Icy Strait.

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

Implications: The zooplankton densities in 2023 suggest neutral to negative feeding conditions for larval and juvenile fish such as larval herring, juvenile gadids, and juvenile salmon that reside in Icy Strait and inland waters of SEAK. A decrease in the abundance in preferred prey items may represent unfavorable feeding conditions, which may directly or indirectly influence early stage fish growth and recruitment. However, zooplankton nutritional quality was above average for the calanoid copepods, which, when in conjunction with the abundance data, suggest neutral feeding condition available in Icy Strait.

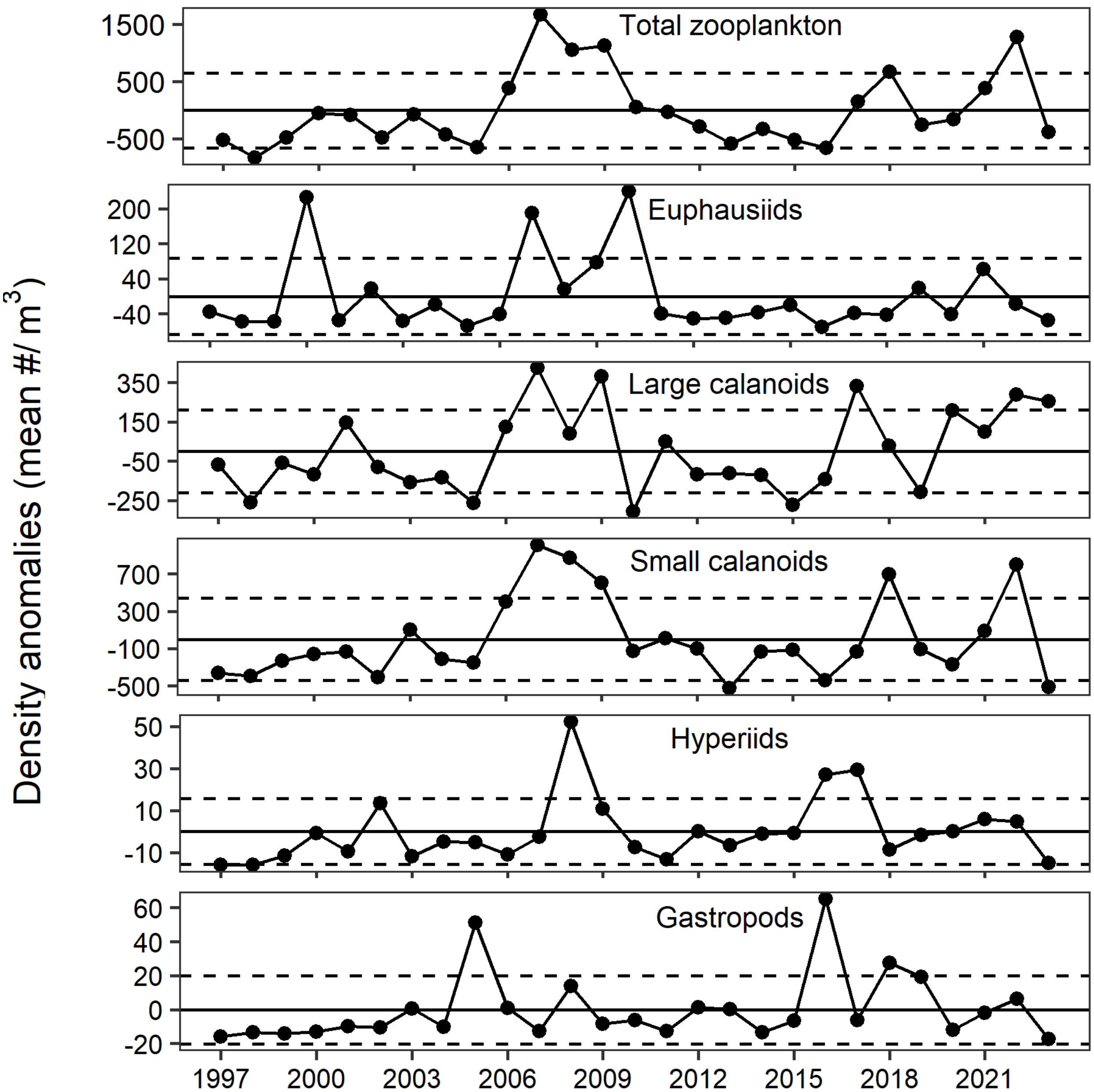

Figure 46: Average annual total zooplankton and taxa specific density anomalies for the northern region of southeastern Alaska (Icy Strait) from the Southeast Coastal Monitoring project time series, 1997 – 2023. Dashed lines denote ± 1.0 SD from the long-term mean (solid line). Annual densities are the grand mean of the monthly means from May to July in Icy Strait. No samples were available for May 2007.

Zooplankton Nutritional Quality Trends in Icy Strait, Southeast Alaska

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Last updated: September 2023

Description of indicator: The Southeast Coastal Monitoring project (SECM, 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 (Murphy et al., 2020; Fergusson et al., 2020). Spring/summer zooplankton lipid content data have been collected annually in Icy Strait since 2013.

This report presents 2023 zooplankton mean lipid content (% wet weight) anomalies for specific taxa in relation to the 11-year trend in Icy Strait. These zooplankton are an important prey resource to fish that reside in Icy Strait. These taxa include: large and small calanoid copepods, *Calanus marshallae* and *Pseudocalanus* spp., respectively, young euphausiids (furcillia and juveniles), *Limacina helicina* (gastropod), and *Themisto pacifica* (hyperiid amphipod). Total percent lipid content was determined using a modified colorimetric method (Van Handel, 1985).

Status and trends: In 2023, percent lipid anomalies for small and large copepods were positive while anomalies for *T. pacifica* were negative (Figure 47). Abundance of young euphausiids was extremely low which precluded obtaining samples for lipid analysis. For fish feeding on copepods, the positive lipid anomalies indicates positive nutritional quality while fish feeding on *T. pacifica* may encounter low nutritional quality. Trends from 2013 to 2023 for all taxa showed mean percent lipids ranging from 0.1% to 17%. Percent lipids of multiple zooplankton taxa over time represents trends in prey quality available to higher trophic levels and their energetic response to climate and ocean conditions.

Factors influencing observed trends: Subarctic zooplankton communities are influenced by physical and biological factors including basin-scale events, water temperature and salinity, advection, freshwater discharge, phytoplankton community and abundance (zooplankton food), and predator abundance (top-down control). Changes in the zooplankton community influence the food web and trophic relationships, which may alter fish growth and recruitment. For example, a complete restructuring of the North Sea zooplankton community's copepod population was observed after the 1990's regime shift (Beaugrand, 2004) that eventually propagated up the food web (Alvarez-Fernandez et al., 2012). In the Bering Sea, high-lipid copepods are more abundant during cold years relative to warm years, when lower-lipid copepods dominate the prey field (Coyle et al., 2011). The abundance of high-lipid copepods has been trophically linked to the overwinter survival of Bering Sea age-0 pollock (Heintz et al., 2013). During cold years in the Bering Sea, juvenile pollock enter winter with a higher energy content, reached by consuming a lipid-rich diet, which can drive recruitment success of age-1 pollock relative to recruitment during warm years.

Implications: The zooplankton nutritional quality in 2023 suggest positive feeding conditions for larval and juvenile stages of many commercially and ecologically important species of fish (ex. pollock, salmon, and herring) that reside in Icy Strait, which may directly or indirectly affect fish growth and recruitment. However, zooplankton abundance was below average for most zooplankton taxa, which, in conjunction

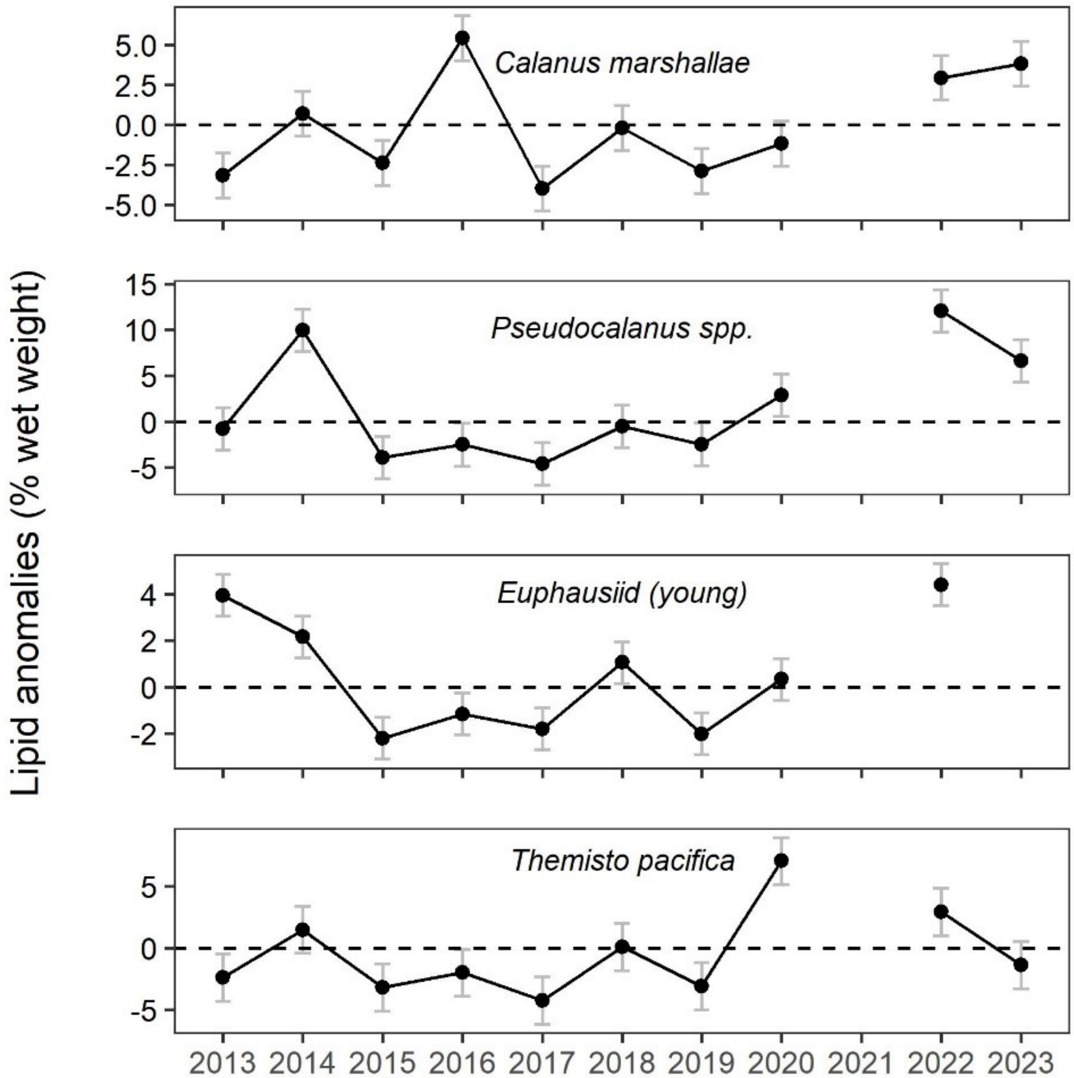

Figure 47: Lipid content (% wet weight) anomalies with error bars (standard error) from key zooplankton taxa collections in Icy Strait, AK by the Southeast Coastal Monitoring project, 2013 – 2023. The dashed line represents the time series mean lipid content. There is no data for 2021 and no data for euphausiids in 2023.

with the nutritional quality, suggests neutral feeding conditions available in Icy Strait.

Sea Jellies—Gulf of Alaska Bottom Trawl Survey

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Last updated: October 2023

Description of indicator: The Resource Assessment and Conservation Engineering Division's Groundfish Assessment Program (RACE-GAP) fishery-independent summer bottom trawl surveys in the Gulf of Alaska (GOA) are designed to assess populations of commercially and ecologically important fishes and invertebrates. Since 1990, we have deployed the same standardized trawl gear (footrope and trawl net) as is presently in use in the GOA bottom trawl survey. Sea jellies (a.k.a. jellyfish) commonly occur in the water column. Trawling operations attempt to minimize midwater catch by setting and retrieving the net quickly from the bottom. Despite this emphasis on minimizing midwater catches, we commonly collect sea jellies in our trawl catches though our trawl gear is not well suited to the intact capture of sea jellies and we recognize that the relative abundance presented here may not be representative of these organisms' true abundance in the GOA. Using these data to provide an index of relative sea jelly abundance, annual biomass estimates were scaled to the largest estimate over the time series which was then arbitrarily scaled to a value of 100 and all other values were scaled in reference to that. The standard error ($\pm$ 1) was weighted proportionally to the biomass estimate to get a relative standard error. The percentage of positive sea jelly catches in the bottom trawl hauls was also calculated.

Status and trends: In much of the GOA, relative sea jelly biomass continues to decline from it's recent high in 2019 with southeast Alaska as a potential exception to this rule (Figure 48). Sea jelly prevalence in trawl catches increases from west to east across the GOA with prevalence in recent surveys declining in the western GOA survey districts of the Shumagins and Chrikof, increasing in the central survey districts of Kodiak and Yakutat, and remaining fairly stable and high in southeast Alaska.

Factors influencing observed trends: Unknown

Implications: The primary habitat for these animals is open water and, therefore, the observed patterns of abundance and prevalence could reflect differing oceanographic conditions across the GOA survey area. Alternatively, the observed patterns could reflect that the spatial and temporal progression of the bottom trawl survey that begins in the western GOA in May and moves eastward during the summer until the survey is completed in August in southeast Alaska. More directed study of the ecology and biology of the species in this group is needed to develop a mechanistic understanding of their distribution and abundance patterns.

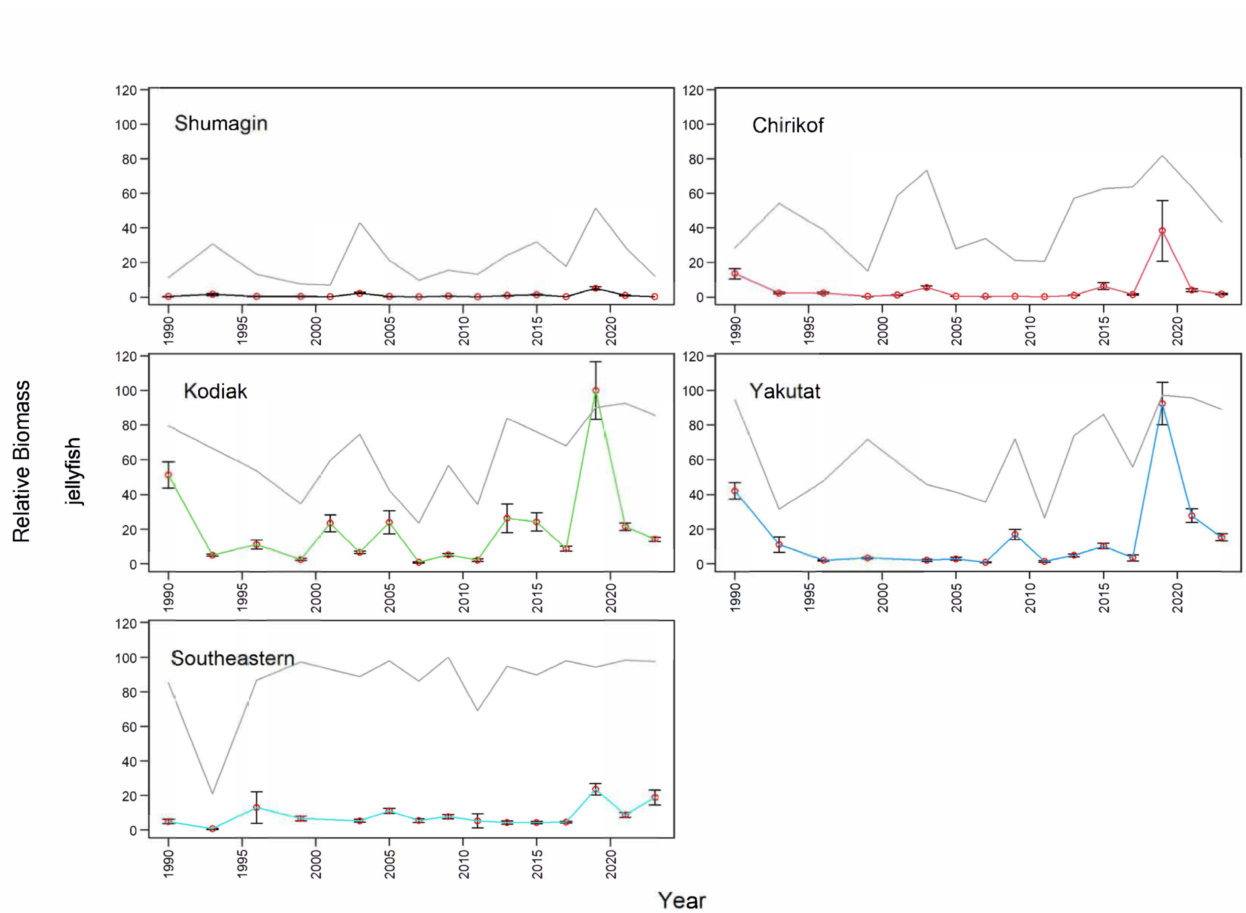

Figure 48: Relative biomass estimates of sea jellies (a.k.a. jellyfishes) collected from International North Pacific Fisheries Commission (INPFC) statistical districts during fishery-independent summer bottom trawl surveys of the Gulf of Alaska (1990–2023). Error bars represent standard errors and the gray lines represent the prevalence (percentage) of non-zero catches for this group.

Ichthyoplankton

Larval Fish Abundance in the Gulf of Alaska 1981–2023

Contributed by Lauren Rogers, and Kelia Axler
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Last updated: September 2023

Description of indicator: The Alaska Fisheries Science Center's (AFSC) Ecosystems and Fisheries Oceanography Coordinated Investigations Program (EcoFOCI) conducts spring larval fish surveys in the Gulf of Alaska (GOA), with annual sampling from 1981 – 2011 and biennial sampling thereafter (Matarese et al., 2003, Ichthyoplankton Information System[16]). A subset of data from a consistently sampled time window (mid-May through early June) and area (Figure 50) has been developed into time series of relative abundance. While quantitative data require a year for full laboratory processing and verification, Rapid Larval Assessments are conducted for 7 species by sorting samples at sea, allowing us to provide provisional time-series updates in the year of collection. In 2023, time-series calculations were updated to use a model-based approach (sdmTMB; Anderson et al., 2022) instead of the previous area-weighted mean, in part to better account for variable survey coverage in recent years due to ship-time constraints. Correlations between time-series estimated using the two approaches ranged from r = 0.91 – 0.99. In 2023, the EcoFOCI survey was truncated due to vessel staffing, resulting in only partial coverage of the core survey area. The 2023 data will be updated and are subject to change once laboratory processing is complete.

Status and trends: Reduced survey coverage limited our ability to assess larval fish abundance and distribution in 2023. Based on the stations sampled, all species sampled were below their long-term means, relative to a 1981 – 2021 baseline (Figure 49). Walleye pollock abundance was particularly low, similar to 2021. Pacific cod abundance increased very slightly from 2021 but remained low, although catches were higher to the SW of the core sampling area. Arrowtooth flounder abundance increased towards the long-term mean, while northern and southern rock sole declined from 2021 levels. Pacific sand lance abundance was lower than the previous 4 years surveyed, and rockfishes (*Sebastes* spp.) continued a declining trend observed since 2015.

Factors influencing observed trends: Sea surface temperatures in the Gulf of Alaska were cool-to-average during the winter and spring of 2023 (baseline 1985 – 2014, Lemagie in this Report, p.40), which are typically associated with higher abundances of late winter and early-spring spawners including Pacific cod, pollock, and northern rock sole (Doyle et al., 2009; Laurel and Rogers, 2020). We did not see that pattern this year. A prolonged period of offshore gap winds in the area of Kodiak in April may have altered the flow of the Alaska Coastal Current and advection patterns for larvae (Wilson and Laman, 2021, and see Rogers in this Report, p.56), but we were unable to investigate whether distributions were unusual with our abbreviated survey.

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

[16] https://apps-afsc.fisheries.noaa.gov/ichthyo/index.php

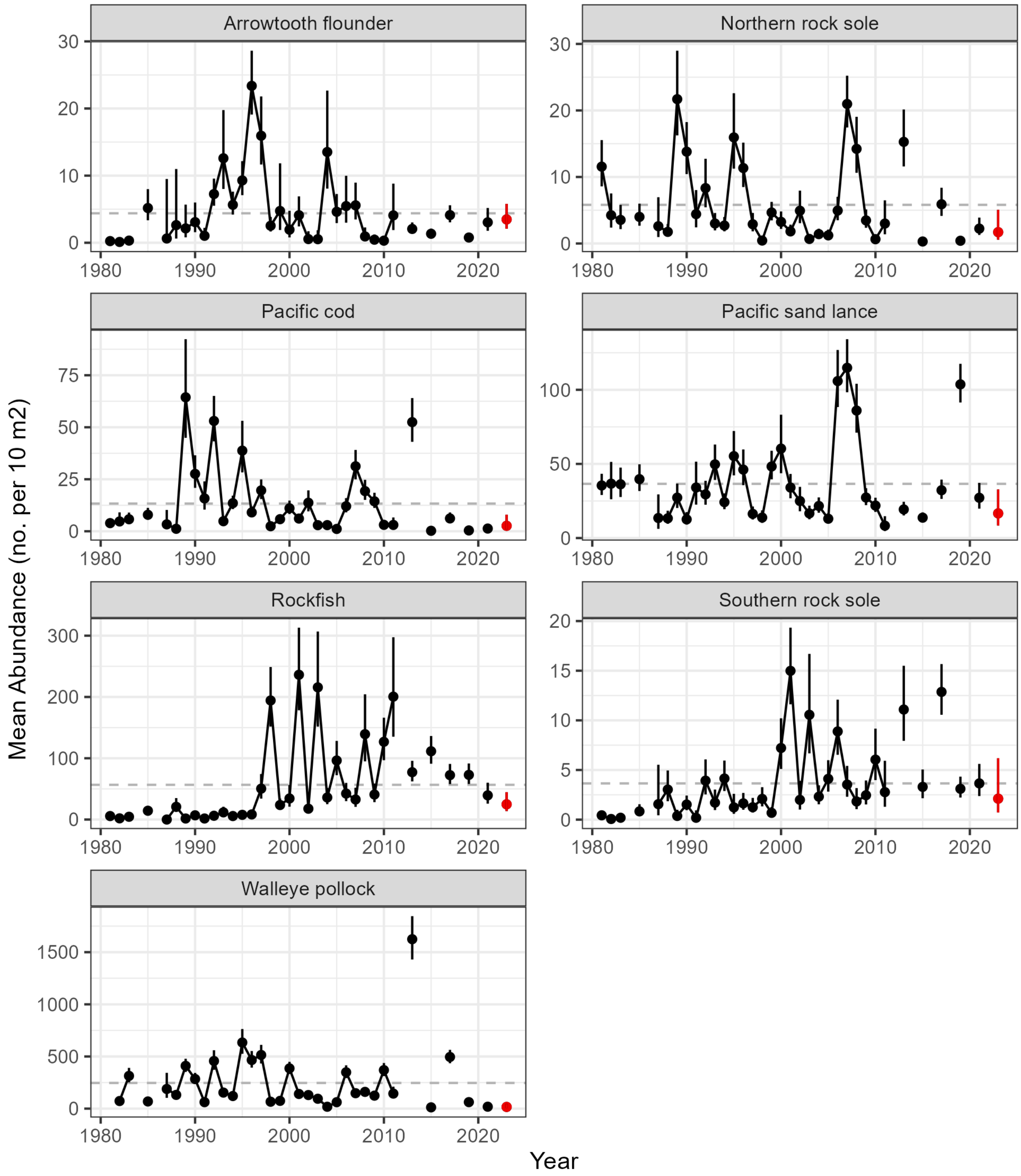

Figure 49: Interannual variation in late spring larval fish abundance in the Gulf of Alaska, 1981 – 2023. The larval abundance index is expressed as the mean abundance (no. 10 m^{-2}), and the long-term mean (1981-2023) is indicated by the dashed line. Error bars show ±1 SE. The 2023 values (red) are from the onboard Rapid Larval Assessment and are subject to change.

and Pacific cod larvae were the first indicators of failed year-classes for those species. In 2023, abundance of walleye pollock and Pacific cod larvae were again low, suggesting another poor year class, although

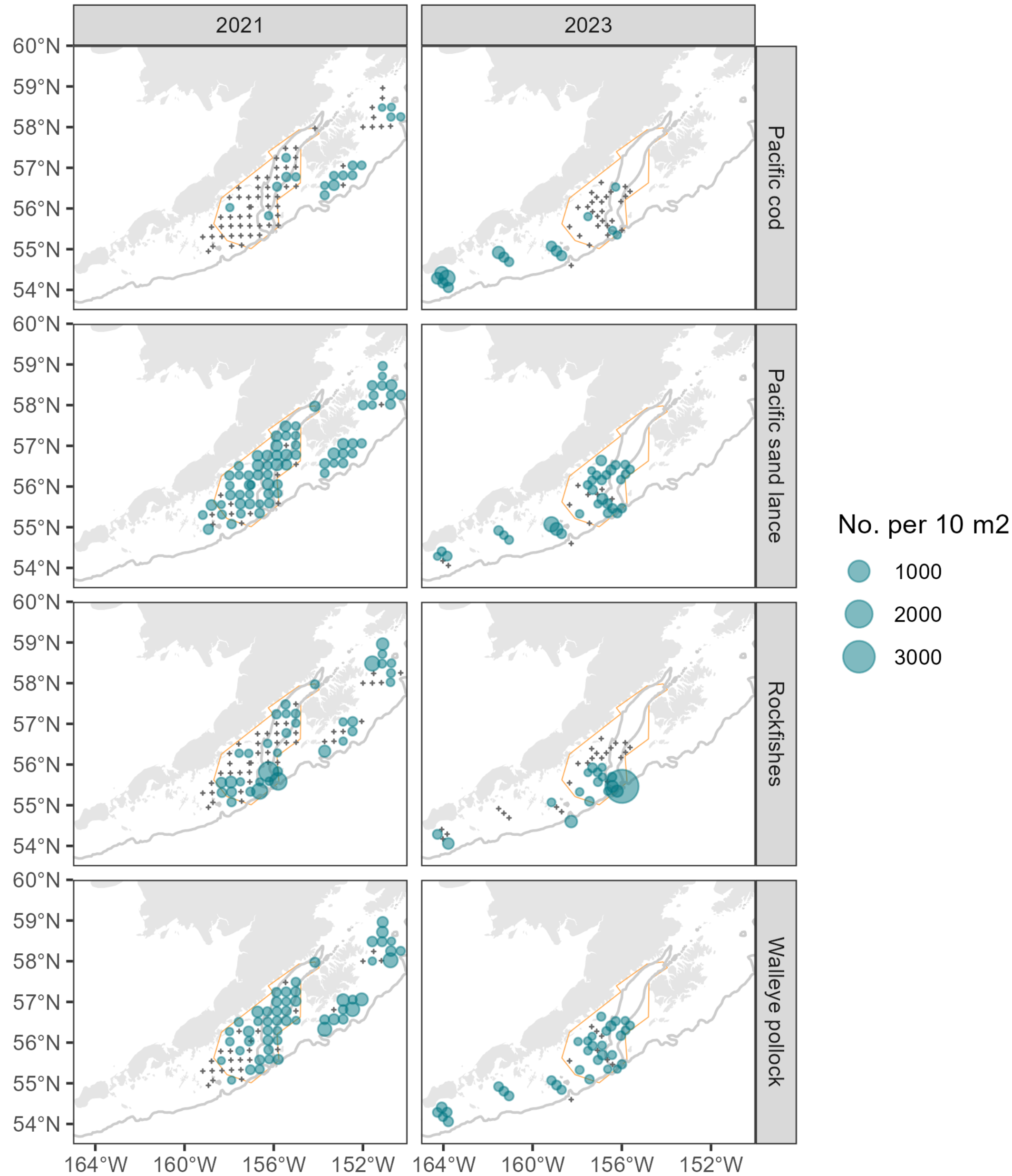

Figure 50: Abundance of larval Pacific cod, Pacific sand lance, rockfishes, and walleye pollock on the EcoFOCI spring larval survey for 2021 and 2023. The at-sea rough counts were used to generate the distribution for 2023 whereas quantitative laboratory data are shown for 2021. The orange polygon indicates the consistently sampled "core area" from which time-series are estimated.

abundances may have been higher outside the surveyed region. The low abundance of gadid larvae, combined with low to average abundance of the other indicator species, suggests poor to average forage for piscivorous predators, including seabirds, who rely on larval and juvenile fish.

Forage Fish and Squid

Summary of Forage Conditions

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Last updated: October 2023

The abundance of forage fish 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. The monitoring of seabird diets and reproductive success 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.

The appears to have been moderate to above-average availability of GOA shelf forage fish in 2023, bouyed by a rebound in capelin populations and continued elevated herring populations. Capelin populations rebounded in 2023 for the first year since their decline during the 2014-2016 marine heatwave. While these are traditionally cold water species, they did not immediately return to the GOA once ocean temperatures cooled. Capelin were most abundant in their core areas (e.g., offshore of Kodiak Island, Cook Inlet) (McGowan et al., 2020) and did not reach their pre-2014 levels of abundance or distribution, but were observed from surveys, in seabird diets, or spawning aggregations across the GOA (Whelan in this Report, p.105, McGowan in this report, p.110). One exception was the summer NOAA EcoFOCI survey in western GOA that did not observe capelin (Rogers in this report, p.102). Herring continued to have relatively elevated populations but their biomass has been declining as the strong, GOA-wide 2016 year class dies off (Hebert in this Report, p.115, Pegau in this Report, p.202).

Forage species that are relatively lower in abundance include juvenile pollock, eulachon, sandlance, and juvenile salmon. Age-0 pollock were not abundant in 2023 (Rogers in this report, p. 102). Age-1 pollock biomass are relatively high byt have below-average predation mortality by apex groundfish predators due to relatively decreaed populations of Pacific cod, arrowtooth flounder, and Pacific halibut (Adams in this report, p.153). Juvenile sablefish and sandlance (both associated with warm surface waters) were observed in relatively low levels in seabird diets (Whelan in this Report, p.105). Sandlance (affiliated with warmer waters) was more dominant in seabird diets on Middleton Island from 2016–2022 but was relatively low in 2023. Eulachon populations experienced a range of returns in southeast AK (above-average returns in Yakutat) but remain below previous population highs (Pochardt in this Report, p.118). Indicators of juvenile salmon abundance in southeast Alaska have been consistently near or below average for all species since 2016 (Chinook salmon), 2017 (chum, pink, and sockeye salmon), and 2018 (coho salmon). In 2023 juvnile salmon CPUE in Icy Strait (SEAK) all declined to or remained below average with reduced juvenile lenghs and reduced energy density for pink and sockeye salmon (Strasburger in this Report, p.127, Fergusson in this Report, p.129).

Piscivorous surface-feeding and diving seabirds had below (black-legged kittiwakes on Chowiet) to above-average reproductive success across the western and eastern GOA, implying adequate amounts of forage fish were available (Seabird Synthesis in this Report, p.161). The reproductive failure of black-legged kittiwkaes on Chowiet Island (WGOA) is potentially due to a lack of sandlance and age-0 pollock, common prey in that regions.

Abundance of YOY pollock and capelin in Western Gulf of Alaska

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Last updated: October 2023

Description of indicator: The Ecosystems & Fisheries-Oceanography Coordinated Investigations (EcoFOCI) Program monitors and researches small neritic fishes to improve our understanding and management of the Gulf of Alaska (GOA) ecosystem and fisheries. Longstanding objectives of EcoFOCI late-summer field work in the western Gulf of Alaska (GOA) are to extend a time series of age-0 walleye pollock abundance, monitor the neritic environment including zooplankton and abiotic conditions, and collect samples for research (e.g., trophic and spatial ecology, bioenergetics, age and growth).

During September 3 – 12, 2023, the NOAA vessel *Oscar Dyson* sampled the western Gulf of Alaska from SW of Kodiak to just NE of the Shumagins. The survey was truncated due to ship staffing constraints, resulting in a reduced survey extent compared to recent years. At each of 44 stations, target fishes were collected using a Stauffer trawl (also called the anchovy trawl) equipped with a small-mesh (2x3-mm) codend liner towed obliquely to a maximum headrope depth of 200 m.

Time series of abundance for age-0 pollock and for capelin were constructed from late-summer surveys since 2000 (only odd years since 2001) for the consistently sampled region between Kodiak Island and the Shumagin Islands (Figure 51). Mean catch per unit area was calculated using an area-weighted mean. Due to significant differences in catches of capelin during day versus night, mean CPUE for the night stations only is also shown.

Status and trends: Catches of age-0 pollock were third lowest on record, with the majority of fish found on the bank to the southwest of the Shelikof Sea Valley (Figures 51 and 52). No pollock were caught at over 1/3 of the stations. The spatial distribution was similar to 2019 in the areas sampled. Capelin abundance remained low in 2023, similar to the low abundance observed 2013 – 2017, Figure 52). However, note that no sampling occurred in even years and the time-series estimate does not include catches from near Kodiak, where capelin catches are typically higher. In particular, capelin were observed in abundant schools on Albatross Bank in 2023.

Factors influencing observed trends: The abundance of age-0 pollock in late summer reflects the number of surviving larvae from spawning in the spring and survival processes through the summer. In spring of 2023, catches of larval pollock were low (see Rogers, p.97), suggesting that the 2023 year class was already reduced in size prior to summer. The direction of springtime winds has been suggested to be important for retention of pollock in favorable nursery habitats (Wilson and Laman, 2021). In April of 2023 there was an extended period of gap winds near Kodiak Island that may have affected the strength of the Alaska Coastal Current as well as local oceanographic processes, but it's unknown whether this affected survival and distribution of pollock early life stages. Capelin experienced widespread declines in the GOA associated with the 2014 – 2016 heatwave, but beyond this, capelin dynamics don't appear

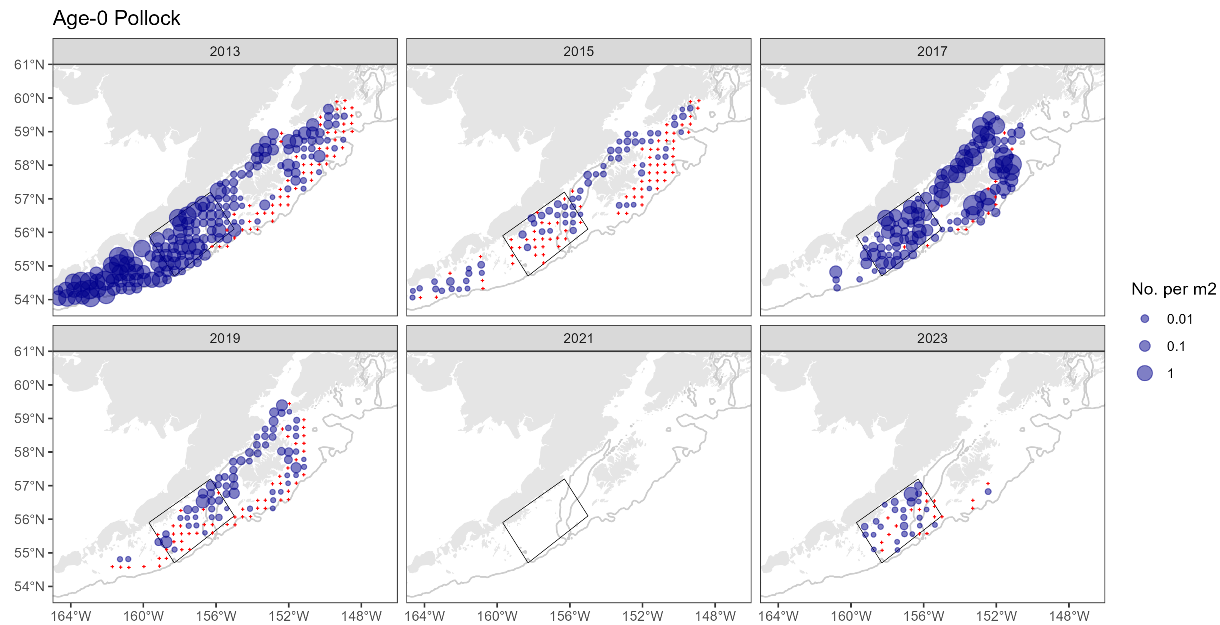

Figure 51: Catches of age-0 walleye pollock in the EcoFOCI late-summer small-mesh trawl survey for 2013 – 2023. The area in the black outlined box indicates the region most consistently sampled since 2000 and includes the stations used to develop CPUE time-series. Note there was no survey in 2021.

to have a clear link with temperature in the western GOA (McGowan et al., 2020).

Implications: Capelin and young-of-year pollock are key forage fish species in the Gulf of Alaska, providing prey for seabirds, fishes, and mammals. This late-summer survey also provides an assessment of the abundance, size, and condition of young-of-year pollock before entering their first winter, giving an early indicator of potential year-class strength. Low catches of juvenile pollock, together with previously observed low larval abundance, suggest a weak 2023 year class. Capelin abundances remain relatively low across the shelf to the SW of Kodiak, suggesting limited forage food for piscivorous predators in this region

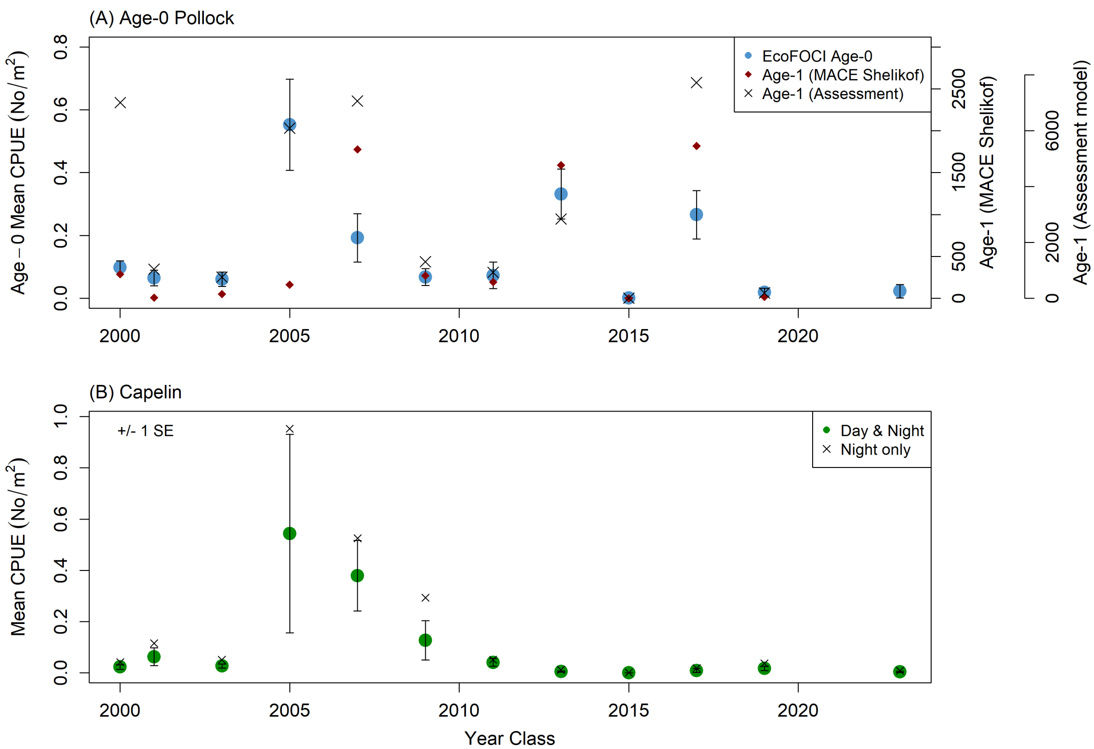

Figure 52: Estimated indices (+/- 1 standard error) of abundance for a) age-0 pollock and b) capelin. For pollock, the EcoFOCI age-0 estimate is shown relative to subsequent indicators of year-class strength, including an estimate of age-1 abundance in winter from the MACE acoustic survey in Shelikof Strait (Table 1.20 in Monnahan et al., 2022) and the estimated age-1 abundance from the stock assessment for GOA pollock (Table 1.20 in Monnahan et al., 2022).

Seabird-Derived Forage Fish Indicators from Middleton Island

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Last updated: September 2023

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 (59.4375°N, -146.3277°W), Middleton's seabirds sample both neritic shelf habitat and deep ocean waters beyond the shelf break. GPS-tracking 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 ($>$ 9,000 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, 5889 auklet prey samples have been collected on Middleton Island, and auklet diet monitoring provides the single best available 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: Totals of 1121 kittiwake diet samples and 183 rhinoceros auklet samples were obtained in 2023. Following an apparent "boom" in 2022, age-0 sablefish were scarce in both seabird diets, comprising only 0.8% of prey biomass in rhinoceros auklets and 0.1% relative occurrence in kittiwakes (Figure 53).

Capelin made a robust return to the kittiwake diet in the spring of 2023 (relative occurrence of 31% in April and 46% in May) and became slightly less prevalent by late-summer (25% relative occurrence in July-August; Figure 53). The auklet diet also signaled the return of capelin (14% of prey mass; Figure 53), though the increase was more muted than observed in the kittiwake diet. Cold surface conditions returned to the Gulf more than three years ago (since $\sim$ January 2020), and the delayed 2023 return of capelin suggests either persistent heat storage at depth following the 2014–2016 heatwave or a lagged effect of cooling on capelin availability.

After a post-heatwave re-emergence (2016–2022), Pacific sand lance became less frequent in both seabird diets in 2023 (Figure 53). This shift is consistent with a generally inverse relationship between capelin and sand lance (Sydeman et al., 2017). Middleton kittiwakes have historically consisted of primarily Pacific sand lance, capelin, and invertebrates, with lesser amounts of herring, sablefish, salmon, and myctophids, depending on stage of the season. Since1978 (Figure 53) diets of both seabird species indicate a sustained decline of sand lance availability around 2008, in accordance with the emergence of capelin as a dominant forage species through the cool period that lasted from 2008 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 their prey-switching behavior to alternate species such as myctophids, salmon, greenlings, sablefish, and herring. While alternate prey species continue to comprise most of both the auklet and kittiwake diets, Hexagrammid species (kelp and rock greenlings, lingcod, and Atka mackerel) declined further after surging over a 3-year period (2018–2020) post-heatwave (Figure 54).

Pacific herring continued their run (since 2015) as important prey of Middleton seabirds during 2023. The occurrence of herring, juvenile salmon, and other coastal species in seabird diets from Middleton possibly reflects greater use of nearshore/inner shelf habitats in response to reduced availability of offshore prey resources. Indeed, GPS-tracking of foraging seabirds conducted during chick-rearing reveals that in recent years birds from Middleton have commuted a considerable distance ($\sim$ 80–100 km one-way) and foraged principally in nearshore waters, especially at the southern end of Montague Island.

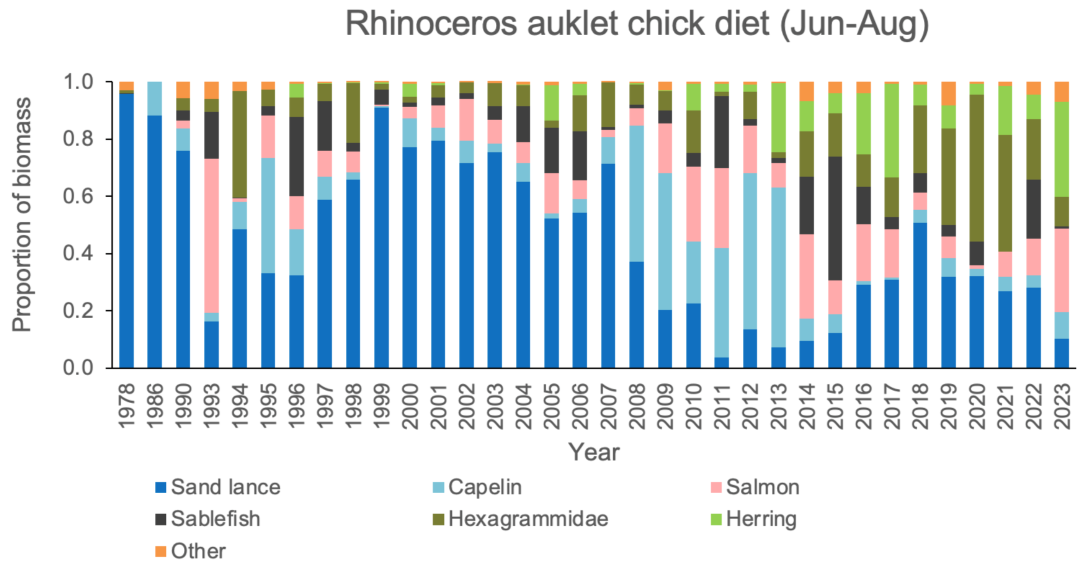
Though generally thought to be associated with warmer water than normally occurs in the northern GOA, Pacific saury (*Cololabis saira*) were present again in both seabird diets in 2023. Sauries first appeared in the rhinoceros auklet diet in 2014 (at the height of the heatwave) and in the kittiwake diet in 2019. In 2023, sauries were particularly prevalent in the kittiwake diet and comprised a large proportion of their late-season prey (first occurrence on 26 July); in August, 36% of the kittiwake diet samples contained at least one saury.

Auklet data plotted separately by prey type highlight the interannual dynamics of particular species of interest (Figure 54). Sand lance were the overwhelmingly dominant forage species in the northern Gulf in the late 1970s through the early 1980s but have fluctuated over the seabird diet time-series. The reappearance of sand lance in the auklet diet from 2016 until 2022 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 ended in 2023, when this species constituted only 10% of the auklet diet by weight (Figure 54). Herring and Hexagrammid species became predominant after the heatwave, but Hexagrammids have since declined while herring remain common (Figure 54).

Factors influencing observed trends: Seabird diets at Middleton reflect ecosystem shifts in the GOA. 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 the 6 prior years when capelin were predominant (Figure 53). 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 2023). Though the return to cool-water conditions occurred three years prior, capelin did not return to the seabird diets in robust numbers until 2023.

Implications: Seabird diets provide evidence that capelin disappeared from 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.



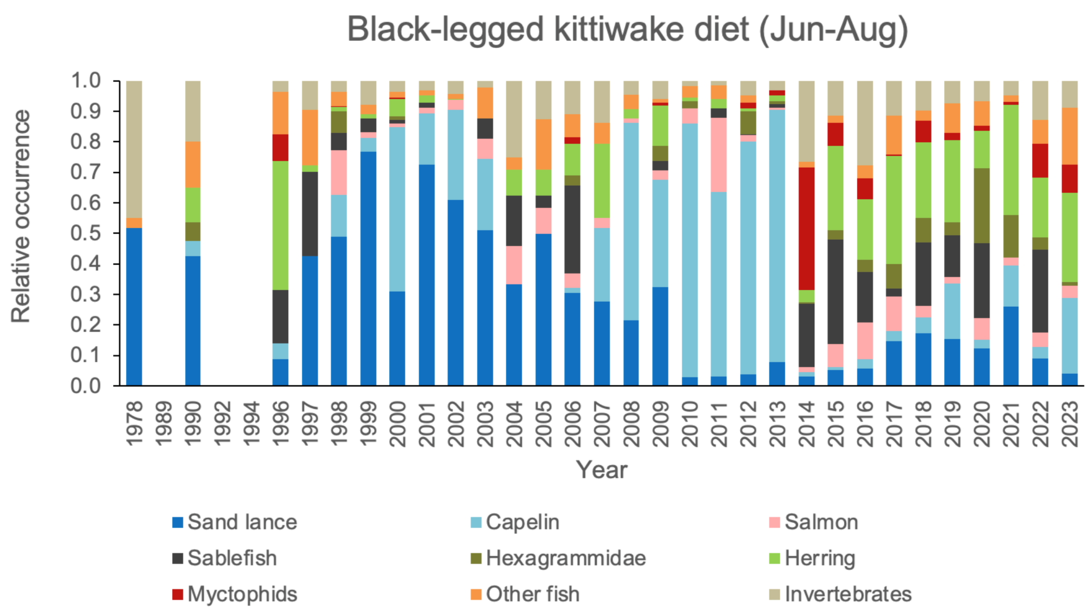


Figure 53: Interannual variation in diet composition of chick-rearing rhinoceros auklets (upper panel) and black-legged kittiwakes (lower panel) on Middleton Island, 1978–2023.

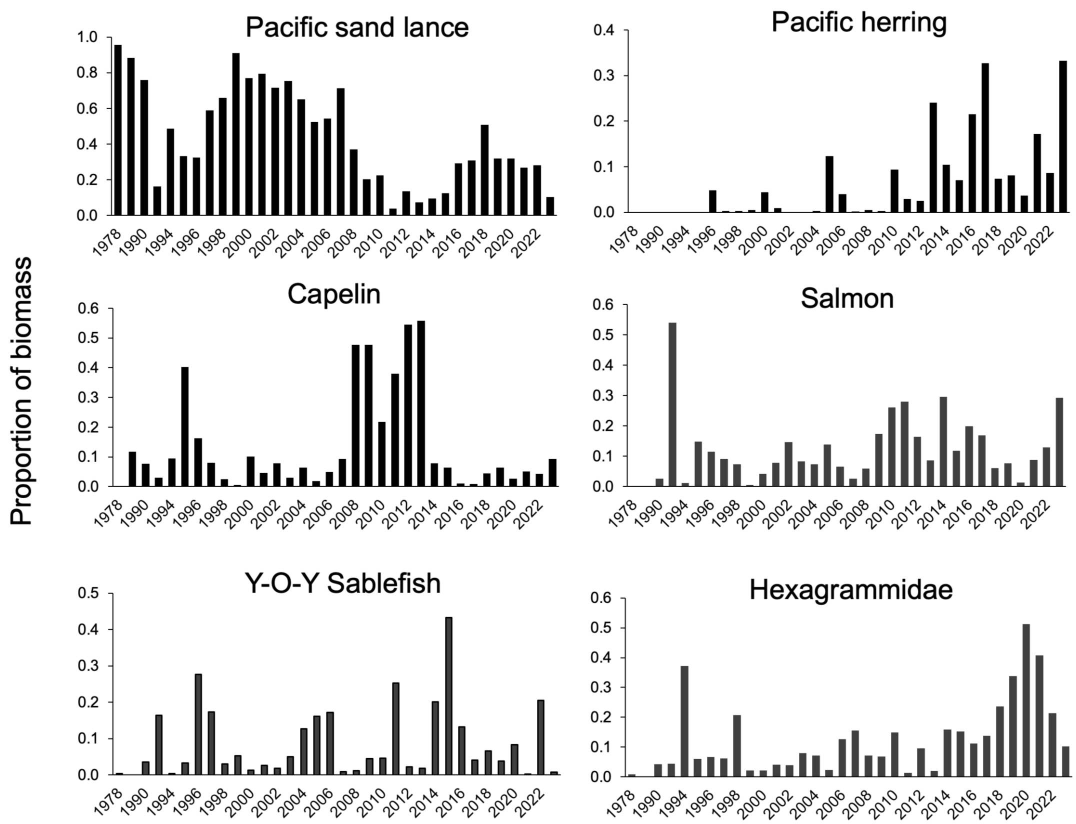


Figure 54: Yearly signal strength of selected prey species in the nestling diet of rhinoceros auklets on Middleton Island from 1978–2023.

Fisheries-independent Survey-based Indices of Capelin Relative Abundance

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Last updated: October 2023

NOAA Fisheries Gulf of Alaska Summer Acoustic Trawl Survey is conducted every other year. Please see the archives for past reports.

Description of indicator: Survey-based indices of Pacific capelin (*Mallotus catervarius*) relative abundance were derived from annual estimates of mean biomass density (t nmi $^{-2}$) from the summer Gulf of Alaska (GOA) acoustic-trawl (AT) survey conducted by the NOAA Alaska Fisheries Science Center. The AT survey is designed for estimating abundance of age-1+ walleye pollock (*Gadus chalcogrammus*) over the GOA continental shelf. An index of mean biomass density for age-1+ capelin (>6 cm fork length, Arimitsu et al., 2021) was calculated from the AT survey (2003–2023; Jones et al., 2019) following McGowan et al. (2020). The survey is conducted biennially in odd years, with no surveys conducted in 2007 or 2009. While this survey is not designed specifically to sample capelin, it has been used to track years of relatively high and low capelin abundance (Arimitsu et al., 2021; McGowan et al., 2020). The survey has consistently sampled from ∼170° W near the Islands of Four Mountains 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, key areas have been sampled around the Kodiak Archipelago where capelin have concentrated the past two decades (McGowan et al., 2020; Piatt et al., 2018). Separate indices of mean capelin biomass density were calculated for west and east of 147° W to produce separate time series for the western and eastern GOA.

Status and trends: Acoustic-based indices of mean biomass density indicate that capelin relative abundance is consistently higher in the western GOA compared to the eastern GOA (Figure 55). Between 2001 and 2023, capelin densities peaked in 2013, declined sharply, and remained at relatively low levels until this year when there was a small, but notable increase from the index low in 2021 (capelin abundance was too low to assess in 2015 and 2017 using current analysis methods). Capelin densities over Albatross and Portlock Banks to the south and east of Kodiak (Figure 56) were the highest observed since 2013 (Jones et al., 2014), but their distribution was mostly limited to these shallow banks and over the shelf to the southwest of Shelikof Strait. Capelin were rarely observed in deeper waters of the shelf (>100 m) or near Middleton Island in the eastern GOA where capelin have historically been abundant.

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 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

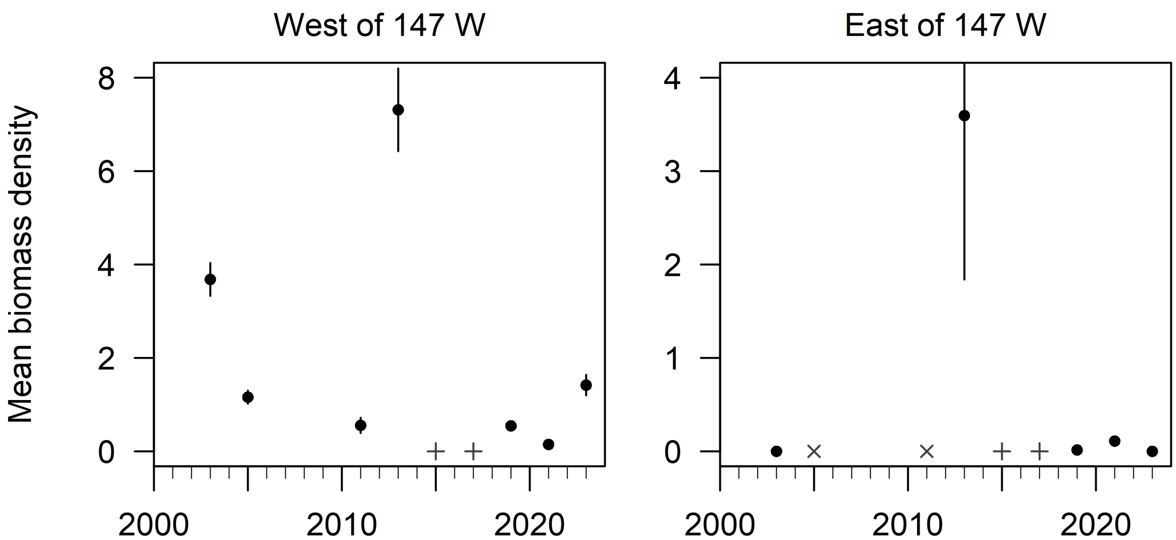

Figure 55: Indices of mean capelin biomass density (mean ± SE, t nmi^{-2}) in western and eastern Gulf of Alaska from summer acoustic-trawl survey. There are no AT survey data for the eastern GOA in 2005 and 2011 ('x') and capelin densities were too low in both regions to assess in 2015 and 2017 ('+'). Mean biomass densities are not corrected for potential spatial autocorrelation, and standard errors of the mean should be interpreted with caution.

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 in 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 (Andrews et al., 2016). 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). The AT survey index indicates 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 slowly 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, the AT survey index and a similar time series based on bottom trawl survey catches (see Fig. 44 in Ferriss and Zador, 2021) 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). Therefore, the availability of capelin to predators cannot be simply predicted based on current ocean conditions.

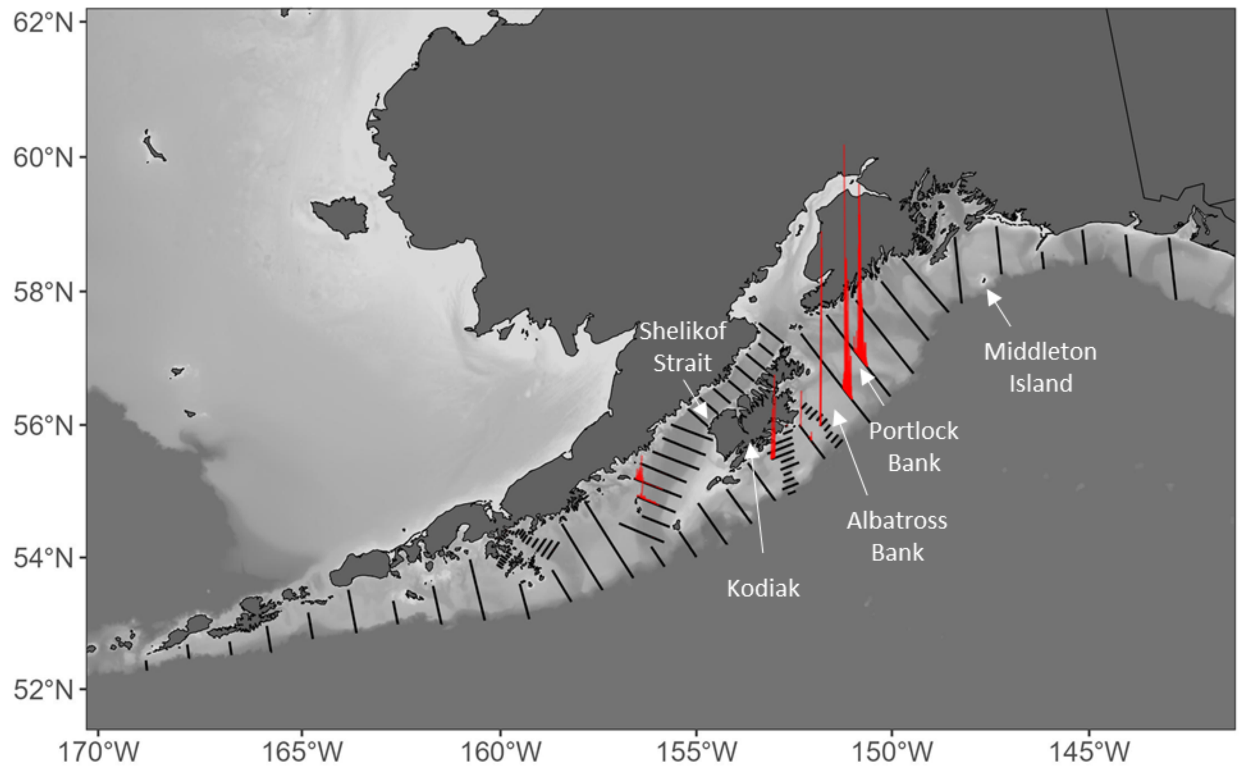

Figure 56: Acoustic-based biomass density (t/nmi^{-2}) attributed to Pacific capelin (red lines) along tracklines surveyed during the summer 2023 GOA acoustic-trawl survey (black lines).

This uncertainty may in part reflect that the summer GOA AT survey was not 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. In addition, a model-based approach that incorporates data from other sources to interpolate coverage gaps in the AT survey is currently in development.

Implications: 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 slow to recover. 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 during this period, 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). Current capelin abundance levels in the GOA appear to finally be increasing from decadal lows, primarily east of Kodiak over shallow banks, but are well below levels observed prior to the marine heatwave.

Fisheries-independent Survey-based Indices of Forage Fishes in the Gulf of Alaska

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Last updated: October 2023

Description of indicator: The Resource Assessment and Conservation Engineering Division's Groundfish Assessment Program (RACE-GAP) fishery-independent summer bottom trawl surveys in the Gulf of Alaska (GOA) are designed to assess populations of commercially and ecologically important fishes and invertebrates. Since 1990, we have deployed the same standardized trawl gear (footrope and trawl net) as is presently in use in the GOA bottom trawl survey. The North Pacific Fishery Management Council has identified several forage fish species or groups of species for federal management. The survey catches Pacific sandlance, eulachon, capelin, sandfish, and pricklebacks though the trawl mesh size is sufficiently large to allow escapement for most of these species. Because of the highly variable design-based biomass estimates from the trawl survey, the biomass of each forage fish was log-transformed to better show trends. For each species or species group, the largest log-transformed biomass estimate over the time series was arbitrarily scaled to a value of 100 and all other values were scaled in reference to that. The standard error ($\pm$ 1) was weighted proportionally to the biomass to get a relative standard error.

Status and trends: The biomass of forage fishes in the GOA is difficult to measure in NOAA Fisheries' bottom trawl survey catches due to issues such as gear selectivity and catchability. Therefore, we anticipate that the relative biomass estimates presented here for forage fishes are imprecise so that apparent trends should be interpreted cautiously. Eulachon have been most prevalent in the Yakutat survey district though their greatest biomass has historically occurred in the Kodiak district where biomass appears to be increasing in recent surveys after highs recorded between 2000 and 2015 (Figure 57). Capelin biomass has historically been highest in the Kodiak district. Sandfish, prickelbacks, and sand lance are uniformly uncommon in trawl catches across the GOA survey years and districts, though there are episodic years with large biomass estimates for these species over the survey history.

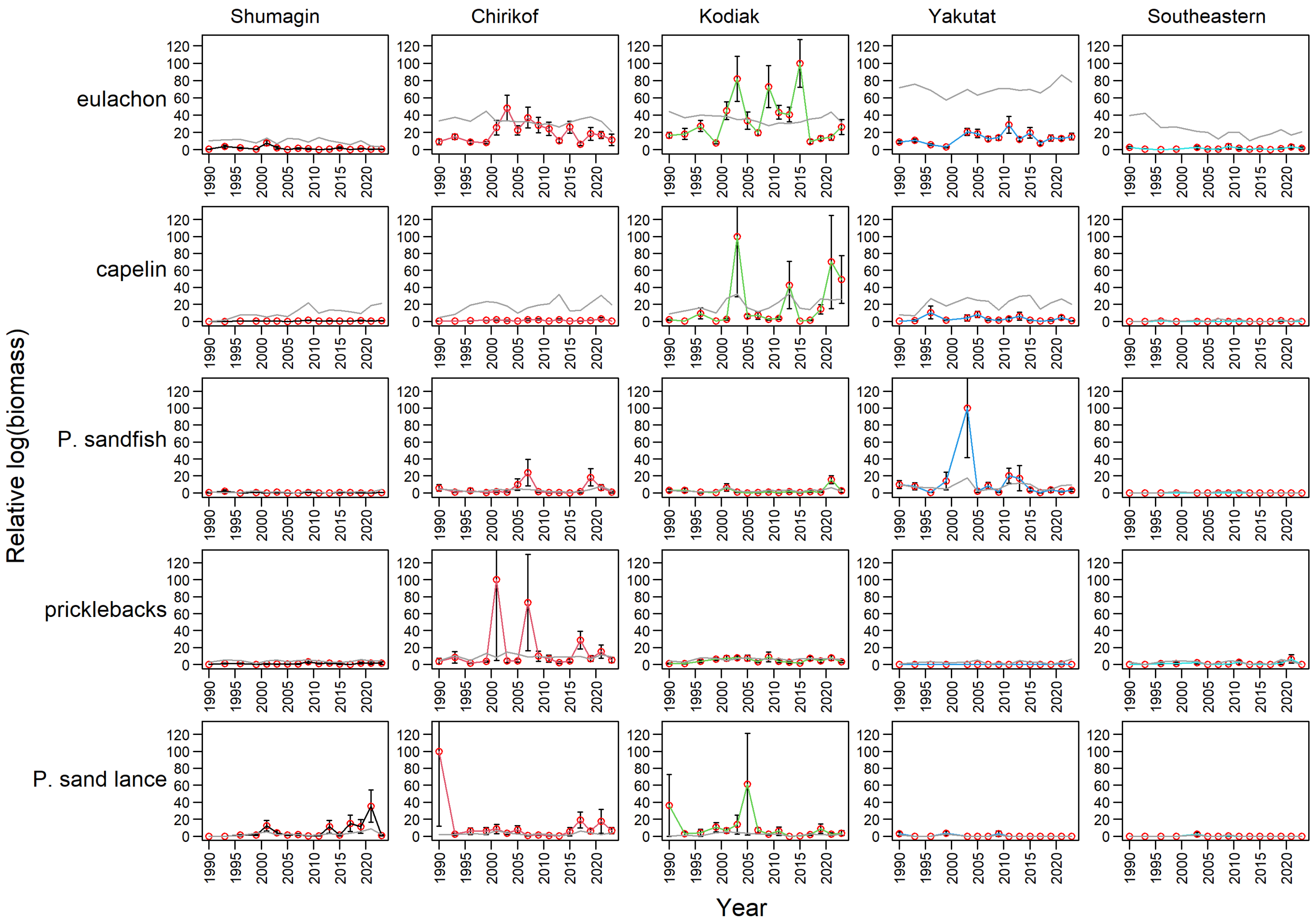

Figure 57: Relative mean log(biomass) of forage fishes collected from International North Pacific Fisheries Commission (INPFC) statistical districts during fishery-independent summer bottom trawl surveys of the Gulf of Alaska (1990–2023). Error bars represent standard errors and the gray lines represent the prevalence (percentage) of non-zero catches for these taxa.

Factors causing observed trends: Unknown.

Implications: The NOAA Fisheries' survey trawl gear has catchability and selectivity issues for forage fishes that impact their catch and retention. Therefore, relative biomass estimates for these species are of limited value for interpreting long-term abundance trends or population status.

Southeastern Alaska Herring

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Last updated: August 2023

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 58). Monitoring of spawning stock size has been conducted at some of these areas for over 50 years by the Alaska Department of Fish and Game, primarily by combining estimates of egg abundance made using SCUBA with herring age and size information (Hebert, 2019). Starting in 2016, surveys and stock assessments were suspended for many stocks in southeastern Alaska due to budget cuts, which coincided with a decrease in spawning of many spawning stocks. Although the nine surveyed areas account for a large proportion of the spawning biomass in Southeast Alaska in any given year, other areas typically of more limited spawning also exist throughout Southeast Alaska. However, 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 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 the greatest or the soonest.

Status and trends: Mature biomass for Sitka Sound and Craig herring remain at a high level, as the extremely large 2019 recruitment (2016 year class) continues to dominate these stocks. The 2019 age-3 recruitment event was by far the largest recruit class in the Sitka Sound and Craig model time-series (since 1976 for Sitka Sound and since 1988 for Craig). Although model estimates indicate that the 2022 mature biomass and the proportion of herring from 2016 year class (age-6) for Sitka and Craig stocks were again very high, the biomass was lower than in 2021 and a further decrease for both stocks was forecasted for 2023 (Figure 59).

Although 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 those data collected by the State of Alaska within the last 50 years, which are discussed here. Prior to Alaska statehood (1959), herring fisheries were first managed and studied by the U.S. Department of Commerce, Bureau of Fisheries, in the 1930s, then by the U.S. Department of the Interior, Fish and Wildlife Service in the 1940s and 1950s. Over the past 50 years, the biomass of Southeast Alaska herring has generally increased over time (Figure 59). Following low biomass in the 1970's and a period of intermediate biomass during the 1980s through the mid-1990s, Sitka Sound herring increased to

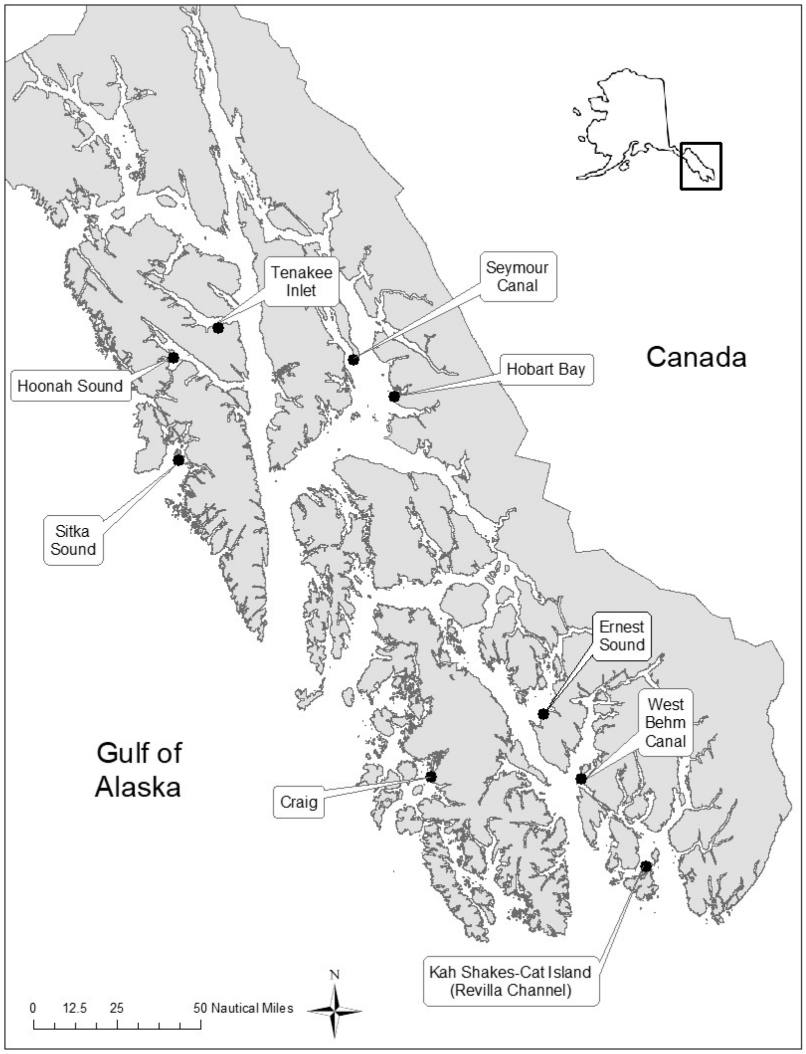

Figure 58: Location of nine Pacific herring spawning locations, historically surveyed in Southeast Alaska. Sitka Sound, Craig, and Kah-Shakes/Cat Island are considered "outside stocks" with greater ocean exposure, while all others are considered "inside stocks", less exposed to open ocean influence.

relatively high levels between 2008 and 2011. Craig and other Southeast stocks were variable until 2011. Southeast stocks then declined substantially until 2016–2018. Despite the decline, Sitka Sound and Craig, the two largest and most consistently abundant stocks, declined to moderate levels, but still 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. The large 2016 year class has been documented across the Gulf of Alaska in aerial surveys of age-1 herring in Prince William Sound (Pegau et al., 2022), high mean frequency of occurrence of age-0 and age-1 herring in both diving and surface feeding birds at Middleton Island in 2016 and 2017 (Arimitsu et al., 2021), and age-3 herring in age composition samples and population abundance indices of mature herring in Prince William Sound (Pegau et al., 2022), Southeast Alaska and Kodiak Island (Hebert and Dressel 2022). Biomass levels for stocks in Southeast Alaska other than Sitka Sound and Craig are currently unknown because most egg abundance surveys were suspended starting in 2016, but limited aerial surveys of spawn events suggest that these stocks remain at relatively low levels compared to cumulative spawn

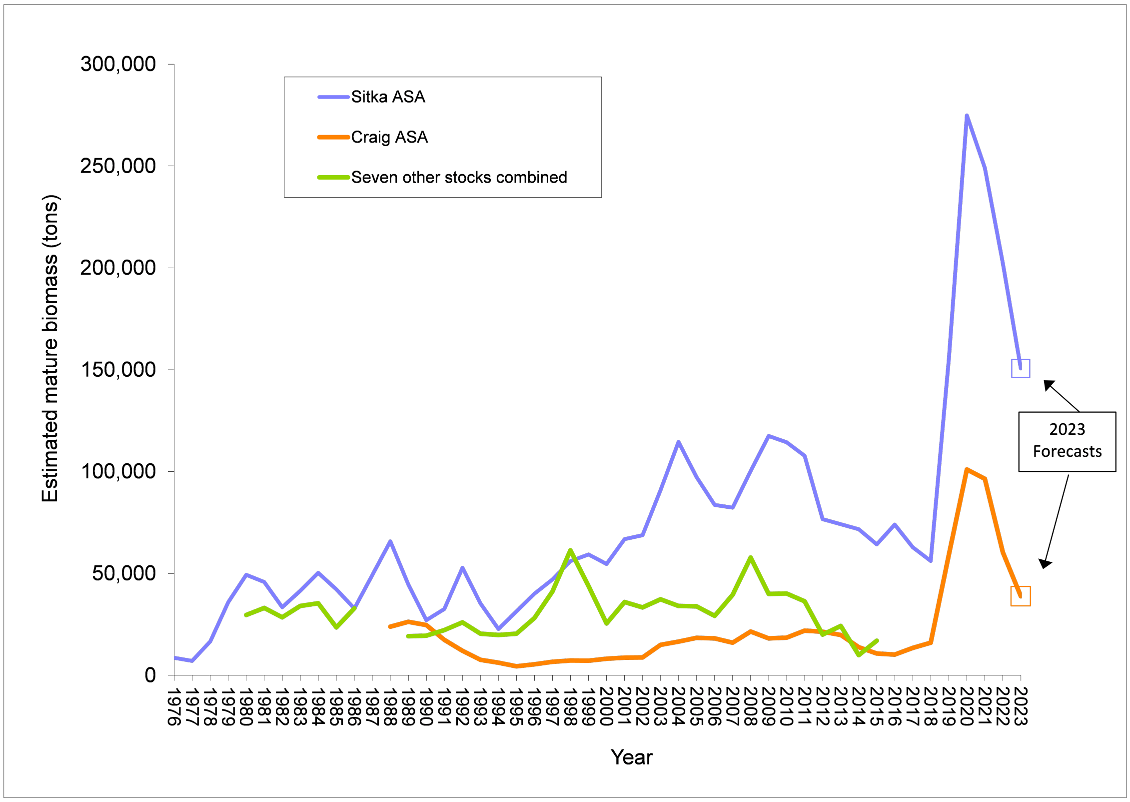

Figure 59: Estimated mature herring biomass (i.e., pre-fishery biomass) and forecasts for herring spawning areas historically surveyed in Southeast Alaska. Biomass estimates for Sitka Sound and Craig are based on integrated statistical catch-at-age models (the Sitka model starts in 1976 and Craig model starts in 1988). For all other stocks, biomass estimates are based on spawn deposition or hydroacoustic estimates, which began in different years, but for simplicity are shown starting in 1980. For years 1987–1988, biomass estimates for the combined seven stocks were excluded from the plot because not all stocks were surveyed in those years. For years 2016–2022, biomass estimates for the combined seven stocks were excluded because starting in 2016 stock assessment surveys were suspended for most of the seven areas due to budget reductions and low spawn activity.

mileage observed since 1980.

Mature biomass for Sitka Sound and Craig herring remain at a high level, as the extremely large 2019 recruitment (2016 year class) continues to dominate these stocks. The 2019 age-3 recruitment event was by far the largest recruit class in the Sitka Sound and Craig model time-series (since 1976 for Sitka Sound and since 1988 for Craig). Although model estimates indicate that the 2022 mature biomass and the proportion of herring from 2016 year class (age-6) for Sitka and Craig stocks were again very high, the biomass was lower than in 2021 and a further decrease for both stocks was forecasted for 2023 (Figure 59).

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 overall increase in herring biomass in Sitka Sound and Craig and the general decline in other stocks since 2011 are likely due to multiple factors. Contributing factors may include 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 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 similarity in declines of inside stocks, which for some occurred in the absence of fishing, suggests that the declines may have been primarily environmentally driven. The Sitka Sound and Craig mature biomass declines observed in 2022 and forecasted for 2023 since their peaks in 2020 are primarily due to the aging of the 2016 year class and the cumulative effects of natural and fishing mortality. The 2022 age-3 recruitment was relatively weak and not large enough to offset the mortality of the record 2016 year class. Preliminary information from age composition sampling of multiple Southeast Alaska stocks in 2023 suggests that a strong age-3 recruitment may have occurred.

The very high recruitment event of 2019 (2016 year class) in Sitka Sound and Craig is unprecedented in recent times, 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 were large 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 year class. Ocean temperature has been positively correlated with recruitment in Atlantic herring (*Clupea harengus*) (Toresen, 2001), and Pacific herring (Zebdi and Collie, 1995). While age-3 and older mature herring in Prince William Sound had strong negative anomalies in weight at age 2016–2017, juvenile (age-0) herring in 2016 had both high total energy and high energy densities, suggesting the 2016 year class had relatively high lipid reserves at a large size compared to other years (Arimitsu et al., 2021), which is consistent with higher survival.

Implications: There are distinct differences between herring biomass trends for Southeast Alaska spawning stocks that are exposed directly to Gulf of Alaska waters (outside stocks) and those found in more protected inside waters. Sitka Sound and Craig are considered "outside stocks" with greater ocean exposure, while all others except Kah-Shakes are considered "inside stocks" and less exposed to open ocean influence (Kah Shakes/Cat Island is not distinctly outside or inside). While all spawning stocks declined substantially from about 2010 to 2018, outside spawning stocks declined only to moderate levels, while inside stocks declined to low levels. The 2019 recruitment event has made the differences more pronounced. While all Southeast Alaska spawning stocks that were sampled revealed a dominant or substantial 2016 year class, the outside stocks increased from moderate to very high biomass, whereas smaller inside stocks remained low. The high herring biomass along the outer coast has persisted for four years through 2022. The forecasted 2023 biomass for outer coast stocks is still relatively high compared to historical levels and is expected to be available to support marine predators and fisheries for the next year as the strong 2016 year class continues to contribute despite its aging and decline. Additionally, the probable strong recruitment observed in 2023 has potential to maintain outer stocks at a relatively high level for the next few years. Herring biomass for inside stocks appears to persist at low levels, which is considerably different than pre-2016, when these stocks contributed a substantial proportion to overall biomass in Southeast Alaska.

Southeast Alaska Eulachon

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Description of indicator: In Southeast Alaska, eulachon (*Thaleichthys pacificus*) are a culturally and biologically important anadromous fish. Eulachon populations have declined throughout their range since the 1990's and today all populations south of the Nass River in British Columbia have been severely depleted or become extinct (Hay and Mccarter, 2000). There are at least thirty-five rivers in Alaska where eulachon are known to spawn (Moffitt et al., 2002); however, it is thought that most runs are either undocumented or anecdotal (Betts, 1994). To better understand the eulachon spawning population in northern Southeast Alaska the Chilkoot Indian Association initiated a mark-recapture study on the Chilkoot River in 2010. In 2014 this was complemented with the addition of environmental DNA (eDNA) sampling. Furthermore, to monitor the annual eulachon spawning populations in 2017 eDNA sampling was expanded to five additional rivers within the northern Southeast Alaska region. In 2022 the use of eDNA to monitor eulachon spawning populations was expanded to include the Unuk River in southern Southeast Alaska in partnership with the Ketchikan Indian Community and US Forest Service. And in 2023 the Southeast Alaska Eulachon Monitoring Network was further expanded with eDNA monitoring on the Situk and Ahrnklin Rivers near Yakutat in partnership with the Yakutat Tlingit Tribe and US Forest Service (Figure 60).

Status and trends: In 2023, eulachon populations in southeast Alaska saw a range of returns from some slightly below average to some above average (Table 1). In recent decades a decline in eulachon populations has increased concern about the health of eulachon across their range. In 2007 the Cowlitz Indian Tribe petitioned NOAA Fisheries to list eulachon under the Endangered Species Act. And in May 2010, the southern Distinct Population Segment (SDP) including California, Oregon, and Washington was listed as"threatened" under the Endangered Species Act (NOAA, 2010). In May 2011 the Canadian Committee on the Status of Endangered Wildlife listed three British Columbia populations for protection including the Central Pacific Coast, Fraser River, and Nass/Skeena River populations (COSEWIC, 2011). In Southeast Alaska there has been limited monitoring of eulachon spawning populations. The Forest Service has conducted aerial surveys along the Unuk River since 2001 and a mark-recapture population estimate on rivers within Berners Bay from 2004–2008. However, these studies only represent a small portion of the eulachon spawning habitat in Southeast Alaska. On the rivers north of Berners Bay there was no population data being collected until the Chilkoot Indian Association initiated a mark-recapture study in 2010 out of concern for declining eulachon populations elsewhere and a lack of data available.

The mark-recapture population estimate for the Chilkoot river near Haines, Alaska has seen a wide range in eulachon spawning abundance; estimates have ranged from a couple hundred thousand to over 20 million (Figure 61). The 2023 Chilkoot River eulachon mark-recapture population estimate was 4.7 million (2.3–7.1 million 95% CI). Although this was a decent run and harvesters were excited to be able to harvest after two straight years of no return in 2021 and 2022, it was slightly below the overall mark-recapture average of 8.1 million since the mark-recapture program began in 2010.

The eulachon eDNA surveys were conducted at the Chilkoot River from 2014–2023. The ease of collecting eDNA samples (i.e., only one technician necessary to collect samples) and the sensitivity of the methods allowed for eDNA surveys to be conducted in years when the mark-recapture method was not at the Chilkoot River (2020–2022). The eDNA concentration at the Chilkoot River followed similar trends to the mark-recapture data in the years that the methods coincided. Sample years 2014, 2015, 2016, 2017, 2018, 2021, and 2022 were much lower than the large returns observed in 2019 and 2020 (Figure 62). The eDNA data for 2023 is still pending.

The regional population structure of eulachon initiated the need to begin a regional population monitoring effort in 2017 through the use of eDNA. The 2023 eDNA data is still pending, but the regional trends observed are depicted in Table 1. Most noteworthy of the 2023 eulachon spawning returns is the above-average returns in the Yakutat area. This was above what had been observed in over 10 years, according to local knowledge. Also, the Unuk River run occurred while there was still ice at the mouth of the river. Fish were observed moving beneath the ice.

Table 1: 2023 Southeast Alaska eulachon return observations

River	Adjacent community	2023 Eulachon Return Observations
Chilkoot	Haines	Below average
Chilkat	Haines	Below average
Ferebee	Haines	Unknown/observations difficult
Katzehin	Haines	Unknown/observations difficult
Taiya	Skagway	Below average
Skagway	Skagway	Below average
Berners Bay	Juneau	Average
Unuk	Ketchikan	Below average
Situk	Yakutat	Above average
Ahrnklin	Yakutat	Above average

Factors influencing observed trends: Eulachon populations are sensitive to environmental influences and the annual spawning population at a river can vary substantially (Olds et al., 2016). Additionally, there is little known about the life history of eulachon (Spangler, 2002), which makes assessing trends between parent-year and offspring difficult. It is thought that eulachon in Alaska are approximately two to five years of age at spawning (Spangler, 2002). Most eulachon are thought to be semelparous (Clarke et al., 2007), however it has been observed that eulachon do move back into the marine environment after spawning.

Implications: Anecdotal information and traditional knowledge indicates that eulachon spawning populations have historically varied in abundance (Olds et al., 2016). The limited timeseries of data available on eulachon spawning populations across the Southeast Alaska region limits any inference concerning the health of the overall eulachon population. Continued, and expanded, monitoring will be necessary to reliably assess the overall eulachon spawning population. A decline in the eulachon population in Southeast Alaska would have adverse impacts both culturally and ecologically. Eulachon have been termed the "salvation fish" by Northwest Coast Native peoples and eulachon oil was the most important trade item on a network of 'grease trails' between coastal and interior peoples (Moody and Pitcher, 2010). Today, eulachon are still valued as a subsistence resource. Additionally, eulachon are an important prey item for seabirds and marine mammals. Eulachon spawn prior to the breeding season for many predators, thus providing a high-energy resource at an energetically demanding time (Sigler et al., 2004).

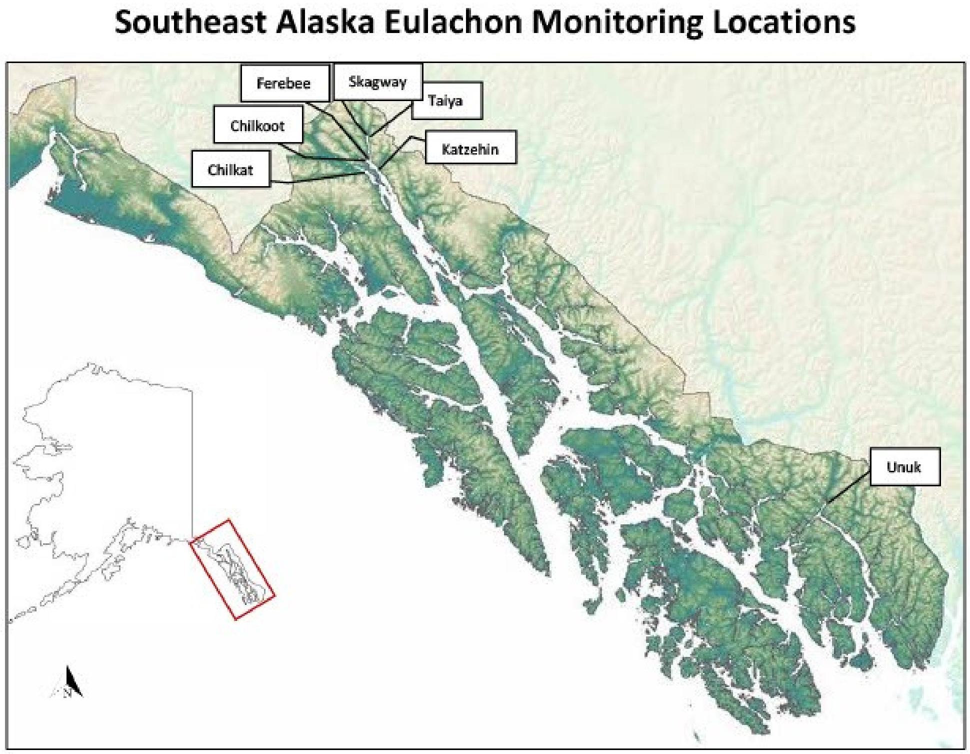

Figure 60: Location of Eulachon eDNA population monitoring sites in 2023.

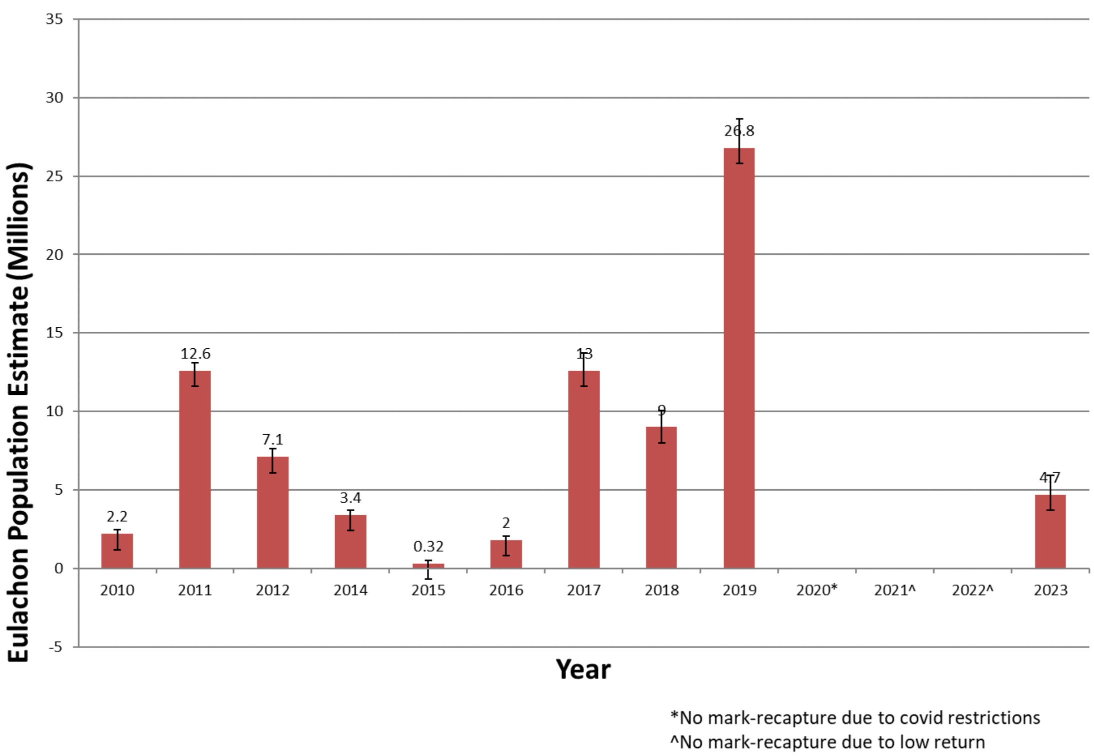

Figure 61: Eulachon population estimate on the Chilkoot River using mark-recapture method. Error bars represent 1 standard deviation.*No mark-recapture survey conducted in 2020 due to covid-19 restrictions. ^No survey conducted in 2021 and 2022 due to lack of return.

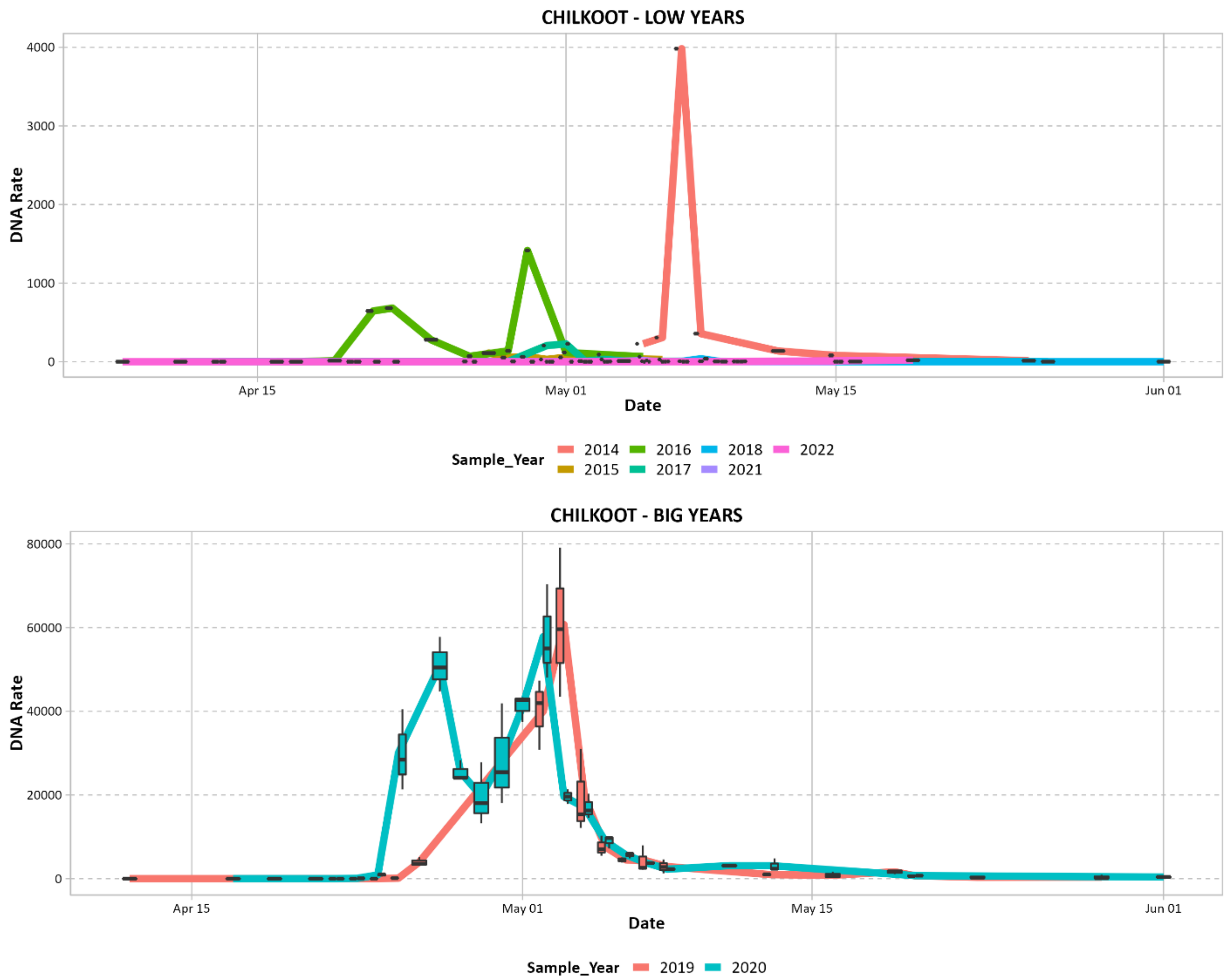

Figure 62: Chilkoot River Eulachon spring eDNA rate (eDNA concentration x Discharge) for low return years (top panel) and big return years (bottom panel).

Salmon

2022 and 2023 marine conditions for pink salmon growth and survival in the Gulf of Alaska

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Several marine indicators relevant to Gulf of Alaska salmon growth and survival are reported in the Ecosystem Status Reports. We retrospectively examine these indicators to determine why the CPUE of juvenile pink salmon from the SECM survey during 2022 did not capture the large returns of adult pink salmon to southeast Alaska in 2023 (Whitehouse in this report, p.124). We found that although the CPUE of juvenile pink salmon was low during 2022 there were favorable conditions for growth and survival. Favorable foraging conditions included above-average zooplankton densities across the GOA (Hopcroft and Fergusson in this report, p.89 and p.91) and above- average lipid contents of zooplankton (*Calanus marshallae*, *Pseudocalanus*, and *Themisto pacifica*) in Icy Strait, northern southeast Alaska during July (Fergusson in this report, p.91). In addition, the energy density and body length of juvenile pink salmon was around the 1997–2023 long-term mean following a stretch of above- average energy densities and average or above-average body lengths since 2013 (Fergusson in this report, p.91). At the Auke Creek weir near Juneau monitored since 1980, marine survival of the 2022 ocean entry year pink salmon was well above average with good returns of adult pink salmon to the weir during 2023.

We attribute the reduced predictive accuracy of the SECM survey in 2022 to potential alterations in stock composition, particularly a decrease in the catch of southern SEAK juvenile pink salmon, as well as issues related to catchability and survey timing. The SECM survey spans 10 days in mid-June and another 10 days in late July. However, in 2022, it appears that the survey might not have aligned with the migration timing of juvenile pink salmon. Furthermore, there's a possibility that a change in the migration pattern of southern stocks of juvenile pink salmon to the Gulf of Alaska occurred via southern routes rather than the traditional northern route through Icy Strait, causing historic sampling locations to completely miss the southern pink salmon stocks.

In 2023, conditions for growth and survival of juvenile pink salmon appear less favorable for juvenile pink salmon than during 2022. In 2023, juvenile pink salmon were again in low abundance but also much shorter ($\sim$1 cm) and had lower body condition than during 2022 (Strasburger and Fergusson, p.127 and p.129). Neutral conditions for prey fields of zooplankton were indicated by low densities but high lipid contents (*Calanus* and *Pseudocalanus*) in northern southeast Alaska inside waters (Fergusson in this report, p.91). The 2023 ocean and body conditions appear less favorable for growth and survival of juvenile pink salmon than during 2022.

Trends in Alaska Commercial Salmon Catch—Gulf of Alaska

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Last updated: October 2023

Description of indicator: This contribution provides historic and current commercial catch information for salmon of the Gulf of Alaska. This contribution summarizes data and information available in current Alaska Department of Fish and Game (ADF&G) agency reports (e.g., Donnellan and Munro, 2023) and on their website[17].

Pacific salmon in Alaska are managed in four regions based on freshwater drainage basins[18], 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*—Combined catches from directed fisheries on the five salmon species have fluctuated over recent decades but in total have been generally strong statewide (Figure 63a). The salmon commercial harvests from 2022 totaled 163.2 million fish, which was 2.6 million more than the preseason forecast of 160.6 million fish. The 2022 total commercial harvest was elevated by the harvest of 75.5 million sockeye salmon, primarily from Bristol Bay. Preliminary data from ADF&G for 2023 indicates a statewide total commercial salmon harvest of about 227 million fish (as of 27 September), which is well above the preseason projection of 189.4 million fish. The 2023 harvest has been bolstered by the catch of 134.5 million pink salmon, primarily from Prince William Sound and Southeast Alaska.

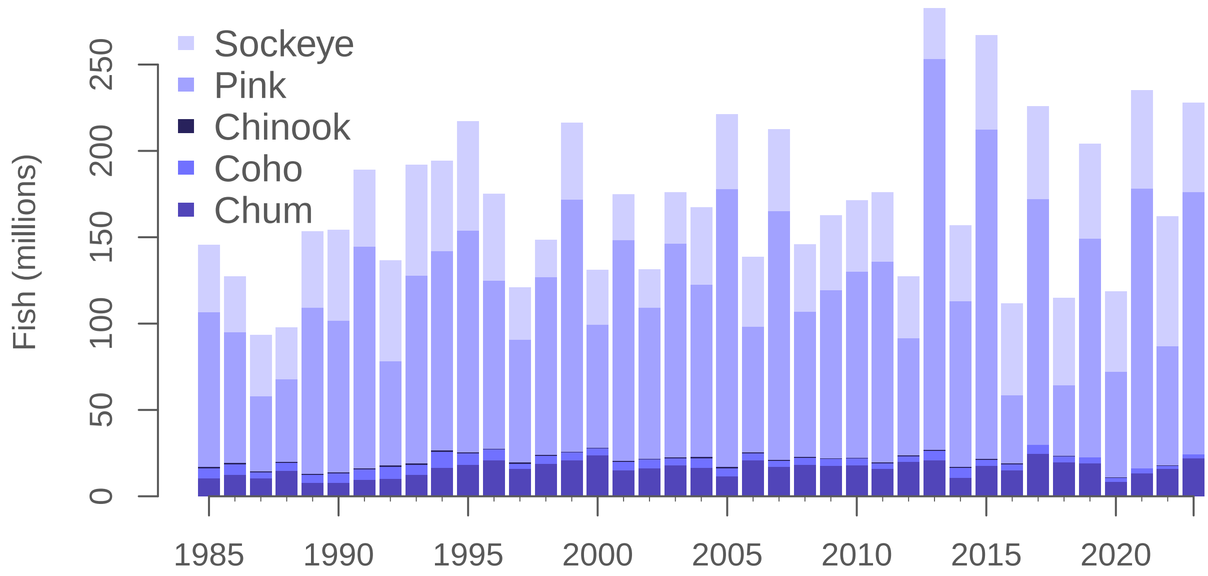
Gulf of Alaska—The total commercial salmon harvests in the Gulf of Alaska are dominated by pink salmon which follow a cycle of strong odd years and weak even years (Figure 63b). In the Prince William Sound Area of the Central region, the 2022 pink salmon harvest continued to follow the pattern of weak even years with a harvest of 28.4 million which was 8% above the even-year average. Preliminary harvest numbers for 2023, indicate another strong odd year for Prince William Sound pink salmon with a total commercial harvest of about 58.5 million fish.

In the Southeast region, the 2022 commercial salmon harvests totaled 31.7 million fish, which was a little more than half the 2021 total harvest in this region. The 2022 harvest of 18.3 million pink salmon was greater than the preseason forecast of 16 million fish. Preliminary data for 2023 from ADF&G indicates the catch of chum are higher in 2023 and pink salmon are maintaining the pattern of strong odd years with a catch of approximately 46.7 million.

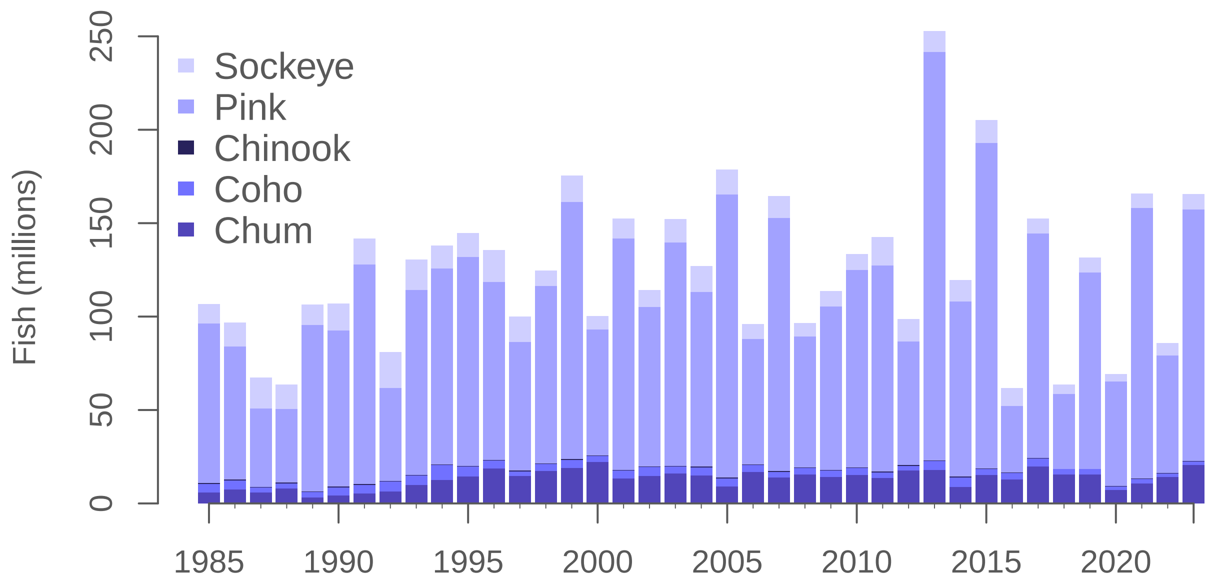
In the Kodiak management area, the 2022 total salmon harvest of 18.2 million fish was below the preseason forecast and the recent 10-year average harvest of 24 million fish. The 2022 sockeye salmon commercial harvest of 2.4 million was below the preseason forecast of 3.3 million fish. The 2022 chum salmon harvest of 550,000 fish was below forecast of 777,500 fish. Preliminary data from ADF&G on the 2023 commercial harvest in the Kodiak management area indicates an increase in total harvest to about 28.3 million fish, including about 24.6 million pink salmon.

Factors influencing observed trends: Historically, pink salmon catches increased in the late 1970s to

[17] https://www.adfg.alaska.gov/
[18] https://www.adfg.alaska.gov/index.cfm?adfg=commercialbyfisherysalmon.salmonareas



(a) Alaska



(b) Gulf of Alaska

Figure 63: Contemporary commercial salmon catches from Alaska (a) and GOA (b), 1985-Sept 2023. Values from 2023 are preliminary. (Source: ADF&G, `http://www.adfg.alaska.gov`. ADF&G not responsible for the reproduction of data, subsequent analysis, or interpretation.)

the mid-1990s and have generally remained high in all regions in the last decade (Figure 63a). While both natural and hatchery populations return to Prince William Sound, a large majority of the returning fish are hatchery fish, with up to one half billion 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).

Chinook runs have been declining statewide since 2007. Size-dependent mortality during the first year in the marine environment is thought to be a leading contributor to low Chinook run sizes (Beamish and Mahnken, 2001; Graham et al., 2019).

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). In odd years when pink salmon are most abundant they can initiate pelagic trophic cascades (Batten et al., 2018) which may negatively impact the population dynamics of several other species, including other salmonids, forage fishes, seabirds, and whales (Ruggerone et al., 2023). A biennial pattern in seabird reproductive success has been attributed to a negative relationship with years of high pink salmon abundance (Springer and van Vliet, 2014). Directed salmon fisheries are economically important for the state of Alaska. The trend in total statewide salmon catch in recent decades has been for generally strong harvests despite annual fluctuations and lower catches for some species in specific management areas.

Juvenile Salmon Abundance in Icy Strait, Southeast Alaska

Contributed by Wesley Strasburger[1], Emily Fergusson[1], Andrew Piston[2], Teresa Fish[2], and Andrew Gray[1]
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Last updated: September 2023

Description of indicator: Juvenile salmon catch-per-unit-effort (CPUE), zooplankton abundance, and data on oceanographic conditions have been collected during the Southeast Alaska Coastal Monitoring (SECM) surveys from 1997 – 2023 (Fergusson et al., 2021; Murphy et al., 2021). SECM data are used in a variety of research applications. 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 southeastern AK.

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 southeastern AK and the GOA. 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 chinook (*O. tshawytscha*), chum (*O. keta*), coho (*O. kisutch*), pink (*O. gorbuscha*), and sockeye (*O. nerka*) salmon are included in Figure 64.

Status and trends: Peak CPUEs have been consistently near or below average (baseline 1997 –

2022) 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 64). Catch rates of juvenile pink salmon decreased in 2023 relative to 2022 and remained well below the long-term mean. Catch rates of Chinook, chum and sockeye salmon also decreased in 2023, all well below their respective long-term mean CPUEs. Coho salmon were the only species to experience a slight increase in CPUE yet remained well below the long-term average and only slightly above the record low observed in 2022.

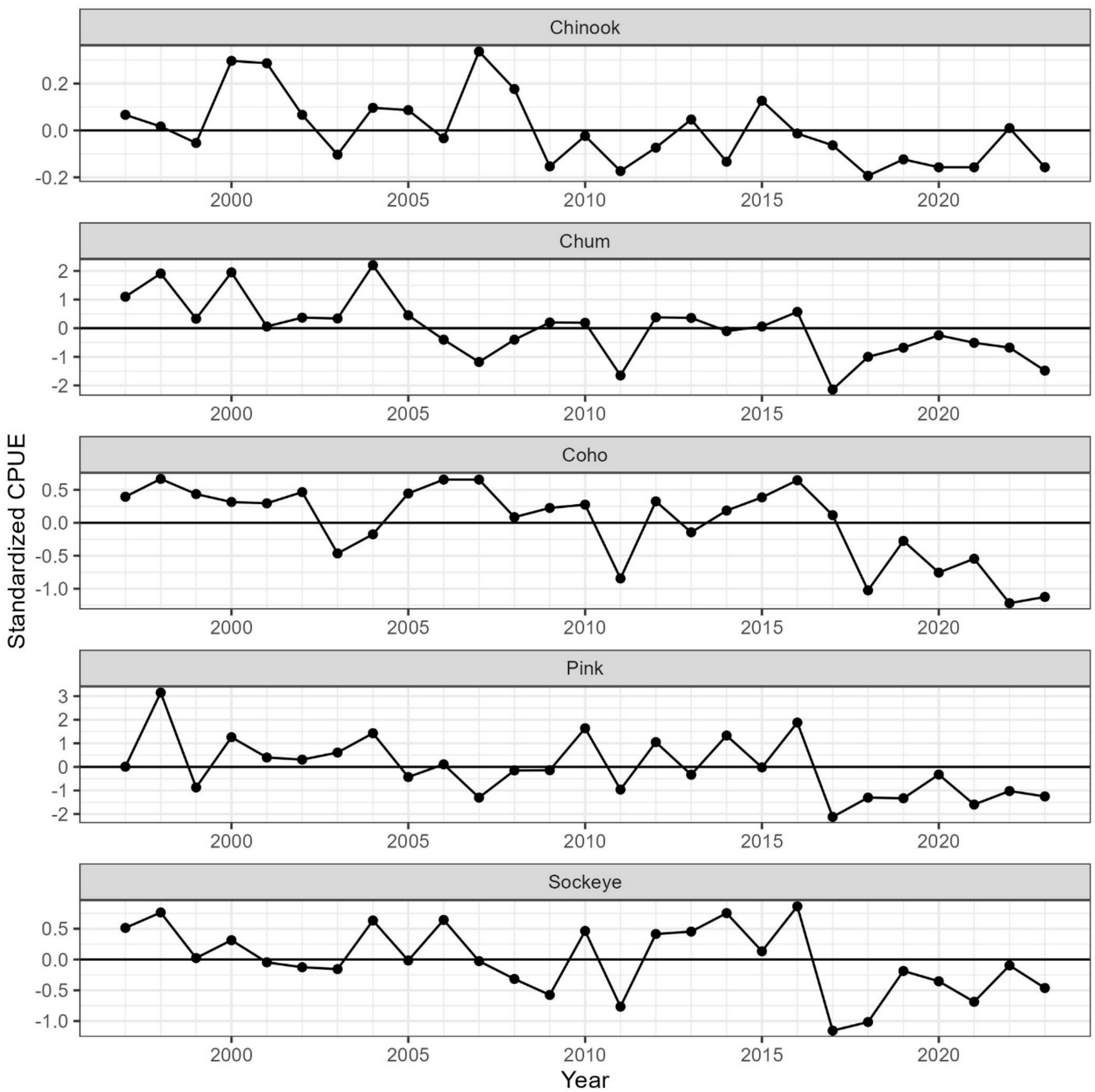

Figure 64: Standardized Catch-per-unit-effort (CPUE, log-transformed catch per 20-min trawl set) of juvenile salmon during Southeast Coastal Monitoring surveys in Icy Strait, 1997–2023. The CPUE index is the peak monthly average catch rate during the months of June and July. The ADF&G is not responsible for the reproduction of data, subsequent analysis, or interpretation.

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 factors influencing juvenile CPUE; however, spawner abundance and the migratory patterns of juveniles can also influence 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 southeastern AK (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. Hatchery fish typically account for >80% of the chum salmon harvested in SEAK; 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 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 in 2022, relative to 2021, but remained well below the long-term average (Figure 64); however, the harvest of SEAK pink salmon in 2023 was above the recent 20-year average (Figure 65). This may reflect improved offshore survival or reduced survey catchability (during juvenile migration) in 2022.

Juvenile sockeye catch rates (Figure 64) as well as southeast harvest (Figure 65) decreased relative to 2022 to further below their respective long-term averages. Both metrics fell to below their long-term average values in 2017, and each metric has remained low since.

Catch rates of juvenile chum salmon have improved after the all-time low in 2017 but remain below the long-term average. Due to the primary contribution of hatchery fish to commercial fisheries, it is difficult to interpret how this may influence the fishery. Marine survival is more likely the limiting factor for this species.

It's challenging to interpret the 2023 harvest of southeast Chinook and coho salmon considering the juvenile CPUE record, primarily because decreased fishing effort probably influenced these harvest figures. Nevertheless, the declining juvenile CPUE for both species might signal reduced harvest opportunities in the future. Additionally, it's worth noting that Icy Strait may not be the most suitable indicator for these species, as many Chinook salmon reside in inside waters for extended periods, and both species likely occupy different ocean habitats compared to other juvenile salmon species.

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

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Last updated: September 2023

Description of indicator: The Southeast Coastal Monitoring project (SECM, Auke Bay Laboratories, AFSC) has been investigating how climate change may affect southeastern Alaska nearshore ecosystems in relation to juvenile salmon (*Oncorhynchus* spp.) and associated biophysical factors since 1997 (Fergusson et al., 2020; 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

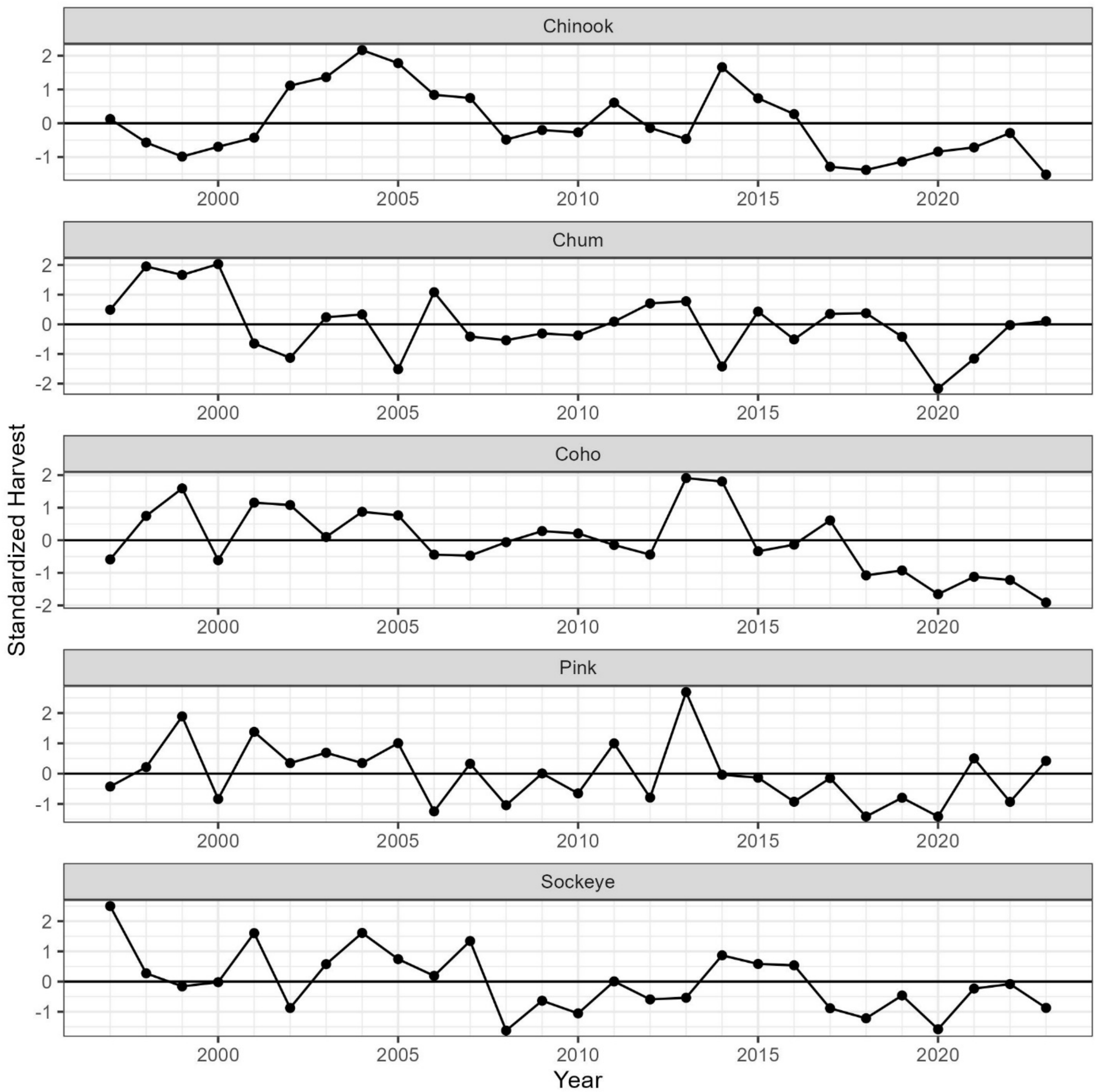

Figure 65: Standardized commercial harvest (numbers) of salmon in Southeast Alaska, 1997–2023. The 1997–2023 harvest data are provided by ADF&G and available at `https://npafc.org/statistics/`. The 2023 harvest data are preliminary data retrieved on Sep 6, 2023, provided by ADF&G and available at `https://www.adfg.alaska.gov/index.cfm?adfg=commercialbyfisherysalmon.bluesheet`

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2023 size (fork length) and energy density data in relation to the past 27 year trend from Icy Strait.

Status and trends: In 2023, juvenile salmon lengths generally decreased from lengths observed in 2022. Juvenile pink and coho salmon length values decreased from average (baseline 1997 – 2022) to negative. Juvenile chum salmon length values decreased from positive to average. Juvenile sockeye salmon length values increased slightly but remained near average (Figure 66).

In 2023, energy density anomalies (ED, kJ/g dry weight) varied among the four juvenile salmon species (Figure 67). For juvenile pink and sockeye salmon, ED decreased from positive 2022 anomalies to negative. For juvenile chum salmon, ED increased slightly from 2022 anomalies, remaining positive. For juvenile coho salmon, ED was similar to 2022 anomalies, remaining just negative of average.

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). Size trends over time represent differences in growth, migration routes, and timing of hatch, outmigration, and hatchery releases of the fish in response to climate and ocean conditions during early marine residency. Energy density trends over time can represent the condition of juvenile salmon and other taxa in response to climate and ocean conditions during their early marine residency.

Implications: The length anomalies observed in 2023 for juvenile salmon continue to 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 2023 length frequency results relative to the long-term averages by species, juvenile salmon are entering the Gulf of Alaska (GOA) in 2023 with average to below-average size. Further growth and survival will be dependent on favorable over-winter conditions in the GOA.

Juvenile chum and coho salmon entered the Gulf of Alaska in 2023 with average to positive energy stores which may contribute to higher survival and escapement. However, juvenile pink and sockeye salmon entered the Gulf of Alaska in 2023 with negative energy stores, which could have negative implications in their overwinter survival when food is limited.

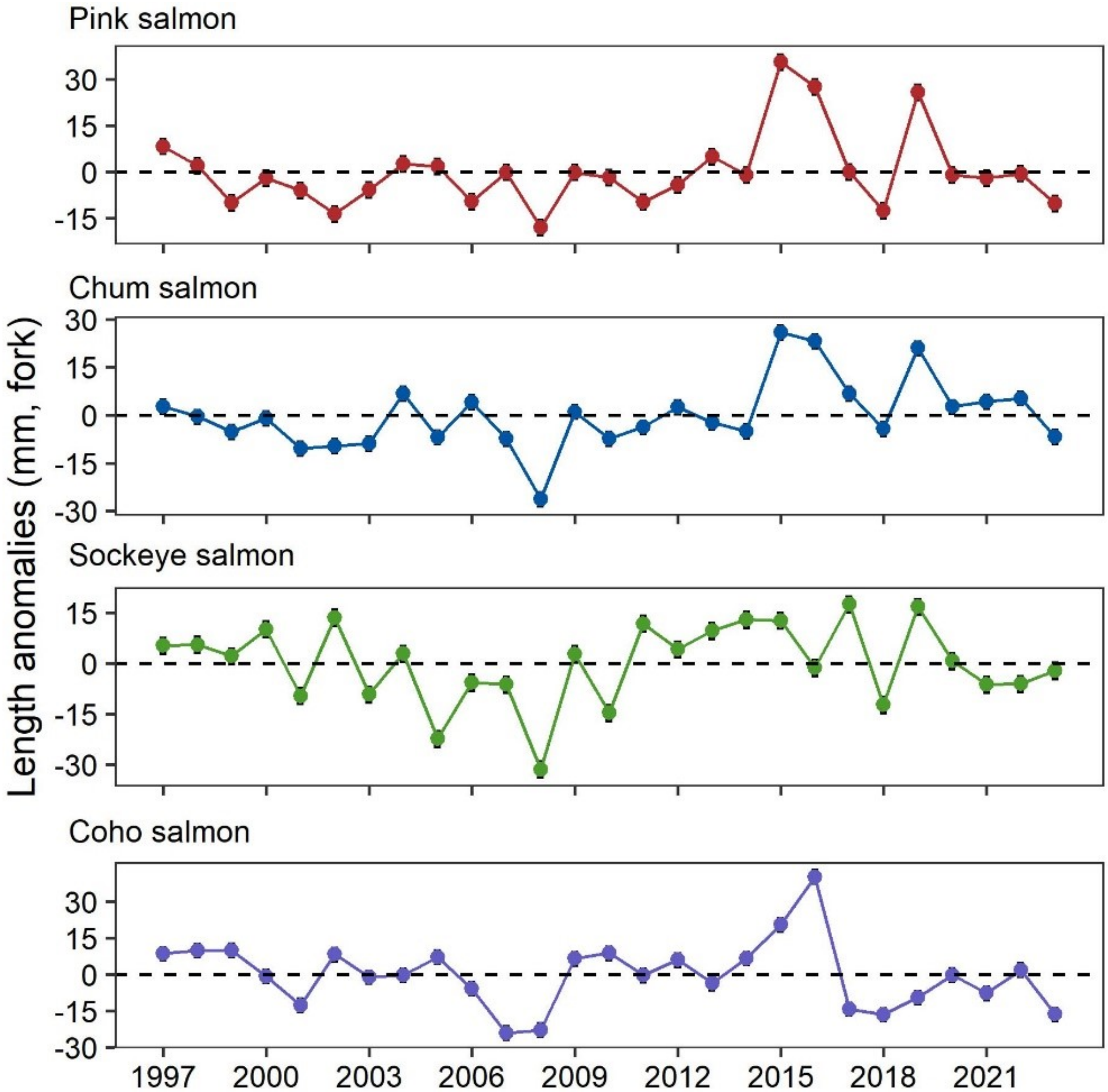

Figure 66: Average fork length (mm; ±1 standard error) anomalies of juvenile salmon captured in Icy Strait, AK by the Southeast Coastal Monitoring project, 1997 – 2023. Time series average is indicated by the dashed line.

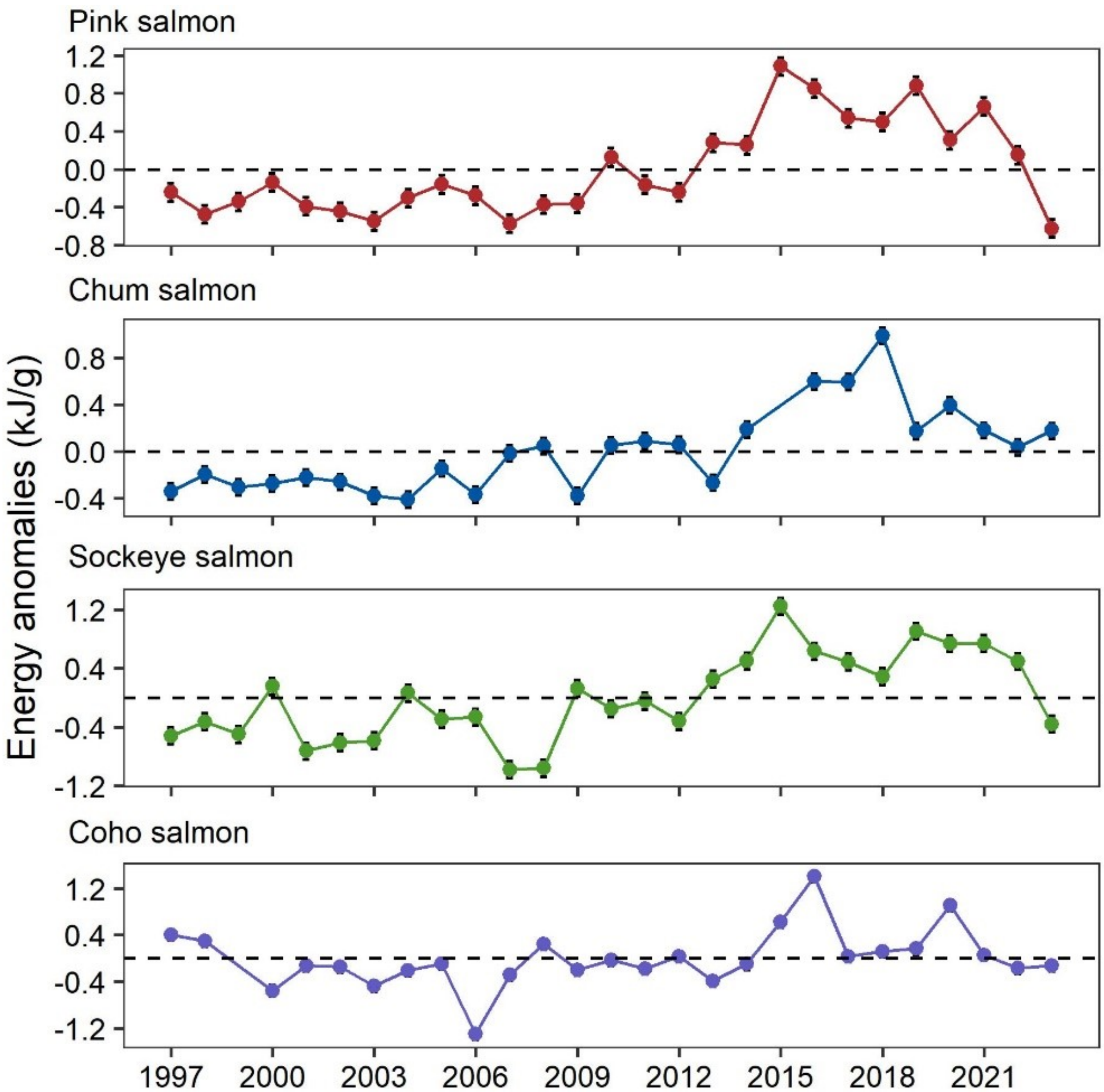

Figure 67: Average energy density (kJ/g, dry weight; ± 1 standard error) anomalies of juvenile salmon captured in Icy Strait, AK by the Southeast Coastal Monitoring project, 1997 – 2023. The dashed line indicated the time series average.

Trends in Survival of Coho, Sockeye, and Pink Salmon from Auke Creek, Southeast Alaska

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Last updated: September 2023

Description of indicator: The time series of marine survival estimates for wild coho, sockeye, and pink 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 salmon survival in 1980. The Auke Creek weir structure facilitates near-complete capture of all migrating sockeye smolt and returning adults and is the only weir capable of such precision on a wild system in the North Pacific. All coho salmon smolts leaving the Auke Lake watershed have been counted, subsampled for age and length, and injected with coded wire tags (CWT). These migrating fish included those with both 1 and 2 freshwater annuli and 0 or 1 ocean annuli. Coho marine survival is estimated as the number of adults (harvest plus escapement) per smolt. The index is presented by smolt (outmigration) year. It is the only continuous marine survival and scale data set in the North Pacific that recovers all returning age classes of wild, CWT coho salmon as ocean age 0 and 1. The precision of the survival estimate was high due to 100% marking and high sampling fractions that minimized the variance in the survival estimate and made the series an excellent choice for model input relating to nearshore and gulf-wide productivity. While no stock-specific harvest information is available for Auke Creek sockeye and pink 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.

Status and trends: The historical trends show marine survival of wild coho salmon from Auke Creek varies from 5.1% to 47.8%, with an average survival of 21.1% from smolt years 1980 – 2021 (Figure 68a). Marine survival for 2022 was the second lowest on record at 10.8% and overall survival averaged 10.1% over the last 5 years and 11.0% over the last 10 years. The survival index for ocean age-0 coho varies from 0.2% to 11.2% from smolt years 1980 – 2022 (Figure 68b). Productivity of wild sockeye salmon smolts from Auke Creek varies from 1619 to 33616, with an average productivity of 15724 from ocean entry years 1980 – 2023.

Productivity for the 2023 saw 10896 outmigrant smolts, the thirteenth lowest on record (Figure 68c). Escapement of wild sockeye salmon from Auke Creek has varied from 325 to 6123, with an average escapement of 2532 from return years 1980 – 2023. The 2023 season saw the fifth lowest escapement of sockeye salmon to Auke Creek with 962 returning adults (Figure 68d).

Marine survival of wild pink salmon from Auke Creek varies from 1.1% to 53.3%, with an average survival of 11.5% from ocean entry years 1980 – 2022 (Figure 68e). Marine survival for the 2022 ocean entry year was 18.4% and overall survival averaged 15.2% over the last 5 years and 14.8% over the last 10 years. 2023 saw the tenth highest return of pink salmon to Auke Creek with 14746 returning adults (Figure 68f).

Factors influencing observed trends: Factors influencing observed trends in coho survival include: smolt age, smolt size, migration timing, fishery effort and location, and marine environmental conditions (Briscoe et al., 2005; Robins, 2006; Malick et al., 2009; Kovach et al., 2013*a*). Coho salmon marine

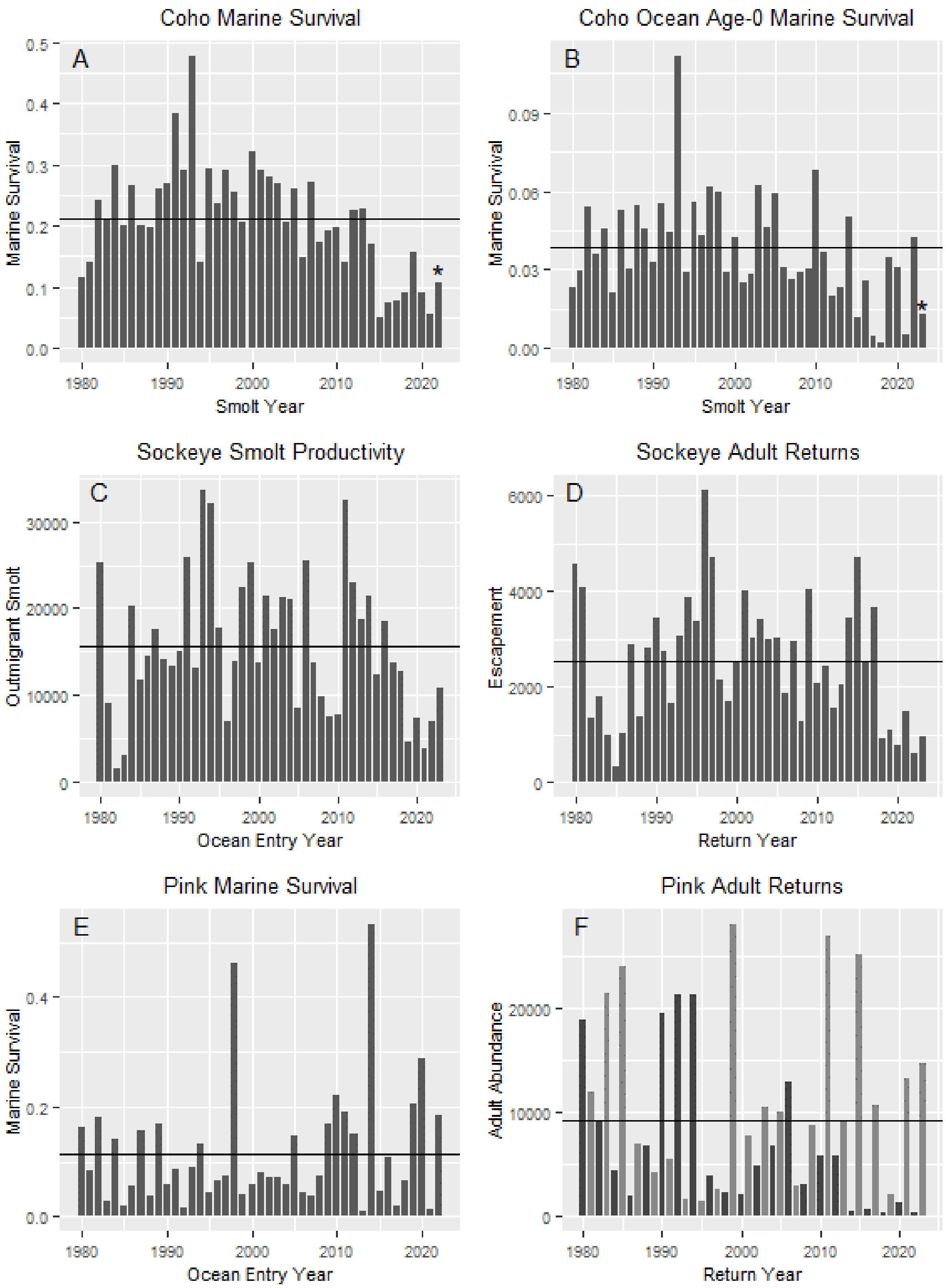

Figure 68: Auke Creek (SE Alaska) salmon marine survival and productivity indices. Coho salmon are represented by total marine survival (ocean age-0 and age-1 harvest plus escapement) (A), and percentage of ocean age-0 coho per smolt (escapement only) by smolt year (B). Sockeye salmon are represented by smolt productivity by ocean entry year (C) and adult returns (D). Pink salmon are represented by marine survival index is represented by ocean entry year (E) and adult returns by year (F). Return year 2023 data are denoted with an asterisk as these may change by the end of the year. For coho, sockeye and pink indices, the solid, horizontal line indicates the 1980 – 2023 average.

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*a*). 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 over all of southeast Alaska (Shaul et al., 2011). The marine survival of Auke Creek coho salmon and growth inferred by scales samples is influenced and reflective of broad scale oceanographic indices in the GOA (Briscoe et al., 2005; Robins, 2006; Malick et al., 2009; Orsi et al., 2013).

Sockeye salmon marine survival has been influenced by trends that include: smolt age, smolt size, migration timing, predation, and marine environmental conditions. Age and size at saltwater entry, along with regional sea surface temperature 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-1.0 smolts, while age-2.0 smolts are trending earlier (Shanley et al., 2015; Kovach et al., 2013*a*). Additionally, positive effects of temperature have been observed on sockeye biomass and length of age-2.0 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).

Factors that have influenced these observed trends in pink salmon survival 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). 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 do to their size (Parker, 1971). During juvenile development, the local conditions of stream discharge and temperature are strong determinants of egg and fry survival. 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 index of coho, sockeye and pink salmon at Auke Creek is related to ocean productivity indices and to important rearing habitats shared by groundfish species. The productivity and escapement indices of Auke Creek salmon provide an opportunity for the examination of annual variation in habitat quality of rearing areas and general ocean conditions and productivity. 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. 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. As a result of these implications, 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. Due to the one ocean year life history of pink salmon, we are able to use their marine survival as a proxy for the general state of the Gulf of Alaska. Additionally, as pink fry are a numerous 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.

Groundfish

Gulf of Alaska Groundfish Condition

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Last updated: September 2023

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

The groundfish morphometric condition indicator is calculated from paired fork lengths (mm) and weights (g) of individual fishes that were collected during the biennial summer bottom trawl survey of the Gulf of Alaska (GOA) conducted by the Alaska Fisheries Science Center Resource Assessment and Conservation Engineering (AFSC/RACE) - Groundfish Assessment Program (GAP). Fish condition analyses were applied to walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), Pacific ocean perch (*Sebastes alutus*), northern rockfish (*Sebastes polyspinis*), dusky rockfish (*Sebastes variabilis*), shortraker rockfish (*Sebastes borealis*), rougheye rockfish (*Sebastes aleutianus*), blackspotted rockfish (*Sebastes melanostictus*), sharpchin rockfish (*Sebastes zacentrus*), arrowtooth flounder (*Atheresthes stomias*), southern rock sole (*Lepidopsetta bilineata*), northern rock sole (*Lepidopsetta polyxystra*), flathead sole (*Hippoglossoides elassodon*), Dover sole (*Microstomus pacificus*), and rex sole(*Glyptocephalus zachirus*) 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 69).

To calculate indicators, length-weight relationships were estimated from linear regression models based on a log-transformation of the exponential growth relationship, $W = aL^b$, where W is weight (g) and L is fork length (mm) for all areas for the period 1984 – 2023. Unique intercepts (a) and slopes (b) were estimated for each survey stratum, sex, and stratum-sex interaction to account for sexual dimorphism and spatial-temporal variation in growth and bottom trawl survey sampling date. Length-weight relationships for 100 – 250 mm fork length walleye pollock (corresponding with ages 1 – 2 years) were calculated separately from adult walleye pollock ($>$ 250 mm). Residuals for individual fish were obtained by subtracting observed weights from bias-corrected weights-at-length that were estimated from regression models. Individual length-weight residuals were aggregated and averaged for each stratum and weighted proportionally to total biomass in each stratum from area-swept expansion of mean bottom-trawl survey catch per unit effort (CPUE; i.e., design-based stratum biomass estimates). Variation in fish condition was evaluated by comparing average length-weight residuals among years. To minimize the influence of

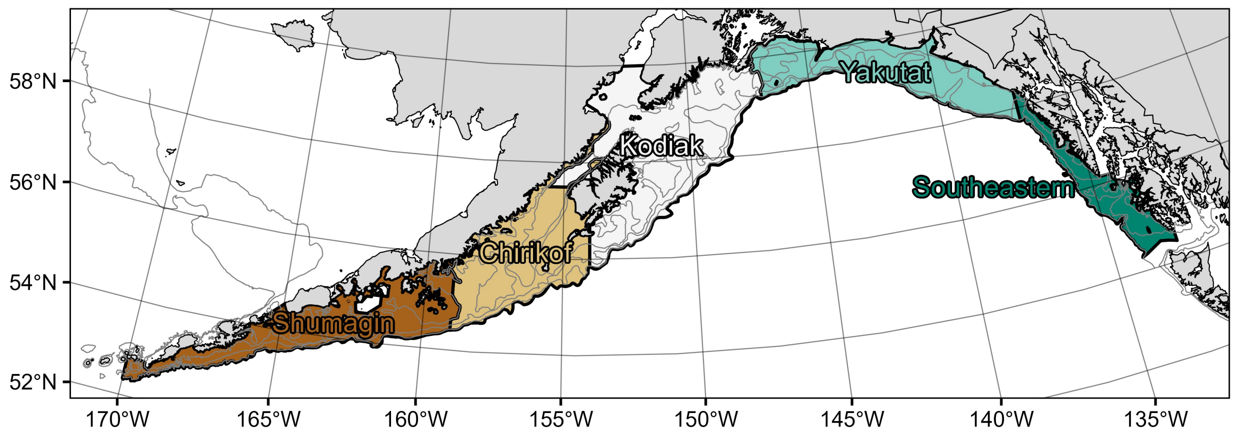

Figure 69: NOAA Fisheries, Alaska Fisheries Science Center Gulf of Alaska summer bottom trawl survey area with International North Pacific Fisheries Commission (INPFC) statistical fishing strata delineated by the red lines.

unrepresentative samples on indicator calculations, combinations of species, stratum, and year with a sample size < 10 were used to fit length-weight regressions but were excluded from calculating length-weight residuals. Morphometric condition indicator time series, code for calculating the indicators, and figures showing results for individual species are available through the *akfishcondition* R package and GitHub repository[19].

Methodological Changes: In Groundfish Morphometric Condition Indicator contributions to the 2022 Bering Sea and Aleutian Islands Ecosystem Status Reports, historical stratum-biomass weighted residual condition indicators were presented alongside condition indicators that were calculated using the R package VAST. The authors noted there were strong correlations between VAST and stratum-biomass weighted condition indicators for most species ($r = 0.79 - 0.98$). The authors received the following feedback about the change from the BSAI Groundfish Plan Team meeting during their November 2022 meeting:

"The Team discussed the revised condition indices that now use a different, VAST-based condition index, but felt additional methodology regarding this transition was needed. The Team recommended a short presentation next September to the Team to review the methods and tradeoffs in approaches. The Team encouraged collaboration with the NMFS longline survey team to develop analogous VAST indices."

Based on feedback from the Plan Team, staff limitations, and the lack of a clear path to transition condition indicators for longline survey species to VAST, analyses supporting the transition to VAST were not conducted during 2023. Therefore, the 2023 condition indicator was calculated from stratum-biomass weighted residuals of length-weight regressions.

In 2023, we present condition indicator results for eight new species (shortraker rockfish, rougheye

[19]https://github.com/afsc-gap-products/akfishcondition

rockfish, sharpchin rockfish, Dover sole, northern rock sole, flathead sole, and rex sole).

Status and trends: Residual body condition varied among survey years for all species considered (Figures 70 and 71). Fish condition indicators for fourteen of the fifteen species were below average in 2023. Many of these species condition in 2023 was the same or reduced relative to 2021. The exception to this was rougheye rockfish, which were in above-average fish condition in 2023, representing an improvement from their below- average condition in 2021. Residual body condition for walleye pollock, shortraker rockfish, arrowtooth flounder, flathead sole, Dover sole, and rex sole were below average and similar to condition in 2021. Residual body condition for Pacific cod, dusky rockfish, and sharpchin rockfish declined from 2021 to 2023. Southern rock sole morphometric condition has been below average since 2013, but had shown a positive trend over the previous four surveys (2017 to 2021) before declining slightly in 2023. Northern rock sole had the opposite trend, where body condition decreased from 2017 to 2021 before increasing slightly in 2023, though it remains below average. Residual body condition for northern rockfish, Pacific ocean perch, and blackspotted rockfish also improved, but are still below average. With respect to the 2014 – 2016 marine heatwave in this system, the following species have been in below-average condition since 2015: walleye pollock, northern rockfish, dusky rockfish, flathead sole, northern rock sole, southern rock sole, and rex sole. Dover sole have been in below-average condition since 2013. Pacific ocean perch reached average condition for the first time since the marine heatwave.

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 (Figures 72 and 73). 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 pollock, Pacific ocean perch, and dusky rockfish in Southeast was positive while the majority of other locations for other fish trended negative. Exceptions include rougheye rockfish in Chirikof and Kodiak and rex sole in Kodiak. While Pacific cod residuals trended negative again, residual body condition in the Kodiak stratum remained positive. Patterns of fish distribution were 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 2023; 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 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

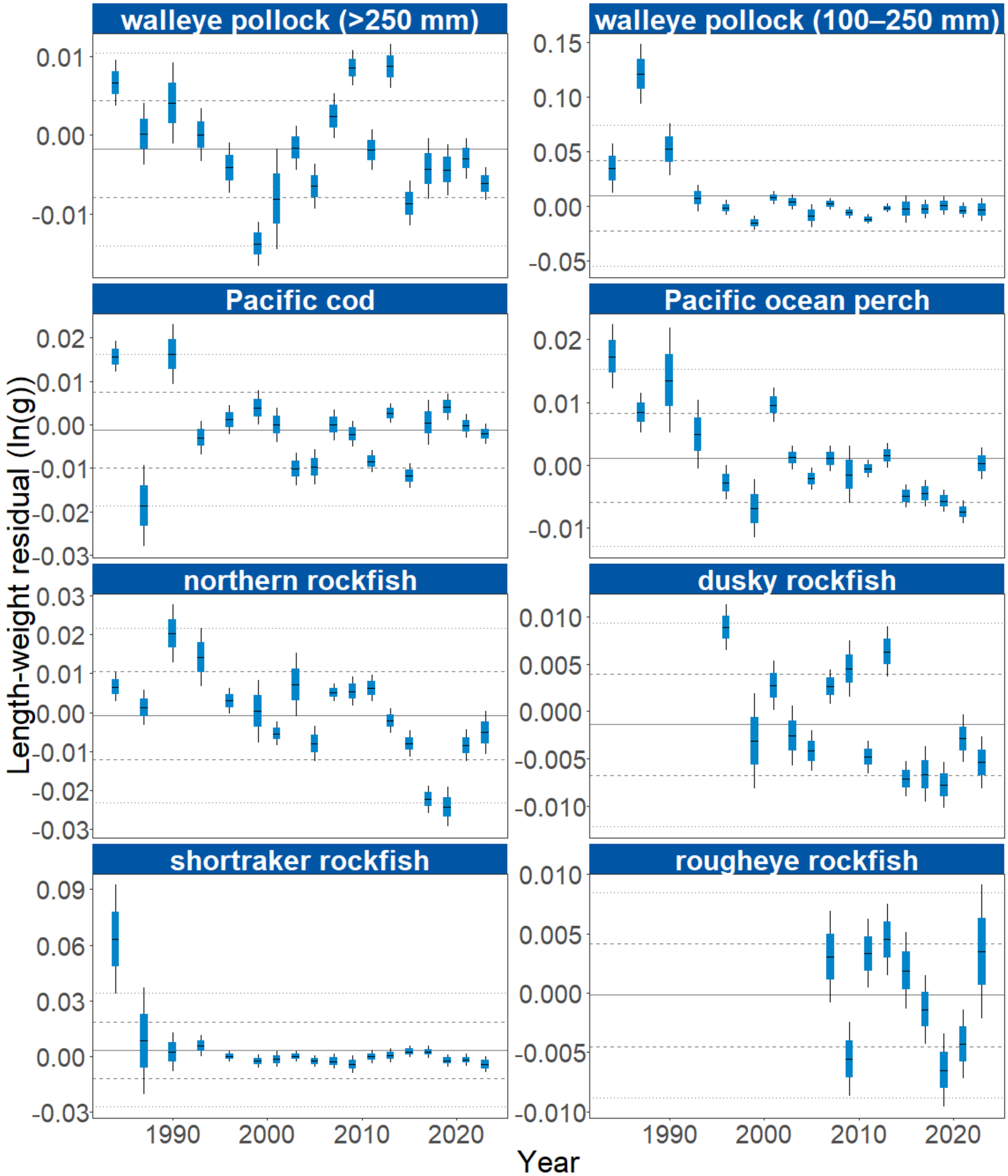

Figure 70: Biomass-weighted residual body condition index across survey years (1984 – 2023) for fifteen Gulf of Alaska groundfish species collected on the NOAA Fisheries, Alaska Fisheries Science Center Resource Assessment and Conservation Engineering (AFSC/RACE) Groundfish Assessment Program (GAP) standard summer bottom trawl survey. Filled bars denote weighted length-weight residuals, error bars denote two standard errors.

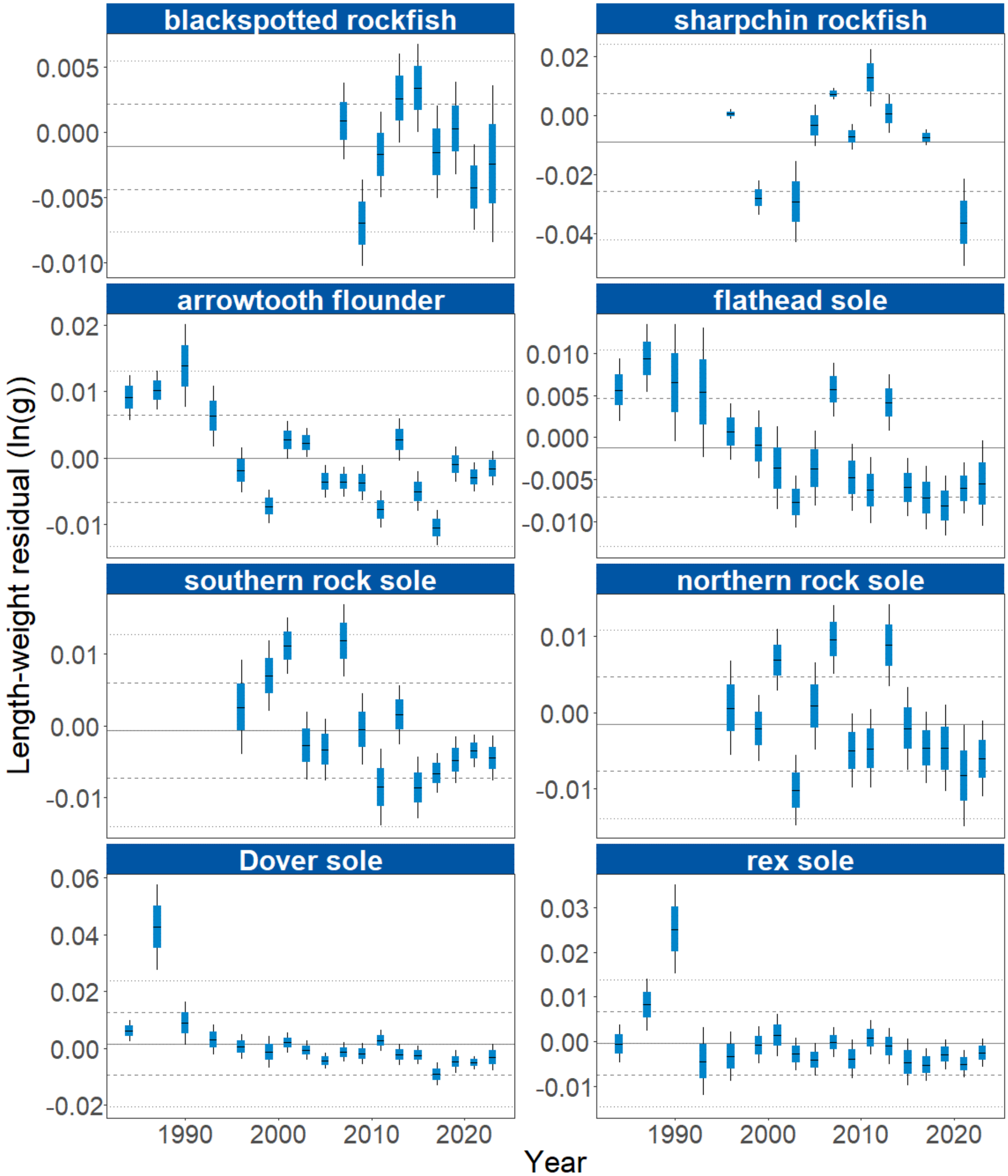

Figure 71: Biomass-weighted residual body condition index across survey years (1984 – 2023) for fifteen Gulf of Alaska groundfish species collected on the NOAA Fisheries, Alaska Fisheries Science Center Resource Assessment and Conservation Engineering (AFSC/RACE) Groundfish Assessment Program (GAP) standard summer bottom trawl survey. Filled bars denote weighted length-weight residuals, error bars denote two standard errors.

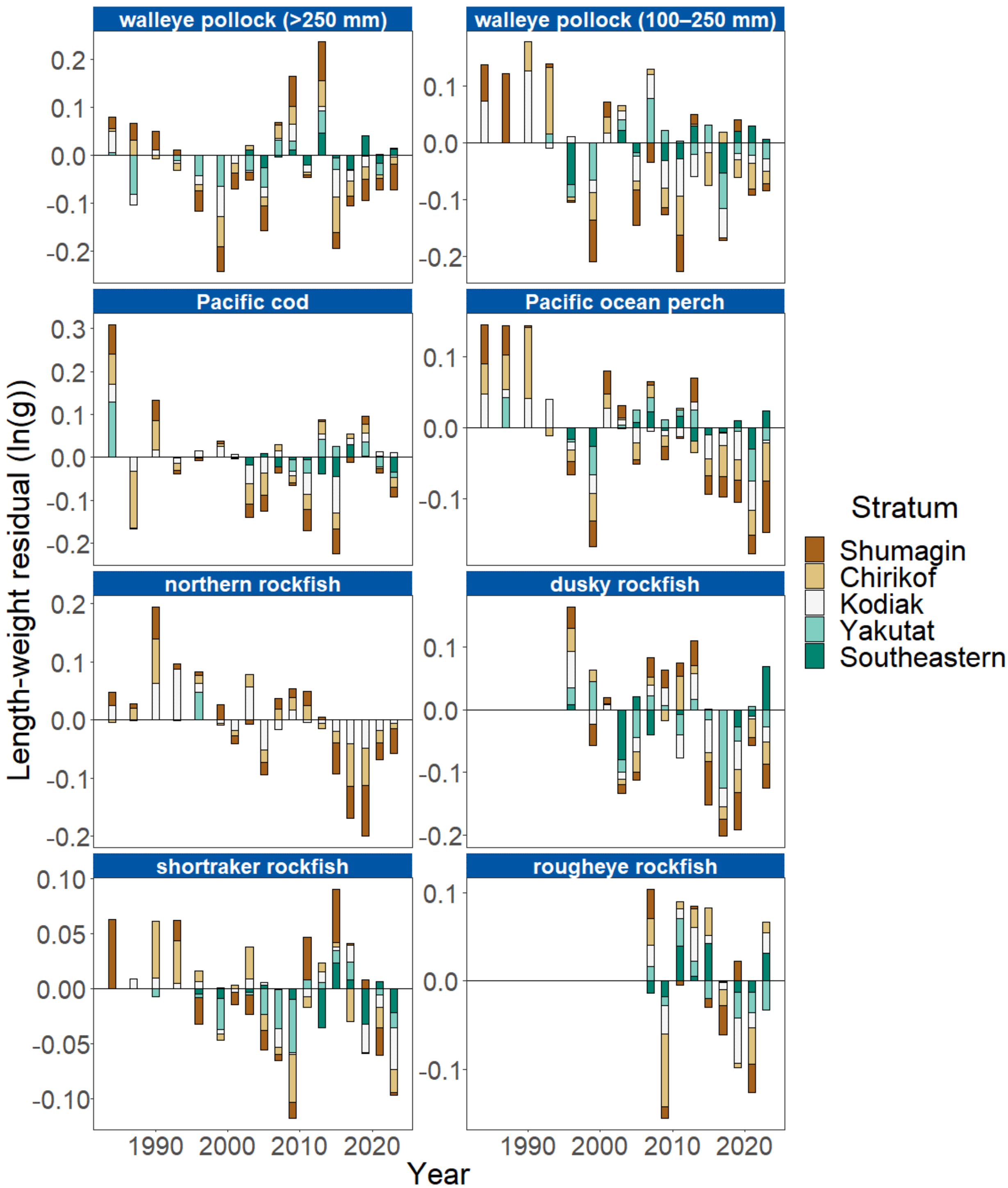

Figure 72: Residual body condition index for fifteen Gulf of Alaska groundfish species collected on the NOAA Fisheries, Alaska Fisheries Science Center Resource Assessment and Conservation Engineering (AFSC/RACE) Groundfish Assessment Program (GAP) standard summer bottom trawl survey (1984 – 2023) grouped by International North Pacific Fisheries Commission (INPFC) statistical sampling strata.

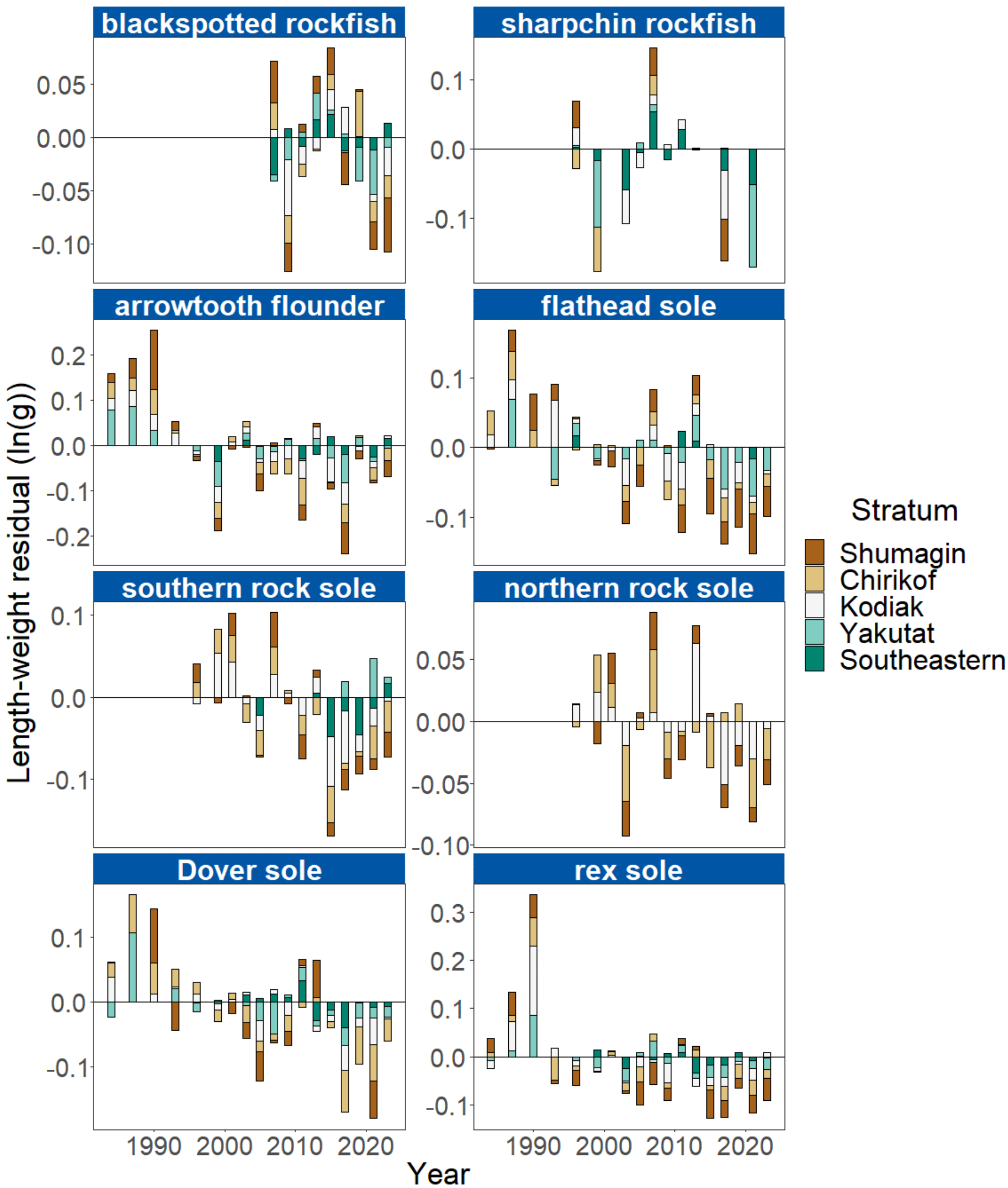

Figure 73: Residual body condition index for fifteen Gulf of Alaska groundfish species collected on the NOAA Fisheries, Alaska Fisheries Science Center Resource Assessment and Conservation Engineering (AFSC/RACE) Groundfish Assessment Program (GAP) standard summer bottom trawl survey (1984 – 2023) grouped by International North Pacific Fisheries Commission (INPFC) statistical sampling strata.

east. In addition, spatial variability in residual condition may also reflect local environmental conditions that influence growth and prey availability in the areas surveyed (e.g., local differences in average cross-shelf transport of heat via eddies reported this year in International Pacific Halibut Commission (IPHC) regions).

Implications: Variations in body condition likely have implications for fish survival. The condition of GOA groundfish may contribute to survival and recruitment. 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. In the future, it may be more informative to examine body condition by life history stage (e.g., early juvenile, subadult, and adult phases), age, or sex.

Below-average body condition for many GOA species over the last four to five 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 influence changes in fish condition in the species examined. It should be noted that while many GOA species' body condition remained below average this year, most species' condition improved relative to 2021; southern rock sole, dusky rockfish, Pacific cod, walleye pollock adults, and sharpchin rockfish were the exceptions. 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

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Last updated: September 2023

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, with the most consistent time series beginning in 1988. 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 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. While the survey covers a large portion of the central and western GOA, 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 74).

In 2023, 50 stations were sampled from July 9 through July 17. The survey catches (mt/km) from Kiliuda and Ugak Bays and Barnabas Gully were summarized by year for selected species groups. 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*. Temperature anomalies were calculated using average bottom temperatures recorded for each haul from 1990 to present.

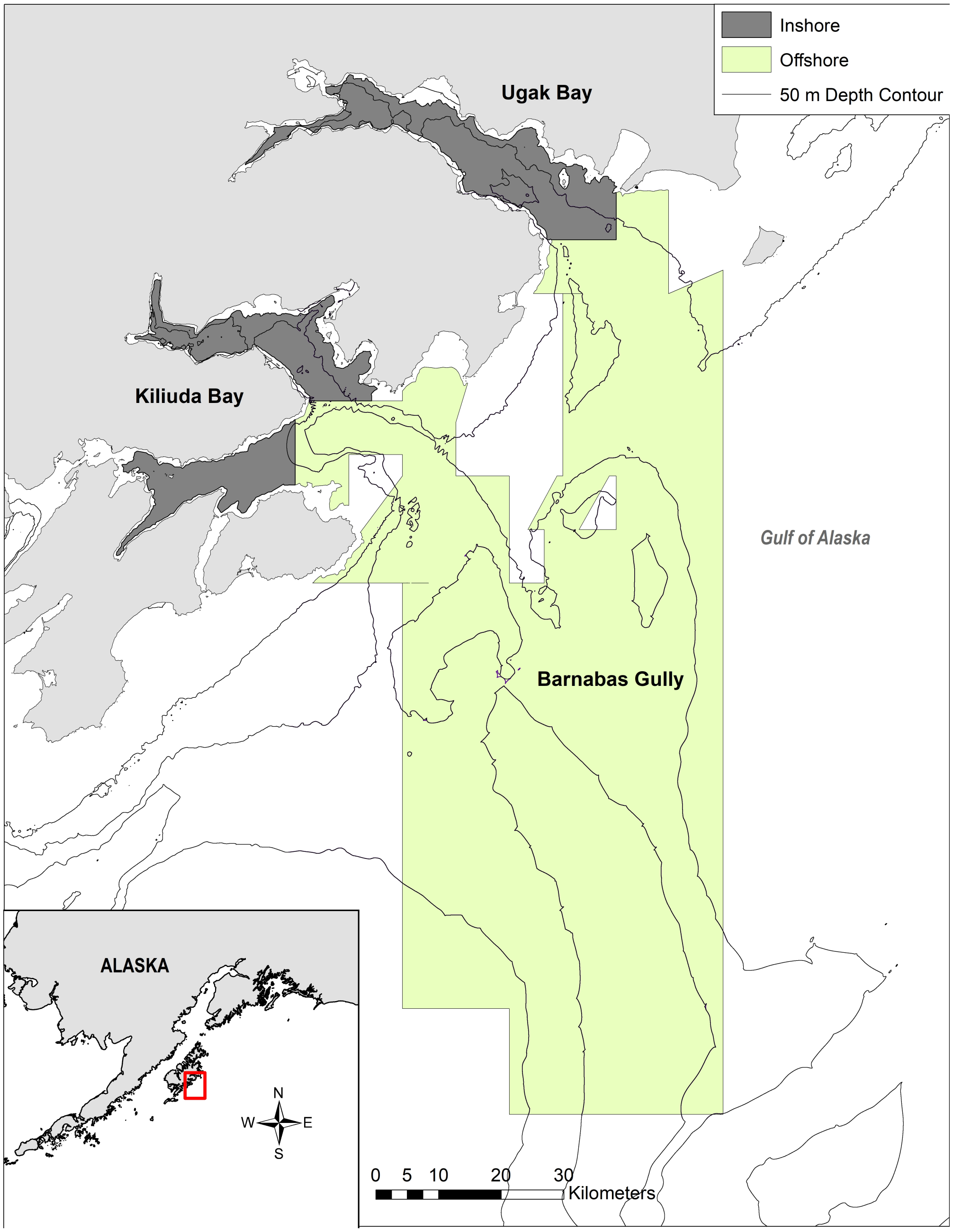


Figure 74: Kiliuda Bay, Ugak Bay, and Barnabus Gully survey areas used to characterize inshore (dark gray, 14 stations) and offshore (light gray, 36 stations) trawl survey results.

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 75). The 2023 survey data showed a decrease in overall biomass in the both the inshore and offshore stations. Arrowtooth flounder and Tanner crab have been the predominant species in the ADF&G trawl survey catches in the last 3 years, with slight decreases in both the inshore and offshore stations in 2023. Gadids in the inshore station showed a slight increase in 2023 along with starfish. Of the starfish group, *Pychnopodia helianthoides* (sunflower sea star), although at historically low numbers, continues to be the predominant species in the catches.

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 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 19.4% of catch and walleye pollock 80.6% in 2023.

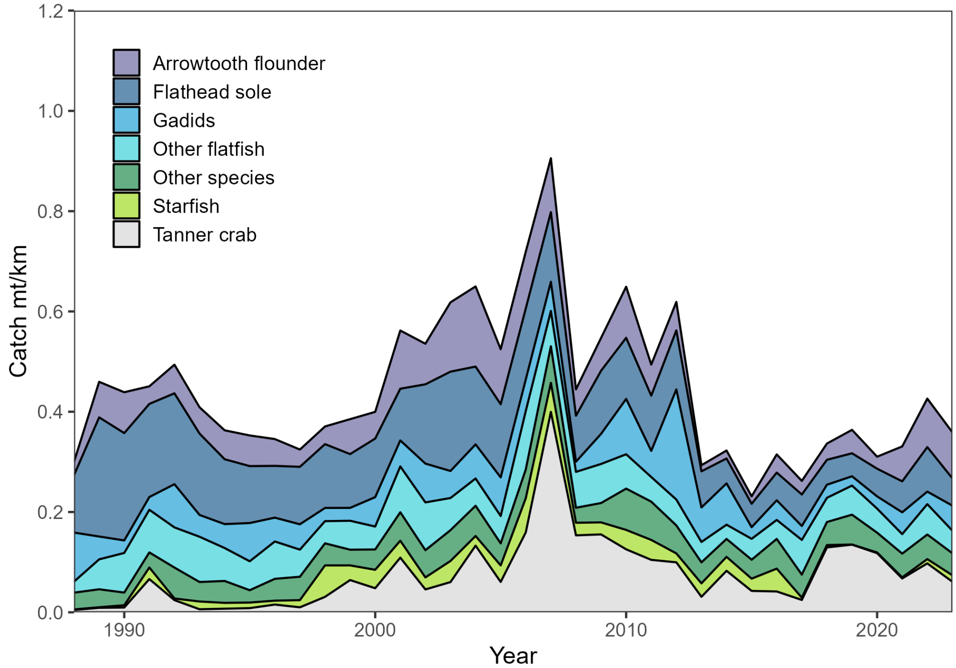
Below-average anomaly values (baseline 1988 – 2022) for flathead sole were recorded again in 2023 for both offshore and the inshore areas, while arrowtooth were above-average in shore and below-average offshore (Figure 76). Pacific cod, Pacific halibut, walleye pollock, and skates were also below average for both inshore and offshore stations. The above-average anomaly values for Tanner crab continued in 2023 only in the offshore stations, due to a large recruitment event (Spalinger and Silva, 2023).

Summer temperature anomalies for both inshore and offshore stations were below-average in 2023 in contrast to previous years (see western GOA summer temperatures in this Report, p.44). The higher-than-average temperatures in past years frequently occurred during moderate and strong El Niño years[20].

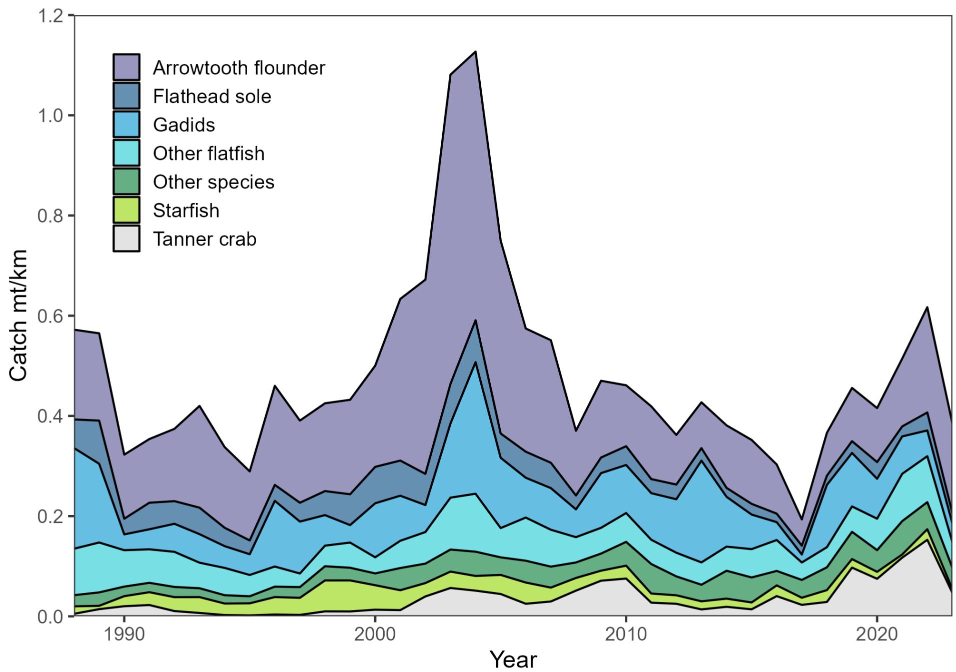
Factors influencing observed trends: It appears that significant changes in volume and composition of the catches on the east side of Kodiak are occurring, but it is unknown to what extent predation, environmental changes, and fishing effort are contributing. The lower overall catch from 1993 to 1999 (Figure 75) 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 correspondingly higher catches. Lower than average temperatures were 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 in the GOA were 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 during years with lower-than-average Pacific cod, arrowtooth flounder, flathead sole, and halibut catches.

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. These survey data are 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.

[20] `http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml`



(a) Kiliuda and Ugak Bay



(b) Barnabas Gully

Figure 75: Total catch per km towed (mt/km) of selected species from Kiliuda and Ugak Bays (a) and Barnabas Gully (b) survey areas off the east side of Kodiak Island, 1987–2023.

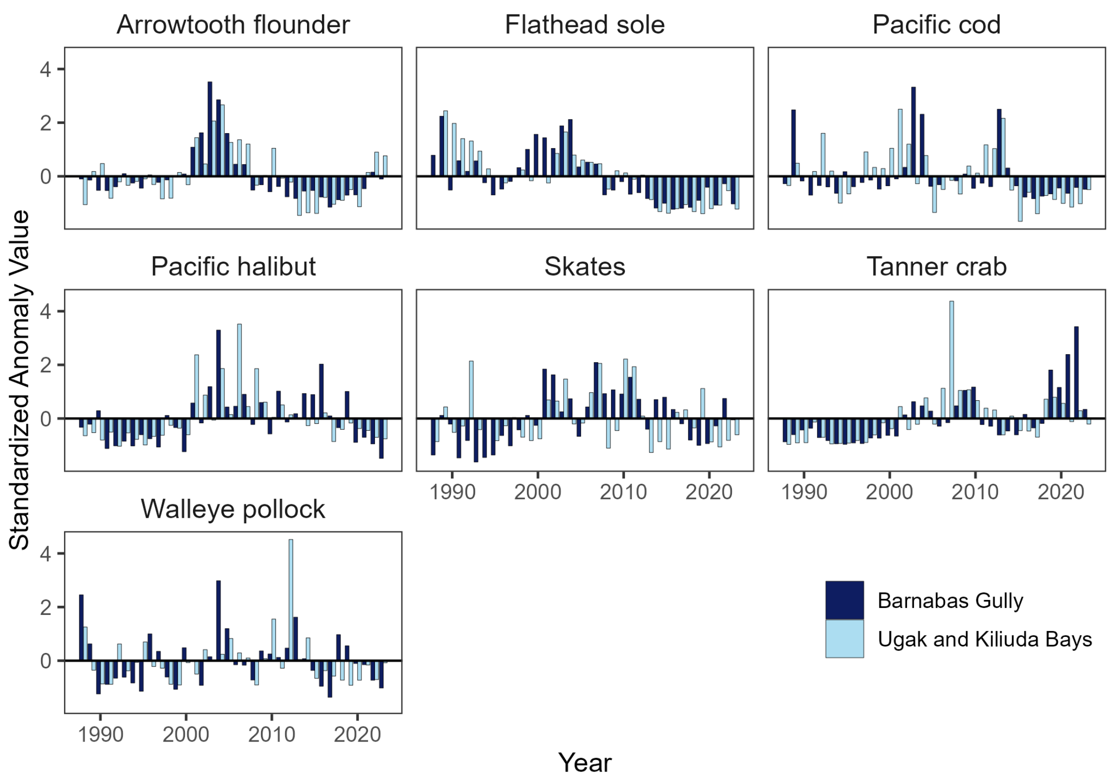


Figure 76: A comparison of standardized anomaly values, based on catch (kg) per distance towed (km) for selected species caught from 1988 to 2023 in Barnabas Gully and Kiliuda and Ugak Bays during the ADF&G trawl survey.

Distribution of Rockfish Species along Environmental Gradients in NOAA Fisheries Bottom Trawl Surveys

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Last updated: October 2023

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 (four *Sebastes* spp., rougheye-blackspotted rockfish complex, 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.

In 2001, the Yakutat to Southeast Alaska International North Pacific Fisheries Commission (INPFC) districts were not sampled due to budgetary constraints and so this year is excluded from the position data time series (Raring et al. 2011). The 2001 catch data remain in the depth and temperature gradient time series.

Status and trends: Several trends were observed with rockfishes along the three environmental gradients examined in the Gulf of Alaska time series through 2023 (Figure 77). Rougheye-blackspotted rockfish complex, northern rockfish, and shortspine thornyhead demonstrated significant distribution trends westward of Hinchinbrook Island over the time series while northern rockfish and shortspine thornyhead depth distributions appear to be trending significantly shallower and dusky rockfish distribution got deeper ($p \leq 0.05$). The mean-weighted depth distributions of the other three taxa examined remained relatively stable. There were no significant rockfish distribution trends with temperature and all of the taxa examined were found within about a 1.5°C temperature envelope. There appears to be an interesting shift in the distribution of adult Pacific ocean perch (POP) along the geographical position gradient. In 2013, the highest mean-weighted position occurred for POP around 270 km west of Hinchinbrook Island, Alaska. Over the last 10 years, the mean-weighted distance from Hinchinbrook shifted approximately 500 km and was approximately 220 km southeastward of Hinchinbrook Island in 2023.

Factors causing observed trends: In the Gulf of Alaska, most rockfish distributions appear to be relatively stable along environmental and geographical gradients examined. As temperatures rise and fall around the mean, the depth distribution does not change, indicating that distributions aren't changing in response to temperature. The significant geographic shifts and changes in depth distribution over time for most rockfishes, and the southeastward shift of adult Pacific ocean perch, could be explained by changing abundance. As population sizes change, species' occupation of different parts of their range can change as well.

Implications: The trends in the mean-weighted distributions of rockfishes should continue to be monitored, with special attention to mechanisms that could explain the shifting depth and geographic distributions, especially as they relate to changing temperatures and fluctuating population sizes. In 2019, five of the six rockfish species were found at the highest mean-weighted temperature in the time series with the exception of adult rougheye-blackspotted rockfish complex.

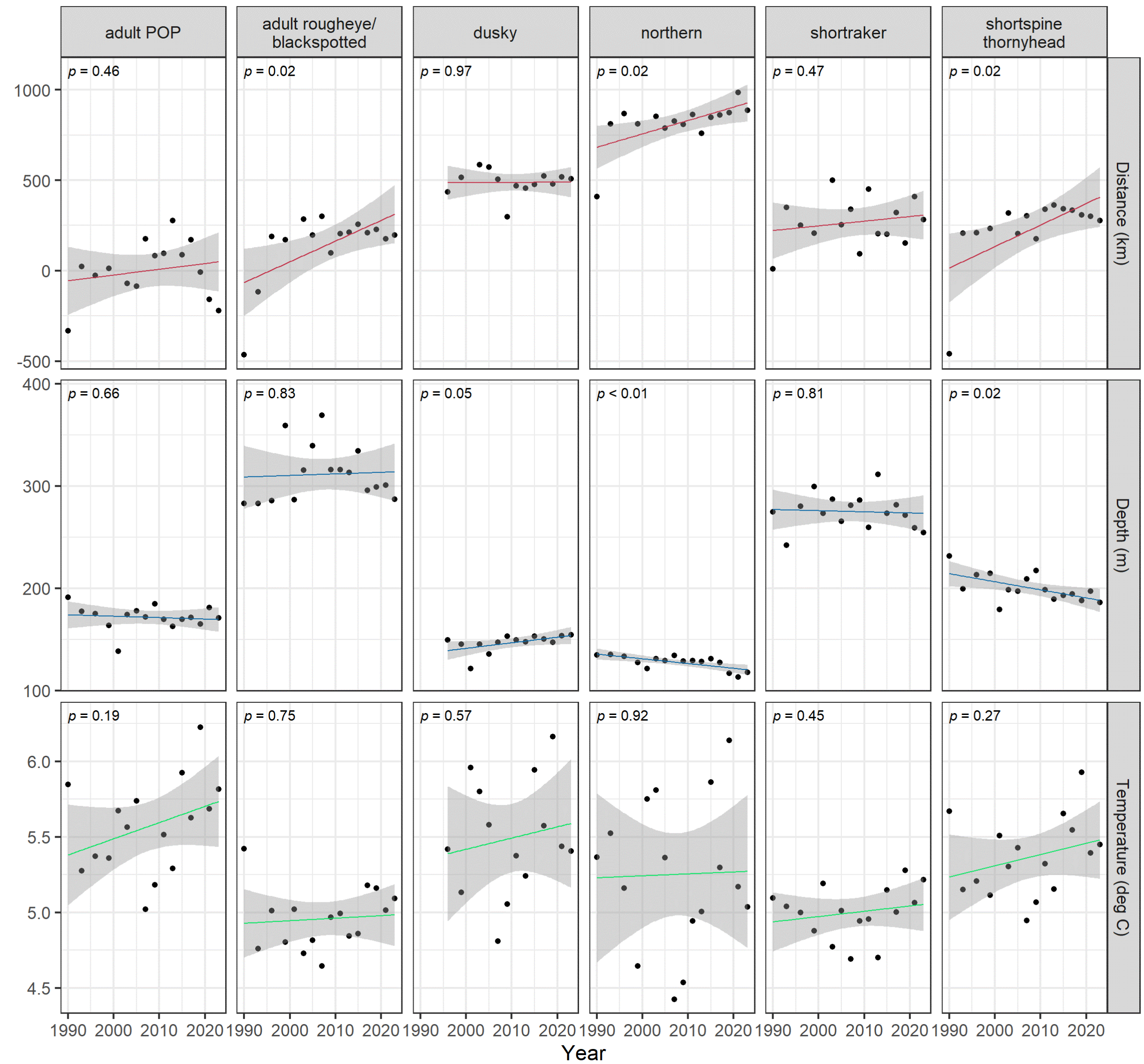

Figure 77: Plots of mean weighted (by catch per unit effort) distributions of six rockfish taaxa along three environmental gradients in the Gulf of Alaska. Mean weighted distributions of rockfish species-groups are shown for A) distance from Hinchinbrook Island, B) depth, and C) temperature. For distance, positive values are west of Hinchinbrook Island, Alaska and negative values are southeastward. P-values were reported on each plot; $p \leq 0.05$ was considered statistically significant.

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

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Last updated: November 2023

Description of indicator: We report trends in age-1 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, time- and age-invariant residual mortality (M1) and model estimates of time and age varying annual predation mortality (M2) produced from the multi-species statistical catch-at-age assessment model (known as CEATTLE; Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics, 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 (see Adams et al., 2022, for more details). The model is fit to data from five fisheries and seven surveys between 1977 and 2022, and includes inputs of abundance-at-age from recent stock assessment models for Pacific halibut scaled to the proportion of age-5+ biomass in IPHC management area 3 (Stewart and Hicks, 2021). Model estimates of predation mortality are empirically derived by bioenergetics-based consumption information and diet data from the GOA to inform predator-prey suitability (Holsman and Aydin, 2015; Holsman et al., 2019).

Status and trends: Estimated age-1 natural mortality (M) for walleye pollock, Pacific cod, and arrowtooth flounder peaked in 2005 for pollock, 2005 for Pacific cod, and 1991 for arrowtooth flounder (Figure 78). Average age-1 M estimated by CEATTLE was greatest for pollock (1.23 $yr^{(-1)}$) and lower for Pacific cod (0.58 $yr^{(-1)}$) and arrowtooth (0.37 $yr^{(-1)}$ for females and 0.47 $yr^{(-1)}$ for males). After increasing slightly in recent years, pollock age-1 M still remained lower in 2023 at 1.09 $yr^{(-1)}$ relative to the long-term mean 1.23 $yr^{(-1)}$ and the values used for single species assessment (age-1 M = 1.39; Figure 78). Additionally, Pacific cod and arrowtooth flounder age-1 M were below the long-term mean after increasing and decreasing, respectively, in recent years (Figure 78), but above the values used/estimated for the single species assessment of 0.46 $yr^{(-1)}$ (Pacific cod), 0.2 $yr^{(-1)}$ (arrowtooth females), and 0.35 $yr^{(-1)}$ (arrowtooth males), with total age-1 M at around 0.57 $yr^{(-1)}$ for Pacific cod 0.36 $yr^{(-1)}$for arrowtooth females, and 0.45 $yr^{(-1)}$ for arrowtooth males. 2023 age-1 M across species is 6.41% to 33.11% lower than in peak years.

On average 150,013 mt of age-1 pollock, 2,7 18 mt of age-1 Pacific cod, and 6,317 mt of age-1 arrowtooth flounder was consumed annually by species included in CEATTLE between 1977 and 2023. For 2023, we estimated 32 mt of age-1 pollock, 1,571 mt of age-1 Pacific cod, 4,210 mt of age-1 arrowtooth females, and 1,571 mt of age-1 arrowtooth males was consumed by species included in

CEATTLE. Across all ages 514,436 mt of pollock, 29,151 mt of arrowtooth flounder, 5,653 mt of Pacific cod was consumed annually, on average, by species included in CEATTLE. The total biomass consumed of pollock as prey across all ages decreased in 2023 compared to 2022 (Figure 79). The total biomass consumed of arrowtooth flounder and Pacific cod has decreased in recent years. However, the total biomass consumed as prey across all ages for all species is currently below the long-term mean.

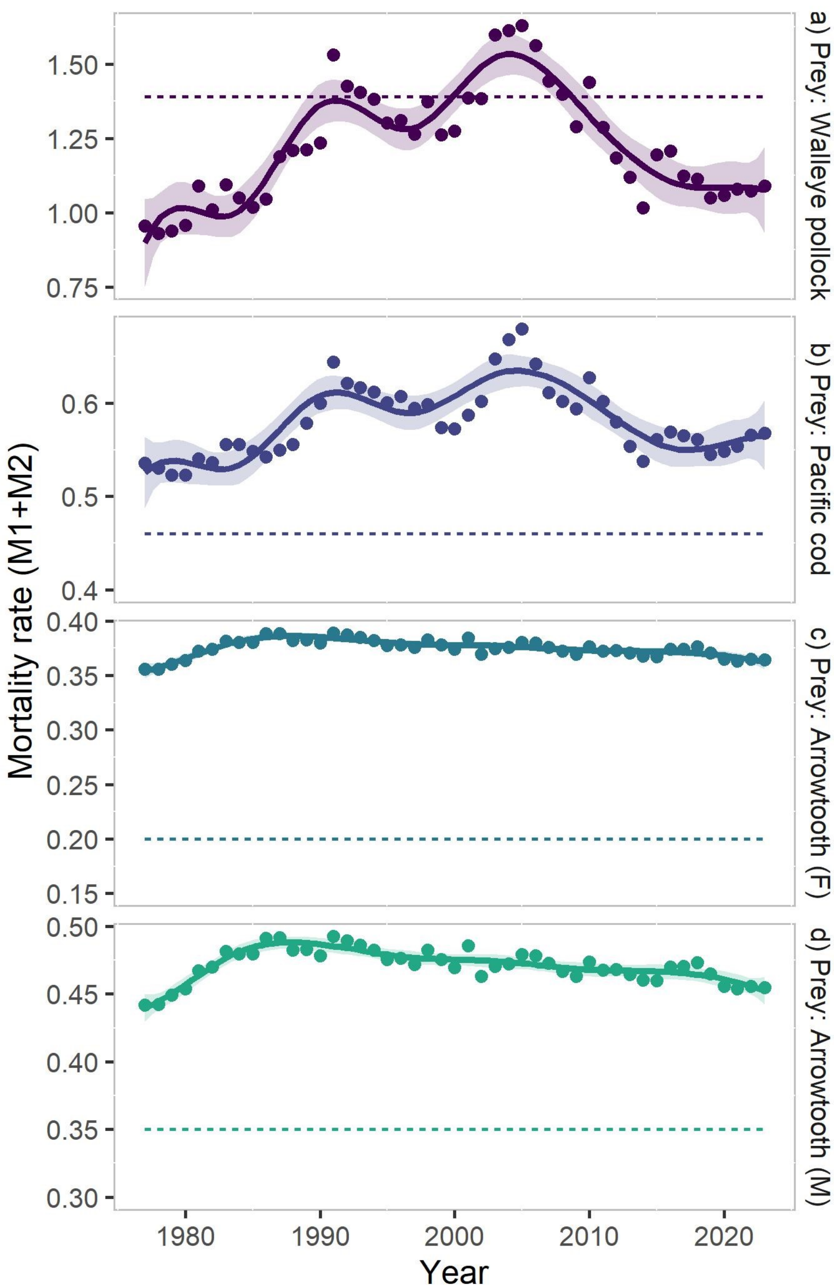

Figure 78: Annual variation in total mortality (M1 + M2) of age-1 walleye pollock, Pacific cod, and arrowtooth flounder (females and males) from the single-species models (dashed line), and the multi-species models with temperature (points; solid line is a loess polynomial smoother indicating trends over time).

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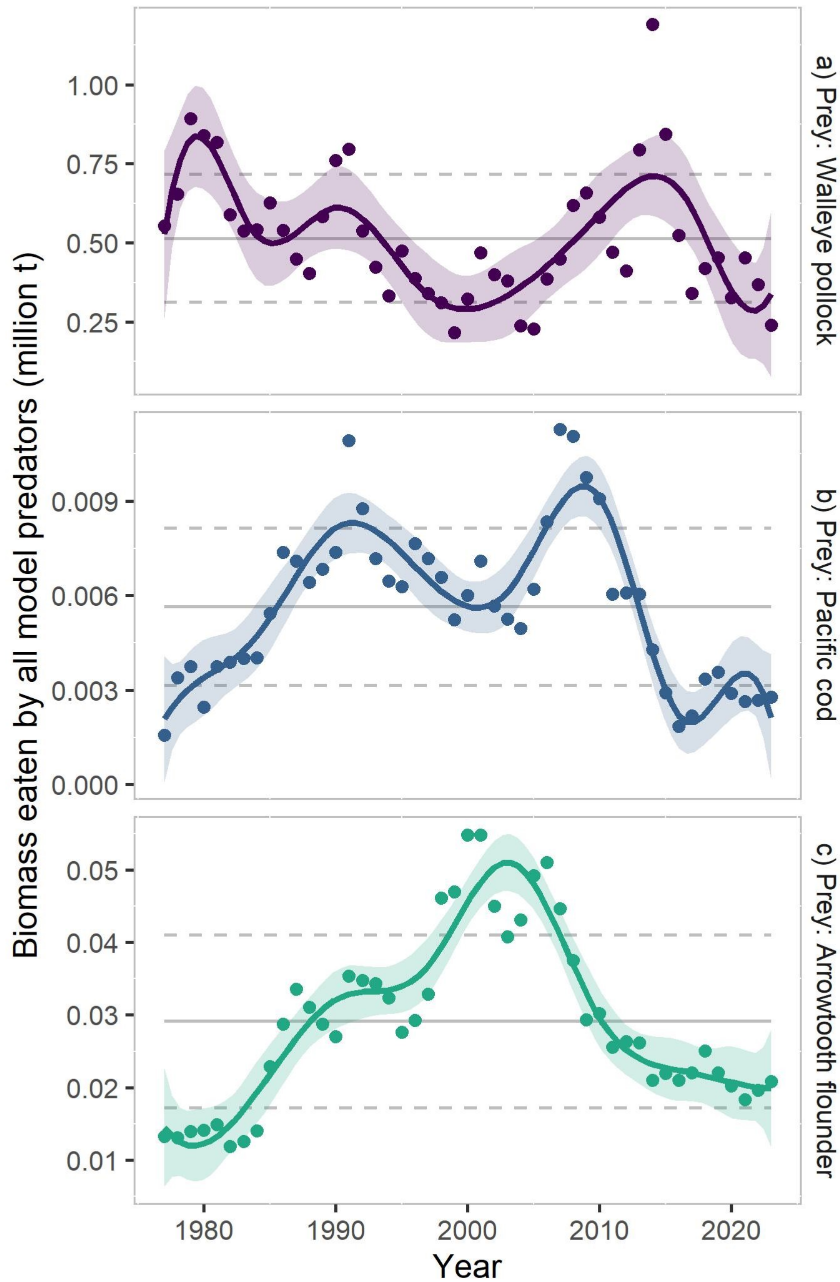

Figure 79: Multispecies estimates of biomass consumed as prey across all ages by all predators annually in the models for walleye pollock, Pacific cod, and arrowtooth flounder. Points represent annual estimates, gray lines indicate 1979–2023 mean estimates for each species, and the solid line is a 10 year (symmetric) loess polynomial smoother indicating trends over time.

Factors influencing trends: Temporal patterns in total natural mortality reflect annually varying changes in predation mortality by pollock, Pacific cod, Pacific halibut, and arrowtooth flounder that primarily impact age-1 fish (but also impact older age classes). Predation mortality at age-1 for all species in the model was primarily driven by arrowtooth flounder (Figure 80) and arrowtooth flounder biomass has declined in recent years. Increases in biomass consumed of walleye pollock in 2021 relative to 2020 reflect elevated recruitment of age-1 pollock in 2021 that was available to the modeled predators. Combined annual predation demand (annual ration) of age-4+ pollock, Pacific cod, and arrowtooth flounder in 2022 was 5.2 hundred thousand tons, down from the 6.73 hundred thousand ton annual average (Figure 81).

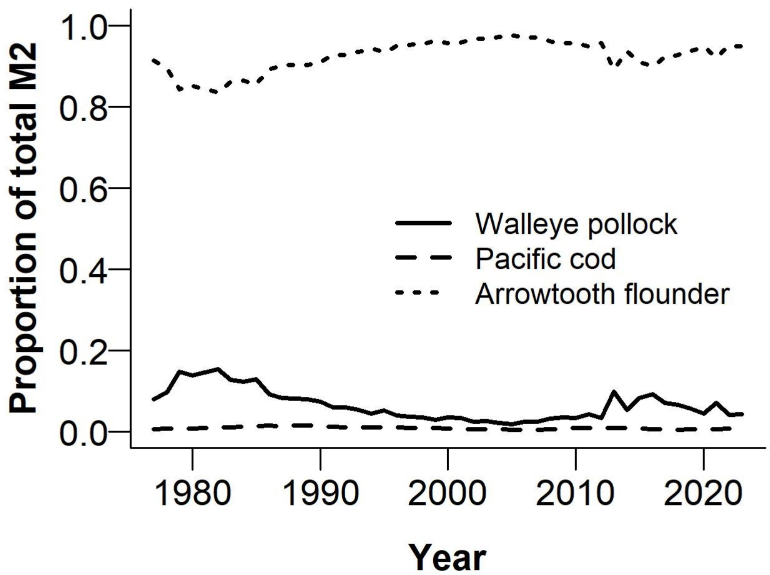

Figure 80: Proportion of total predation mortality for age-1 pollock from pollock (solid), Pacific cod (dashed), and arrowtooth flounder (dotted) predators across years. Updated from Adams et al. (2022)

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Implications: We find evidence of continued decline in predation mortality on age-1 walleye pollock, Pacific cod and arrowtooth flounder, due to the species modeled in CEATTLE. Previous ecosystem modeling efforts have estimated that mortality of pollock is primarily driven by P. cod (16%), Pacific halibut (23%) and arrowtooth flounder (33%) (Gaichas et al., 2015). 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 pollock in 2021 led to an increase in biomass of pollock being consumed by predators.

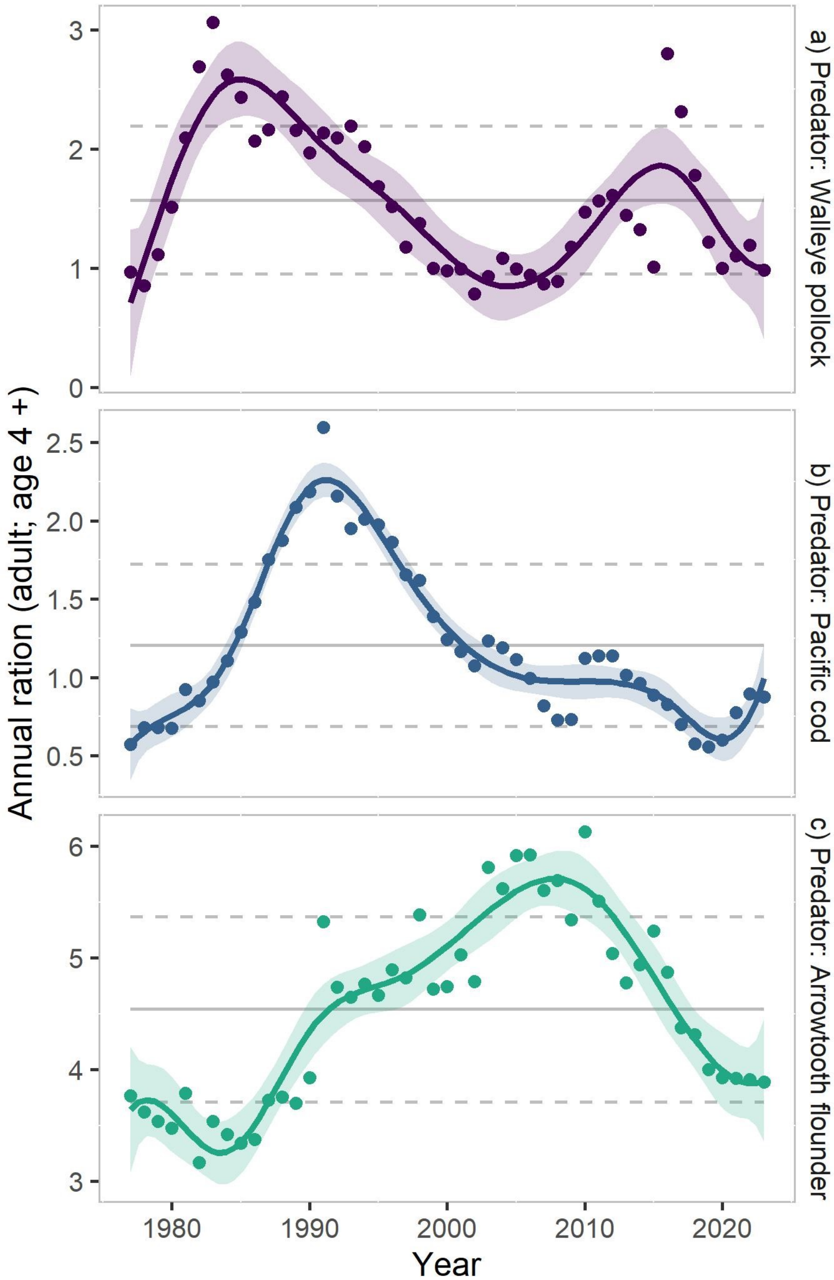

Figure 81: Multispecies estimates of annual ration (hundred thousand tons consumed per species per year) for adult (age 4 +) predators: a) walleye pollock, b) Pacific cod, and c) arrowtooth flounder. Gray lines indicate 1979–2023 mean estimates and 1 SD for each species; solid line is a 10 y (symmetric) loess polynomial smoother indicating trends in ration over time.

Benthic Communities and Non-target Fish Species

Miscellaneous Species—Gulf of Alaska Bottom Trawl Survey

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Last updated: October 2023

Description of indicator: The NOAA Fisheries' Groundfish Assessment Program (RACE-GAP) fishery-independent summer bottom trawl surveys in the Gulf of Alaska (GOA) are designed to assess populations of commercially and ecologically important fishes and invertebrates. There are some species and taxonomic groups which occur commonly in survey catches or are of particular interest and which can provide additional context when assessing the status of the ecosystem; some of these are presented here. Since 1990, we have deployed the same standardized trawl gear (footrope and trawl net) as presently in use in the GOA bottom trawl survey. The taxonomic groups presented here are neither targeted by our survey nor are they ideal for collection by our standard trawl gear. Issues of selectivity, catchability, and retention affect the precision and accuracy of biomass estimates generated for these taxa so that any apparent trends should be interpreted with caution. Biomass estimates for these taxa were scaled to the largest estimate in the time series for each, and this value was then arbitrarily scaled to a value of 100 and all other values were scaled in reference to that. The standard error ($\pm$ 1) was weighted proportionally to the biomass to yield a relative standard error. Prevalence in survey catches is also presented as the percentage of positive bottom trawl hauls for each taxon.

Status and trends: Echinoderms and shrimp are relatively commonly caught in our survey catches, while eelpouts and poachers occur with less frequency (Figure 82). Echinoderm biomass has been highest in the Chirikof and Kodiak districts historically and appears to be increasing in the latter in recent surveys; this group of benthic invertebrates is common in trawl catches throughout the Gulf. Shrimp biomass has also historically been higher in the Chirikof and Kodiak districts than elsewhere in the Gulf, but appears to be declining in those two districts in recent surveys. Eelpouts occur episodically in catches throughout the GOA, but seem to be more abundant in the Yakutat district where their biomass may be increasing over the time series. Poachers are more common in the Shumagin district than elsewhere in the Gulf where they are uncommon and their highest biomass has historically occurred in the Shumagin and Kodiak districts.

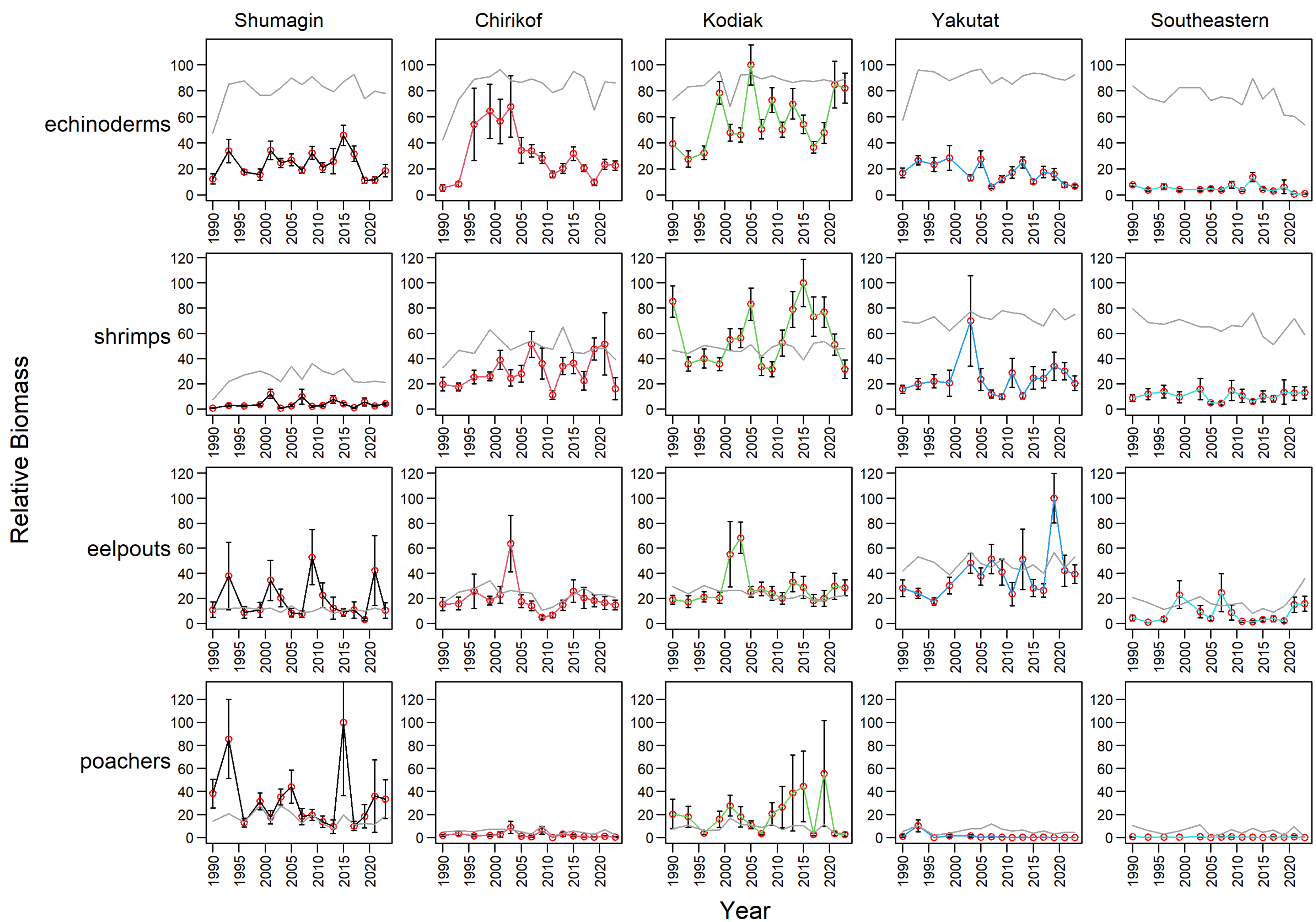

Figure 82: Relative biomass estimates of echinoderms, shrimps, eelpouts, and poachers collected from International North Pacific Fisheries Commission (INPFC) statistical districts during fishery-independent summer bottom trawl surveys of the Gulf of Alaska (1990–2023). Error bars represent standard errors and the gray lines represent the prevalence (percentage) of non-zero catches of these taxa.

Factors influencing observed trends: Unknown

Implications: It is difficult to discern a consistent pattern of biomass or prevalence across these taxonomic groups. There are some patterns within groups (e.g., echinoderms are common throughout the Gulf, eelpout biomass has cycled between highs and lows over the course of the time series and in most districts). Directed research into the population ecology of these taxonomic groups could help to elucidate relationships between their population status and the health of the region.

Seabirds

Seabird Synthesis

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Last updated: October 2023

Summary Statement: Indicators of seabird reproduction, mortality events, and distribution indicated approximately average to below-average environmental conditions in the Gulf of Alaska, in 2023, with signs of declining ecosystem productivity from previous highs in 2022 (Figure 83). There were no large-scale mortality events recorded via monthly beach surveys in the Western Gulf of Alaska. Reproductive success off the AK peninsula for fish-eating seabirds (an indicator of sufficient forage fish) all declined from previous highs to a range of average, below average, and reproductive failure (black-legged kittiwakes). This decline can be partially explained by a small age-0 pollock year class, common prey in that region (Rogers in this report, p.102). Zooplankton-eating seabirds declined from above average to approximately average reproductive success across the GOA in 2023, with later breeding times. These metrics indicate adequate but less productive zooplankton resources to meet reproductive needs. The distribution of seabirds observed on the Seward Line spring survey (central GOA cross shelf transect) showed dramatic changes, including the lowest densities of common murres since 2007, a continued shift inshore of black-legged kittiwakes, and the 3rd lowest densities observed of fork-tailed storm-petrels since 2007. Increased densities of common murres and black-legged kittiwakes were observed further west, over banks east of Kodiak, potentially related to higher abundance of capelin observed in those regions (McGowan in this report, p.110, M. Arimitsu, personal communication). The exceptionally low densities of murres on the Seward Line is an important indicator to monitor as they can indicate major declines in ecosystem productivity (i.e., if the population has declined and has not just redistributed). The downturn in productivity, and some selected observations, highlight trends of concern to monitor as we enter a potentially less productive pelagic system affiliated with El Niño conditions in 2024. Implications for groundfish include sufficient but potentially declining zooplankton and forage fish prey resources to meet metabolic needs in 2023, with concern these might further decrease in 2024.

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 government, university and non-profit partners, we provide a summary of the best available data on seabird productivity in the Gulf of Alaska in 2023. 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).

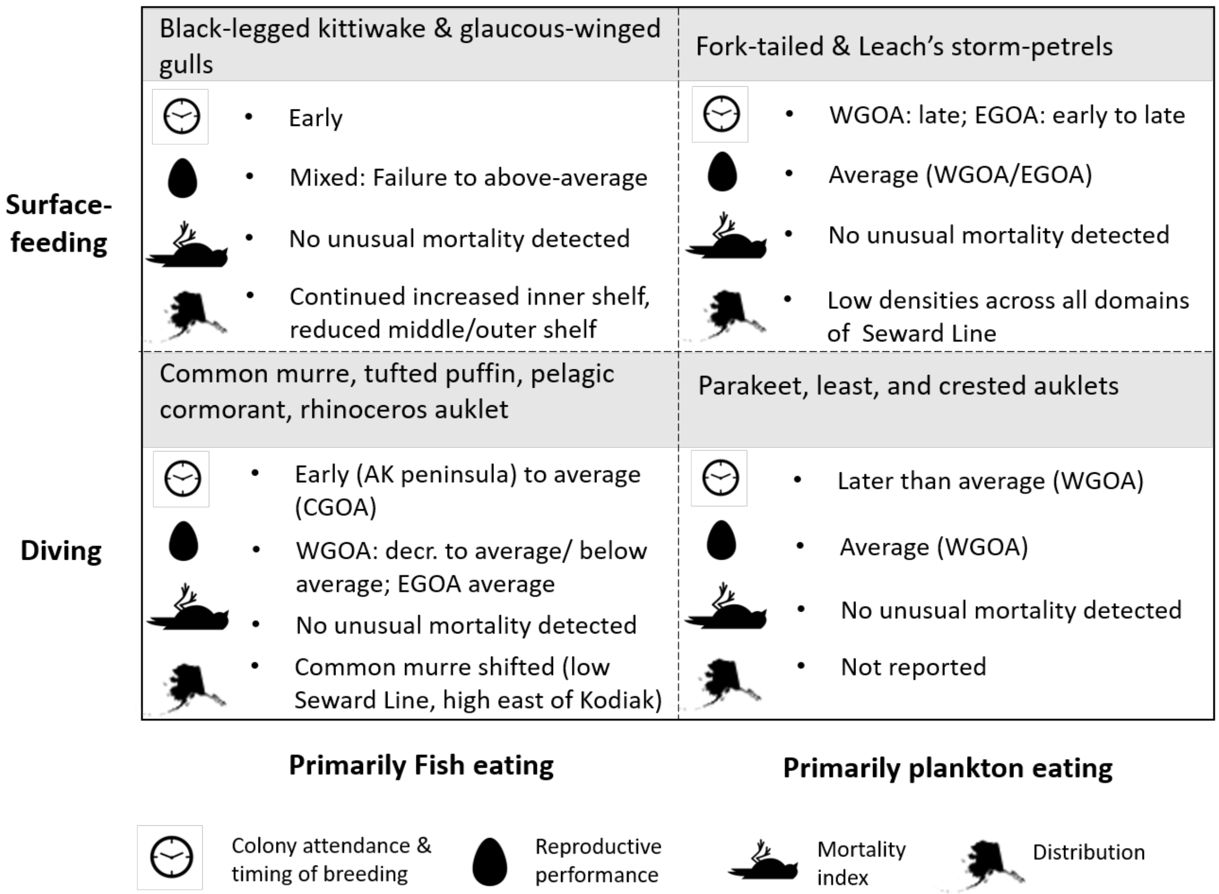

Figure 83: Summary of 2023 status for seabird feeding guilds (surface-feeding and diving, fish and plankton-eating) in the Gulf of Alaska.

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. This metric is defined as hatch date for USFWS data and clutch initiation for data from Middleton Isl.

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. This metric is defined as the following:

   - The ratio of fledged chicks to eggs for murres, auklets, puffins, and storm-petrels (USFWS)
   - The ratio of nests producing fledglings to nests for black-legged kittiwakes (USFWS)
   - Chicks fledged per laying pair for pelagic cormorants on Middleton Isl.
   - Late-stage chicks per egg for rhinoceros auklets on Middleton Isl.

3. **Mortality** which gives insight into environmental 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:

Primarily 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 in western GOA appeared early to average in 2023*. Moving from west to east in the western GOA, black-legged kittiwakes continued a multiyear trend of earlier than average breeding timing on Chowiet Isl. (day 193 or July 12, 1990-2023 baseline, Figure 84) and estimated average breeding timing on E. Amatuli Isl. (preliminary data). Glaucous-winged gulls were estimated to have early timing on E. Amatuli Isl. On Middleton Isl. (central GOA near shelf edge), the timing of breeding (clutch initiation date) by black-legged kittiwakes was close to average (June 5; Figure 85). Birds part of the experimental, supplemental feeding program laid eggs, initiated their clutches 6 days later in 2023, compared to 3 days later in 2022 (average = ± 4 days, range = 0 to + 9), suggesting relatively poor foraging conditions during the pre-lay period (April through mid-May) in 2023.

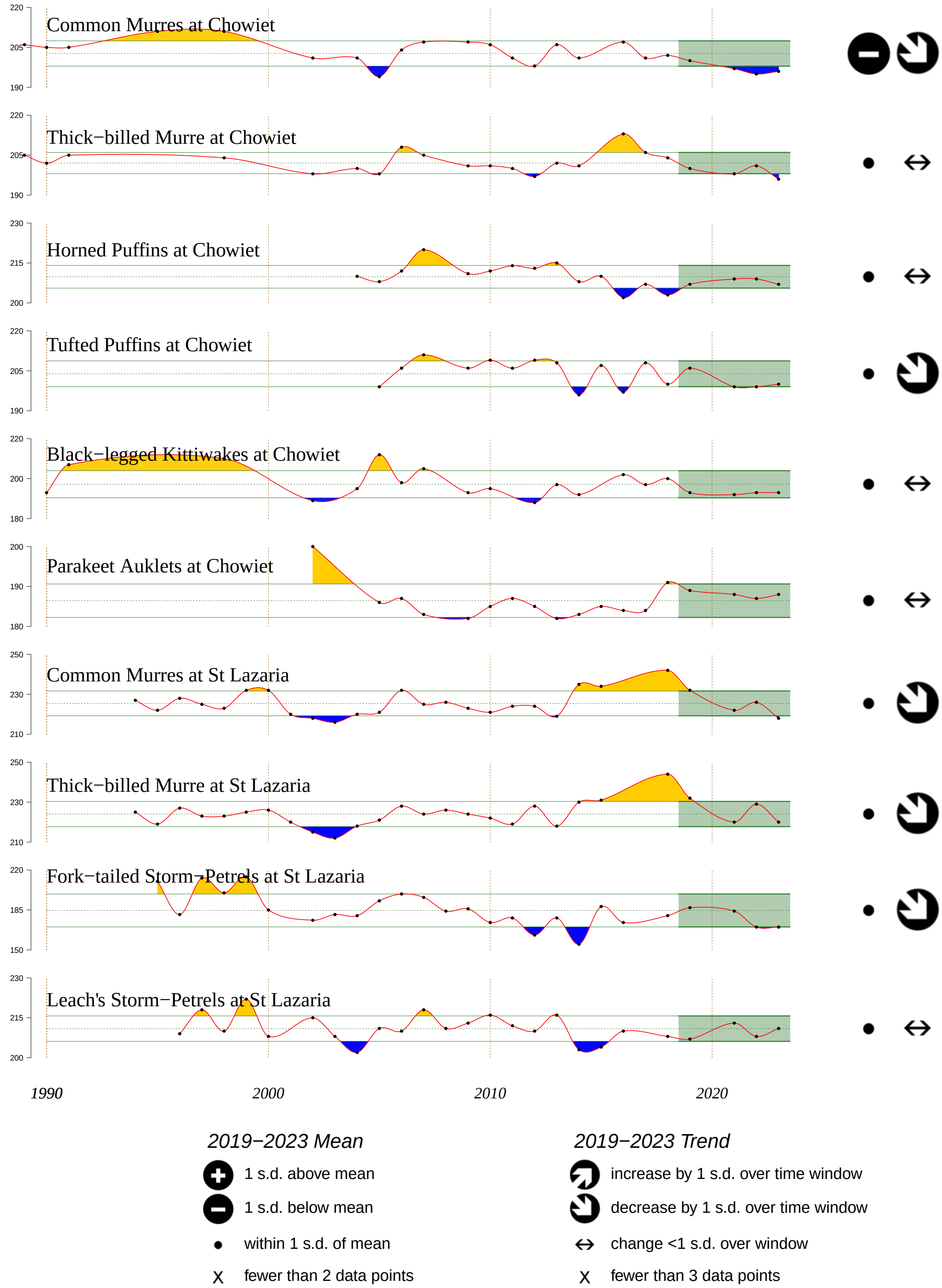

Figure 84: Reproductive timing of piscivorous (common murre, thick-billed murre, horned puffin, tufted puffin, black-legged kittiwakes) and planktivorous (black-legged kittiwakes, parakeet auklets, fork-tailed storm-petrels, Leach's storm-petrel) Gulf of Alaska seabird species on Chowiet Isl. (western GOA) and St. Lazaria Isl. (eastern GOA), as assessed by the Alaska Maritime National Wildlife Refuge. The dashed line is the long-term average and solid green lines are ± 1 SD. Yellow/blue shading indicates values greater than 1SD above/below the mean.Green shading highlights the previous 5 years. Data provided by the U.S. Fish and Wildlife Service, Alaska Maritime National Wildlife Refuge.

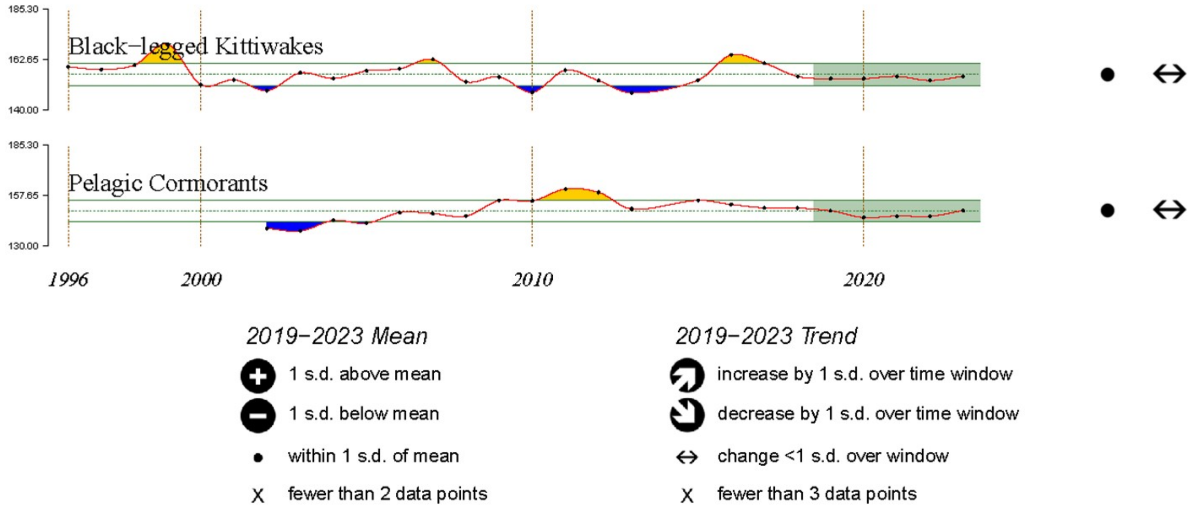

Figure 85: Breeding chronology (mean clutch initiation date) of black-legged kittiwakes, pelagic cormorants, and rhinoceros auklets on Middleton Isl. (2002–2023). The dashed line is the long-term average and solid green lines are ± 1 SD. Yellow/blue shading indicates values greater than 1SD above/below the mean.Green shading highlights the previous 5 years. Data provided by the Institute for Seabird Research and Conservation.

Reproductive success: *Reproductive success ranged from above average to failure.* Black-legged kittiwakes on Chowiet experienced reproductive failure in 2023 after a record high (baseline 1989-present) in 2022 (Figure 86). The drop could reflect poor spring conditions for egg lay rates and reduced summer prey availability for hatching success. Glaucous-winged gull colonies on E. Amatuli Isl. had the 4th highest count of fledglings (preliminary data), while black-legged kittiwakes had low fledglings per nest-site (preliminary data), potentially due, in part, to eagle predation. Naturally foraging kittiwakes on Middleton Isl. had above-average productivity (Figure 87), despite the relatively low proportion of energy-rich capelin *Mallotus villosus* in their diets.

Mortality: *No large-scale mortality event of fish-eating surface-feeding birds was recorded in 2023.* based on beach surveys in the Western Gulf of Alaska (Figures 6 and 7). Like much of Alaska, beach surveys show a late summer, post-breeding mortality pattern; however the values observed in 2023 were similar to those observed in previous monitored years (2006-present), suggestive of typical rates of mortality (Figures 88, 89).

Distribution: *Continued increased use of inner shelf and reduced middle and outer shelf.* Surveys along the Seward line observed black-legged kittiwake densities in early-May 2023 that were above the 2007–2023 mean on the inner shelf, but below the mean on the middle and outer shelf (Figure 90). This continues a pattern of decreased use of the middle shelf and outer shelf during and after the 2014–2016 marine heatwave compared to the preceding period 2007–2013 period during which cooler temperatures predominated. In contrast, densities of kittiwakes were elevated over banks east of Kodiak Isl. compared to other recent years (2018, 2019, 2021, 2022).

Historical GPS-tracking shows that kittiwakes tagged on Middleton Isl. tended to forage close to the island when capelin were abundant prior to the heatwave, then expanded their foraging range during and after the heatwave (Osborne et al., 2020). In 2023, GPS-tracking throughout the breeding season showed that kittiwakes continued to forage far from the island, rather than exhibiting the contracted foraging range expected with the return of capelin. Thus, it is possible that capelin were not available locally.

Primarily 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 *Urile pelagicus*. The status of this group is impacted by changes in the availability of small, schooling fish up to $\sim$ 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 (AK peninsula) to average (central GOA)*. Breeding timing of these seabirds on Chowiet Isl. was early, continuing a multi-year trend (common murre: July 15th (baseline: 1990–2023) and tufted puffins: July 19th (baseline: 2005–2023) (Figure 84). Breeding timing of pelagic cormorants on Middleton Isl. was average (baseline: 2002–2023), and 3 days later than 2022 (Figure 85).

Reproductive success: *Reproductive success decreased to below-average/average (western GOA) and average (eastern GOA) for fish-eating, diving seabirds in 2023.* In the western GOA, this group of seabirds all had reduced reproductive success on Chowiet Isl. relative to 2022. Common murres and tufted puffins were approximately average, dropping from 5–6 years of above-average success. Thick-billed murres and horned puffins decreased from above average (2022) to below- average success in 2023 (Figure 86). On E. Amatuli Isl. Tufted puffins experienced low reproductive success (preliminary data) in the form of a low proportion of burrows used and low number of chicks observed. On Middleton Isl., rhinoceros auklets had unusually low productivity while pelagic cormorants had above-average productivity (numbers of chicks fledged per laying pair), a 5th year of elevated numbers (Figure 87). In the eastern GOA, common murres on St. Lazaria continued a multi-year trend of approximately average reproductive success (baseline 1994–2023). .

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 2023.* This marks 7 years since the mass mortality event of common murres linked to the 2014–2016 marine heatwave (Figure 88).

Distribution: *Common murres shifted: extreme low on Seward Line and above average east of Kodiak).* Surveys along the Seward line observed densities of common murres along the Seward Line in early-May 2023 were the lowest observed since 2007. On the inner shelf, murre densities were well below average, while they were absent from the middle shelf in this area (Figure 90). This continued a trend of below-average use of the middle shelf along the Seward Line following the 2014–2016 marine heatwave, when an influx of murres into coastal waters preceded an unprecedented mass-mortality event during the winter of 2015–2016. While murre densities along the Seward Line were very low during spring 2023, murres were much more abundant over Albatross and Portlock Banks east of Kodiak than during other recent years.

Primarily plankton-eating seabirds: Plankton-eating seabirds in the Gulf of Alaska include surface-feeding species such as Leach's and fork-tailed storm-petrels (*Hydrobates leucorhous, Hydrobates furcatus*), and diving species such as least auklets (*Aethia pusilla*), crested auklets (*Aethia cristatella*), and parakeet auklets (*Aethia psittacula*). The status of these groups are impacted by changes in zooplankton 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: *Breeding timing was late (western GOA) to late/average (eastern GOA).* Parakeet auklets continued a multi-year trend of later than average breeding timing on Chowiet Isl. (July 7, baseline: 2002–2023; Figure 84). Fork-tailed storm-petrels on E. Amatuli were very late (preliminary data). In the eastern GOA, fork-tailed storm-petrels had a second year of earlier than average breeding timing (June 19th, baseline 1995–2023) while Leach's storm-petrels had approximately average timing (July 30th, baseline 1996–2023) (Figure 84)

Reproductive success: *Reproductive success was average for plankton-eating seabirds in 2023.* In the western GOA, parakeet auklets increased to approximately average success on Chowiet (1998–2023), potentially reflective of local foraging conditions around the colony (Figure 86). On E. Amatuli Isl. fork-tailed storm-petrels had approximately average success (similar to post 2007 values but lower than 2004–2007). In eastern GOA, earlier breeding St. Lazaria fork-tailed and later breeding Leach's storm-petrels both declined to average success (baseline starting in 1994 and 1995 respectively) from higher 2022 values (Figure 86).

Mortality index: *No large-scale mortality event was recorded for plankton-eating seabirds based on beach surveys in the Gulf of Alaska in 2023.* Few small alcids were observed in 2023, primarily ancient murrelets (*Synthliboramphus antiquus*) and parakeet auklets (*Aethia psittacula*), but neither species in abundances suggestive of unusual/elevated mortality (Figure 91). Crested auklets last appeared dead on beaches, 2015-2016, following the marine heatwave; no least auklets have been found in the Gulf of Alaska since monitoring was established (2006).

Distribution: *Change in distribution or decrease in density on Seward Line.* Densities of fork-tailed storm-petrels along the Seward Line in early-May 2023 were the 3rd lowest observed since 2007. Densities of storm-petrels were below the 2007–2023 mean in all domains, and on the outer shelf, densities were the lowest observed since 2007 (Figure 90). This continues a trend away from the middle and outer shelf after the heatwave, but contrasts with observations during the heatwave, when above-average densities of storm-petrels occurred in these habitats. Densities of storm-petrels during the spring 2023 cruise showed a clear increasing trend from late April to early May, with the lowest densities in the Middleton Isl. region, surveyed at the beginning of the cruise, the highest densities along the Seward Line, surveyed at the end of the cruise, and intermediate densities in the Kodiak region.

Factors influencing trends and implications for ecosystem productivity: The suite of seabird indicators imply average to below-average lower trophic level productivity across the GOA in 2023, a decline from the strong breeding performance and related higher ecosystem productivity of 2022. While numerous reproductive success metrics were approximately average, reflecting sufficient prey resources to meet reproductive needs, the majority indicated a declining trend from 2022. This downturn in productivity, and some selected observations, highlight trends of concern to monitor as we enter a potentially less productive pelagic system affiliated with El Niño conditions in 2024. Implications for groundfish include sufficient but potentially declining zooplankton and forage fish prey resources to meet metabolic needs in 2023, with concern these might further decrease in 2024.

Numerous seabird observations in the central GOA exhibited signs of reduced productivity. Rhinoceros auklets on Middleton Isl. experienced a decrease to 1SD below-average reproductive success in 2023, a cause for concern given their adaptations for more consistent breeding performance. As diving seabirds with a relatively broad foraging range (e.g., further than pelagic cormorants), a decline in reproductive success can indicate poor fish and zooplankton prey availability across a broader range of the marine system. The observations of low seabird densities (common murre, black-legged kittiwakes, and fork-tailed storm-petrels) observed along the Seward Line spring survey (a cross-shelf transect), are another point of concern. The common murres and black-legged kittiwakes may be explained by distributional shifts, potentially in response to increased capelin and prey resources to banks east of Kodiak and elsewhere in the region. In contrast, distributional patterns of planktivorous fork-tailed storm-petrels during the April-May 2023 cruise appeared primarily related to phenology.

Reduced reproductive success of fish-eating seabirds on Chowiet Isl., including reproductive failure of black-legged kittiwakes, may be partially explained by a low age-0 year class of pollock typically found in that region. Early onset of breeding can indicate good availability of forage fish prey, potentially indicating availability of other forage species. While kittiwakes have more variable reproductive performance in response to short-term environmental fluctuations, the decline from higher to average/below-average reproductive success of the more consistently breeding murres are potentially indicative of broader foraging conditions, and indicators to monitor for next year.

The abundance of capelin, a highly nutritious forage fish, has been aligned with cooler ocean temperatures and more successful seabird reproduction in the past. Capelin populations were considered to be rebounding in 2023 with relatively high densities observed in core capelin habitat on banks east of Kodiak (McGowan, 2020). Capelin was not observed in surveys west of this region (Rogers in this report, p.102) and was not dominant in seabird diets on Middleton Isl. to the east of this region, indicating spatially limited impacts of capelin in the GOA this year (Whelan in this report, p.105). If the population continues to increase (and potentially expand its range), capelin could provide a positive contribution to the forage fish prey base and resulting predator productivity. The decreased and delayed reproductive performance of zooplankton-eating seabirds is in agreement with observations of reduced zooplankton biomass and increased competition by other planktivorous fish. Zooplankton surveys observed below-average total zooplankton spring and summer biomass across the GOA, including reduced copepods but average/above-average euphausiids (Kimmel in this report, p.81, Hopcroft in this report, p.89, Fergusson in this report, p.91). Potential competitors for zooplankton prey include large returns of pink salmon (Whitehouse in this report, p.124, Vulstek in this report, p.134), a relatively large population of Pacific ocean perch (Hulson et al., 2023), large year classes of juvenile sablefish (Goethel et al., 2023), and increasing populations of walleye pollock (Monnahan et al., 2023).

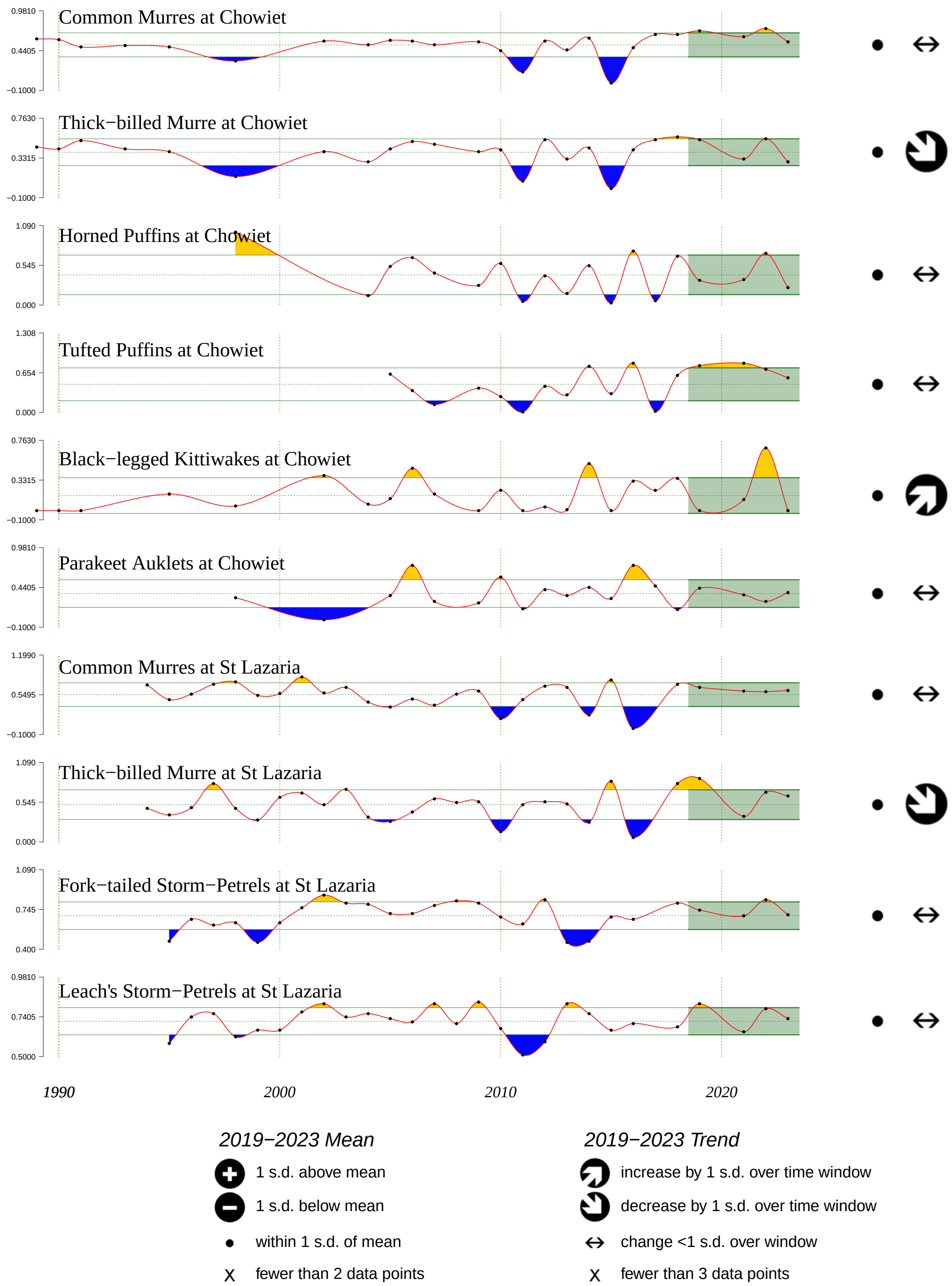

Figure 86: Reproductive success of piscivorous (common murre, thick-billed murre, horned puffin, tufted puffin, black-legged kittiwakes) and planktivorous (black-legged kittiwakes, parakeet auklets, fork-tailed storm-petrels, Leach's storm-petrel) Gulf of Alaska seabird species on Chowiet Isl. (western GOA) and St. Lazaria Isl. (eastern GOA), as assessed by the Alaska Maritime National Wildlife Refuge. The dashed line is the long-term average and solid green lines are $\pm$ 1 SD. Yellow/blue shading indicates values greater than 1SD above/below the mean.Green shading highlights the previous 5 years. Data provided by the U.S. Fish and Wildlife Service, Alaska Maritime National Wildlife Refuge.

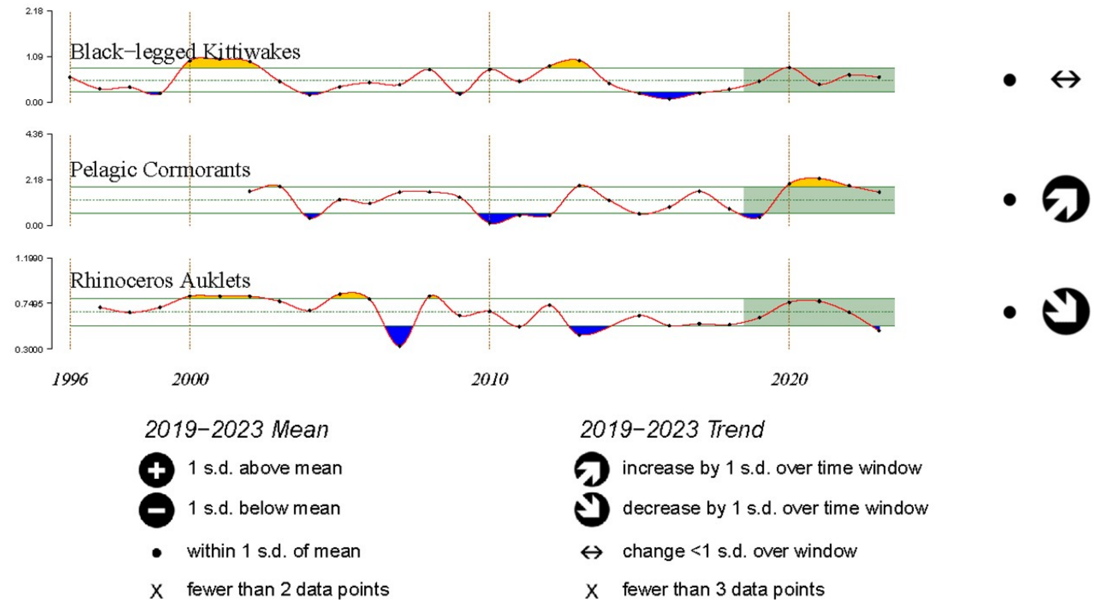

Figure 87: Annual reproductive output for black-legged kittiwakes (chicks fledged per pair), pelagic cormorants (chicks fledged per pair: 2002–2023), and rhinoceros auklets (late-stage chicks per egg: 1997–2023) on Middleton Isl., central Gulf of Alaska. The dashed line is the long-term average and solid green lines are ± 1 SD. Yellow/blue shading indicates values greater than 1SD above/below the mean.Green shading highlights the previous 5 years. Data provided by the Institute for Seabird Research and Conservation.

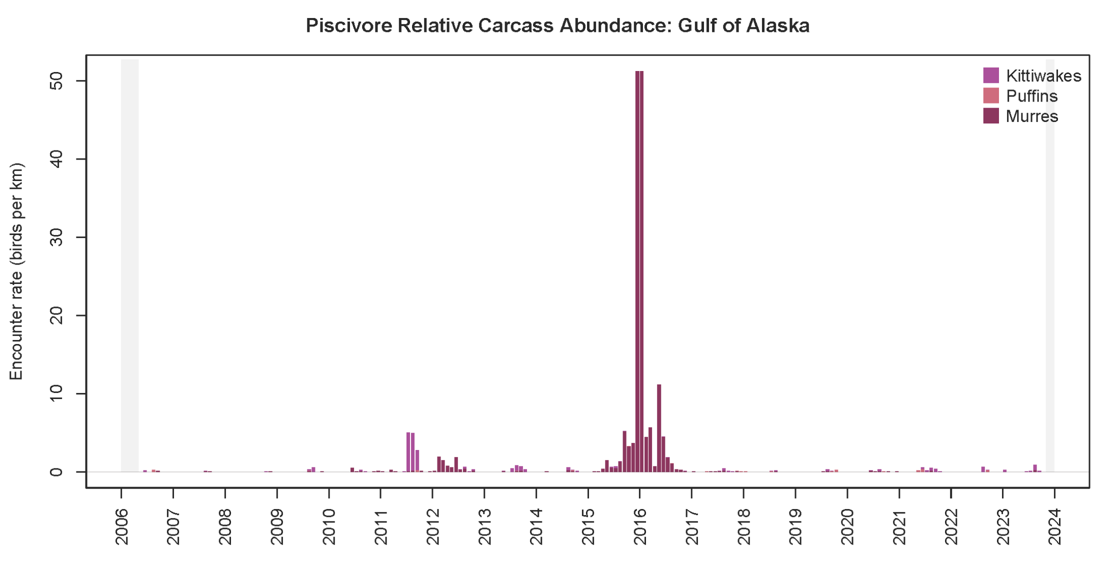

Figure 88: The number of kittiwakes, puffins, and murres (fish-eating seabirds) encountered per km of beach surveyed by citizen scientists in the Gulf of Alaska. Data were insufficient to produce meaningful measures of long-term baseline variation. Data indicate regional trends, but are biased toward more accessible beaches in areas of higher human population density. Light gray shading indicates time-periods where surveys were not performed. Figure provided by the Coastal Observation and Seabird Survey Team (COASST), October 2023.

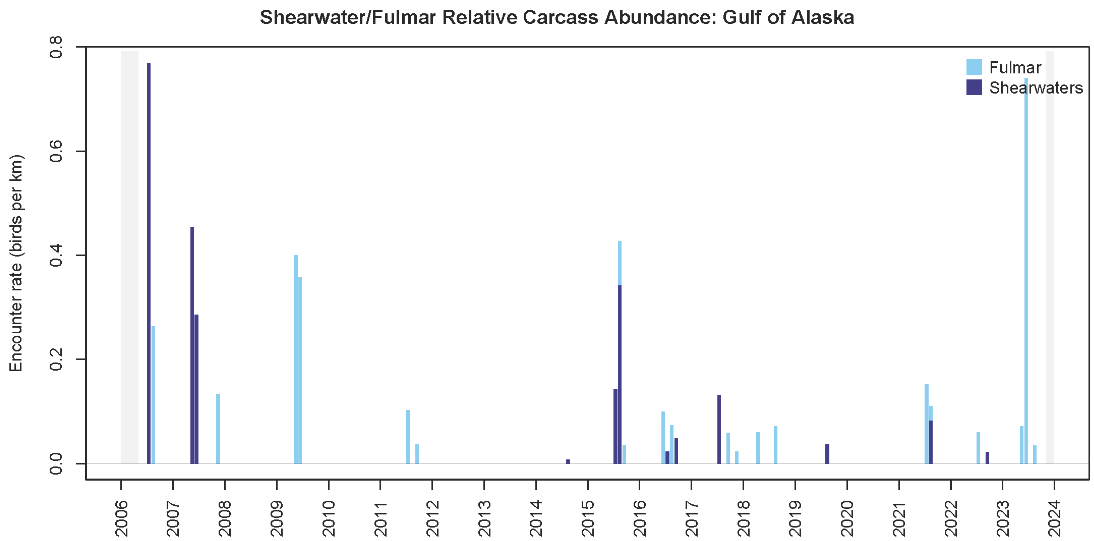

Figure 89: The number of fulmars and shearwaters (fish-eating seabirds) encountered per km of beach surveyed by citizen scientists in the Gulf of Alaska. Data indicate regional trends, but are biased toward more accessible beaches in areas of higher human population density. Light gray shading indicates time-periods where surveys were not performed. Figure provided by the Coastal Observation and Seabird Survey Team (COASST), October 2023.

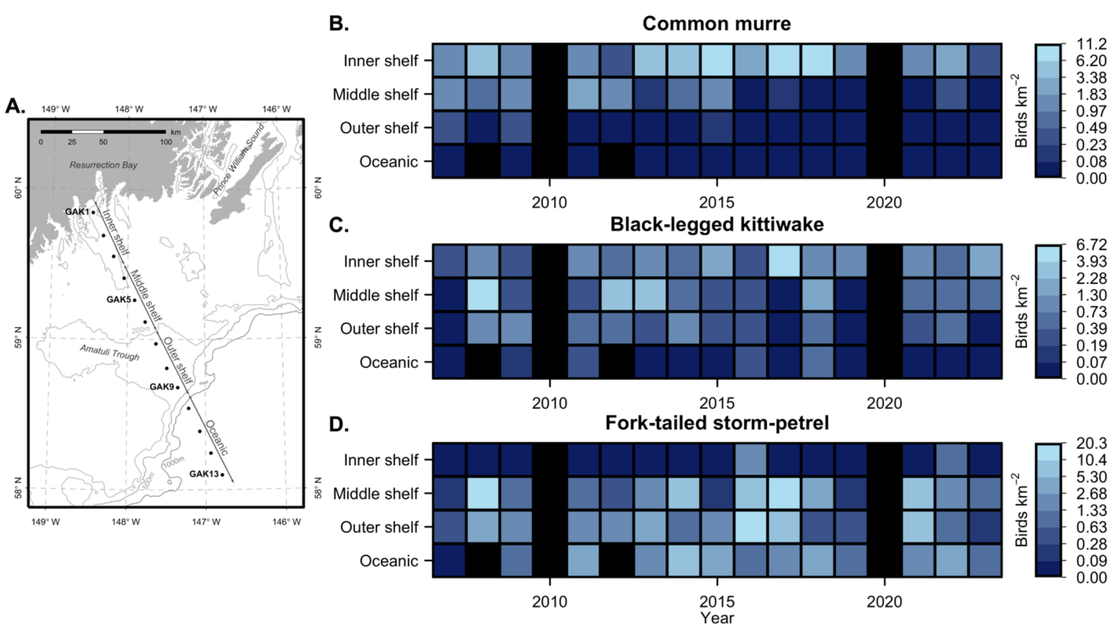

Figure 90: The spring Seward Line in the Northern Gulf of Alaska, and four domains used for analysis (A). Mean densities (birds pre square km) of common murres, black-legged kittiwakes, and fork-tailed storm-petrels within domains during spring Seward Line cruises, 2007–2023 (B to D).Black indicates no seabird surveys were conducted. Figure provided by Pole Star Ecological Research, and US Fish and Wildlife Service, Migratory Birds - Alaska.

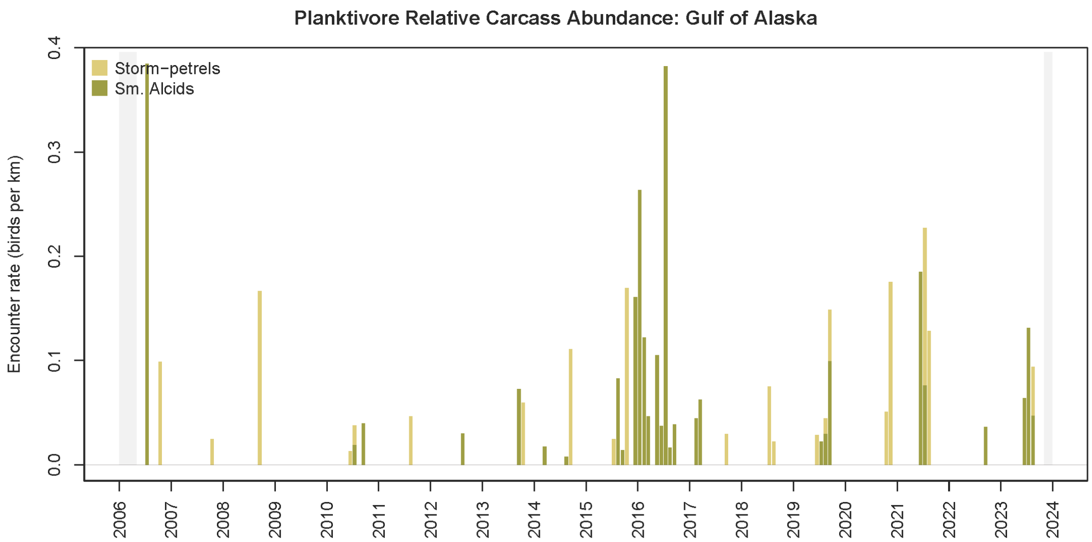

Figure 91: The number of plankton-eating seabirds (storm-petrels and small alcids) encountered per km of beach surveyed by citizen scientists in the Gulf of Alaska. Data indicate regional trends, but are biased toward more accessible beaches in areas of higher human population density. Light gray shading indicates time-periods where surveys were not performed. Figure provided by the Coastal Observation and Seabird Survey Team (COASST), October 2023.

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 human population centers.
- 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. 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), 2007–2023, 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 GOA, Aleutian Islands, and Bering and Chukchi Seas. Monitored colonies in the GOA include Chowiet (Semidi Islands), East Amatuli (Barren Islands), and St. Lazaria (southeast Alaska) islands.

Marine Mammals

Trends in Humpback Whale Calving in Glacier Bay and Icy Strait

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Last updated: September 2023

Description of indicator: Humpback whale (*Megaptera novaeangliae*) reproductive success in Glacier Bay and Icy Strait as an indicator of changes in prey quantity and/or quality available for groundfish in the eastern Gulf of Alaska. Groundfish and whales target the same lipid-rich prey (i.e., forage fish and euphausiids). From 1985 to present, biologists in Glacier Bay National Park and Preserve used consistent methods and levels of effort annually from June 1 – August 31 to document individually-identified humpback whales and their reproductive parameters in Glacier Bay and Icy Strait (Gabriele et al., 2017). Consistent methods and a high level of annual effort make this one of the world's most complete long-term datasets on a baleen whale population.

We photographically identified whales by matching the markings on the ventral tail flukes and dorsal fin of each whale to curated catalogs of identification photos. From these data we 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 June - August each year); 4) within-season calf survival; 5) return rate of calves in subsequent years as juveniles and adults; and 6) indicators of health/body condition for mothers and calves.

Working with the collaborative Southeast Alaska Database and the North Pacific Humpback Whale Collaboration, we used an automated humpback whale fluke identification system[21] to access an enormous North Pacific-wide data repository (Cheeseman et al., 2023) which allows us to augment our knowledge of the movements, survival, and reproductive status of Glacier Bay and Icy Strait whales when they are elsewhere in the North Pacific. Individual sightings from other collaborators are reported with their permission.

Status and trends: Humpback whales in southeastern Alaska are in the process of recovering from the Northeast Pacific marine heatwave (PMH), which was a prolonged and intense marine heatwave that dominated the Northeast Pacific Ocean from late 2013 through 2016.

1. Humpback whale abundance declined by 56% between 2013 and 2018 related to the Northeast Pacific marine heatwave (Figure 92). Since then, whale numbers have stabilized to about 70% of their former abundance (**?**) including 2023. We observed 11 calves in 2023 (Table 2).

2. Calf survival dropped by a factor of ten (from 39% to 3%) during and immediately after the marine heatwave period (Gabriele et al., 2022). In the summers of 2022 and 2023, we detected no definite calf mortalities. All of the 2023 calves were with their mothers on our final observations of the cow/calf pairs for the season. A charter fishing captain reported that on August 14 in Icy

[21] https://www.Happywhale.com

Strait, killer whales successfully separated an unidentified humpback whale mother from her calf and attempted to drown the calf. The mother was seen fleeing the area but it was not clear if the calf was with her.

3. Far fewer calves were born during and after the heatwave (Table 2) but calf production has improved somewhat in recent years. In 2023, calf production was equivalent to 2021, with a CBR of 6.4% (Table 2, Figure 92). None of the CBRs since 2019 (range 1.3% – 7.4%) have reached the pre-PMH mean (9.2%). While reproductive rates in 2020–2023 have shown some improvement (mean CBR 6.0%), calf production has not recovered to pre-PMH average levels.

4. Juvenile survival appears to be improving after an abrupt decline during and after the PMH. None of the Glacier Bay/Icy Strait calves born during the PMH or in the two years following it (2014 – 2018) have been documented as juveniles in Southeast Alaska or elsewhere, but several calves born 2019 – 2021 have been re-sighted in subsequent years. No new calf returns to Alaska have been documented since last year's Ecosystem Status Report (Table 2) although calf #2704 (born in 2022 to #219) was sighted in Maui in mid-January 2023 by Captain Steve's Rafting Adventures. Four-year-old #2652 (2019 calf of #219) returned to Glacier Bay/Icy Strait for the fourth year in a row.

5. Seven of the 11 mothers in 2023 were denoted "skinny" based on physical indicators such as visible scapulae, an overall "angular" appearance, and/or the presence of a post-cranial depression. Only one calf, whose mother #2533 was also skinny, looked thin (Figure 93). The rest of the 2023 calves appeared to be in relatively good physical condition.

Table 2: Humpback whale calf production and survival observations in Glacier Bay and Icy Strait, Alaska. Crude birth rate is calculated by dividing the number of calves by the total number of whales in June – August. In this table, crude birth rate is based on a preliminary total number of whales in 2023. *Not all calves show their flukes so they are much harder to re-identify in future years. **The median age at which juveniles tend to return to the study area is 3 years (Gabriele et al., 2017)

Time Period	Number of Calves	# Fluke-identified Calves (June-Aug)*	Crude Birth Rate (%)	Number of calves lost (%)	# Fluke-identified Calves Resighted in Later Years (%)**
1985–2013	mean 9.1 (range 2–21)	191 (range 3.3–18.2)	mean 9.2	8 (4%)	128 (67%)
2014	14*	6	7.9	5 (36%)	0
2015	5*	1	3.0	0	0
2016	0*	0	0.0	0	0
2017	2*	1	1.6	1 (50%)	0
2018	1*	0	1.0	1 (100%)	0
2019	2	1	1.3	0	1(100%)
2020	12	8	7.4	0	3(35%)
2021	11	8	6.5	1(9%)	2(25%)
2022	6	2	3.6	0	0
2023	11	8	6.4	0	NA

Factors influencing observed trends: The PMH was associated with a wide variety of severe population-level effects on seabirds, fish, and marine mammals (Von Biela et al., 2019; Piatt et al., 2020; Arimitsu et al., 2021; Suryan et al., 2021) including humpback whales in Glacier Bay and Icy Strait (Gabriele et al., 2022). Post-PMH crude birth rates remain lower than the long-term mean CBR prior to 2014 (9.2%; Table 2, Figure 92), suggesting that prey availability and/or quality could be insufficient to support pre-heatwave rates of conception and/or full-term pregnancy. Some adult females are exhibiting

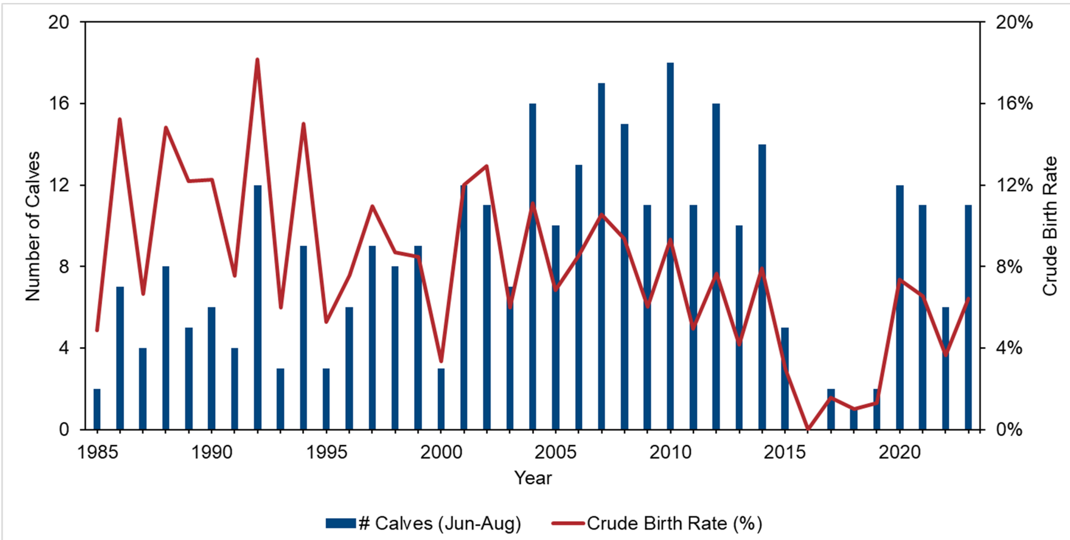

Figure 92: Annual number of calves (blue bars) and crude birth rate (CBR, red line) in Glacier Bay-Icy Strait, 1985–2023. CBR is calculated by dividing the number of calves by the total number of whales identified in June-August each year. The preliminary CBR for 2023 is 6.4% based on a preliminary whale count of 171 individually identified whales for June-August.

unusually long calving intervals or have not successfully resumed calving since the PMH. Female #1246 was sighted with a calf this year with a nine-year calving interval (though she was absent from the study area in 2016–2018, very few females had a calf in those years, Table 2) which is much longer than the typical 2–3 year calving interval for this population (Baker et al., 1987; Gabriele et al., 2017). Two females noted in last year's Ecosystem Status Report (#1088 and #1486) have still not been documented with a calf since 2013 and 2014, respectively, although we sighted them every year. Their failure to resume calving may be a response to physiological stress (Kraus et al., 2007; Kershaw et al., 2021), insufficient prey resources to support conception or pregnancy, or may indicate a potential increase in neonatal mortality before or during the migration to Alaska.

However, the lower CBR may also reflect lasting demographic effects brought on by the PMH. First, preliminary analysis suggests that females who happened to have a calf immediately prior to or during the PMH (2013–2016) may have experienced a higher mortality rate than adult females who did not

Figure 93: Health assessment photographs of (A) calf #2713 on July 29, 2023, showing a lack of nuchal fat behind the blowholes. (B) For comparison, the rounded profile of four-year-old #2023 in 2010 shows a healthy amount of nuchal fat.

have a calf during these years. This may have removed enough females of prime breeding age from the population to create a detectable population level effect; this will be explored in future work. Second, the low CBR may in part reflect the missing cohort of females born 2011–2016 that died as juveniles during the PMH (Figure 4 in Gabriele et al., 2022) who would have been starting to have their first calves around age 12 (Gabriele et al., 2017). Note that only the 2011 calves would have been age 12 by 2023, so this missing-cohort effect may continue for the next several years. And finally, female age at first calving may have increased. In 2021, we documented three females who had their first known calf at ages 10–11 years (Gabriele et al., 2021). However, four of this year's mothers that were documented with their first known calf are several years older (range 16–18). One of them (#2033) has a complete sighting history except when she was 5 years old, therefore this was likely her first calf at age 16. Three other females had their first documented calf this year (#2455, age 18; #2456, age 16; and #2220, minimum age 18); however, these females have incomplete sighting histories and may have had a calf in years that they were not documented.

Implications: Humpback whales in southeastern Alaska remain in the process of recovering from a major ecological disruption. The effects of the PMH on humpback whale (and numerous other taxa) abundance, survival and reproduction are believed to be rooted in a decline in the quantity and quality of forage fish and zooplankton prey available. The long recovery of humpback whale productivity may indicate that lasting demographic effects on humpback whales are at play or that groundfish and humpback whales both experienced variable prey availability and/or quality.

Marine Mammal Strandings in the Gulf of Alaska

This contribution was not updated in 2023.

Steller Sea Lions in the Gulf of Alaska

NOAA Fisheries' GOA Steller sea lion survey is usually every other year (odd years). The survey did not occur in the GOA in 2023.

Ecosystem or Community Indicators

Foraging Guild Biomass—Gulf of Alaska

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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, 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).

The foraging guild biomasses are reported separately for the western and 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.

Status and trends: Motile epifauna in the east and west GOA are both below their long-term mean but within one standard deviation (Figure 94). Apex predators in the west GOA are more than 1 standard deviation below their long-term mean, while apex predators in the east are more than one standard deviation above their long-term mean (Figure 94).

Western GOA Motile epifauna: The biomass of motile epifauna increased from 2021 to 2023 and is near the long-term mean (1984 – 2023). The biomass of this guild is dominated by hermit crabs, brittle stars, other echinoderms, and octopus. In 2023, brittle star biomass has declined from 2021 while the biomass of hermit crabs, octopus, and other echinoderms have all increased.

Western GOA Apex predators: The biomass of apex predators in the western GOA decreased from 2021 to 2023 and is more than one standard deviation below the long-term mean. The biomass trends for apex predators are primarily driven by arrowtooth flounder, Pacific cod, Pacific halibut, and sablefish. In 2023, arrowtooth flounder, Pacific halibut, and sablefish all declined from 2021 and are below their long-term means. Pacific cod biomass increased from 2021 to 2023 but remain below their long-term mean.

Eastern GOA Motile epifauna: The biomass of motile epifauna in the eastern GOA has decreased from 2021 to 2023 and is below the long-term mean. Eelpouts, hermit crabs, brittle stars, and other echinoderms are dominant components of this guild. Brittle stars have decreased from 2021 to 2023

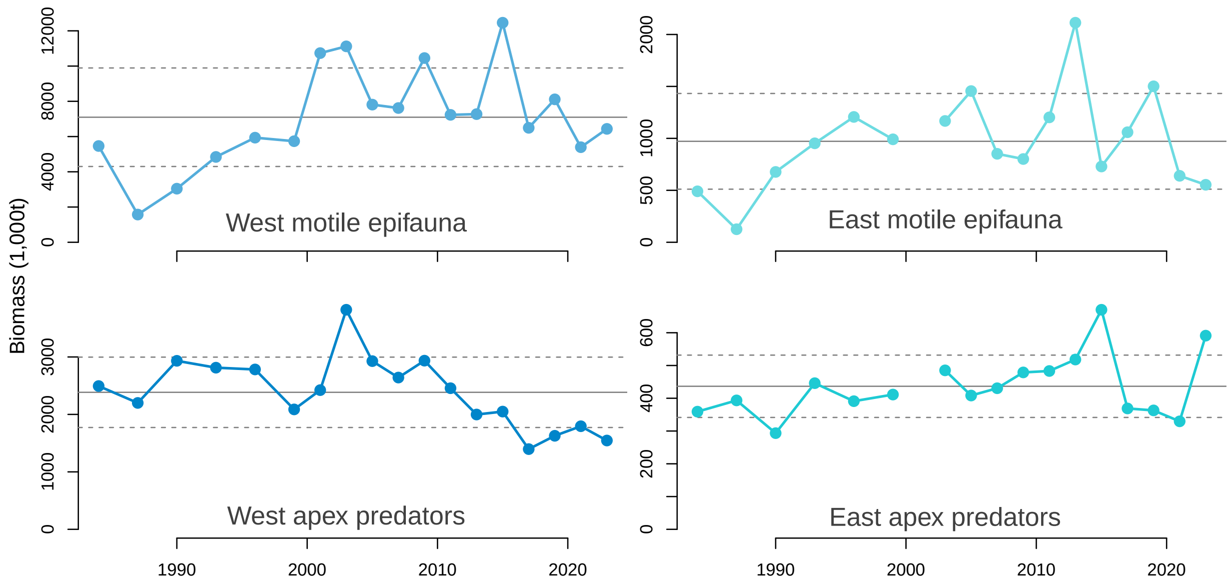

Figure 94: The biomass of apex predator and motile epifauna foraging guilds in the western and eastern GOA shelf from 1984–2023 (data from the NMFS AFSC biennial summer bottom trawl survey). The dashed line is the long-term mean and solid straight lines are ± 1 standard deviation.

and are one standard deviation below their long-term mean, while eelpouts, hermit crabs, and other echinoderms have increased from 2021 to 2023.

Eastern GOA Apex predators: The biomass of apex predators in the eastern GOA has increased 79% from 2021 to 2023 and is more than one standard deviation above their long-term mean. Apex predator biomass in the eastern GOA is primarily driven by arrowtooth flounder and Pacific halibut, both of which increased in biomass by more than 100% from 2021 to 2023. Pacific cod biomass continued to increase in 2023 from their low in 2017 and are above their long-term mean.

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).

Apex predators in the western GOA have remained well below their long-term mean while there was a sharp increase in apex predators in the eastern GOA to well above their long-term mean. Arrowtooth flounder are a primary driver of the apex predator foraging guild in both the western and eastern GOA, accounting for 53% and 55% of apex predator biomass respectively, and their biomass trends help explain the guild trends. In the western GOA, arrowtooth experienced a modest decline in biomass while in the eastern GOA their 2023 biomass more than doubled their 2021 biomass.

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 western GOA 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
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textbfLast updated: October 2023

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 biomass 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 – 2023).

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 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.179) and in the Report Card (p.4 and p.5).

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 index, including sandlance, capelin, and other pelagic smelts. Herring and eulachon are included in the survey index, so this indicator is presented with and without herring and eulachon included to examine their influence on indicator values.

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 95) and the series without (Figure 95). Both series have generally trended upward since 2007. When herring and eulachon are removed, this indicator has slightly higher values from 2007 – 2017 (Figure 95), and follows the same overall trends of the indicator with herring and eulachon. From 2019 to 2023, 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 95). From 2009 – 2021, when herring and eulachon are excluded from the indicator, the values are slightly lower indicating more variability in total groundfish biomass (Figure 95). In 2023, both series increased to time series high values.

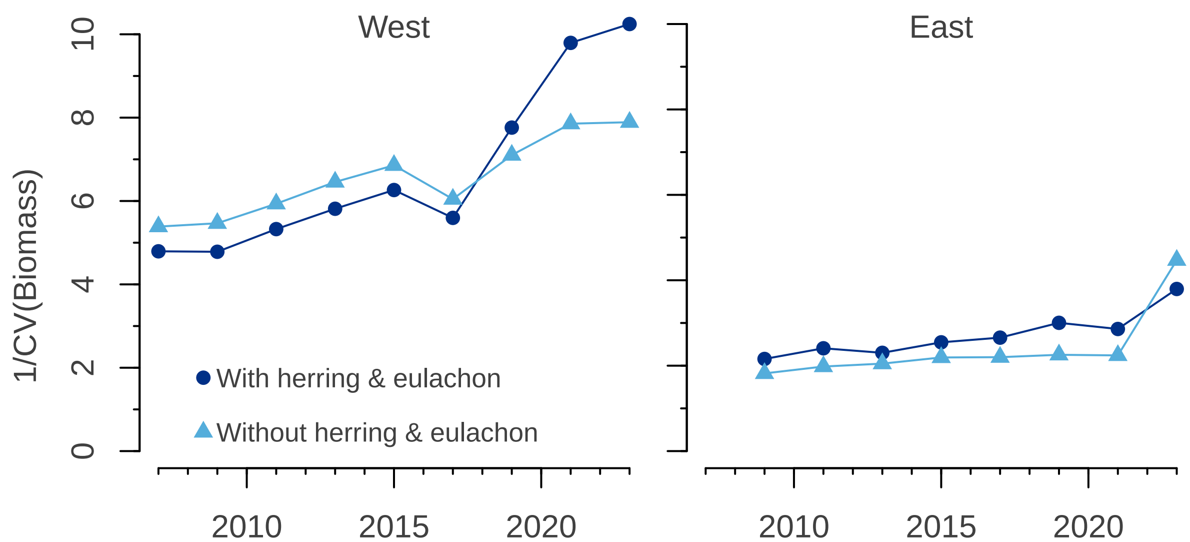

Figure 95: The stability of groundfish in the western and eastern GOA represented with the inverse biomass coefficient of variation (1/CV[B]), 1984 – 2023. Ten years of data are required to calculate this metric, so this time series begins in 2007 for the western GOA and in 2009 for the eastern GOA (no 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.

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 its highest level in 2023, 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.

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 from 2009 to 2021, resulting in the nearly flat trajectories. There was a sharp increase in herring in the eastern GOA survey index from 2021 to 2023, which led to the series without herring surpassing the series with herring included.

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

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Last updated: October 2023

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 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.179) and in the Report Card (p. 4 and p. 5).

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 index, including sandlance, capelin, and other pelagic smelts. Herring and eulachon are included in the survey index, so this indicator is presented 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 37.9 cm, up from 35.9 cm in 2021, and is nearly equal to the long-term mean of 37.7 cm (Figure 96). In the eastern Gulf of Alaska, the mean length of the groundfish community is 33.6 cm, up from 32.9 cm 2021, and is above the long-term mean (Figure 96).

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 96) 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 96). The value in 2023 is 37.3 cm and is above the long-term mean of 34.4 cm. Due to a scaling error in the 2021 contribution, the values for the series without herring and eulachon in the eastern GOA were inflated. That error has been corrected here.

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 both the western and eastern GOA coincided in time with the "blob" marine heatwave. The indicator values in all four series have increased since 2019 and are greater than 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. 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

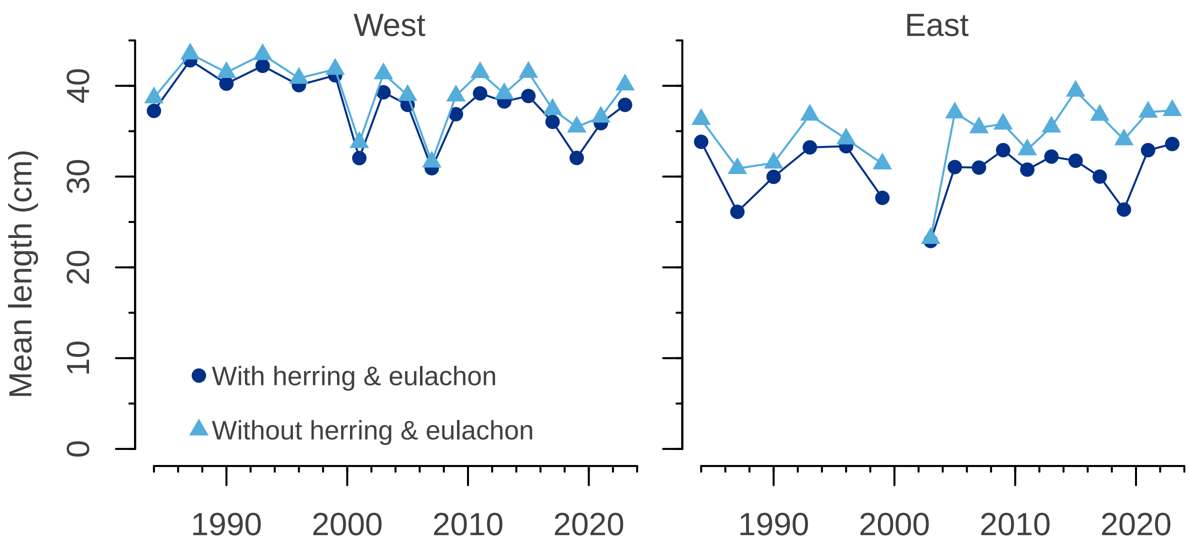

Figure 96: Mean length of the groundfish community sampled during the NMFS/AFSC summer bottom-trawl survey of the Gulf of Alaska (1984 – 2023). The groundfish community mean length is weighted by the relative biomass of the sampled species. The circles represent the indicator series with herring and eulachon included and the triangles are the indicator series with herring and eulachon excluded.

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 – 2023). Low indicator values are broadly attributed to peaks in the biomass index of smaller, shorter-lived forage species. The downward trend from 2015 – 2019 aligned with the presence of warmer water ("the blob") but the indicator has since increased in 2021 and 2023.

Mean Lifespan of the Fish Community in the Gulf of Alaska

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Last updated: October 2023

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[22]. 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 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. 179) and in the Report Card (p. 4 and p.5).

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 2023 with herring and eulachon included is 30.5, which is down from 42.0 in 2021, and is below the long-term mean of 33.6 (Figure 97). 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 2023 with herring and eulachon included is 43.1, up from 36.3 in 2021 (Figure 97). 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 above their long-term means.

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. The drop in indicator value from 2021 to 2023 was due to a decrease in the biomass index of POP. High values in mean lifespan are driven by higher biomass indices

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

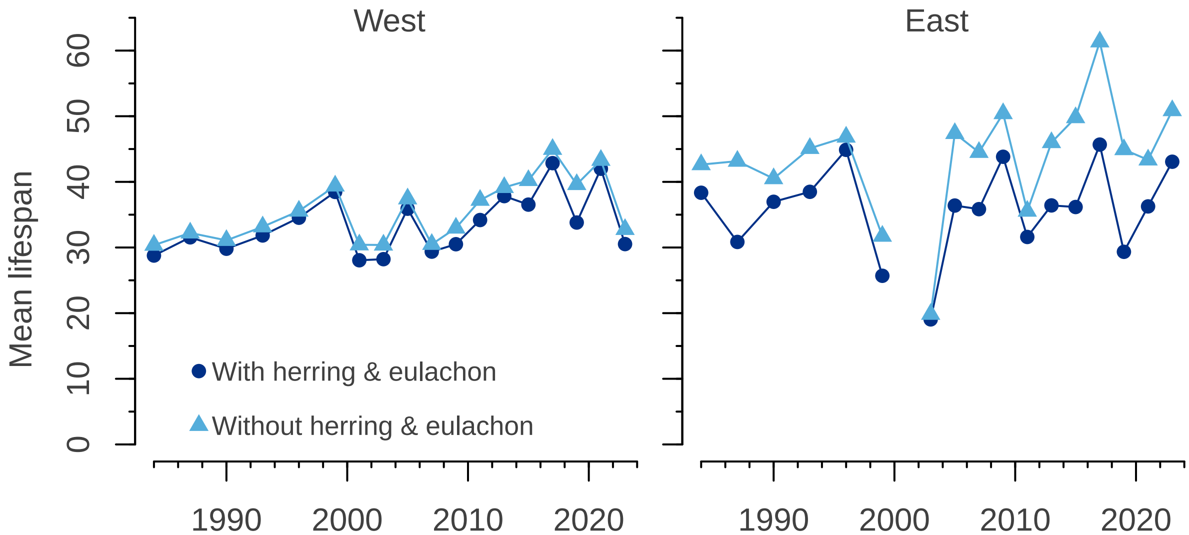

Figure 97: The mean lifespan of the eastern and western Gulf of Alaska demersal fish communities, 1984 – 2023, weighted by relative biomass calculated from the NMFS/AFSC summer bottom-trawl survey. The circles represent the indicator series with herring and eulachon included and the triangles are the indicator series with herring and eulachon excluded.

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 1, right panel, circles). The high mean lifespans in 1996, 2009, 2017, and 2023 in the series with herring and eulachon corresponded to years with below- average herring biomass and/or high biomass in long-lived rockfish, such as POP. When herring and eulachon are excluded, high mean lifespans in the eastern GOA in 2009, 2017, and 2023 are driven by long-lived rockfishes, including POP, shortraker rockfish, rougheye/blackspotted rockfish, and shortspine thornyhead (Figure 97).

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

NOAA Fisheries Bottom Trawl Surveys are conducted every other year (odd years). This contribution was not updated in 2023. Please refer to the archives for past reports.

Species Richness and Diversity of the Gulf of Alaska Groundfish Community

NOAA Fisheries Bottom Trawl Surveys are conducted every other year (odd years). This contribution was not updated in 2023. Please refer to the archives for past reports.

Disease & Toxins Indicators

Harmful Algal Blooms in the Gulf of Alaska

Contributed by Thomas Farrugia[1], Jasmine Maurer[2], Dom Hondolero[3], Grace Ellwanger[4], Andy Wall[4], Emily Mailman[5], Annette Jarosz[5], Maile Branson[5], Kari Lanphier[6], Shannon Cellan[6], Natalie Rouse[7], Emma Pate[8], Kathleen Easley[9], Louisa Castrodale[9]

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[4] Kodiak Area Native Association, Kodiak, AK
[5] Alutiiq Pride Marine Institute, Seward, AK
[6] Sitka Tribe of Alaska, Sitka, AK
[7] Alaska Veterinary Pathology Services, Eagle River, AK
[8] Norton Sound Health Corporation, Nome, AK
[9] AK Department of Health and Social Services, Anchorage, AK

Contact: farrugia@aoos.org
Last updated: September 2023
Sampling Partners:

Alaska Ocean Observing System
Alaska Sea Grant
Alaska Veterinary Pathologists
Aleut Community of St. Paul Aleutian Pribilof Island Association
Central Council of Tlingit and Haida*
Chilkoot Indian Association*
Craig Tribal Association*
Hoonah Indian Association*
Hydaburg Cooperative Association*
Kachemak Bay NERR
Ketchikan Indian Association*
Klawock Cooperative Association*
Knik Tribe of Alaska
Kodiak Area Native Association
Metlakatla Indian Community*
NOAA Kasitsna Bay Lab
NOAA WRRN-West
North Slope Borough
Norton Sound Health Corporation
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*
University of Alaska Fairbanks
USGS Alaska Science Center
Woods Hole Oceanographic Institution
Wrangell Cooperative Association*
Yakutat Tlingit Tribe*

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

Description of indicator: Alaska's most well-known and toxic harmful algal blooms (HABs) are caused by *Alexandrium* spp. and *Pseudo-nitzschia* spp. *Alexandrium* produces saxitoxin (STX) which can cause paralytic shellfish poisoning (PSP) and has been responsible for five deaths and over 100 cases of PSP in

Alaska since 1993 (State of Alaska, 2022). Analyses of paralytic shellfish toxins are commonly reported as μg of toxin/100 g of tissue, where the FDA regulatory limit is 80μg/100g. Toxin levels between 80μg - 1000 μg/100 g are considered to potentially cause non-fatal symptoms, whereas levels above 1000 μg/100g ($\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 (DA) has been detected in 13 marine mammal species and has the potential to impact the health of marine mammals and birds in Alaska. No human health impacts of domoic acid have been reported in Alaska, although both acute and chronic amnesic shellfish poisoning has been reported in several states, including Washington and Oregon.

The Alaska Department of Environmental Conservation (ADEC) tests bivalve shellfish harvested from classified shellfish growing areas meant for commercial market for marine biotoxins including paralytic shellfish toxin (PST) in all bivalve shellfish and domoic acid (DA) specifically in razor clams. The Environmental Health Laboratory (EHL) is the sole laboratory in the state of Alaska certified by the FDA to conduct regulatory tests for commercial bivalve shellfish. The EHL also does testing for research, tribal, and subsistence use.

Department of Health, Section of Epidemiology (SOE) continues to partner with the AHAB network. Nurse consultants join in on the monthly meetings and collaborate with stakeholders so they can be made aware of reportable illness such as Paralytic shellfish Poisoning (PSP). In April 2022, an Epidemiology Bulletin describing cases was released[23]. More information about PSP and other shellfish poisoning can be found on the SOE website[24].

The State of Alaska tests all commercial shellfish harvest. However, there is no state-run shellfish testing program for recreational and subsistence shellfish harvest. Regional programs, run by Tribal, agency, and university entities, have expanded over the past five years to provide test results to inform harvesters and researchers, and to reduce human health risk (Figure 98). 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[25] or through the sampling partners listed above.

Status and trends:

Alaska Region: Results from shellfish and phytoplankton monitoring showed a slight uptick in the presence of harmful algal blooms (HABs) and toxins throughout all regions of Alaska in 2023 compared to 2022, although the overall levels were still lower than in 2019–2021. Bivalve shellfish from areas that are well known for having PSP levels above the regulatory limit, including Southeast Alaska and the Aleutians, continued to have samples that tested above the regulatory limit, albeit less frequently than since 2019 and 2020. Overall, 2023 seems to have been slightly less active for blooms and toxin levels than 2021, 2020 and 2019, but 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 2023 continued that trend. We are also seeing a geographic expansion of areas that are sampling for phytoplankton species, so the decrease in the number of HABs detected may be more related to generally cooler water temperatures, especially in the Gulf of Alaska.

[23] `http://www.epi.alaska.gov/bulletins/docs/b2022_05.pdf`
[24] `https://health.alaska.gov/dph/Epi/id/Pages/dod/psp/default.aspx`
[25] `http://ahab.aoos.org`

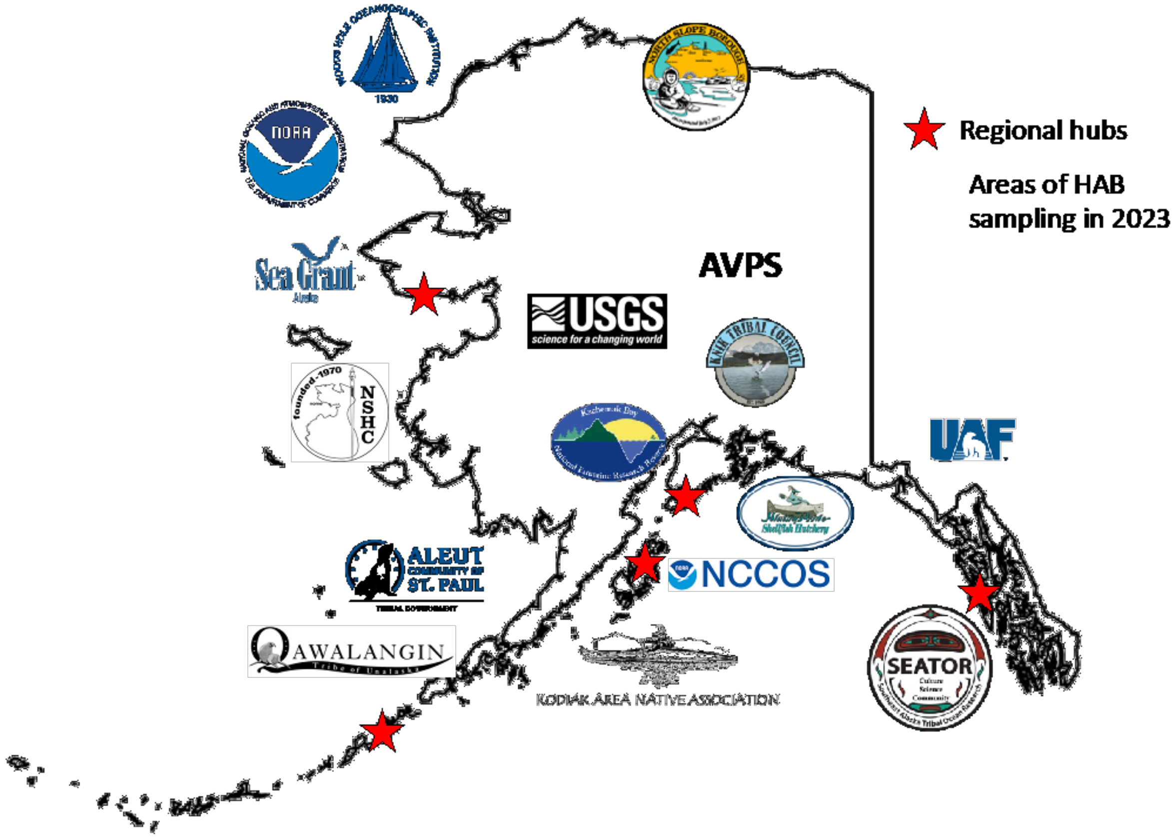

Figure 98: Map of 2023 sampling areas and partners conducted by partners of the Alaska Harmful Algal Bloom Network (AHAB). Opportunistic sampling of marine mammal tissue and other marine species occurs statewide and is not shown here.

Eastern GOA:
Southeast Alaska & Kodiak — In 2023, Southeast Alaska Tribal Ocean Research Consortium (SEATOR) partner Tribes have collected 234 subsistence shellfish samples to be tested for paralytic shellfish toxins (PSTs) by the Sitka Tribe of Alaska Environmental Research Lab (STAERL). These samples represent seven different species of shellfish from 12 different communities in Southeast Alaska. Forty-four of the 234 samples exceeded the FDA regulatory limit of 80 μg of toxins per 100 g of tissue (Figure 99). Blue mussels (a sentinel species for an active bloom) collected from Ketchikan were the first samples to exceed the regulatory limit on May 23, 2023. The highest PST result from shellfish thus far in 2023 was a blue mussel from Juneau, collected on July 7, 2023. This sample contained 1684 μg of toxins per 100 g of tissue, more than 20x the regulatory limit. If previous years' trends hold, we expect to see a fall bloom in southern Southeast Alaska in October. STAERL is continuing the expansion of its toxin testing program to look at the presence of 'emerging' toxins of concern (i.e., okadaic acid, which causes diarrhetic shellfish poisoning and domoic acid, which causes amnesic shellfish poisoning) that can impact communities in Southeast Alaska. (Kari Lanphier, SEATOR and Shannon Cellan, Sitka Tribe of Alaska)

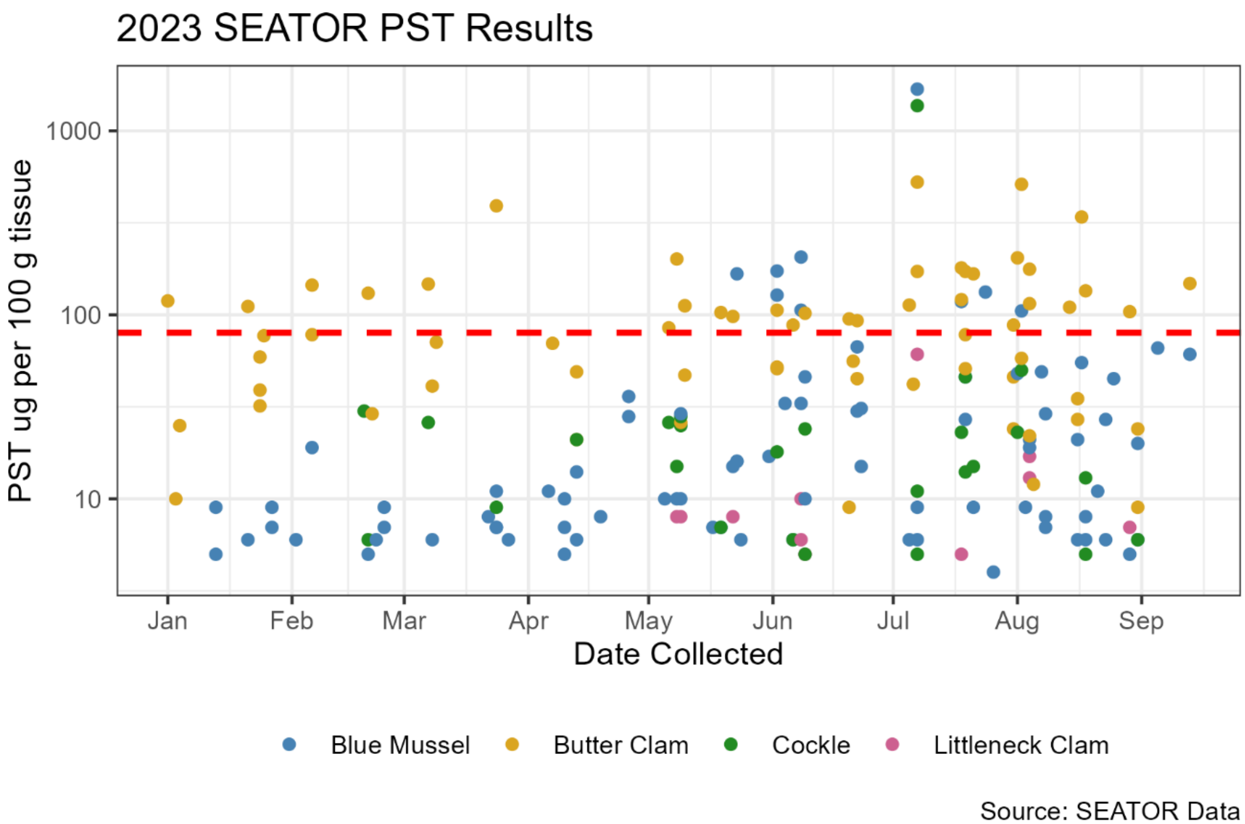

Figure 99: Paralytic shellfish toxicity (PST) results from samples collected in 2023 from seven different species of shellfish from 12 different communities in Southeast Alaska. Data provided by SEATOR.

Western GOA:
In July 2023, the Alaska Department of Fish and Game (ADFG) opened the recreational razor clam fishery in Cook Inlet. The Alaska Ocean Observing System worked with ADFG staff to have razor clam samples sent to ADEC for testing. Four samples were collected before the fishery opened (collected in April, May and June 2023) and one sample was collected during the opening on July 6. All the samples tested below the regulatory limit for both PSTs and DA. In addition, no illness was reported from the razor clam fishery.

Kachemak Bay — The Kachemak Bay National Estuarine Research Reserve (KBNERR) collected and identified phytoplankton in over 180 samples so far in 2023. *Dinophysis* spp. were present in low numbers in 23% of samples, Pseudo-nitzschia sp. were present often (60.4% of samples), but *Alexandrium* spp. were seen in only 1% of samples this year. KBNERR did not conduct any shellfish toxin testing. (Jasmine Maurer, KBNERR)

Lower Cook Inlet and Prince William Sound — Alutiiq Pride Marine Institute (APMI) conducted phytoplankton and shellfish monitoring at seven locations in the Lower Cook Inlet and in the Prince William Sound. The phytoplankton monitoring did not observe bloom levels of *Alexandrium* or *Pseudo-nitzschia* at any of the sample locations. A total of 15 bivalve samples were tested for PSTs and 20 samples were tested for domoic acid (DA) concentrations using enzyme-linked immunosorbent assay. None of the bivalve tissue samples tested higher than the FDA regulatory limit for either PST or DA. Testing for toxins will continue into fall and over winter. Additionally, APMI is working to establish the capacity to conduct receptor binding assays. Phytoplankton and toxin testing data can be found on the Alutiiq Pride Marine Institute website[26]. (Emily Mailman/Annette Jarosz/Maile Branson, APMI)

Kodiak Island — The Kodiak Area Native Association's (KANA) Environmental Department began sampling at 2 locations in August of 2023 after a pause in consistent sampling through KANA. During this time period, staff have identified *Pseudo-nitzschia* spp., *Dinophysis* spp., and *Chaetoceros* spp. among a variety of other centric and pennate diatoms and dinoflagellates. During the break in sampling through KANA, individuals were able to sample at South Trident Basin through the AHAB network and also identified *Pseudo-nitzschia* spp., *Dinophysis* spp., and *Chaetoceros* spp. as well as, *Alexandrium* spp. During this time period, samplers conducted and analyzed 30 phytoplankton samples, and *Pseudo-nitzschia* was particularly common, showing up in 23 of those samples. Moving forward, KANA will continue to sample at South Trident Basin and Mission Beach on a weekly basis. Individual samplers have begun sampling at a new location, Mill Bay Beach and will continue to sample here into 2024. (Grace Ellwanger/Andie Wall, Kodiak Area Native Association)

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.

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.

[26] `http://alutiiqprideak.org/hab-watch`

"Mushy" Halibut Syndrome Occurrence

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Last updated: September 2023

Description of indicator: Mushy Halibut Syndrome was first detected in GOA halibut in 1998. Increased prevalence occurred in 2005, 2011, 2012, 2015, and 2016. It was apparently absent in 2013, 2014, 2019, and 2020, and there were relatively few occurrences in 2017, 2018, and 2021. 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 by port samplers, 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 2023. Mushy halibut was reported on a couple of occasions during 2022 and 2021. There were no reports of mushy halibut during the 2019–2020 sport fishing seasons in central Alaska[27]. 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 availability 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 there there is not a simple link between environmental conditions and the prevalence of this condition.

[27] http://www.adfg.alaska.gov/sf/fishingreports/

Prince William Sound

Temperature Trends in Prince William Sound

Contributed by Rob Campbell, Prince William Sound Science Center, Cordova, AK
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Last updated: August 2023

Description of indicator: A 49-year time series of water temperature was compiled in Prince William Sound (PWS), western GOA region for the period, 1974 – 2023. Temperature anomalies were calculated as the residual of the 2nd order cosine fit to daily temperature data, to remove seasonality (Campbell, 2018). Data were collected from the World Ocean Database (NOAA), an unpublished database of casts done by the University of Alaska Fairbanks (UAF), and ongoing surveys (2009 - present). 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) are from ongoing Gulf Watch Alaska[28] projects conducted by the PWS Science Center, UAF, and NOAA.

Status and trends: In 2023 near surface temperature anomalies appear to have flipped, trending towards negative anomalies, which may be a result local impacts of the prolonged La Niña pattern in the North Pacific (2020 – 2022), which lead to cooler near surface temperatures on the adjacent shelf. Temperature anomalies deeper in the water column (25 m), have been similar to the pattern at the surface, but are smaller and with a higher preponderance of negative anomalies. Temperature anomalies at depth (200 m) show a long-term warming trend and have been positive since 2013.

Near surface temperature has been increasing in central PWS for the last four decades, at approximately 0.1°C per decade (Figure 100), although there is substantial year-to-year variability. In 2013, near surface anomalies shifted towards strongly positive, and have for the most part stayed that way into 2022 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 as 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 GOA with a lag of about 12 months, which is driven by circulation within the region (Campbell, 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 GOA (Royer and Grosch, 2006; Janout et al., 2010). The negative anomalies observed at mid-depths (25 m) may reflect an overall shallowing of the seasonal mixed layer, as well as advective impacts from shelf waters. High frequency observations of the surface layer at a profiler site in central PWS (Campbell, unpubl.) also support this idea. The deep waters of PWS are renewed annually (Halverson, 2014), and above-average temperatures at depth (200 m) are likely a manifestation of warmer than average shelf and slope waters being mixed and advected onto the continental shelf (Janout et al., 2010).

[28] http://gulfwatchalaska.org

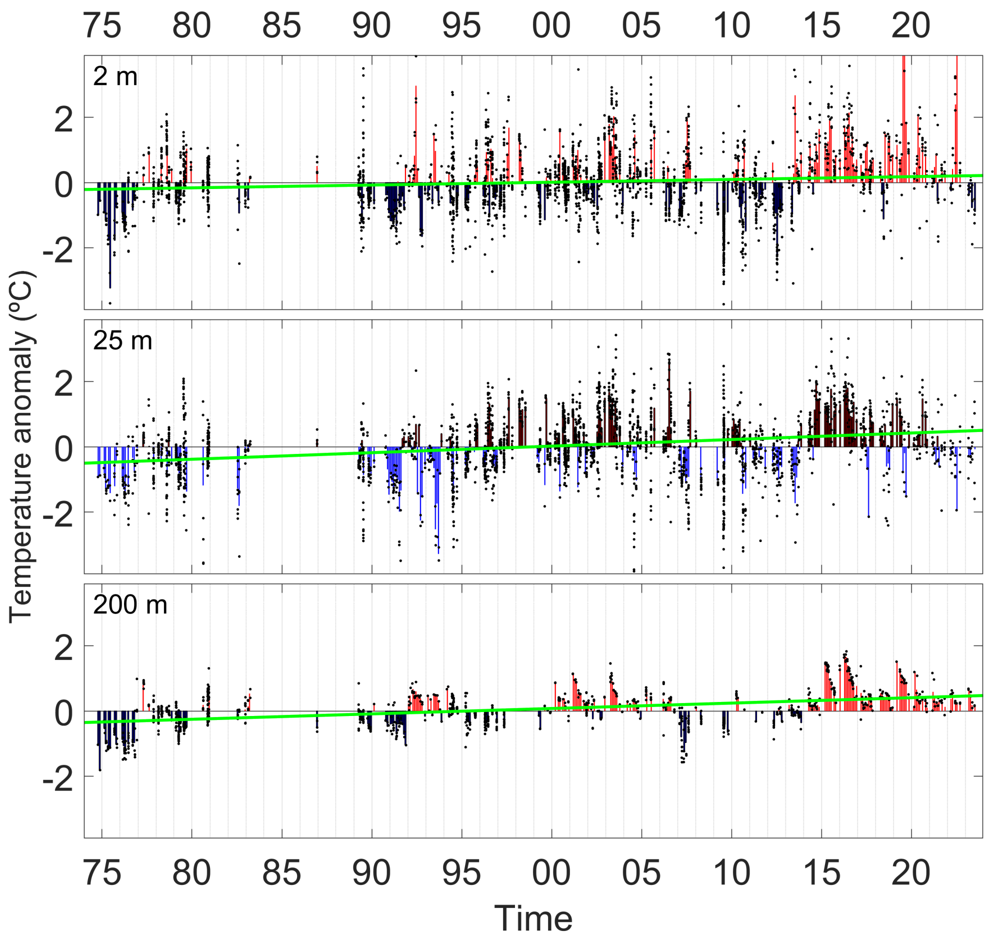

Figure 100: Temperature anomalies at three depths (2 m, 25 m, and 200 m) in central Prince William Sound, 1974 – 2023. Black dots indicate observations, and bars are monthly averages; the green line is the long-term trend. Anomalies were calculated as the residuals of a second order cosine curve fit to all years' data (to remove seasonality).

Implications: The changes in temperature in PWS in the last few decades mirror those observed basin-wide in the GOA 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

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Last updated: September 2023

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 four regions in the northern GOA: western Prince William Sound (WPWS), Kenai Fjords National Park (KEFJ), Kachemak Bay (KBAY), and Katmai National Park and Preserve (KATM). Since 2018, we have reported on one physical indicator (intertidal water temperature) and three biological indicators using data from sampling beginning in 2005–2007. Respectively, these data 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 are represented by density estimates of large ($\geq$ 20 mm) Pacific blue mussels (*Mytilus trossulus*) sampled quantitatively within mussel beds. The nearshore predator abundance indicator is density of sea star species, estimated along an approximately 200 m^2 transect at each rocky intertidal monitoring site. Indicators are presented as annual anomalies compared to the long-term mean of the data record, which is an average across sites within each region.

Status and trends: Nearshore water temperature across the GOA from Prince William Sound to the Alaska Peninsula showed a warming trend beginning in 2014 that persisted across all regions through 2016 and into 2017 in WPWS and KEFJ (Figure 101). These results confirm that the 2014–2016 Pacific marine heatwave (PMH) in the GOA was expressed in intertidal zones in addition to open ocean environments. While temperatures returned to cooler conditions in 2017, a new heat spike in 2019 in all regions was recorded. After that, temperatures started to cool again, although with much higher variability among the four regions, which was not observed prior to the heat wave. In 2023, at the time of collection (mid-summer), all four regions were cooler than average.

For algal cover, despite considerable variability in percent cover among regions and generally positive anomalies through 2014, KATM and KEFJ regions showed consistently negative values during the recent PMH and continued through 2021. *Fucus* in WPWS also indicated strongly negative values in 2021 while KBAY did not show any specific trend over time (Figure 102). By 2023, KATM and WPWS remained negative while KEFJ had increased steadily to a positive anomaly since 2022. KBAY continued to have roughly average *Fucus* cover without a noticeable response in percent cover of *Fucus* to temperature fluctuations.

Large mussel densities ($\geq$ 20 mm) showed an overall positive trend across regions consistent with timing of the PMH, in this case switching from generally negative to positive for the regional long-term mean after 2014 (Figure 103) – an opposite response compared to algal cover and sea stars (Figures 102 and 104). In 2021, it appeared that large mussel density had returned to the long-term average across all regions. But, by 2022, negative anomalies in KATM and WPWS were evident with average values in KBAY and positive values in KEFJ. 2023 data indicated that KATM was still experiencing negative

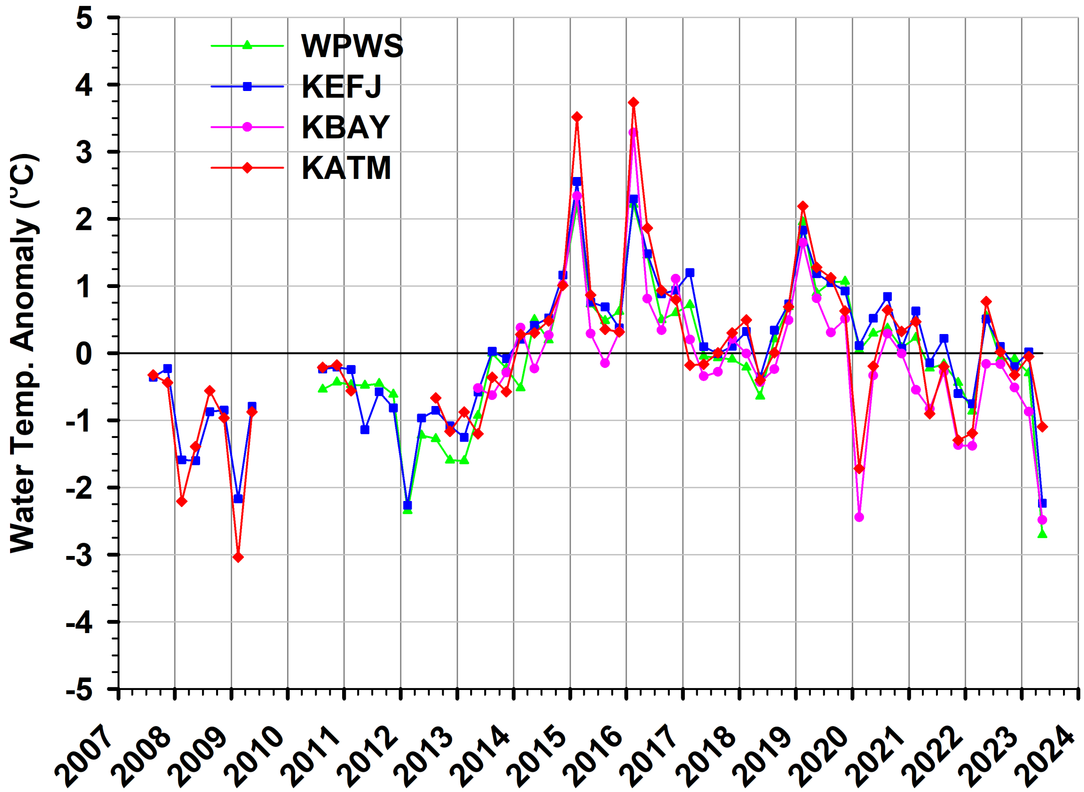

Figure 101: Seasonal intertidal water temperature anomalies at the 0.5 m tide level four regions of the western Gulf of Alaska (west of 144˚W), western Prince William Sound (WPWS; 2011–2023), Kenai Fjords National Park (KEFJ; 2008–2023), Kachemak Bay (KBAY; 2013–2023), and Katmai National Park adjacent to Shelikof Strait (KATM; 2006–2023). Long tick marks indicate the start of the calendar year (January) while short tick marks are quarterly divisions within the year (April, July, October).

large mussel density anomalies, while average (WPWS) and positive anomalies were present in the other regions (KEFJ and KBAY). As oceanographic conditions returned to cooler temperatures, variability in mussel abundance at these regional spatial scales supports our conclusion that, in the absence of broad-scale perturbations, other variables and local conditions are more important drivers of mussel abundance (Bodkin et al., 2018; Traiger et al., 2022; LaBarre et al., 2007).

Variability in density and species composition of sea stars varied greatly among regions through 2015 but between 2015 and 2017, abundance declined and remained strongly negative across all regions through 2019 (Figure 104), likely due to sea star wasting (Konar et al., 2019), possibly exacerbated by the PMH (Harvell et al., 2019). In 2020, there was some recruitment and recovery observed in WPWS and KEFJ (as indicated by the close to average anomaly value). However, the sea star species thought to be least affected by sea star wasting in the northern GOA (primarily *Henricia* and *Dermasterias*) accounted for the positive anomalies through 2020 in all regions surveyed.

In 2023, density anomalies within each region indicated that WPWS and KBAY were approximately average compared to the long-term mean density within each respective region, while KATM density remained somewhat positive (higher density than average in KATM) and KEFJ density was strongly

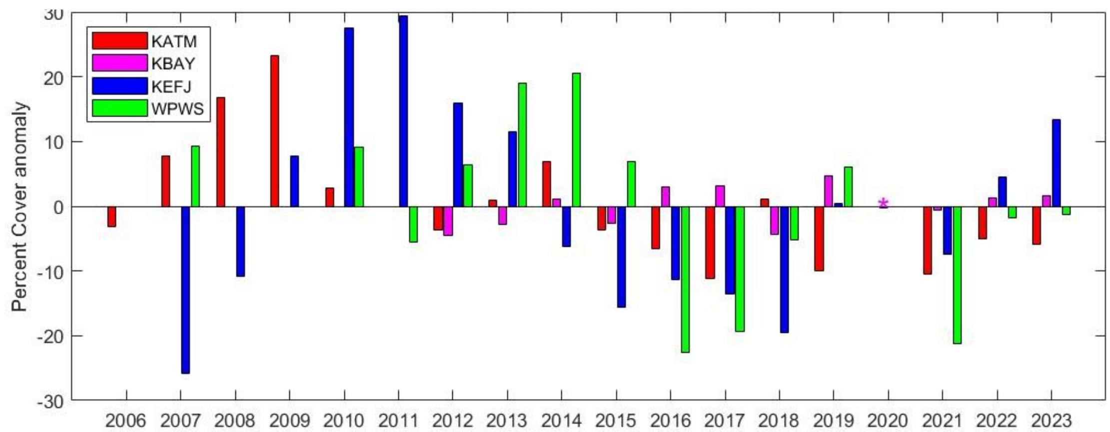

Figure 102: Percent cover anomalies for rockweed (Fucus distichus) in four regions of the western Gulf of Alaska, WPWS (2007, 2010–2019, 2021–2023), KEFJ (2008–2019, 2021–2023), KBAY (2012–2023), and KATM (2006-2010, 2012–2019, 2021–2032). WPWS, KEFJ and KATM were not sampled in 2020 due to COVID-19. Note: KBAY anomaly in 2020 and 2021 were close to 0, hence the lack of clearly visible bars for KBAY in 2020 (symbolized by an asterisk in 2020) and 2021.

positive (significantly higher density than the long-term average in KEFJ). Preliminary analyses for 2023 also indicated that variability in species composition among regions has increased. For example, Pisaster were the dominant species in KEFJ (72%) and KATM (76%). In WPWS, *Dermasterias* dominated at 34% followed by almost equal proportions of *Evasterias* (26%), *Pisaster* (19%) and *Pycnopodia* (20%). In KBAY, densities are still slightly lower than average, however of the few stars observed in KBAY, *Orthasterias* was proportionally dominant at 64%.The variability in the sea star community (both by density and species composition) among regions may be an indication of the ecosystem returning to one dominated by local-scale conditions as opposed to driven by large-scale perturbations such as sea star wasting and the PMH.

Factors influencing observed trends: During the PMH, negative anomalies of *Fucus* in three of the four regions and of 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 (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; Harvell et al., 2019). These factors were associated with increased mussel abundance across our study regions (Traiger et al., 2022), with a general trend of algal dominated systems turning more into invertebrate dominated systems (Weitzman et al., 2021). However, as nearshore waters appeared to cool after the PMH, especially in recent years, large-scale patterns of abundance of the three biological indicators are becoming less synchronous across regions. Cooler temperatures have not led to increases in *Fucus* percent cover except in KEFJ. Assuming that low cover of *Fucus* would continue to provide open space for mussel settlement, high densities of large mussels have not persisted through time. In fact, one of the coolest regions (KATM) has had negative *Fucus* cover and negative large mussel density anomalies since 2022. Variation in these metrics will continue to be evaluated. Currently, it appears that regional patterns are diverging from one another, perhaps reflecting a shift from broader responses to a large-scale phenomenon (i.e., the PMH) to more local conditions specific to each region.

Implications: Collectively, these indicators demonstrated consistent and persistent, broad-scale per-

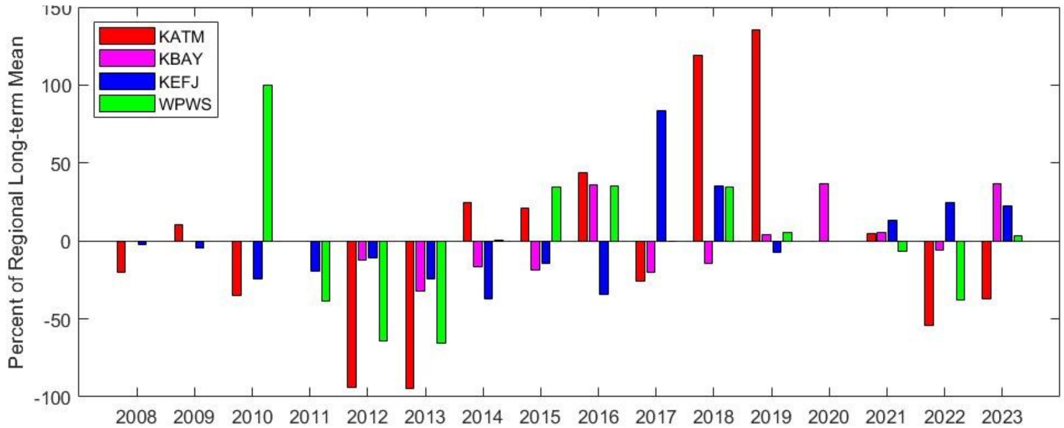

Figure 103: Percent of density anomalies for large mussels ($\geq$ 20 mm) in four study regions spanning the northern Gulf of Alaska. WPWS (2010–2019, 2021–2023), KEFJ (2008–2019, 2021–2023), KBAY (2012–2023), and KATM (2008–2010, 2012–2019, 2021–2023).

turbations of nearshore ecosystems coincident with the PMH throughout much of the western GOA, 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 change 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 found that the loss of sea stars likely contributed to the increase in large mussel density due to a decline in predation pressure from sea stars. However, other factors such as predation pressure from nearshore vertebrates, shifts in primary productivity, and changes in environmental variables (salinity) may also influence mussel density (Traiger et al., 2022) and will be evaluated over time. We hypothesize that more local conditions will drive regional nearshore communities, now that broad, Gulf-wide effects of the PMH have dissipated.

Intertidal and nearshore ecosystems provide valuable habitat for early life stages of various commercially important species in the GOA, including Dungeness crab, Pacific cod, salmonids and several species of rockfish. Our indicators suggest that some nearshore biological responses to the PMH appeared to continue into 2021 at least in some regions and could have affected recruitment and survival of species whose life stages rely on nearshore habitat. For some metrics, evidence of return to more average conditions in nearshore habitats suggests that PMH effects, both positive and negative, are dissipating. A major trend that is emerging, however, is that the variability of biological indicators across regions is larger than it was before the PMH. Marine heatwaves are expected to become more common and widespread as a consequence of climate change. From primary producers to top-level consumers, our studies offer insight as to the varying extent of species' responses to these wide-scale perturbation and the timescales over which effects are expressed. Further, we also hypothesize that in the long-term, 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 GOA.

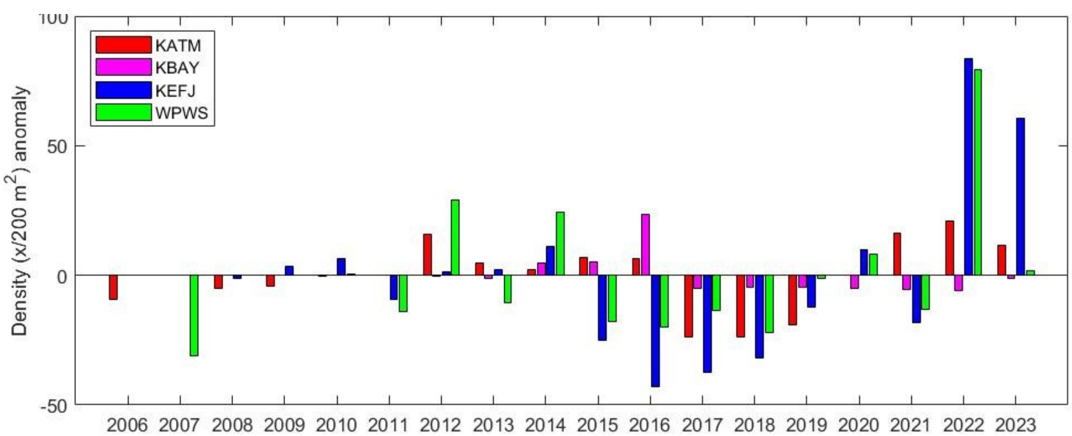

Figure 104: Density anomalies of sea stars (primarily *Dermasterias imbricata*, *Evasterias troschelii*, *Pisaster ochraceus*, and *Pycnopodia helianthoides*) in four study areas spanning the northern Gulf of Alaska. WPWS (2007, 2010–2023), KEFJ (2008–2019, 2021–2023), KBAY (2011–2023), and KATM (2006, 2008–2010, 2012–2019, 2021–2023).

Prince William Sound Herring

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Last updated: August 2023

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. (2008). 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. It is the sum of miles of spawn observed each day during the spawning season. Acoustic surveys collected by the Prince William Sound Science Center were conducted from the mid-1990s–2021. 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 prefishery biomass occurred in the 1980s and a subsequent decline in the 1990s (Figure 105). 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 and continued through 2022 (Figure 105). The decline in the observed mile-days of milt is more rapid than the model decline (Figure 106) 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 2020 continued to increase as the 2016 year class continued to recruit into the spawning biomass. By 2021 the 2016 year class was fully recruited to the spawning biomass and the mile-days of milt continued to increase through 2022 due to other recruit classes or increased fecundity as the herring grew older. In 2023 the observed mile-days of milt decreased from the previous year. The 2016 cohort reached age-7 and annual mortality was likely not offset by new recruitment. A similar trend in mile-days of milt was observed at Kayak Island between 2021 and 2023, the limited time series when aerial surveys were flown more consistently.

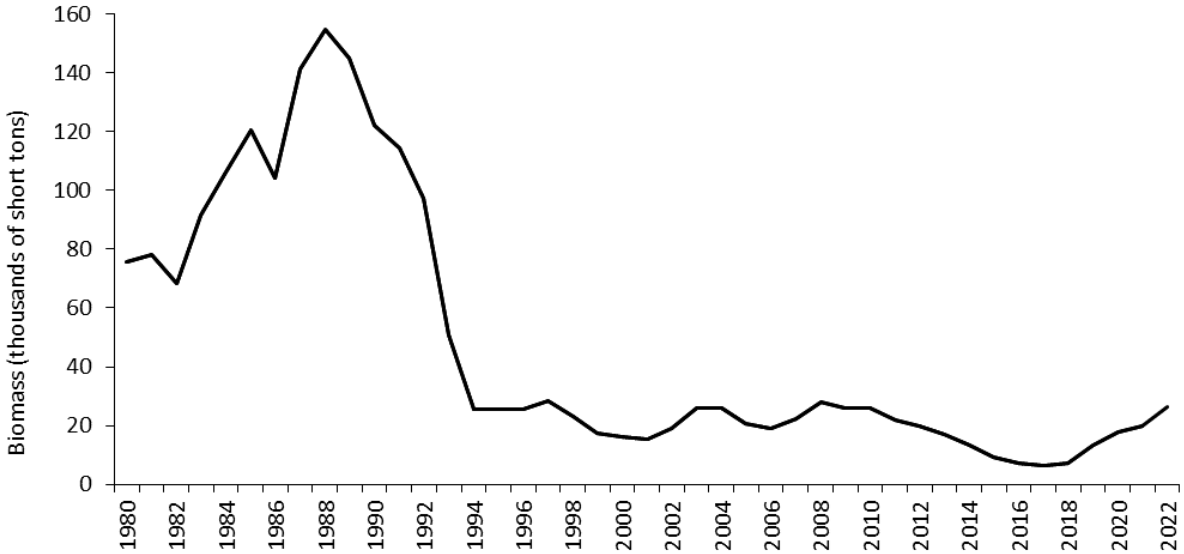

Figure 105: The Bayesian age-structured assessment model median estimate of the pre-fishery biomass.

The time series of the age-1 herring school observations is shown in Figure 107. 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. This year we observed fewer schools than in the recent past. The level is consistent with what is expected after a potentially large year class such as those observed the last two years.

Factors influencing observed trends: The building trend in herring biomass was 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. It is not possible to determine if the continued increasing mile-days of milt was caused by the recruitment of new recruit classes or was a result of increased milt production as the fish from the 2016 year class grew in size. In 2023, this cohort reached age 7 and annual mortality may not have been offset by new recruitment so the observed mile -days of milt declined. Preliminary spring 2023 ASL data indicates that there was a large recruitment of age-3 fish to the spawning population and age 3 became the dominant age class however this cohort appears considerably smaller than the 2016 year class ageing out of the population.

Implications: The PWS herring population has increased from the historic low biomass that occurred in 2017 but has not remained consistently above the minimum spawning biomass threshold for consideration of commercial fisheries. Preliminary 2023 age compositions show age 3 and 4 fish represent a significant portion of the spawning population although these recruitments may not be large enough to offset the natural mortality of the 2016 year class age class. The number of age-1 herring observed in 2023 does not suggest that it will be a particularly large or small year class.

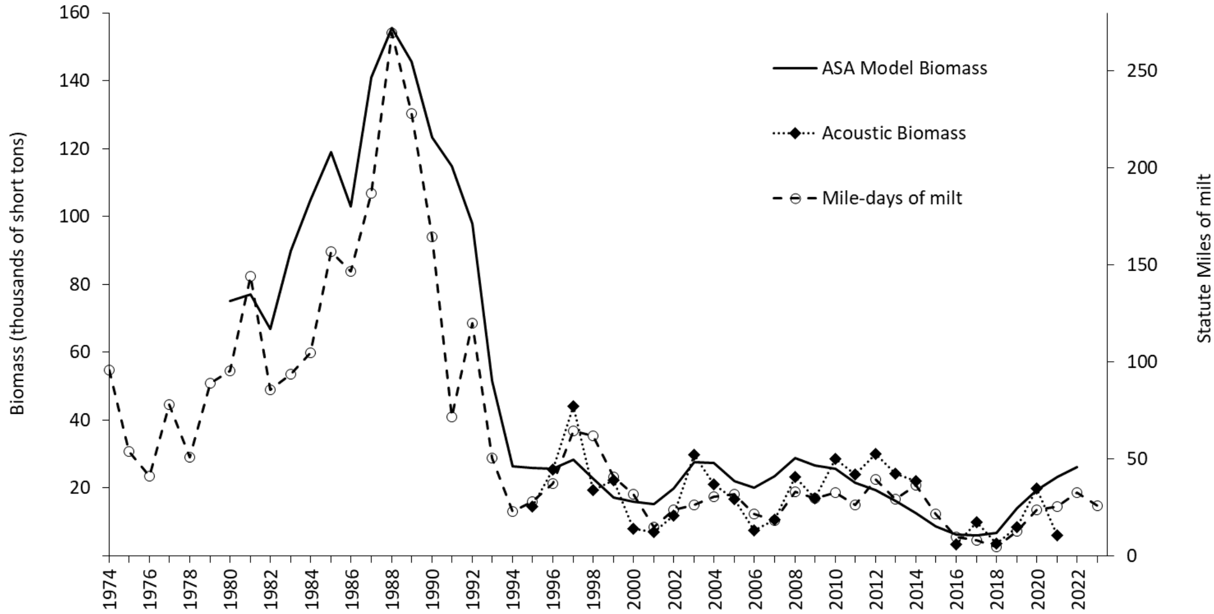

Figure 106: Mile-days of milt in Prince William Sound based on aerial surveys, and biomass estimates from acoustic surveys. Includes preliminary results of the 2023 survey from Alaska Department of Fish and Game.

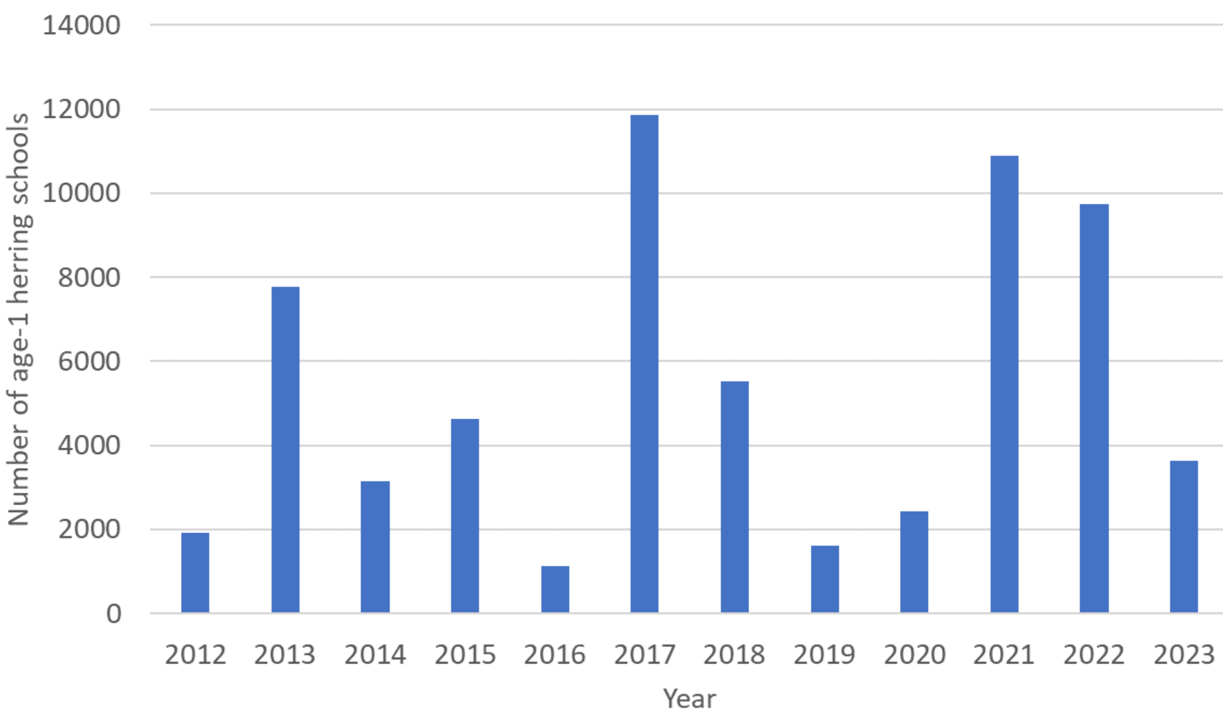

Figure 107: The school-size weighted number of age-1 herring schools in Prince William Sound.

Fall Surveys of Humpback Whales in Prince William Sound

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Last updated: Ocotber 2023

Description of indicator: The humpback whale population in the North Pacific rebounded from near extinction in the late 1960s to over 22,000 individuals in 2006 (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 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 (beginning 2008), 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 2023 survey, yielded similar results to our 2017–2022 effort with the exception of calf counts. Four mother calf pairs were seen in September. The encounter rate for humpback whales (number of whales/nm traveled) improved slightly relative to the 2017–2022 surveys (Table 3). Acoustic surveys for prey in 2023 have yet to be quantified, however, whales were targeting euphausiids in the Whale Bay, Bainbridge Pass area and small schools of juvenile herring throughout the rest of the Sound. Only one whale was see feeding on adult herring during the September survey.

Table 3: Index of humpback whale abundance and counts of calves in Prince William Sound.

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
Sep-22	19	1	504	0.04
Sep-23	34	4	497	0.07

Factors influencing observed trends: The abundance of suitable whale prey in Prince William Sound seems to be stable, but the abundance of humpback whales is not. We did not encounter any exceptionally large concentrations of prey as in 2023. The factors influencing limiting the return of humpback whales to the Sound remains uncertain.

Implications: The trend in low whale numbers within Prince William Sound continues to differ with observations from Southeast Alaska and Hawaii where sightings of adults are showing signs of recovery towards pre-heatwave levels. However the increase in calf production demonstrates that whales are foraging successfully, a positive sign for ecosystem health.

Fishing Indicators

Maintaining Diversity: Discards and Non-Target Catch

Time Trends in Groundfish Discards

Contributed by Anna Abelman, Resource Ecology and Fisheries Management Division, AFSC, NOAA Fisheries, and Alaska Fisheries Information Network, Pacific States Marine Fisheries Commission
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Last updated: September 2023

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 108, are calculated as the weight of groundfish discards divided by the total (i.e., retained and discarded) catch weight for the relevant areagear-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.

Status and trends: Discard biomass in the fixed gear sector, in 2023, is trending lower relative to the previous 5 years through week 37, whereas trawl pollock and non-pollock trawl sectors discard biomass is trending in line with previous years (Figure 109). 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 108). 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. The 2022 discard biomass for non-pollock trawl is at its lowest at 3,882 mT and rate of 8%. 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.

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

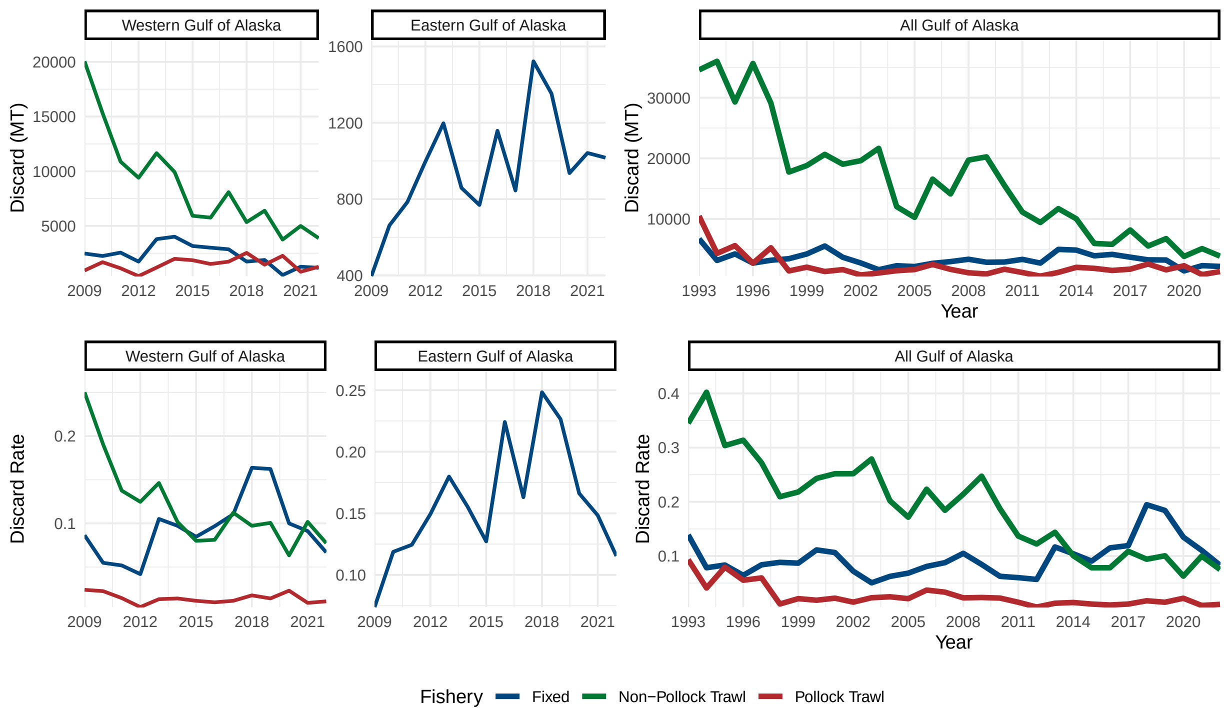

Figure 108: Total biomass and percent of total catch biomass of FMP groundfish discarded in the fixed gear, pollock trawl, and non-pollock trawl sectors for the Gulf of Alaska region, 1993–2022; and for and eastern and western GOA subregions, 2009–2022. Discard rates are calculated as total discard weight of FMP groundfish divided by total retained and discarded weight of FMP groundfish for the sector (includes only catch counted against federal TACs).

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

In the GOA, 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 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 GOA arrowtooth flounder fishery, including an increase from 0 to 20 percent for flatfish species (74 Federal Register 13348). Under

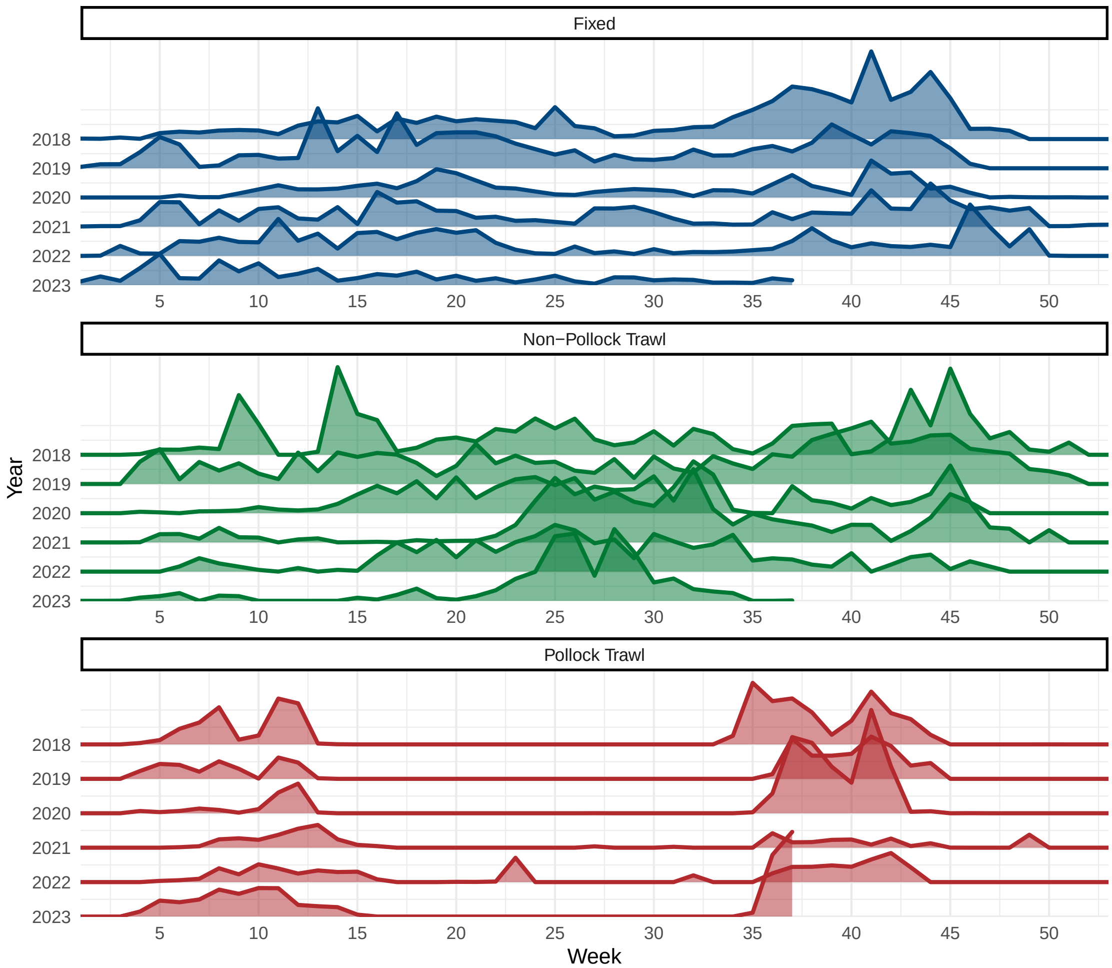

Figure 109: Total biomass of FMP groundfish discarded in the Gulf of Alaska by sector and week, 2018 - 2023 (data for 2023 is shown through week 37). Plotted heights are not comparable across fisheries.

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. As of March 2020, the regulations 50 CFR 679.20(j) and 50 CFR 679.7(a)(5) were implemented to require operators of catcher vessels using hook-and-line, pot, or jig gear (fixed gear) to fully retain rockfish landings in the BSAI or GOA. These regulations also limit the amount of rockfish that can enter into the market with the overall purpose of limiting total catch of rockfish.

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

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Description of indicator: This indicator reports the catch of non-target species in groundfish fisheries in the Gulf of Alaska (GOA). 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. Since 2013, the three categories of non-target species tracked 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).

The catch of non-target species/groups from the GOA includes the reporting areas 610, 620, 630, 640, 649, 650, and 659[29]. Within reporting area 610, the GOA and Aleutian Islands (AI) Large Marine Ecosystems (LMEs) 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 – 2022, with peaks in 2012, 2015, 2016, and 2019 (Figure 110). The catch of jellies in 2022 was the lowest over this time series. 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 2022 where it is at its second lowest level since 2011. Sea anemones comprised the majority of the structural epifauna catch from 2011 – 2019, and have been co-dominant with unidentified corals and bryozoans from 2020 – 2022. Structural epifauna has primarily been caught in hook and line and non-pelagic trawl fisheries. The catch of assorted invertebrates increased from 2012 to a peak in 2015 then decreased each year to a low in 2021 and has remained low in 2022. 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 pot and hook and line 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 population 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).

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

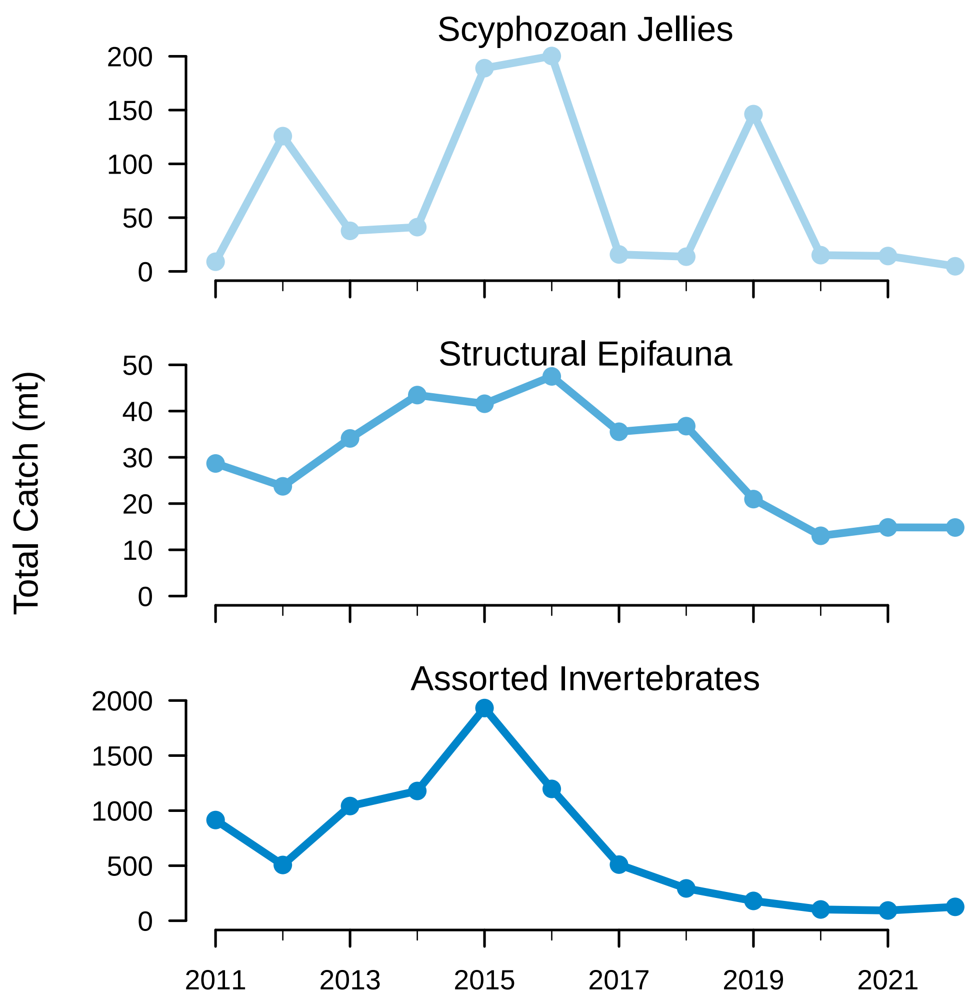

Figure 110: Total catch of non-target species (tons) in the GOA groundfish fisheries (2011–2022). Note the different y-axis scales between species groups.

Seabird Bycatch Estimates for Groundfish Fisheries in the Gulf of Alaska

This contribution was not updated in 2023.

Maintaining and Restoring Fish Habitats

Fishing Effects to Essential Fish Habitat

Contributed by Molly Zaleski[1], Mason Smith[1], Scott Smeltz[2], and Felipe Restrepo[2]
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Last updated: August 2023

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. The time series for this indicator is available since 2003, when widespread VMS data became available, through August 2022.

We used the fishing effects model developed for the 2017 EFH 5-year Review and updated for the 2023 EFH 5-year Review (Smeltz et al., 2019; Zaleski et al., 2023). The model combines VMS data, gear-specific contact adjustments, and susceptibility and recovery rates for habitat characteristics to estimate the percent area disturbed by commercial fishing gear. We produced a time series for each region of estimated disturbance to benthic habitat by commercial fishing gear for all gear types (Gulf of Alaska, Aleutian Islands, and the Bering Sea divided into southern and northern subregions at latitude 60˚N).

Status and trends: The time series indicates little change in habitat disturbance over time with a very slight decrease from the beginning of the data series in 2003 to the latest available estimate in 2022 (1.71% in January 2003 and 0.9% in August 2022, Figure 111). Figure 112 shows the location of the areas with the highest impact for August 2022.

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, susceptibility and recovery rates of living substrates in the areas fished, and management or

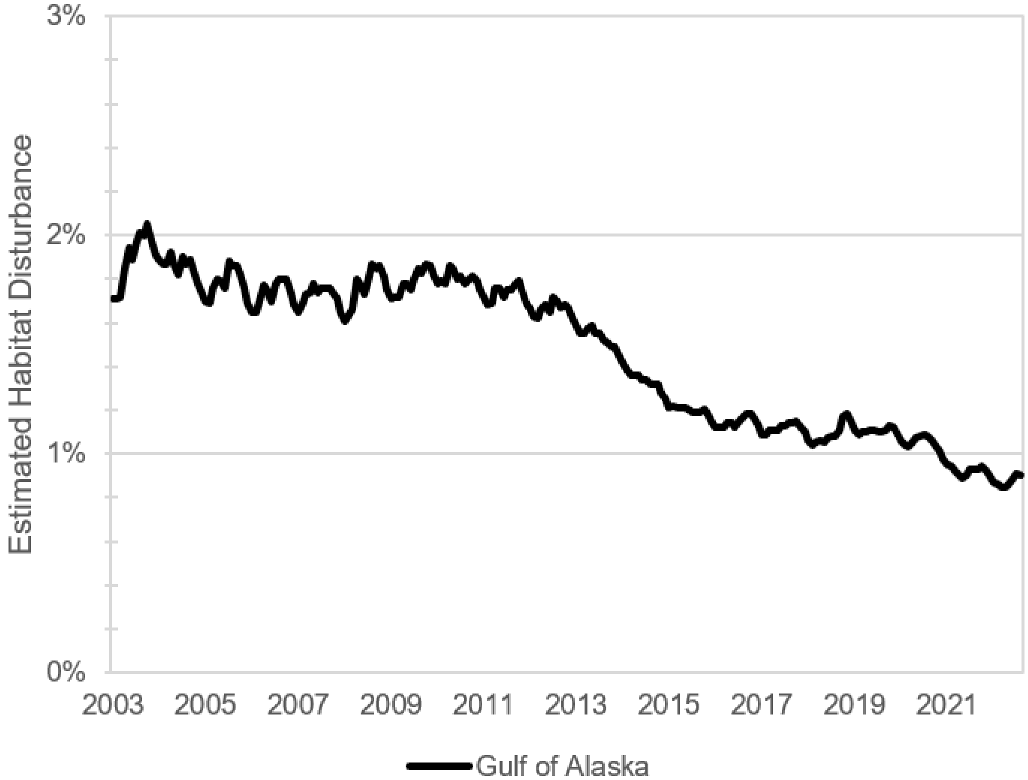

Figure 111: A time series of the estimated % habitat disturbance by bottom contact of commercial fishing gear in the Gulf of Alaska (2003–Aug 2022).

economic changes that result in spatial redistribution of fishing effort. Bottom trawling is not permitted in the Eastern Gulf of Alaska; hook-and-line is the predominant gear type in the eastern GOA.

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 (Simpson et al., 2017) and the updated model for the 2023 EFH 5-year Review (Zaleski et al., 2023). During the 2023 EFH 5-year Review, stock authors and experts were provided model output through December 2020 to evaluate if the estimated disturbance adversely impacted FMP species' core EFH areas. For the Gulf of Alaska, no species were determined to have more than minimal and not temporary effects from fishing, and no stock authors elevated species for mitigation measures against fishing gear impacts to habitat (Zaleski et al., 2023). 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. No new closure areas have been added in the BSAI or GOA regions.

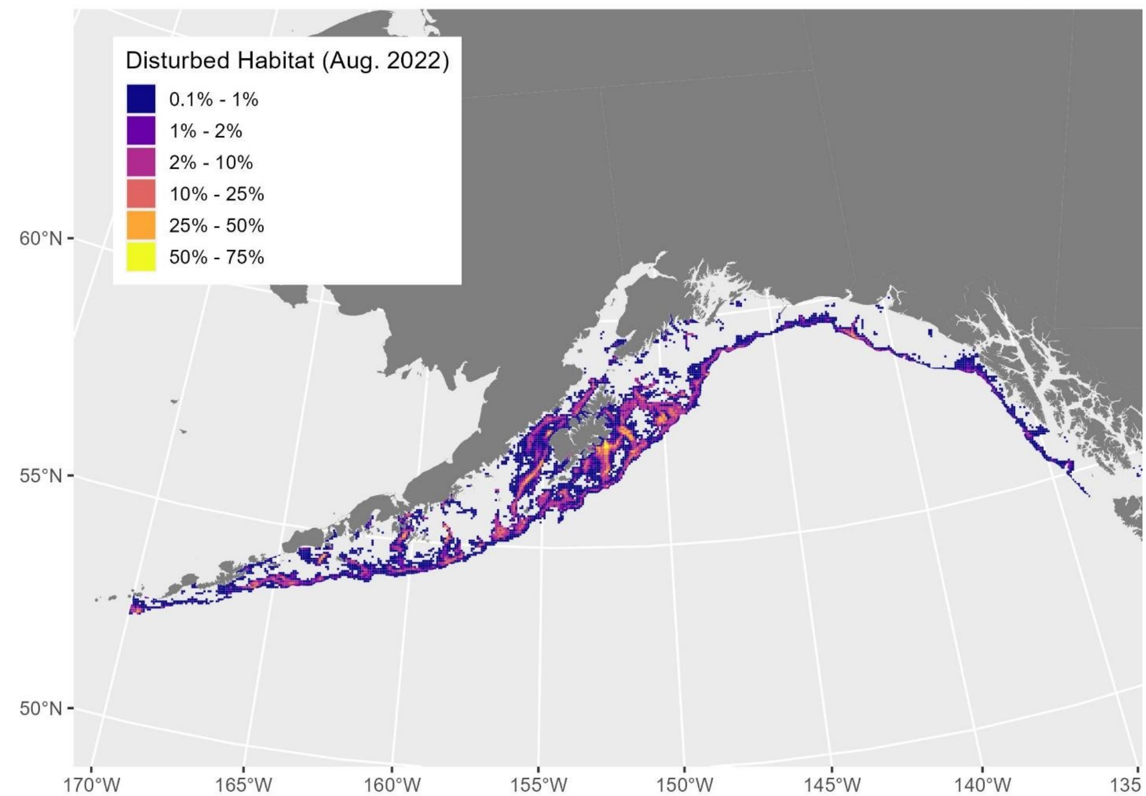

Figure 112: A map of the Gulf of Alaska cumulative percentage habitat disturbed, all gears combined (August 2022)

Sustainability (for consumptive and non-consumptive uses)

Fish Stock Sustainability Index—Gulf of Alaska

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Last updated: August 2023

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[30]. 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%).

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. Additionally, in Alaska there are 26 non-FSSI stocks, three 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[31].

[30] https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates#2023-quarterly-updates
[31] https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates#2023-quarterly-updates

Status and trends: The GOA FSSI in 2023 has increased from 84.8% in 2022 to 86.6% in 2023 (Figure 113). As of June 30, 2023, 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 4). Points continue to be deducted for the shortraker rockfish stock, the demersal shelf rockfish complex, and the thornyhead rockfish complex for unknown status determinations and not estimating B/B_{MSY}.

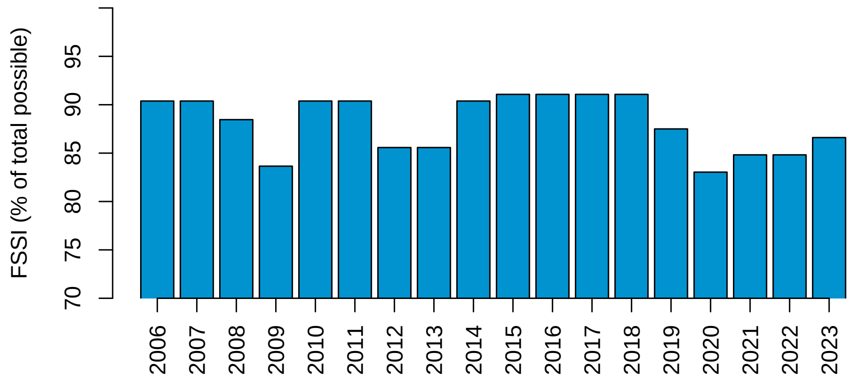

Figure 113: The trend in GOA FSSI from 2006 through 2023 as a percentage of the maximum possible FSSI. All scores are reported through the second quarter (June) of each year, and are retrieved from the NOAA Fishery Stock Status Updates[32].

Table 4: GOA FSSI stocks under NPFMC jurisdiction updated June 2023 adapted from the NOAA Fishery Stock Status Updates[33]. See FSSI and Non-FSSI Stock Status Table on the Fishery Stock Status Updates webpage for definitions of stocks and stock complexes.

Stock	Overfishing	Overfished	Approaching	Progress	B/B_{MSY}	FSSI Score
GOA Arrowtooth flounder	No	No	No	N/A	2.05	4
GOA Flathead sole	No	No	No	N/A	2.83	4
GOA Shallow water flatfish complex[a]	No	No	No	N/A	2.32	4
GOA Rex sole	No	No	No	N/A	2.794/2.187	4
GOA Blackspotted and rougheye rockfish complex[b]	No	No	No	N/A	1.68	4
GOA Shortraker rockfish	No	Unknown	No	N/A	Not estimated	1.5
GOA Demersal shelf rockfish complex[c]	No	Unknown	Unknown	N/A	Not estimated	1.5
GOA Dusky rockfish	No	No	No	N/A	1.79	4
GOA Thornyhead rockfish complex[d]	No	Unknown	No	N/A	Not estimated	1.5
Northern rockfish-western / central GOA	No	No	Unknown	N/A	1.51	4
GOA Pacific ocean perch	No	No	No	N/A	1.91	4
GOA Pacific cod	No	No	No	N/A	1.369	3
Walleye pollock-western / central GOA	No	No	Unknown	N/A	1.31	4
GOA BSAI Sablefish[e]	No	No	No	N/A	1.25	4

The overall Alaska FSSI generally trended upwards from 80% in 2006 to a high of 94% in 2018, then trended downward from 2018 to 2020 (Figure 114). It has remained generally flat since at 88.9% in 2023.

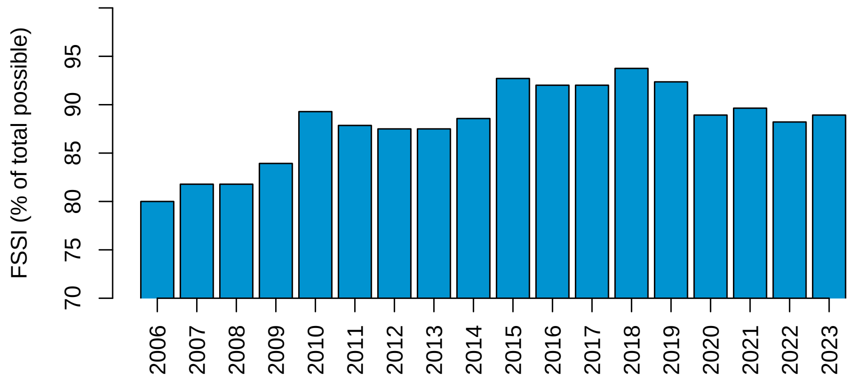

Figure 114: The trend in Alaska FSSI, as a percentage of the maximum possible FSSI from 2006 through 2023. The maximum possible FSSI is 140 for 2006 to 2014, 144 from 2015 to 2019, and 140 since 2020. All scores are reported through the second quarter (June) of each year, and are retrieved from the NOAA Fishery Stock Status Updates website[34].

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_{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_{MSY}. In 2012 and 2013, 2.5 points were lost for having unknown status determinations and not estimating B_{MSY} for the deepwater flatfish complex. The drop in 2019 was due to biomass dropping below 80% B_{MSY} for Pacific cod and sablefish. An additional point was gained in 2023 for GOA Pacific cod biomass increasing above B_{MSY}.

Implications: The majority of Alaska groundfish fisheries appear to be sustainably managed, including GOA groundfish fisheries. However, the biomass of GOA Pacific cod remains below 80% of B_{MSY}. 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

This contribution was not updated this year.

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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[35].

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 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 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 for the current year. These concerns could be categorized as those reflecting the assessment model, the population dynamics of the stock, and environmental and ecosystem concerns—

[35]The Arctic report is under development

including those based on information from Ecosystem Status Reports. In the past, concerns used to justify an ABC below the maximum estimated by the assessment model were documented in an ad-hoc manner in the stock assessment report or in the minutes of the Groundfish Plan Teams or Scientific and Statistical Committee (SSC) 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 as specified by the stock assessment model or a lower value. The recommended ABC (whether at maximum or lower) from the lead stock assessment author is subsequently reviewed and adjusted or accepted by the Groundfish Plan Team and the Scientific and Statistical Committee. Five risk tables were completed in 2018 as a test case. After review, the Council requested risk tables to be included in all full stock assessments in 2019. The SSC also requested a fourth category of concern to be added to the risk tables. The fishery performance category serves to represent any concerns related to the recommended ABC that can be inferred from commercial fisheries performance. Importantly, these concerns refer to indications of stock status, not economic performance.

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. Some ecosystem information can also be used to inform concerns related to the population dynamics of the stock. Initially, there were 4 levels of concern from no concern to extreme. In 2023, based on a recommendation from the SSC, the levels of risk were reduced to 3, from low (no concern) to high (major/extreme). For stock assessments which include and Ecosystem and Socioeconomic Profile (ESP), the ESP is also used to inform the ecosystem risk column as well as the population dynamics and fisheries performance columns.

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 115). 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.

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.

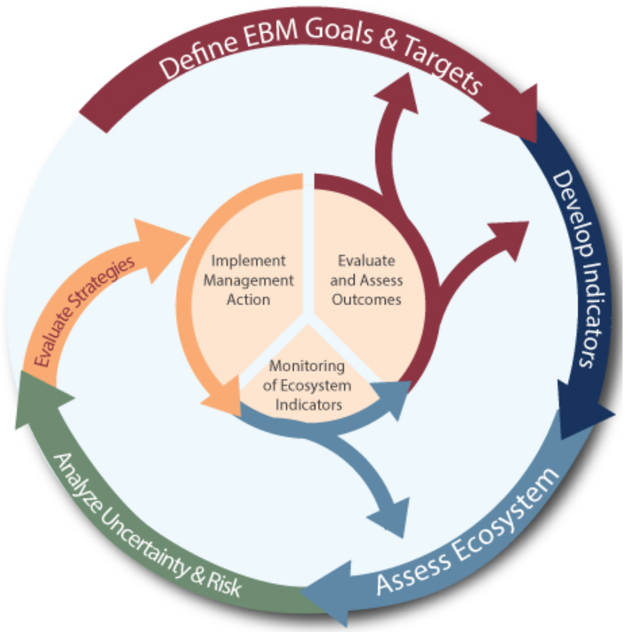

Figure 115: The IEA (integrated ecosystem assessment) process.

Responses to Comments from the North Pacific Fishery Management Council's Science and Statistical Committee (December 2022 and October 2023 meetings) and the Groundfish Plan Team (September 2023 meeting)

December 2022 SSC Final Report to the NPFMC

C-3 BSAI and C-4 GOA Ecosystem Status Reports

The SSC received presentations from Elizabeth Siddon (NOAA-AFSC), Ivonne Ortiz (University of Washington), and Bridget Ferriss (NOAA-AFSC). Lauren Divine (Aleut Community of St. Paul Island) provided public testimony on the eastern Bering Sea (EBS) Ecosystem Status Report (ESR); there was no public testimony for the Aleutian Islands (AI) or Gulf of Alaska (GOA) ESRs. The SSC thanks the presenters for their efforts in providing excellent, clear, and well-focused summaries of information on the status of the marine ecosystems that support federally managed fisheries off Alaska. The SSC appreciated the structure of the reports and the In-Briefs and noted that the various ways of communicating the information in the reports was valuable in reaching different audiences and informing different purposes. The SSC welcomed the addition of graphics in each report demonstrating how this information is incorporated into Council processes and was pleased to hear from communities and stakeholders that they value seeing their contributions in the report and the "In Brief" products.

Thank you. We want to acknowledge the effort and thank all those involved in collecting, analyzing, interpreting, and communicating the observations included in these reports.

General Comments applicable to all three ESRs

The SSC was pleased to see several instances where authors provided very long time series, which provided a context for present observations. The SSC notes that there is a need for some authors to define what is "normal" and when some aspect of the environment is considered an anomaly that is above or below "normal." When there is a reference to "long-term-mean", the SSC requests that authors for each section be encouraged to state the period over which "normal" (the mean, or median) is calculated, and the degree of departure from the mean or median needed to identify something as an anomaly. It would also be helpful if authors would state the source(s) of their data and the website/url where the data can be found, if applicable.

ESR authors and contributors paid close attention to defining time series length, defining the average or median (authors are trying to move away from using "normal"), and articulating what constitutes an anomaly. Data sources are provided, where appropriate.

The SSC recognizes that considerable thought has gone into developing a statistically sound definition of marine heat waves based on excursions above the mean temperature for a given time of the year at a given place. The SSC suggests that it would be useful to consider that different species may react differently to a given temperature, regardless of location and time of year. Is there a need, and a way, to present marine heat waves in relation to the temperature sensitivities of the species of concern?

ESR authors believe the role of the ESR is to provide whole-ecosystem context. We work closely with ESP teams as those documents are developed and produced and believe ESPs are a more appropriate report for documenting species-specific thresholds. For stock assessments without ESPs, the ESR authors review reference temperatures (that may come for the stock assessment itself or from new literature review) and/or phenology (spawning, egg development, hatching timing, location, growth curves) and discuss with the stock assessment authors to assess which need further discussion or data analysis for the next update.

The SSC understands the challenges of reporting zooplankton to species in the Rapid Assessments. That said, the SSC suggests that additional information indicating the abundance of key copepod species that are large and lipid-rich at later stages (C4 or C5) would be valuable.

The ESR editors communicated this recommendation to AFSC zooplankton expert, David Kimmel. Below is Dr. Kimmel's response: "We agree with the SSC that additional information on key copepod species that are lipid rich and in the C4/C5 stage would be useful. We Will determine if our large copepod time-series correlates with key species, such as *Calanus glacialis*, later in the year. Identifying copepods at sea is simply not possible given the time and expertise necessary to carry out such a task across multiple ecosystem surveys."

For indicators that do not have any updated data in 2022 (e.g., groundfish surveys, Steller sea lion surveys), the SSC recommends that the authors are consistent in providing headers but omit repetition of data that was presented in the prior year without any additional updates.

The ESR editors will be consistent in not including contributions that have not been updated since the previous year's ESR. Where appropriate we will provide headers identifying contribution that were not updated but are expected to return when new data are available. While the ESR has been largely successful in working with our collaborators to include present year data, there are still some contributions that are 1 year lagged due to data analysis requirements or the delayed availability of survey data.

GOA Ecosystem Status Reports

The SSC supports continued monitoring for patterns of invasive and southern latitude species in Alaska waters, and the potential impacts they may have on habitat and species interactions.

The GOA ESR editor agrees with the value of routinely monitoring changes in distribution and ecological implications of souther latitude species, invasive species, and shifts of GOA 'resident' species. Given the dome shape of the GOA, and the response of some species to change their vertical distribution versus latitudinal distribution in response to ecosystem changes presents some challenges in interpretation. Nonetheless, this is a topic the GOA ESR is pursuing thoughtfully.

There were no new data for Steller sea lions in 2022, but Skipper Science contributions reported more fish with 'seal/sea lion' bites on salmon with observations reported from WGOA and SEAK. **The SSC appreciates this on-ramp for information into the ESR and supports continued integration of this type of data to complement indicators.** *Depredation is important to continue to track and the SSC looks forward to receiving more details on direct interactions between marine mammals and fisheries in the future.*

The ESR editors value our growing collaboration with the Skipper Science group, and the industry members represented in the group. We will stive to include more of these data, including depredation, when applicable.

October 2023 SSC Draft Report to the NPFMC
C-1 BSAI Crab
Ecosystem Status Report Preview

The SSC appreciates the effort to provide this information at the October meeting as data are still incoming and being incorporated.

Thank you. We appreciate the opportunity to participate in your October meeting.

September 2023 Groundfish Plan Team
Joint Plan Team
Ecosystem Status Report – Climate Overview
Relative to SST and sea ice extent data, the Teams suggest that a consistent baseline be used year to year to aid in comparisons, and if different baselines are used, to explicitly note them as such.

The ESR editors agree with the challenge of interpreting data relative to different baselines. The ESRs will continue to strive for consistency and alignment in the reporting of baselines in the written report and presentations.

The Teams again acknowledge the immense effort of the ESR authors to collate and synthesize a broad array of environmental indices into a succinct summary that is useful for management advice. The Teams support continued presentation of the ESR to the Teams and appreciate the author's concise presentation format.

Thank you, The ESR team appreciates the opportunity to participate in the September Groundfish Plan Team meeting.

Ecosystem Status Report – CIE Review
The Teams requested clarification on potential refinements to the ecosystem section of the risk table based on the ESR CIE review.

The ESR team hopes to work with stock assessment authors to find ways of adding value, improving efficiency, standardizing, and formalizing the inclusion of ecosystem information into risk tables. The ESR team is not proposing any specific changes to the risk table development process this year.

The Teams requested clarification on terminology used in the submitted table of CIE recommendations on the ESRs and a revised table was reposted in response to this request.

Thank you for calling attention to the need for clarification. As noted, the ESR team provided a revised table for posting on the Groundfish Plan Team Sept. meeting e-agenda.

The Teams encouraged the ESR authors to put ESR data on AKFIN where possible to improve accessibility in the future.

The ESR team is currently in discussions with AKFIN to better integrate our process. Individual ESR contributors (including data collection programs and PIs) decide where they store their data, but the ESR team completely supports data centralization and accessibility where possible.

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.27)

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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.40)

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Copepod biomass

Total copepod biomass (g m^{-3}) is the sum of large and small calanoid copepod biomass, sampled south of Seward Alaska typically during the first 10 days of May. Data are averaged over the top 100 m of the water column to provide estimates of wet-weight biomass of zooplankton represented by all calanoid copepods retained by a 0.150 mm mesh net. (See Hopcroft, p.89)

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Copepod community size

The ratio of large calanoid copepods to total large and small calanoid copepods is used to represent copepod community size. Zooplankton are sampled south of Seward Alaska typically during the first 10 days of May. Data are averaged over the top 100 m of the water column to provide estimates of wet-weight biomass of zooplankton represented by all calanoid copepods retained. Small copepods data is taken from a vertical 0.15 mm net and large copepod data is taken from a towed 0.5 mm mesh net. (See Hopcroft, p.89)

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Motile epifauna biomass

The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 1999. 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 in the western GOA. (See Whitehouse, p.179)

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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 rhinoceros 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. We have continued using the percent biomass of capelin from rhinoceros auklets (*Cerorhinca monocerata*) chick diets at Middleton Island since then (See Hatch, p 105).

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Apex predator biomass

The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 1999. 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, Pacific halibut, sablefish, large sculpins, rougheye/blackspotted rockfish, and skates. (See Whitehouse, p.179)

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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 161)

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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).

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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.27)

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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.40)

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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.91)

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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.91)

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Motile epifauna biomass

The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 1999. 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 in the GOA. These values are summarized for the eastern region, where survey efforts vary among years. (See Whitehouse, p.179)

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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.115)

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Apex predator biomass

The NOAA bottom trawl survey has been conducted triennially since 1984, and biennially since 1999. 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, Pacific halibut, sablefish, large sculpins, rougheye/blackspotted rockfish, and skates. These values are summarized for the eastern region, where survey efforts vary among years. (See Whitehouse, p.179)

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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.161)

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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.

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Methods Description for the Report Card Indicators

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

The shaded green window shows the most recent 5 years prior to the date of the current report. The symbols on the right side of the graph are all calculated from data inside this 5-year moving window (maximum of 5 data points). The first symbol represents the "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 purpose 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 $\pm$1 SD from the mean within 5 years or less) for further consideration, rather than serving as a full statistical analysis of recent patterns.