Exxon Valdez Oil Spill
Long-Term Monitoring Program (Gulf Watch Alaska) Final Report

Long-term Monitoring of Oceanographic Conditions in Cook Inlet / Kachemak Bay

Exxon Valdez Oil Spill Trustee Council Project 21120114-J
Final Report

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Study History: Oceanographic monitoring has been conducted year-round in Cook Inlet/Kachemak Bay since 2001 by the National Oceanic Atmospheric Administration National Centers for Coastal Ocean Science and Kachemak Bay National Estuarine Research Reserve, as part of long-term monitoring programs and shorter-term projects. As part of the Gulf Watch Alaska program, physical and biological data sets in the region were extended and expanded, with *Exxon Valdez* Oil Spill Trustee Council support for Cook Inlet/Kachemak Bay marine condition monitoring projects in 2012-2016 (project 16120114-G) and 2017-2021 (project 21120114-J). The project included temporally and spatially intensive oceanographic monitoring from boat surveys, as well as from continuous sampling at harbor-based water quality stations. Throughout 2012-2021, small boat surveys were conducted, with water column oceanography, zooplankton and phytoplankton sampling: 1) monthly in Kachemak Bay on cross-bay and along-bay transects; 2) quarterly in southeast Cook Inlet to provide seasonal estuary-shelf ocean gradients out to the Inlet entrance; and 3) annually on spring surveys across the Cook Inlet entrance. During 2012-2016, with additional funding from the National Oceanic and Atmospheric Administration National Centers for Coastal Ocean Science and Bureau of Ocean Energy Management Alaska Region, oceanographic surveys were also conducted quarterly with chartered research vessels on three transects across lower Cook Inlet, to spatially expand characterization of seasonal conditions and with a marine bird/mammal observer on board. The Cook Inlet oceanography project also leveraged support from the National Oceanic and Atmospheric Administration Integrated Ocean Observing System /Alaska Ocean Observing System for oceanographic monitoring in Kachemak Bay during 2011-2021. Oceanographic sampling has been conducted previously in the region along most of the same Cook Inlet and Kachemak Bay transects using similar instruments and protocols (Okkonen and Howell 2003, Okkonen et al. 2009, and Murphy and Iken 2013), thereby providing longer time series data on marine conditions at these locations.

From 2001 to present, as part of the Kachemak Bay National Estuarine Research Reserve System Wide Monitoring Program, continuous (15-minute sampling interval) oceanographic data (temperature, salinity, dissolved oxygen, turbidity, pH) have been collected at two water quality stations in the Seldovia and Homer harbors, with monthly water collection for nutrient and chlorophyll analyses. The Cook Inlet oceanography project supported deployments of an additional water quality mooring in Bear Cove at the head of Kachemak Bay, as well as additional field and data analysis support for water quality station monitoring. The Cook Inlet/Kachemak Bay oceanography and plankton data have provided information on marine conditions for state and federal resource management (fish, shellfish, marine bird, marine mammal), harmful algal bloom research and event response, and for the Gulf Watch Alaska nearshore ecosystem monitoring component in Kachemak Bay (Gulf Watch Alaska project 21120114-H). Data were also used to characterize spatial-temporal variability and marine heatwave response of zooplankton communities (McKinstry et al. 2022) and in oceanography synthesis publications and reports across the northern Gulf of Alaska region (Holderied and Weingartner 2015, Danielson et al. 2022). Project data are published for public use through the Gulf of Alaska Data Portal.

Abstract: Oceanographic and plankton monitoring conducted year-round in lower Cook Inlet and Kachemak Bay from 2017-2021, extending prior 2012-2016 time series, provided detailed information on marine conditions that affect nearshore and pelagic populations injured by the *Exxon Valdez* oil spill. The project produced a 10-year (2012-2021) time-series of shipboard oceanographic and plankton observations made at stations along repeated transects in Kachemak Bay (monthly) and lower Cook Inlet (seasonally) and added a sampling location near the head of the bay to a 21-year (2001-2021) time-series of nearshore water quality, nutrient, and chlorophyll observations at Seldovia and Homer harbors. Data were used to quantify temporal-spatial oceanographic variability, and across- and along-estuary spatial gradients in marine conditions. Zooplankton and phytoplankton net tow data were used to identify temporal-spatial patterns in plankton abundances, community composition, and harmful algal bloom events. Persistently warmer than average conditions were observed during 2014-2020, especially in Pacific marine heatwaves of 2014-2016 and 2019. Estuary water column responses were driven by local freshwater forcing at the surface and by connections with shelf waters at depth. Biological responses to heatwaves included changes in zooplankton community composition, seabird and sea otter mortality events, increased paralytic shellfish poisoning events, and changes in whale distributions.

Key words: Alaska, climate change, Cook Inlet, CTD, harmful algal bloom, Kachemak Bay, nutrients, oceanography, phytoplankton, salinity, temperature, zooplankton

Project Data: Datasets include ship-based station data from vertical hydrographic profiles collected with a conductivity-temperature-vs-depth (CTD) profiler and ancillary sensors, zooplankton net tows, phytoplankton net tows and oceanographic dataloggers mounted on pilings at the Seldovia and Homer harbors and on a mooring in Bear Cove. Specific information for each dataset is provided below. Data are archived in human-readable ASCII files. No limitations or restrictions are placed on these data.

Data are permanently archived with DataONE. The datasets and citations are described as follows:

1) *Conductivity-Temperature-Depth Profiler (CTD) and Ancillary Sensor Oceanographic Data*

Citation: Holderied, K. and M. Renner. 2023. Oceanographic Monitoring in Cook Inlet and Kachemak Bay, CTD Data, 2012-2022, Gulf Watch Alaska Environmental Drivers Component. Research Workspace. https://doi.org/10.24431/rw1k1d, version: 10.24431_rw1k32v_20230307T202919Z.

Description: Vertical profile station data for 2017-2021 study period, with CTD (temperature, salinity, pressure) and ancillary sensor (oxygen, photosynthetically available radiation, chlorophyll [fluorescence], turbidity) data, are provided as annual, comma separated value (.csv) files of processed data in 1-meter vertical depth bins, aggregated from all sampling dates and stations during the year. Note: The 2017-2021 study period is part of a longer time series.

2) *Zooplankton Data*

Citation: Holderied, K., C. McKinstry, C., and J. Schloemer. 2023. Oceanographic Monitoring in Cook Inlet and Kachemak Bay, Zooplankton Data, 2012-2019, Gulf Watch Alaska Environmental Drivers Component. Research Workspace. 10.24431/rw1k21g, version: 10.24431_rw1k21g_20230307T214302Z.

Description: Zooplankton sampling data from 2012-2021 are provided in a single file, with species in all samples identified to lowest possible taxon. Species identification was completed by Prince William Sound Science Center researchers (under Dr. Rob Campbell) for all stations from 2012-2018 and for core station samples from 2019. File will be updated with 2020-2021 data when species IDs are complete. Note: The 2017-2021 study period is part of a longer time series.

3) *Water Quality Station Data*

Citation: Baird, S., C. Guo, and J. Schloemer. 2023. Oceanographic Monitoring in Cook Inlet and Kachemak Bay, Water Quality, Meteorological, and Nutrient Data collected by the National Estuarine Research Reserve System's System-wide Monitoring Program (NERRS SWMP), 2012-2021, Gulf Watch Alaska Environmental Drivers Component. Research Workspace. https://doi.org/10.24431/rw1k21f, version: 10.24431_rw1k21f_20230307T230236Z.

Description: Oceanography (temperature, salinity), nutrient and chlorophyll data for 2017-2021 are provided in annual data files containing National Estuarine Research Reserve (NERR) System-Wide Monitoring Program (SWMP) data from the Seldovia, Homer, and Bear Cove stations. In addition to the nutrient data from the NERR water quality stations, nutrient data from surface and near-bottom water samples collected in

2021 at CTD stations are provided as a single data file. SWMP station data are also available from the NERR Centralized Data Management Office at http://cdmo.baruch.sc.edu/. Note: The 2017-2021 study period is part of a longer time series.

4) *Phytoplankton Data*

Description: Phytoplankton data for 2012-2021 are provided in a single file with species in all samples identified to lowest possible taxon. *Alexandrium* spp. cell abundance data for selected stations are also available in a separate file. Note: The 2017-2021 study period is part of a longer time series. Phytoplankton data are available on request from National Oceanic and Atmospheric Administration National Centers for Coastal Ocean Science (Point of Contact: Dominic.Hondolero@noaa.gov).

These data are also archived by the Alaska Ocean Observing System's Gulf of Alaska Data Portal on behalf of the *Exxon Valdez* Oil Spill Trustee Council: https://gulf-of-alaska.portal.aoos.org/#metadata/4e28304c-22a1-4976-8881-7289776e4173/project

The data custodian is Carol Janzen, Director of Operations and Development, Alaska Ocean Observing System, 1007 W. 3rd Ave. #100, Anchorage, Alaska 99501, 907-644-6703. janzen@aoos.org.

Data are archived by Axiom Data Science, a Tetra Tech Company, 1016 W. 6th Ave., Anchorage, Alaska 99501.

Report Citation:

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EXECUTIVE SUMMARY

The Cook Inlet/Kachemak Bay oceanographic monitoring project collected oceanographic and plankton data year-round at high temporal frequency and spatial resolution from 2017 to 2021, to extend and enhance existing physical and biological time series and assess the effects of oceanographic variability on nearshore and pelagic species injured by the *Exxon Valdez* oil spill. The project is part of Gulf Watch Alaska, the long-term ecosystem monitoring program of the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC), within the Environmental Drivers component of the program. Important fish, shellfish, seabird, shorebird and marine mammal species forage in lower Cook Inlet for some or all of their life history and long-term data on environmental conditions and plankton are required to understand how climate variability and change can affect these species through "bottom-up" ecosystem processes. Characterizing the oceanographic variability of this large, highly productive estuary in detail is important because marine conditions that affect biological production, including water temperature, stratification, fresh water runoff, ocean exchanges with the Alaska Coastal Current, North Pacific climate variability and nutrient conditions, change at a wide variety of time and space scales.

Under this project, oceanographic observations were made throughout the year at nearshore stations in Kachemak Bay, and shipboard oceanography and plankton surveys were conducted monthly in Kachemak Bay, as well as seasonally in lower Cook Inlet, to capture temporal and spatial patterns in marine conditions across the region (Fig. 1). The sampling design provided data to assess variability from seasonal to interannual time scales, with the continuous and monthly sampling frequency in Kachemak Bay additionally allowing assessment of within-season timing of changes in environmental conditions between different years. Shipboard oceanographic observations were made with sufficient spatial resolution to characterize estuarine gradients, as well as to capture local areas of persistent horizontal convergences and enhanced vertical mixing where strong tidal currents interact with sloping bathymetry. The sampling locations: (1) covered estuarine-shelf gradients in marine conditions from the head of Kachemak Bay to the Cook Inlet entrance and offshore from all the Gulf Watch Alaska nearshore monitoring sites in Kachemak Bay; (2) captured estuary waters influenced by glacial (inner Kachemak Bay) and non-glacial (outer Kachemak Bay) watersheds; and (3) provided time-series information on estuarine conditions at a location "downstream" along the Alaska Coastal Current from the shelf water monitoring sites at the GAK-1 mooring and along the Seward Line.

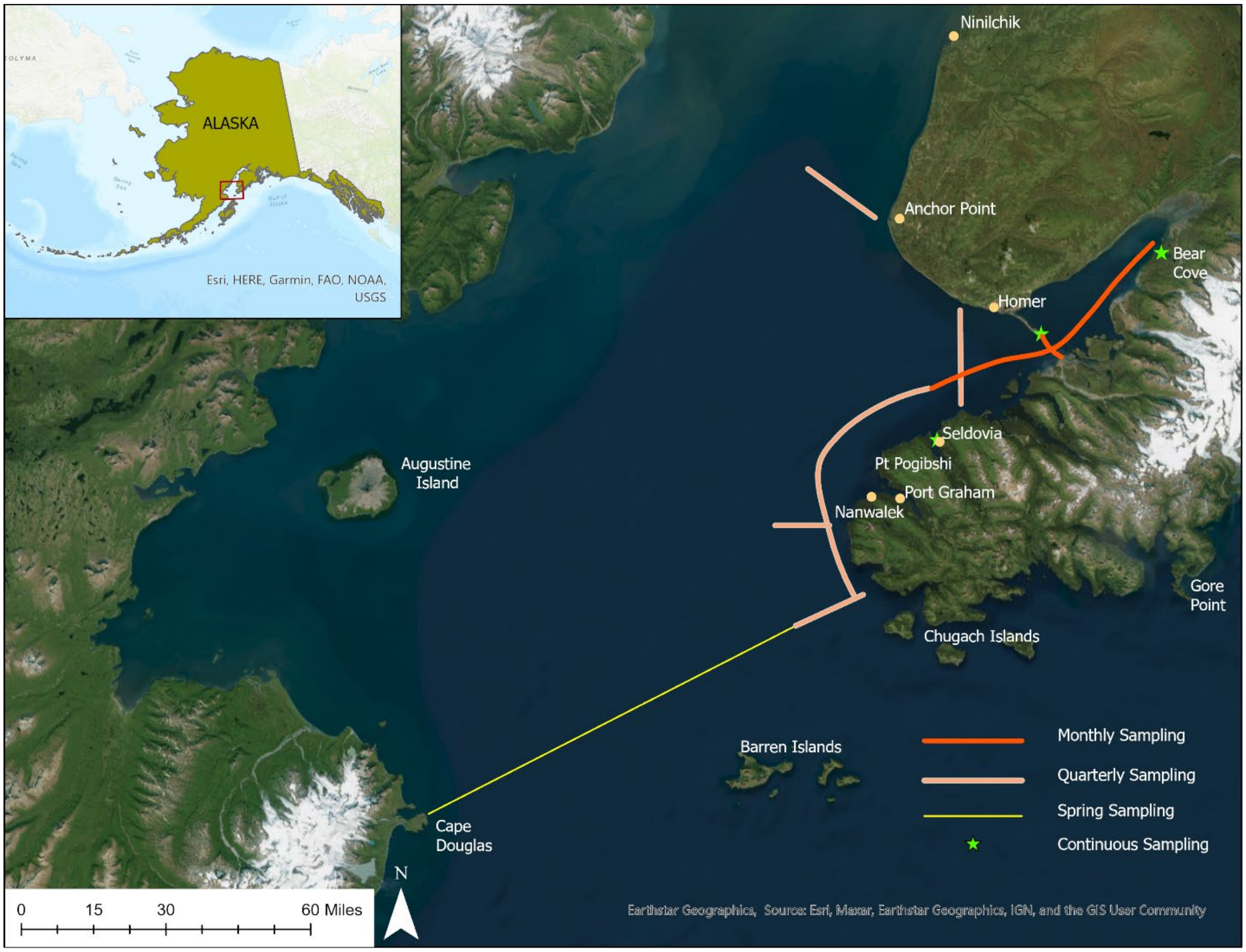


Figure 1. Cook Inlet and Kachemak Bay oceanographic sampling locations and frequency. Green stars indicate sites of continuous water quality monitoring stations at Homer and Seldovia harbors. Boat surveys were conducted monthly (red lines) along and across Kachemak Bay, with expanded spatial coverage quarterly (orange lines) across outer Kachemak Bay, near Anchor Point and to the southeast Cook Inlet entrance. A spring survey (dashed yellow line) was conducted across the Cook Inlet entrance, timed for the spring plankton bloom.

The Cook Inlet/Kachemak Bay oceanography project has produced a 10-year (2012-2021) time-series of shipboard oceanographic and plankton observations made at stations along repeated transects in the bay and lower Inlet. Throughout 2017-2021, shipboard oceanography and plankton surveys were made at stations along repeated transects in Kachemak Bay and southeast Cook Inlet, extending the 2012-2016 time series for cross-estuary monitoring that was conducted at mid-bay (monthly), outer bay (quarterly), southeast Inlet (quarterly) and Cook Inlet entrance (annual in spring) locations. In 2017-2021, additional oceanographic monitoring was conducted at along-estuary sites in the bay (monthly) and into the southeast Inlet (quarterly), to provide more spatial information on the seasonal evolution of and interannual changes in estuary-shelf oceanographic gradients. National Oceanic and Atmospheric Administration (NOAA) Kasitsna Bay Laboratory small boats were used to conduct monthly surveys, with larger vessels chartered for the spring Cook Inlet surveys. Vertical profiles of oceanographic data were collected with conductivity-temperature vs. depth profilers (CTD, SeaBird Electronics 19plus, with ancillary sensors) at stations along each transect, including temperature, conductivity, pressure, dissolved oxygen, turbidity, fluorescence, and photosynthetically-available radiation. Coincident with the oceanographic observations, zooplankton and phytoplankton net tows were conducted at selected stations along each transect to identify spatial and seasonal patterns in plankton biomass and community composition and to assess plankton community response to environmental changes. At plankton station locations, water samples were collected at the surface and near the bottom with a Niskin bottle on the CTD line, for nutrient and carbonate chemistry analyses (separately funded). Vertical zooplankton tows were conducted to 50-meter depth with 333 μm bongo nets and surface water samples were collected and filtered through 20 μm nets for phytoplankton measurements. The project also spatially expanded a 21-year (2001-2021) time series of oceanographic, nutrient and chlorophyll observations at nearshore water quality stations in Kachemak Bay by supporting continuous ocean observations at an added mooring deployed in Bear Cove near the head of the bay. Continuous oceanographic measurements were made year-round at long-term Kachemak Bay National Estuarine Research Reserve (KBNERR) water quality stations located at the Seldovia and Homer harbors, plus in ice-free months from the Bear Cove buoy. Multi-sensor data sondes were deployed at all three sites to collect temperature, salinity, dissolved oxygen, turbidity, fluorescence, pH and chlorophyll data. Each harbor station included two data sondes, located approximately 1 meter below the surface and 1 meter above the sea floor, with a single near-surface sonde on the Bear Cove mooring. Monthly water samples were also collected at both harbor stations and analyzed for nutrient and chlorophyll concentrations, as part of long-term KBNERR monitoring programs. Oceanographic and plankton sampling, including instrument calibration, data collection, sample processing, quality control, and quality assurance, were conducted in accordance with the project sampling protocols as outlined in the original project proposal and annual reports to EVOSTC.

The 10-year time series of shipboard oceanographic and plankton data collected as part of this project, in conjunction with the 21-year record of continuous observations from nearshore water quality stations, enabled detailed assessment of seasonal and interannual variability of marine conditions in Kachemak Bay and lower Cook Inlet, as well as lower trophic biological responses to those changes. The 2012-2021 GWA study period began with a transition from anomalously cold-water temperatures across the northern Gulf of Alaska during most of 2006-2012 to persistently warm water conditions during the 2014-2016 Pacific marine heatwave, with up to 3°C monthly anomalies observed in Kachemak Bay. The 2017-2021 monitoring results included a transition of Gulf of Alaska marine conditions from the 2014-2016 Pacific marine heatwave to closer to average conditions with less intense warming in 2017-2018, followed by more anomalous warming throughout much of 2019, and then cold winter months and warmer than normal summers in 2020 and 2021. In 2019, the most significant warm anomalies were observed during winter months in Kachemak Bay, consistent with a reduction in winter atmospheric cooling and similar to what had been observed in 2015-2016. Overall, 2014-2020 was a strikingly persistent period of warmer than average conditions in Kachemak Bay and Cook Inlet.

Salinity responses observed in Kachemak Bay and Cook Inlet estuary waters differed consistently between surface and deeper layers in the water column, with responses likely driven by local freshwater forcing variability at the surface and by connections with Gulf of Alaska ocean shelf waters at depth. The monthly along-bay sampling frequency made it possible to observe rapid spatial and vertical water column responses to precipitation changes, as well as to distinguish between local (bay) and remote (ocean) forcing effects. Overall, surface salinity conditions in Kachemak Bay responded rapidly to local precipitation changes, as well as more slowly to seasonal snowpack and glacial melt in the bay watershed. Deeper bay and Cook Inlet waters had anomalous freshening in 2019, which was similar to but less intense than freshening observed during the 2015-2016 Pacific marine heatwave. Oceanographic monitoring results are consistent with a freshening of deeper Kachemak Bay estuary waters from intrusions of Gulf of Alaska shelf water, especially in late summer and fall months, that became less saline from increased freshwater input along the coast during persistently warm conditions. Biological responses to marine heatwaves in the GWA study region have included changes in zooplankton community composition, seabird, and sea otter mortality events, increased paralytic shellfish poisoning events, and changes in whale distributions.

Cook Inlet oceanography project data have been used in Gulf Watch Alaska program and other peer-reviewed science journal publications, including on the marine heatwave response of Kachemak Bay harmful algal bloom species and zooplankton community, temperature variations in the northern Gulf of Alaska on multiple time scales and environmental drivers of harmful algal bloom species growth. Project oceanography and plankton data are being used by Gulf Watch Alaska Nearshore Component researchers, as well as for ongoing fish, shellfish, seabird and marine mammal monitoring and management efforts by Trustee agencies in the region, including NOAA, U.S. Fish and Wildlife Service, Alaska Department of Fish and Game, and Alaska Department of Environmental Conservation. Results have also been incorporated into reports and science outreach publications for resource managers and community members, including NOAA Fisheries Ecosystem Status Reports for the North Pacific Fisheries Management Council and annual NOAA "State of Kachemak Bay" reports.

INTRODUCTION

The Cook Inlet and Kachemak Bay estuaries are part of the rich nearshore and pelagic marine ecosystems of the northern Gulf of Alaska, with coastal waters that are influenced by fresh water inputs from precipitation, rivers, snowpack, and glacier melt waters, ocean transport in the along-coast Alaska Coastal Current, and upwelling and downwelling associated with winds and complex bathymetry. The southcentral Alaska project area in lower Cook Inlet and Kachemak Bay (Fig. 1) encompasses a region of diverse marine habitats of rocky intertidal and kelp forests, seagrass beds, salt marshes and rich mudflats that support fish, shellfish, marine bird, and marine mammal species, including spill-affected species managed by Trustee agencies. The maximum tidal ranges of up to 8.7 meters across the region are among the largest in the world and tide rips, water convergences and vertical mixing are produced in areas where strong tidal currents move along steeper sea floor slopes in Cook Inlet. Two areas with these strong, tidally-linked water convergences are found north of the Kachemak Bay entrance by Anchor Point and to the south by Point Pogibshi, and create hotspots for marine birds, fish and marine mammals.

Mundy and Spies (2005) describe the Gulf of Alaska marine ecosystems and how oceanographic factors help determine biological productivity in the region. Water temperature, stratification, fresh water runoff, the strength and position of the Alaska Coastal Current, and nutrient conditions have been observed to change seasonally and inter-annually with regional climate variations such as El Niño/La Niña, Pacific Decadal Oscillation, and Pacific marine heatwaves (Royer 2005; Royer and Grosch 2006; Janout et al., 2010). These changes can have significant impacts on marine species in the region (e.g. Speckman et al. 2005, Suryan et al. 2021a, Weitzman et al. 2021, Danielson et al. 2022). The importance of understanding how lower trophic levels in the Gulf of Alaska change in response to climate-driven variability in marine conditions is underscored both by past events, such as the 1976/1977 North Pacific marine ecosystem regime shift (Mantua et al. 1997, Anderson and Piatt 1999), as well by the recent dramatic biological responses to the prolonged 2014-2016 Pacific marine heatwave (Suryan et al. 2021a) and anomalously warm conditions during much of 2019, which prompted closures of several commercial fisheries in Alaska. Long-term data on oceanographic variability are also required to evaluate hypotheses that are put forward to explain climate-driven changes in Gulf of Alaska biological production, such as the match-mismatch hypothesis (Anderson and Piatt 1999, Mackas et al. 2007), pelagic-benthic split hypothesis (Eslinger et al. 2001), and optimum stability window hypothesis (Gargett 1997). For nearshore and estuary ecosystems in the Gulf of Alaska especially, resource managers still require a better understanding of how nearshore and pelagic food webs respond to climate-driven variations in physical processes.

The *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) Gulf Watch Alaska (GWA) long-term marine ecosystem monitoring program was established to help evaluate how factors other than oil, including climate-driven changes in marine conditions, may adversely affect species injured by the spill. The Cook Inlet and Kachemak Bay oceanographic project is part of the Environmental Drivers component of the GWA program and addressed needs for long-term oceanography and plankton community information across estuary space and time scales. Collectively, the GWA monitoring projects are providing the long-term, high-quality time-series needed to investigate Gulf of Alaska ecosystem dynamics and evaluate the impacts and changes to species populations from climate variations and remaining ecosystem perturbations from the oil spill. Spill-affected fish, shellfish, seabird, shorebird and marine mammal species forage in Cook Inlet for some or all of their life history and the Cook Inlet/Kachemak Bay project has provided long-term data on environmental conditions and plankton that are required to understand how climate variability and change can affect upper trophic species through "bottom-up" ecosystem processes. The Cook Inlet project collected oceanographic and plankton data with high temporal resolution and year-round coverage in order to evaluate seasonal and interannual variability in marine conditions, changes in the timing of seasonal transitions and spatial gradients in estuarine conditions. The high-frequency, year-round Cook Inlet oceanographic data also provided a detailed marine condition context in Kachemak Bay for the GWA Nearshore Component project. By combining oceanographic sampling in the large estuaries of Cook Inlet and Prince William Sound and in waters of the adjacent Gulf of Alaska shelf, GWA program ocean monitoring data has been used to distinguish the effects of local (within estuary) and remote (shelf, North Pacific) climate forcing effects on nearshore ecosystems (Holderied and Weingartner 2015, Weitzman et al. 2021, Danielson et al. 2022). The Cook Inlet/Kachemak Bay project has provided key information on coastal oceanography, plankton, and nutrient patterns to improve understanding of changes in the populations and distributions of marine species. Additionally, these oceanographic data supported science outreach to local communities and resource management efforts for fish, shellfish, marine mammal and seabird species by federal and state Trustee agencies in the region, including the National Oceanic and Atmospheric Administration (NOAA), U.S. Fish and Wildlife Service (USFWS), Alaska Department of Fish and Game (ADF&G) and Alaska Department of Environmental Conservation (ADEC).

OBJECTIVES

The overall project goals were to extend and enhance oceanographic and plankton monitoring from shipboard surveys and shore stations in Kachemak Bay/Cook Inlet, in order to characterize variability in marine conditions and provide environmental time series data to help explain climate-driven changes in marine species and food webs in the region. Specific objectives are listed below:

- Determine the thermohaline structure of Kachemak Bay and the southeastern Cook Inlet entrance at seasonal and longer time scales.
- Determine long-term trends and variability from daily to interannual time scales in Kachemak Bay oceanography.
- Determine seasonal patterns of phytoplankton and zooplankton species abundance and community composition within Kachemak Bay and southeastern Cook Inlet.
- Assess interannual changes in oceanographic structure and phytoplankton/zooplankton species composition across the Cook Inlet entrance.
- Assess seasonal patterns in oceanography, macronutrients, and plankton between Kachemak Bay, southeastern Cook Inlet and the adjacent shelf (collaboration with other GWA Environmental Drivers component projects).

- Determine temporal patterns and linkages in oceanographic conditions and plankton communities between Kachemak Bay/Cook Inlet, the Gulf of Alaska continental shelf and Prince William Sound (collaboration with other GWA Environmental Drivers component projects).
- Provide environmental forcing data for correlation with biological data sets in the GWA Nearshore and Pelagic Components.
- Provide ADF&G, NOAA, and USFWS resource managers with assessments of oceanographic trends and seasonal conditions.

METHODS

Study Area

The study area included Kachemak Bay and lower Cook Inlet, located in southcentral Alaska and adjacent to the northern Gulf of Alaska (Figs. 1 and 2). Ship-based oceanographic surveys and sampling at fixed water quality stations were conducted across an area bounded by 59.82°N, 152.04°W; 59.77°N, 151.04°W; 59.19°N, 151.88°W; 58.86°N, 153.23°W. Water quality sampling station sites were located on the north side of Kachemak Bay at the Homer harbor (59.60203°N, 151.40877°W), the south side of the bay at the Seldovia harbor (59.44097°N, 151.72089°W), and on a mooring in Bear Cove (59.72620°N, 151.04865°W) at the head of Kachemak Bay.

Cook Inlet is a 209-km long, tapered waterbody extending northeast from the Gulf of Alaska, with a constriction between the upper and middle Inlet at the Forelands. It is a major vessel corridor to Anchorage, Alaska's major shipping port that supplies goods to over 70% of Alaska's population. The Inlet is also home to active oil and gas industry that includes exploration, production from offshore platforms, subsea pipelines, and oil and gas tanker vessel traffic. The lower Cook Inlet marine ecosystem contains abundant fish, shellfish, marine bird, and marine mammal populations (including ~20,000 sea otters, Garlich-Miller et al. 2018), and supports commercial, recreational and subsistence fish and shellfish harvests and ecotourism. The region has experienced past and recent declines in fish and shellfish populations and fishery closures. Mariners in Cook Inlet contend with extreme tidal ranges and currents, storm waves greater than 5 m in the lower Inlet, channeled gap winds that can gust over 90 knots, heavy loads of glacial silt, and, in winter, ice pans that surge back and forth with the tides. Interaction of tidal and buoyancy currents with certain bathymetry features cause persistent, strong convergent shear zones, called tide rips, at specific locations along the Inlet, including just to the north and south of Kachemak Bay. Cook Inlet subtidal circulation is also externally forced by the relatively fresh Alaska Coastal Current, which enters Cook Inlet in the east and exits in the west, with the extent of its inundation into Cook Inlet varying seasonally (Okkonen et al. 2009). In addition, cold, saline water seasonally upwells from the Gulf of Alaska into the central and eastern lower Cook Inlet region, including Kachemak Bay.

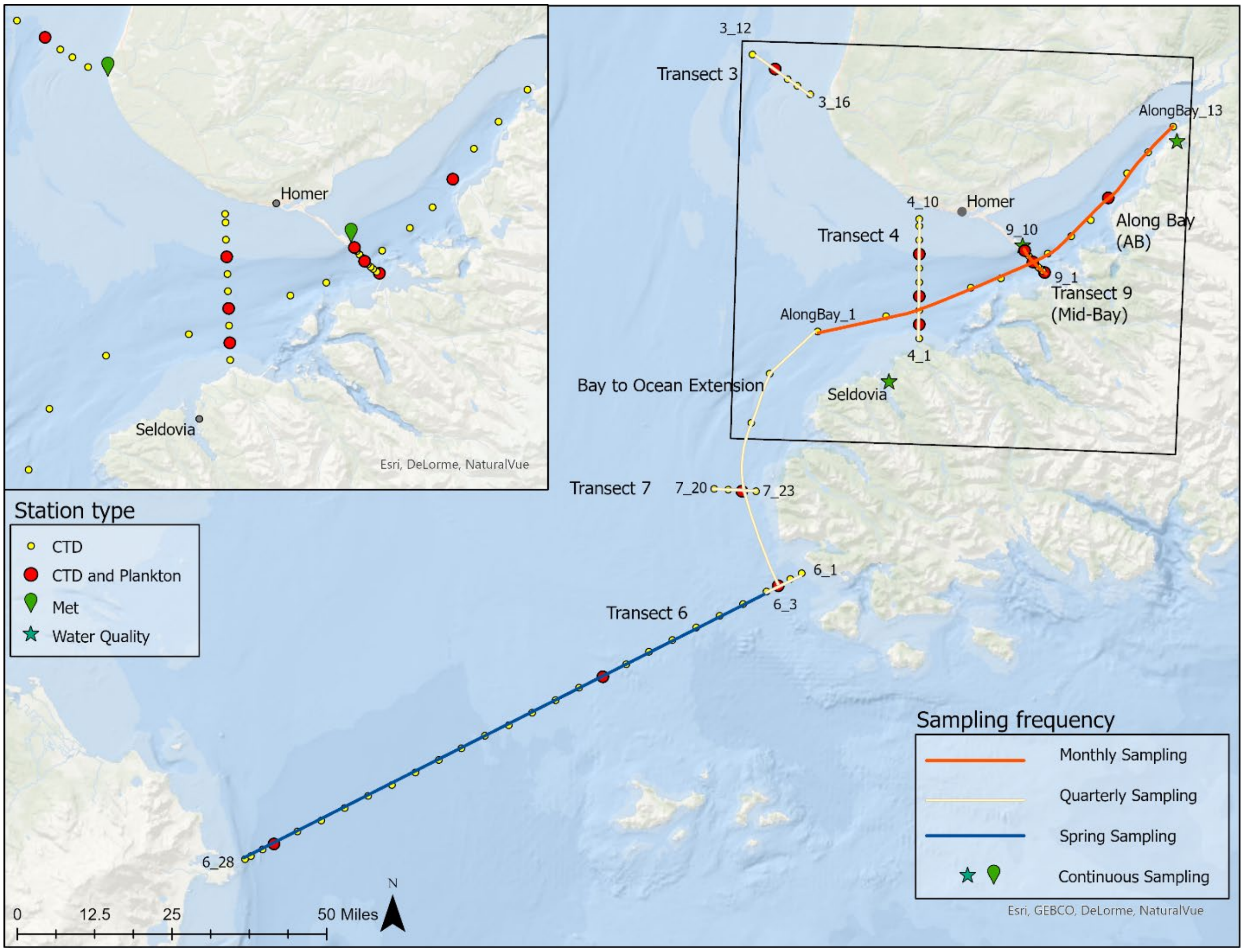


Figure 2. Locations of shipboard conductivity-temperature vs. depth (CTD) and plankton sampling stations (dots) along repeated transects (lines), with sampling frequency noted by color. Kachemak Bay National Estuarine Research Reserve long-term monitoring site locations shown for water quality sites at Homer, Seldovia, and Bear Cove and meteorological (MET) sites at Homer Spit and Anchor Point. Bathymetry shown with blue shading.

Kachemak Bay is located approximately 200 km south of Anchorage on the southeast side of Cook Inlet. The bay is a fjord-type estuary with freshwater input from glacial and non-glacial rivers and connections to adjacent Gulf of Alaska shelf waters from both surface layer circulation and upwelling of deeper nutrient-rich waters. The bay is 35 km wide at its mouth between Anchor Point and Point Pogibshi and approximately 57 km long. The bay has an average depth of approximately 40 m, with a maximum depth of 174 m. The Homer Spit extends into Kachemak Bay from the northern shoreline and splits the bay into inner and outer bays, with the inner bay more influenced by freshwater inputs. Fresh water, introduced primarily by the Fox, Bradley, and Martin rivers and Sheep Creek at the head of the bay, flows along the northwest shore of the inner bay, with additional inputs from smaller rivers on the south side of the bay. Nearshore monitoring in 2003-2009 with the global Census of Marine Life program established that Kachemak Bay has one of the most biodiverse rocky intertidal ecosystems in the world (Konar et al. 2010). Most of the bay is designated as a critical habitat area under ADF&G, as well as a NOAA/University of Alaska Anchorage Kachemak Bay National Estuarine Research Reserve (KBNERR).

Sample collection, data processing and analysis methods

The Cook Inlet/Kachemak Bay ocean monitoring project sampling and data processing methods are summarized below for water quality station monitoring and small boat oceanography and plankton surveys, including instrument calibration, data collection, sample processing, and quality control/quality assurance (QA/QC). Sampling protocols are also available on the GWA program Research Workspace.

Water quality station monitoring methods

During 2017-2021, KBNERR maintained water quality stations for continuous oceanographic observations and monthly nutrient and chlorophyll water sampling at three nearshore sites at Homer harbor, Seldovia harbor, and on a mooring in Bear Cove near the head of Kachemak Bay (Fig. 2). The Homer and Seldovia harbor sites have been part of the long-term National Estuarine Research Reserve (NERR) System-Wide Monitoring Program (SWMP) since 2001, with the Bear Cove mooring deployment supported under the GWA program. The three site locations captured conditions within the outer bay (Seldovia), inner bay (Homer), and near the head of the bay (Bear Cove) to characterize along-estuary conditions at high temporal resolution. At Homer and Seldovia sites, two multi-sensor instrument packages (sondes) were mounted vertically near the surface and near the bottom. Both sondes at Seldovia and the deeper Homer sonde were deployed year-round, while the Homer surface and Bear Cove sondes were deployed during ice-free months (approximately April-November). In Bear Cove, a single near-surface sonde was deployed on a mooring buoy, at approximately one meter depth below the water surface.

At the Homer and Seldovia water quality stations, two YSI EXOII model multi-parameter water quality sondes were deployed vertically in pipes mounted on the Homer and Seldovia ferry docks. The sondes included instruments that measured temperature, conductivity (for salinity), dissolved oxygen, turbidity, fluorescence, pH and depth. More instrumentation details are available at the NOAA NERR system (NERRS) Centralized Data Management Office (CDMO) website (http://cdmo.baruch.sc.edu/). The near-bottom ("deep") sondes were stationary and deployed one meter above the bottom, with water depths that changed with tidal changes in water elevation (~8 m average water depth). The "surface" sondes were attached to a buoy, with a sonde guard that slid vertically on a cable to ensure that the sonde remained one meter below the surface as water elevations changed with the tide. Sondes were switched monthly to maintain accurate sensor calibration, using calibration methods outlined in the YSI Operations Manual, with YSI standards used for calibration of the pH, conductivity, and turbidity sensors. Data from the deep and surface sondes were downloaded monthly and data from the Homer and Seldovia deep sondes were also telemetered in near-real time at 15-minute sampling intervals.

Deployment data were uploaded from the YSI sonde and data files were uploaded to the NERRS CDMO website, where they underwent automated primary QA/QC to include automated depth corrections for changes in barometric pressure and the addition of flags for missing data or out of sensor range values. The data were then made available online as part of the CDMO's provisional database. KBNERR staff conducted secondary QA/QC on the data files to add station codes, review flagged values, identify additional outliers, create summary statistics and graphs for review, and produce the final aggregated data files. Tertiary QA/QC was conducted at CDMO, after which the data were finalized in the online CDMO database and provided to the GWA program data management team. Temporal variability was assessed with time series plots and calculation of statistical mean and anomaly metrics, including the plots of monthly average and anomaly time series for temperature and salinity (Fig. 3).

Macro-nutrient (ammonia, nitrate/nitrite, phosphate) and chlorophyll concentrations were measured from monthly sampling from 2002-2021 at Homer and Seldovia harbor KBNERR SWMP stations. Water grab samples were collected one meter above the bottom ("deep", with 7 m nominal depth) and one meter below the surface ("surface"), coincident with the sonde locations. The Homer station can be accessed year around by vehicle, but water sampling at Seldovia and Bear Cove requires boat or air access and was occasionally limited by weather conditions. Unless delayed by weather, all grab samples from both stations were taken within a 24-hour period and close to high tide, in order to best assess seasonal stratification conditions. At each station, two replicate samples were collected using a triggered vertical Niskin bottle at depths of one meter from the surface and one meter from the bottom. All samples were transferred to wide-mouth Nalgene sample bottles that were previously acid washed (10% HCL), rinsed three times with distilled-deionized water, dried and then rinsed three times with ambient water prior to collection of the sample. Samples were immediately shielded from light and returned to the laboratory. Within the same 24-hour period as the water grab sample collection, an ISCO water sampler was deployed from a floating dock in the Homer Harbor. This device automatically sampled 850 ml of water every 2 hours and 30 minutes. All samples were pumped into polyethylene sample bottles that were previously acid washed (10% HCL), rinsed three times with distilled-deionized water and dried. The 11 samples were kept in the dark and at the end of the 24-hour period returned to the laboratory for immediate processing. Chlorophyll analyses were conducted by KBNERR staff and nutrient samples were sent to the Virginia Institute of Marine Science (VIMS) for orthophosphate, ammonium, nitrate and nitrite analyses (more details can be found on the NERRS CDMO website).

The KBNERR maintained routine monitoring of weather conditions at a meteorological station at the end of the Homer Spit (Fig. 2), including air temperature, barometric pressure, wind speed and direction, precipitation, photosynthetically-available radiation (PAR), and relative humidity.

These data provided local atmospheric forcing information in Kachemak Bay to correlate with GWA oceanography and nearshore monitoring data. Additional information on meteorological datasets can be found at the NERRS CDMO website.

Shipboard oceanography and plankton monitoring methods

Shipboard oceanography and plankton sampling was conducted year-round during 2017-2021, along repeated transects in lower Cook Inlet and Kachemak Bay (Fig. 2, Table 1), extending and expanding time series that were started in 2012. The sampling design provided year-round data at high spatial resolution and monthly frequency to provide long-term oceanographic information at the space and time scales needed to assess seasonal and interannual variability in marine conditions. A total of 73 oceanographic station locations were sampled repeatedly, including 33 stations on one along-bay and two cross-bay transects in Kachemak Bay, 17 stations in southeast Cook Inlet (including the eastern stations of cross-inlet transects sampled during 2012-2016), and an additional 23 stations across the Cook Inlet entrance transect. Monthly cross-bay sampling was conducted along a mid-Kachemak Bay transect (Transect 9, 10 stations) from the end of the Homer Spit to McKeon Flats, on a line that separates the inner and outer areas of the bay. To improve year-round characterization of estuary-shelf water gradients, monthly along-bay sampling was added for 2017-2021, along a transect from near Bear Cove at the head of the bay to the bay entrance (Along-Bay Transect, 13 stations). Quarterly, sampling was extended to more locations in outer Kachemak Bay and southeast Cook Inlet (Fig. 2), in order to seasonally provide enhanced spatial coverage of along-estuary patterns and areas where concentrations of fish, seabirds and marine mammals routinely occur. The quarterly sampling was conducted across outer Kachemak Bay, on a north-south line from Bluff Point to near Barabara Creek (Transect 4, 10 stations), extended south of the bay into southeast Cook Inlet (2 more stations), and conducted on eastern portions of cross-Inlet transects near Flat Island (Transect 7, 5 stations) and at the Cook Inlet entrance near Point Adam (Transect 6, 5 stations). Quarterly sampling was also conducted north of the bay on the eastern portion of a cross-Inlet transect near Anchor Point (Transect 3, 5 stations). The Cook Inlet entrance line (Transect 6, 28 stations total) was sampled annually in spring, when weather conditions permitted.

Vertical oceanographic profile data were collected at every station (all dots in Fig. 2) and zooplankton, phytoplankton and nutrient measurements were added at selected stations along each transect (red dots in Fig. 2). Monthly and quarterly Kachemak Bay and Cook Inlet surveys were conducted from NOAA National Centers for Coastal Ocean Science (NCCOS) Kasitsna Bay Laboratory (KBL) small boats, and larger vessels were chartered for the spring Cook Inlet entrance surveys. Station spacing was designed to capture detailed oceanographic gradients associated with salinity fronts and cross-estuary bathymetry slopes, with approximately 400 m spacing on the mid-Kachemak Bay transect and one nautical mile (1852 m) spacing on the outer bay and Cook Inlet transects. Transect and station locations are consistent with those used previously by Okkonen et al. (2009) and Murphy and Iken (2013) in lower Cook Inlet and Kachemak Bay. Along-bay transect stations intersect with the cross-bay and cross-Inlet transect stations and were repeated during sampling cruises. Sampling was limited to wind speeds less than 25 knots and wave heights less than six feet, with monitoring occasionally prevented at times or at certain sites by adverse weather and sea state conditions.

Oceanographic measurements were made with vertical casts of a SeaBird Electronics (SBE) SEACAT 19plus conductivity-temperature vs. depth (CTD) profiler from the surface to near-bottom at each station, at a nominal drop rate of 1 meter/second. Two SBE 19plus CTD profilers, provided by the NOAA KBL and KBNERR, were used for the project. The KBL CTD profiler included a SBE 43 dissolved oxygen sensor, WETLabs combined chlorophyll fluorometer and turbidity sensor (ECO-FL-NTU(RT)), and Li-Cor PAR sensor. The KBNERR CTD profiler included a SBE 43 dissolved oxygen sensor, Li-Cor PAR sensor, WETLabs fluorometer and a WETLabs transmissometer. The 19plus CTD profilers and ancillary instruments were sent to SBE for routine calibration of the temperature, conductivity, pressure, and dissolved oxygen sensors, with calibrations of other sensors done at the same time by the respective instrument manufacturers. The SBE CTD instruments are well-known for their accuracy, stability and low sensor drift.

SBE 19Plus CTD profiler data from all stations were processed with standard SBE software algorithms (SBE Seasoft V2, SBE Data Processing), using only downcast data to minimize water flow disturbance by the instrument package, and averaged into 1 meter depth bins. Derived parameters were calculated (e.g., depth, density) and data points that were flagged by the SBE processing software as missing or outlier values were removed from the processed dataset. Vertical profiles of estimated chlorophyll concentration were generated from WETLabs fluorometer sensor data. The fluorometer emits light that is absorbed by chlorophyll molecules and causes them to fluoresce at a different wavelength, detected by the fluorometer, with the intensity of the fluorescence proportional to chlorophyll concentrations. The fluorometer-derived chlorophyll estimates at CTD stations provided a relative measure of seasonal, vertical and spatial patterns in chlorophyll concentrations and for the spring phytoplankton bloom. Additional QA/QC steps included generating along-transect distance vs depth contour plots of all derived values from individual transect surveys and generating time series from individual station data to identify additional outlier or suspect data points. Following data processing and QA/QC, all the individual CTD cast data files (1 m binned data) were aggregated into one final data file for each year, organized by transect number and sampling date (text file with comma separated value format).

Table 1. Summary of boat-based project monitoring conducted in Kachemak Bay and lower Cook Inlet during 2017-2021, by sampling type, frequency, and location. Blue color denotes that samples were collected for a given month and location. AB is the along-bay transect; bay-ocean extension stations were sampled with Transects 6/7.

		CTD						**PHYTOPLANKTON**						**ZOOPLANKTON**						**OCEAN ACIDIFICATION**					
		Transect						Transect						Transect						Transect					
Year	**Month**	**AB**	**3**	**4**	**6**	**7**	**9**	**AB**	**3**	**4**	**6**	**7**	**9**	**AB**	**3**	**4**	**6**	**7**	**9**	**AB**	**3**	**4**	**6**	**7**	**9**
2017	January	■					■						■	■					■						■
2017	February	■					■						■						■						■
2017	March	■					■	■					■	■					■	■					■
2017	April	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■
2017	May	■					■						■						■	■					■
2017	June	■					■	■					■	■					■	■					■
2017	July	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2017	August	■					■						■						■						■
2017	September	■					■	■					■	■					■						■
2017	October	■		■			■	■		■			■	■		■			■			■			■
2017	November	■			■	■	■	■			■	■	■	■			■	■	■	■			■		■
2017	December	■					■						■						■						■
2018	January	■					■	■					■	■					■						■
2018	February	■					■	■					■	■					■						■
2018	March	■				■	■	■				■	■	■				■	■	■					■
2018	April	■		■			■	■		■			■	■		■			■	■		■			■
2018	May	■					■	■					■	■					■	■					■
2018	June	■	■	■			■	■	■	■			■	■	■	■			■	■		■			■
2018	July	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■
2018	August	■					■	■					■	■					■	■					■
2018	September	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■		
2018	October	■					■	■					■	■					■	■					■
2018	November	■					■	■					■	■					■	■					■
2018	December	■					■	■					■	■					■	■					
2019	January						■						■						■						
2019	February	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■		■
2019	March	■					■	■					■	■					■	■					■
2019	April	■					■	■					■	■					■	■					■
2019	May	■	■	■	■	■	■	■					■	■	■	■	■	■	■	■		■	■		■
2019	June	■					■	■					■	■					■	■					■
2019	July	■					■	■					■	■					■	■					■
2019	August	■					■	■					■	■					■	■					■
2019	September	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■
2019	October	■					■	■					■	■					■	■					■
2019	November	■					■	■					■	■					■	■					■
2019	December	■					■	■					■	■					■	■					■
2020	January																								
2020	February	■		■			■	■		■			■	■		■			■	■					■
2020	March	■					■	■					■	■					■	■					■
2020	April																								
2020	May																								
2020	June	■					■	■					■												
2020	July	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■		■
2020	August	■					■	■					■	■					■	■					■
2020	September	■		■	■	■	■	■			■	■		■		■	■	■	■	■			■		■
2020	October	■					■	■					■	■					■	■					■
2020	November																								
2020	December	■					■																		

Table 1 continued.

		CTD						PHYTOPLANKTON						ZOOPLANKTON						OCEAN ACIDIFICATION					
		Transect						Transect						Transect						Transect					
Year	**Month**	**AB**	**3**	**4**	**6**	**7**	**9**	**AB**	**3**	**4**	**6**	**7**	**9**	**AB**	**3**	**4**	**6**	**7**	**9**	**AB**	**3**	**4**	**6**	**7**	**9**
2021	January	■					■							■					■	■					■
2021	February	■		■	■	■	■							■			■	■	■	■			■		
2021	March	■		■										■					■	■					■
2021	April	■	■	■	■	■	■	■	■	■			■	■	■	■			■			■			■
2021	May	■					■	■			■	■	■	■			■	■	■	■					
2021	June	■					■	■					■	■					■	■					
2021	July	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■		■			■
2021	August	■					■						■	■					■	■					■
2021	September			■			■	■		■			■			■			■						■
2021	October	■			■	■	■	■			■		■	■			■	■	■	■			■		
2021	November	■					■	■					■	■					■						
2021	December	■					■	■					■	■											

Oceanographic patterns throughout the water column between years were analyzed and visualized to illustrate temporal and spatial variability across Kachemak Bay and southeast Cook Inlet. Monthly, ship-based oceanographic sampling across- and along-Kachemak Bay provided data to resolve seasonal patterns and timing changes (e.g., changing temperature, snowpack melt, shelf water intrusions) in water column structure, cross-estuary patterns, and estuary-ocean gradients. The extended oceanographic surveys conducted each quarter provided data for more robustly characterizing seasonal variability across a larger region between different years, in areas of typically higher concentrations of fish, seabird and marine mammals. The complementary, continuous (15-minute sampling interval) water quality station data provided information to resolve oceanographic responses to higher-frequency events, including tides, precipitation events, and storms. Ocean Data Viewer and R software algorithms were used to construct along-transect distance vs. depth contour plots of temperature, salinity, density, chlorophyll (from fluorescence) and other parameters for each survey (examples in Results section). Contour plots with time series of water column patterns (time vs. depth) of multiple parameters were produced for selected individual stations from each transect.

Temporal variability was assessed with time series plots and calculation of statistical mean and anomaly metrics from repeated monthly oceanographic profile data at each CTD station, and used for comparison to historical data and for construction of ocean climatology products. Fig. 4 shows example water column time series plots of monthly vertical temperature, salinity, and chlorophyll (from fluorescence) profiles from 2021-2022 monitoring at the mid-Kachemak Bay CTD station (Transect 9, station 6 or T9-6) under GWA and NOAA programs. The repeated monthly profiles were used to calculate depth-dependent seasonal water column temperature and salinity climatologies for each CTD station location (shown for the mid-bay station in Fig. 5). To investigate temporal and spatial variability in ocean conditions, depth-dependent monthly anomaly time series were calculated at each CTD station for multiple oceanographic parameters (mid-bay station example in Fig. 6). Depth-integrated anomaly time series were calculated from vertical station data for deeper (Fig. 7) and surface (Fig. 8) water column layers to more readily visualize temporal patterns. Water column densities were derived and used to estimate vertical stratification at each station. Salinity variability over 2012-2021 was also assessed by calculating a vertically and horizontally integrated, monthly freshwater content index using data from the ten CTD stations of the cross-Kachemak Bay survey line (Transect 9). A reference salinity was used to estimate a relative amount of freshwater at individual depths at each station location, then integrated across water layers. Given the observed differences in drivers and temporal patterns of salinity variability in surface and deeper waters (Doroff and Holderied, 2018), separate indices were calculated for surface and deeper parts of the water column (Fig. 9). The freshwater content and stratification metrics were used to assess the effects of seasonal and interannual changes in freshwater input and shelf water intrusions. A seasonal, depth-dependent chlorophyll climatology (mid-bay example in Fig. 10, top plot) was calculated for each station from the monthly profile data (Fig. 10, middle plot), as well as vertically integrated, monthly averages and anomalies of water column chlorophyll (Fig. 10, bottom plot). Horizonal and vertical variability within and between years was visualized with along-transect vs. depth contour plots of temperature, salinity, density and chlorophyll fields (see Fig. 11 for examples from the along-bay transect).

Zooplankton sampling and analysis methods

Between 2017 and 2021, 276 zooplankton samples were collected at select, repeated CTD stations along each routinely sampled ship survey transect (Fig. 2), comprising over 220,000 individuals and 241 taxa. Zooplankton were collected during both daylight (primarily) and nighttime hours, using vertical tows of a 0.6 m diameter bongo net with 333 µm mesh size. To calculate sample volume, a mechanical flow meter (General Oceanics) was attached to the frame of one of the two bongo nets. To assess cross-program zooplankton sampling methods with other GWA Environmental Drivers component researchers, additional duplicate sampling with a 150 µm mesh net was conducted for a portion of the study period. The plankton nets were towed vertically from 50 m to the surface at each plankton station or to 5 m above the sea floor if bottom depths were shallower than 50 m, with a tow rate of approximately 0.5 m/s. The nominal sample volume was 14.2 cubic meters for a 50 m vertical station. Zooplankton samples were taken from the cod end in the net that did not have the flow meter attached and were preserved in 5% formalin solution for later enumeration. Samples from the net with the flow meter were not retained unless there was an issue with the sample from the first net. Preserved zooplankton samples were sent to Dr. Rob Campbell and Caitlin McKinstry (Prince William Sound Science Center), for species enumeration to lowest taxonomic classification possible. Processing and analysis of zooplankton samples followed McKinstry and Campbell (2018) and McKinstry et al. (2022). The samples were subsampled with a Folsom splitter until at least 200 individuals of the most numerous taxa were present and then samples were counted for species composition. Less abundant macrozooplankton, such as euphausiids and ichthyoplankton, were enumerated from higher fraction subsamples or the entire tow sample. For winter samples, which had lower abundances, the zooplankton were enumerated from the entire tow sample, without subsampling. Copepod species of *Neocalanus plumchrus* and *N. flemingeri* were combined as *Neocalanus* spp.

Zooplankton data were analyzed with multivariate approaches to investigate seasonal, interannual and spatial patterns in abundance, species community composition, and responses to changes in environmental conditions. Monthly sampling frequency and year-round data collection allowed detailed characterization of seasonal cycles in zooplankton abundance and community composition. McKinstry et al. (2022) provides an analysis of 2012-2018 zooplankton data patterns in Kachemak Bay and lower Cook Inlet, including the zooplankton community response to the 2014-2016 Pacific marine heatwave. A brief summary of methods used in McKinstry and Campbell (2018) and McKinstry et al. (2022) is provided here. Zooplankton trends were analyzed using R software (R Core Team 2019), with the data log transformed (log10) to stabilize the typically high variance of zooplankton abundance. Spatial and temporal variability of zooplankton species was analyzed using generalized additive models and monthly mean abundance estimates, and the zooplankton abundance patterns were used to understand broad seasonal patterns. Indicator species analysis and multivariate ordination techniques were used to understand zooplankton community structure, and community composition results were also compared with oceanographic variables. In addition, 2012-2020 zooplankton data that were collected at three stations on the most intensively sampled mid-Kachemak Bay transect (Transect 9) were analyzed with non-metric multidimensional scaling (NMDS) methods (Renner et al. unpublished data). Seasonal progression of changes in zooplankton community composition was visualized by plotting the first two major NMDS axes for all collected samples, with individual samples colored and convex hulls drawn around points in a given month.

Phytoplankton sampling and analysis methods

Surface water samples were collected at each plankton station (Fig. 2) on all the shipboard surveys for phytoplankton monitoring. Surface seawater was collected using a bucket with volumetric markings to quantify the amount of water filtered (amount varied seasonally from 40 to 60 L). The seawater sample was filtered through a 20 µm mesh hand net with a 250 mL bottle attached to the cod end of the net to collect a concentrated phytoplankton sample. The samples were preserved with a neutral Lugol's solution. In the lab, an aliquot of the preserved sample was drawn and placed in a Palmer counting cell (0.1 mL volume). Under a light microscope, all phytoplankton cells were identified to the lowest taxa and enumerated, with cell concentrations for each species derived from the Palmer cell counts and total seawater sample volume. Additionally, leveraging other NOAA/NCCOS funded research programs, harmful algal bloom (HAB) species abundance was calculated for a subset of the phytoplankton samples with DNA analysis using polymerase chain reaction (PCR) techniques at the NCCOS Beaufort Laboratory in North Carolina (Vandersea et al. 2017, 2018).

Phytoplankton data analyses of phytoplankton and HAB species followed KBNERR community phytoplankton monitoring and NOAA Phytoplankton Monitoring Network protocols (https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/pmn/). Phytoplankton community composition data were analyzed with multivariate methods (NMDS), similar to the zooplankton data analyses, to examine seasonal patterns and interannual changes in the seasonal evolution of community composition, along with the influence of environmental conditions. For HAB species, time series of cell abundance data were correlated with oceanographic patterns, shellfish toxin data and paralytic shellfish poisoning events that affect people, marine birds, and marine mammals in the region (as in Vandersea et al. 2018). We were also able to leverage our monthly shipboard surveys to collect additional zooplankton and phytoplankton samples for HAB toxin analyses as part of research funded by the North Pacific Research Board to determine the prevalence of paralytic shellfish toxins in the marine food web of southcentral and southwest Alaska. As part of the food web toxin project, we also collected forage fish and predator fish samples for toxin testing to compare levels to regulatory thresholds for safe human consumption of 80 µg of toxin per 100 g of tissue. The forage fish samples were analyzed whole and the predator fish samples were sub-sampled by muscle tissue, digestive organs, liver, kidney, and stomach content.

Nutrient and chlorophyll sampling and analysis methods
In 2021, along-estuary monitoring for macronutrient (nitrate, ammonium, orthophosphate, silicate) and chlorophyll analyses was added to the long-term nutrient and chlorophyll observations at the Homer and Seldovia water quality stations. Both surface and near-bottom water samples were taken at three stations during monthly shipboard surveys on the along-Kachemak Bay transect. Water samples were collected from the same stations where plankton sampling was conducted. Surface samples were collected by bucket and deep-water column samples were collected during CTD deployments, by using a Niskin bottle attached to the line above the CTD, with water samples collected approximately 5 m above the bottom. Samples were processed and filtered with a glass fiber filter the same day and frozen for later nutrient analysis by Virginia Institute of Marine Science, following the same sample processing and analysis protocols used for KBNERR water quality station samples (see above). For chlorophyll measurements, 200 mL samples of surface seawater were collected on the boat and brought back to the KBNERR lab in Homer, where the sample was filtered with a glass fiber filter and analyzed for chlorophyll, following NOAA NERR SWMP protocols. To assess seasonal patterns, monthly climatologies were constructed from the monthly 2002-2021 water station nutrient data (Fig. 12) and compared to the along-estuary nutrient data collected during shipboard surveys in 2021. Fig. 13 shows resulting monthly concentrations of nitrate/nitrite, phosphate, silicate and ammonia analyzed from samples at outer bay (AlongBay-3), mid-bay (AlongBay-6), and inner bay (AlongBay-10) stations.

Coordination and collaboration
The Cook Inlet/Kachemak Bay ocean monitoring project provided year-round, seasonally resolved oceanographic and plankton data to the GWA program, Trustee agency managers and researchers, other federal/state agencies, Alaska Native tribal organizations, academic researchers, and educators. Key collaborations included the following:

Gulf Watch Alaska program: The Cook Inlet/Kachemak Bay project provided spatially-detailed, year-round oceanographic information on along- and across-estuary gradients to the GWA program. We coordinated on oceanographic and zooplankton sampling protocols and synthesis of monitoring results with all GWA Environmental Drivers component investigators through teleconferences, principal investigator (PI) meetings and co-authored peer-reviewed manuscripts. Project data were incorporated into GWA synthesis manuscripts with other GWA PIs (Danielson et al. 2021, Suryan et al. 2021b). We also coordinated with Dr. Rob Campbell at the Prince William Sound Science Center (21120114-G) on zooplankton sample analyses and co-authored a peer-reviewed manuscript on the response of Kachemak Bay zooplankton to the 2014-2016 Pacific marine heatwave (McKinstry et al. 2022). The project data provided information on seasonal and inter-annual patterns in water temperature, stratification, freshwater content and nutrients to the GWA Nearshore component PIs (21120114-H) to assess drivers of intertidal ecosystem changes at their Kachemak Bay monitoring sites. We collaborated with Environmental Driver and Nearshore component PIs on two synthesis manuscripts, one to assess nearshore oceanographic variability (Danielson et al. 2022) and another to assess the effects of heatwaves on rocky intertidal communities (Weitzman et al. 2021) across the GWA study area. Cook Inlet project scientists also participated in the GWA Nearshore Component sampling in Kachemak Bay.

NOAA: We leveraged funding to NOAA KBL from the Alaska Ocean Observing System (AOOS), under the NOAA Integrated Ocean Observing System (IOOS) program, to support shipboard oceanographic data collection and data analysis through the entire study period. We collaborated with researchers at the NOAA/NCCOS Beaufort, North Carolina, and Charleston, South Carolina laboratories to use the project oceanography and phytoplankton sampling data to identify environmental triggers for increases in the phytoplankton species *Alexandrium* spp. that cause paralytic shellfish poisoning (PSP), as well as other HAB species, with results published in two peer-reviewed articles. The HAB phytoplankton species and phytoplankton community composition time series are being used by NCCOS and KBNERR researchers to develop new HAB risk assessment tools, in coordination with ADEC aquatic farm program managers, ADF&G resource managers, oyster farmers, and tribal environmental coordinators. We also coordinated HAB research, monitoring and event response with AOOS, NOAA/NCCOS and NOAA/NMFS offices through the Alaska HAB Network. Both KBNERR and KBL researchers collaborated with NOAA National Marine Fisheries Service (NMFS), as part of the NOAA Kachemak Bay Habitat Focus Area efforts, on clam restoration and PSP risk assessment. We provided project oceanographic and HAB information for NMFS Ecosystem Considerations reports for the North Pacific Fisheries Management Council and for Gulf of Alaska marine mammal mortality events.

State of Alaska agencies: We provided real-time and historical trends for water temperature data for HAB research and monitoring in Kachemak Bay, in coordination with ADF&G shellfish and aquatic farming program managers, ADEC, Alaska Department of Health/Division of Public Health, and the Alaska HAB Network.

USFWS/USGS: We coordinated with the USFWS Marine Mammals Office on sea otter stranding and sampling programs and with USGS Alaska Science Center researchers on Cook Inlet forage fish and seabird monitoring. The project data are available to USFWS Alaska Maritime National Wildlife Refuge and USGS marine mammal and seabird researchers to help understand potential causes of seabird and sea otter population changes and mortality events.

Alaska Native tribal organizations: We collaborated on phytoplankton and HAB monitoring with the Chugach Regional Resources Commission (CRRC) Alutiiq Pride Marine Institute (APMI, formally the Alutiiq Pride Shellfish Hatchery) and Seldovia Village Tribe. Water samples collected during monthly shipboard oceanography surveys were sent to the APMI lab in Seward, Alaska, for carbonate chemistry analysis and monitoring of ocean acidification conditions (leveraging other CRRC funding sources).

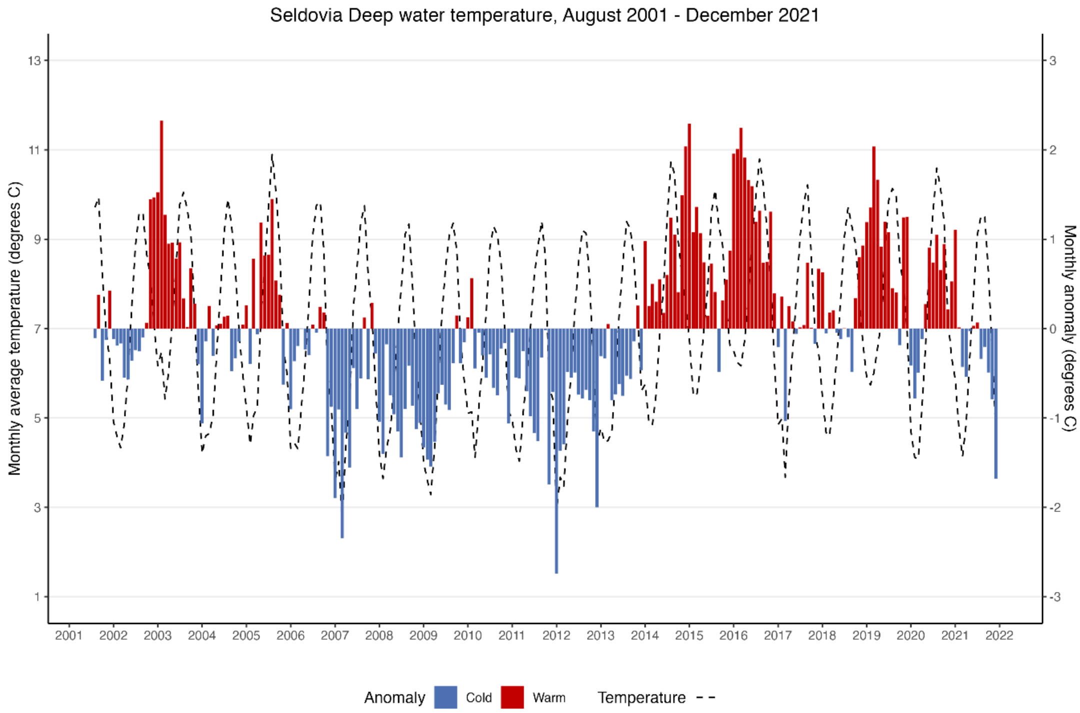
North Pacific Research Board (NPRB) project on transfer of HAB toxins in marine food web: We collaborated with researchers from NOAA/NCCOS, Prince William Sound Science Center (Rob Campbell), and Oregon State University, on an NPRB-funded, Gulf of Alaska HAB project from 2021-2022. The project examined potential transfers of PSP toxins through the marine food web by monitoring abundances of toxic phytoplankton species routinely found on our shipboard surveys to compare with PSP toxin levels measured in zooplankton, forage fish, salmon, and halibut. Samples for this project were collected in Kachemak Bay, Prince William Sound, and the Alaska Peninsula/Aleutian Islands. NPRB project #1801, Prevalence of paralytic shellfish toxins the marine food web of southcentral and southwest Alaska.

RESULTS

Water quality station monitoring results

Kachemak Bay water temperatures were anomalously warm for much of 2017-2020, relative to monthly means from the past two decades, most significantly throughout 2019 and in the summer and fall of 2020 (with up to +2°C monthly anomalies at the water quality stations), before transitioning to cooler than average conditions in 2021 (Fig. 3). While temperatures were closer to normal during parts of 2017-2018, relative to the prolonged warm temperatures of the 2014-2016 Pacific marine heat wave, conditions often remained mostly warmer than average. Overall, 2014-2020 was a strikingly persistent period of warmer than average conditions in Kachemak Bay and lower Cook Inlet. Salinities were mostly fresher than average at the Kachemak Bay water quality stations from fall 2018 through 2020 (Fig. 3). Water salinities were higher in the bay in winter, due to reduced freshwater input when air temperatures dropped below freezing, and then decreased with variable timing in spring through late summer, in response to freshwater inputs from snowpack and glacier melt, as well as precipitation events. Observed salinity differences between Seldovia and Homer harbor sites reflected variability in freshwater inputs between outer and inner Kachemak Bay, with lowest salinities seen in surface waters at the Homer station, since much of the freshwater input from rivers at the head and south sides of the bay moves to the north side of the inner bay and around the end of the Homer Spit. Fall salinity conditions were typically more variable than other seasons (Fig. 3), reflecting increased storm events and variability of precipitation at this time of year. Salinity also decreased in late-summer and fall in the near-bottom sonde observations, particularly at the Seldovia site. Shipboard oceanography results (see below) indicate that this fall freshening at depth reflects intrusion of relatively fresh Alaska Coastal Current waters into the bay at this time of year.

Interannual variability in Kachemak Bay oceanography in 2017-2021 can be compared to the dramatic warming (+3°C monthly temperature anomalies) and persistently fresher than average conditions seen during the 2014-2016 Pacific marine heat wave (Fig. 3). In 2017 and for most of 2018, Kachemak Bay water conditions returned closer to long-term seasonal averages, remaining slightly warmer than normal, with near average salinities. Beginning in October 2018, warm temperature anomalies increased to approximately +1°C at both Homer and Seldovia sites, and waters became fresher than average. Throughout 2019, water conditions remained warmer and fresher than average, with monthly temperature anomalies of up to +2°C and averaging near +1°C. However, salinity conditions were not as extreme or variable as seen during the earlier marine heatwave. In January 2020, air temperatures became anomalously cold with monthly averages well below the long-term (-6°C, KBNERR Long-Term Meteorological Data) and the cooling was reflected in Kachemak Bay water temperature anomalies of -0.5°C from January to April (Fig. 3). However, in response to a shift to warmer than normal air temperatures in May 2020, bay waters warmed quickly and remained warmer and less saline than long-term averages for the rest of the year. Colder than normal weather returned at the start of 2021, producing anomalously cold-water temperatures at both Homer and Seldovia sites. Temperatures at both sites then returned to near the long-term average during hot and dry early summer months, before cooling below normal during the fall and winter months, with -2°C temperature anomalies at the Seldovia site in December 2021 (Fig. 3). Interestingly, relative salinity anomalies differed between the Homer and Seldovia sites early in 2021, with fresher than average conditions at Homer and slightly more saline than average conditions at Seldovia. Salinities became closer to average at both sites in the latter half of 2021.



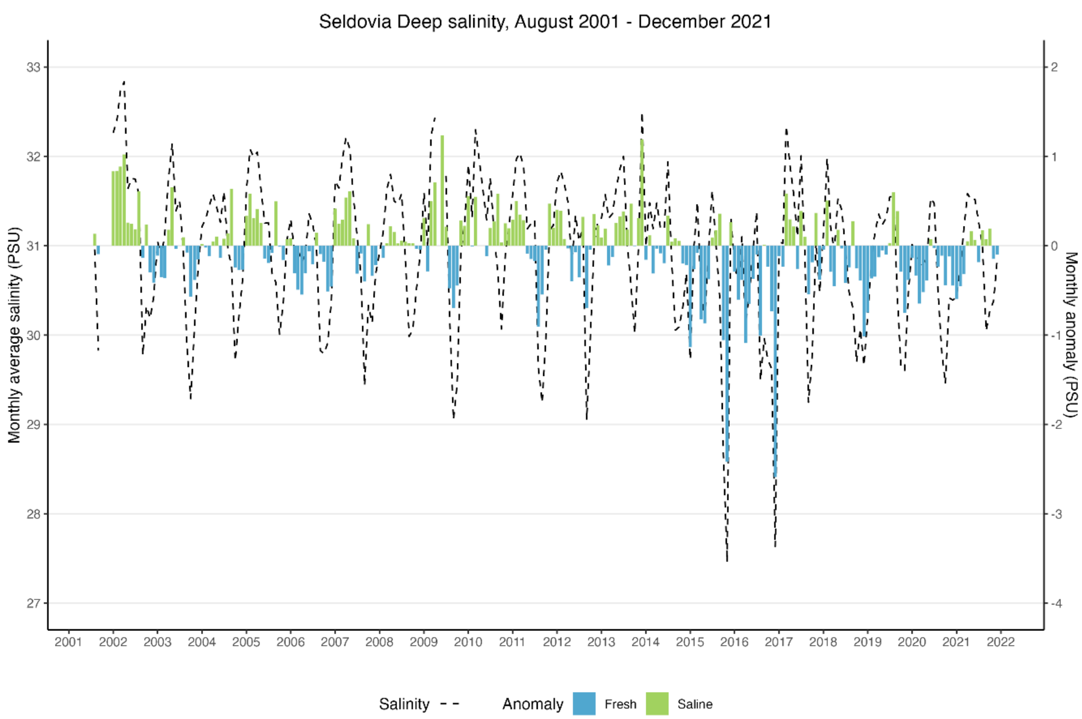


Figure 3. Monthly average (dashed lines, values on left axis) water temperature/salinity (top/bottom), with respective monthly anomalies (colored bars, values on right axis), as measured at the Seldovia Kachemak Bay National Estuarine Research Reserve System Wide Monitoring Program station. Anomalies are shown in red/blue (warm/cold) for temperature and green/blue (saltier, fresher) for salinity.

Shipboard oceanography monitoring results

Over 2012-2021, winter water temperatures in Kachemak Bay (Fig. 4) and Cook Inlet were coldest during 2012 and warmest in the winters of 2015-2016 and 2018-2019 with an over 4°C difference in mid-bay temperatures between these extremes. The degree of winter temperature variability is notable for being approximately 30% of the seasonal temperature range and nearly twice the interannual variability observed in summer months (Figs. 4, 6, 7, 8). The greatest interannual salinity variations during 2012-2021 were the anomalously fresh conditions persistently observed at depth in 2015 and throughout the water column in 2016, and more saline than normal conditions at depth for much of 2017 (Figs. 4, 6, 7, 8). Typical seasonal temperature patterns in the mid-bay have coldest water temperatures in February/March, spring warming starting in late April, and warmest surface temperatures in August (~12°C at this location), with warmest deeper water conditions in September that lag past the start of fall atmospheric cooling (Fig. 5). The water column remains relatively warm into October, before more seasonal cooling in November. For salinity, winter mixing and reduced freshwater inputs result in highest salinities throughout the water column (~31.5 PSU) from February into early April. Freshening of surface waters (to ~15 m depth) occurs from April to October, and is associated with freshwater inputs to the bay from snowpack melt, glacial melt, precipitation (frequently in late summer/early fall storms) and groundwater. From August to November a slighter freshening occurs in deeper waters (below ~20 m), starting when the water column is most stratified. The late summer/fall decrease in salinity at depth may be associated with intrusions of seasonally freshened Alaska Coastal Current waters at depth from the adjacent Gulf of Alaska shelf. Average seasonal patterns across the study region were similar to the mid-bay results shown here, with reduced seasonal variability seen in the outer bay and southeast Cook Inlet and a wider range of temperature and salinity variability observed in inner Kachemak Bay, consistent with the shallower depths and increased freshwater influence in the inner bay.

Kachemak Bay water column temperatures generally remained close to seasonal averages, with smaller warm anomalies during most of 2017 and 2018, in contrast to the more anomalously warm conditions of the 2014-2016 Pacific marine heatwave (Figs. 6, 7, 8). Kachemak Bay and Cook Inlet waters became significantly warmer than average in the winter of 2018-2019, with >2°C monthly average warm anomalies throughout the water column. Less intense seasonal warm anomalies persisted throughout the rest of 2019, as was also seen in the results shown from the KBNERR water quality monitoring sites. Rapid and relatively intense winter cooling in early 2020 produced cold temperatures across the entire water column that had not been observed since 2012-2013; however, this trend reversed quickly in summer 2020, with anomalous seasonal warming observed for the last half of the year. In 2021 water temperatures returned to more average conditions throughout the water column for most of the year. Water column temperatures in Kachemak Bay and Cook Inlet exhibited the same overall pattern of persistently warmer than normal conditions during 2014-2020 that was observed at the water quality stations.

In contrast to the significant freshening observed in Kachemak Bay/Cook Inlet during the marine heatwave in 2015 and 2016, less salinity variability was seen over the 2017-2021 study period. The most notable interannual salinity variations were higher than average salinities observed in 2017, during January-August 2020 and in late 2021 (Figs. 6-8). These interannual changes were more persistent at depth (though much smaller in magnitude than variations in the surface layer), while surface salinities (upper 20 m) varied on shorter time scales of a few months for most of the study period (Fig. 6). The surface waters were slightly fresher than average for much of 2019 and later in 2020 (Fig. 8), consistent with the anomalously warm conditions at those times, but with much less freshening than was observed during the similar intensity, but longer duration warming of the 2014-2016 marine heatwave. Interannual variability increased in fall months, with a lag at depth as was seen in the station climatologies (Fig. 5). The freshening that occurred during heatwave conditions of 2015-2016 still stands out in the longer record, especially the persistent freshening of deeper waters through the first half of each of those years.

Examples of lower trophic biological responses to these environmental changes can be seen in time series of vertical profiles of chlorophyll concentrations, derived from water column fluorescence measured with a fluorometer that was integrated with the CTD profiler. At the mid-Kachemak Bay CTD station, highest chlorophyll concentrations over 2017-2021 were observed between 5 and 20 m depth from May to July, with the spring/early summer blooms in 2017 and 2020 extending to almost 40 m depths, and the highest observed concentrations for the entire period occurring in 2017 (Figs. 4, 10). The mid-Kachemak Bay time series also shows evidence of a second, weaker late summer/fall bloom, particularly in 2018, 2019, and 2020. Highest total water column chlorophyll values for the 2012-2021 period were observed in the summers of 2017 and 2020. Phytoplankton bloom dynamics can vary rapidly on short time scales, so the monthly sampling may not have captured the full range of variability, but did capture year-round patterns. The CTD sampling station distribution also provided robust spatial coverage of vertical chlorophyll patterns both along and across the estuary.

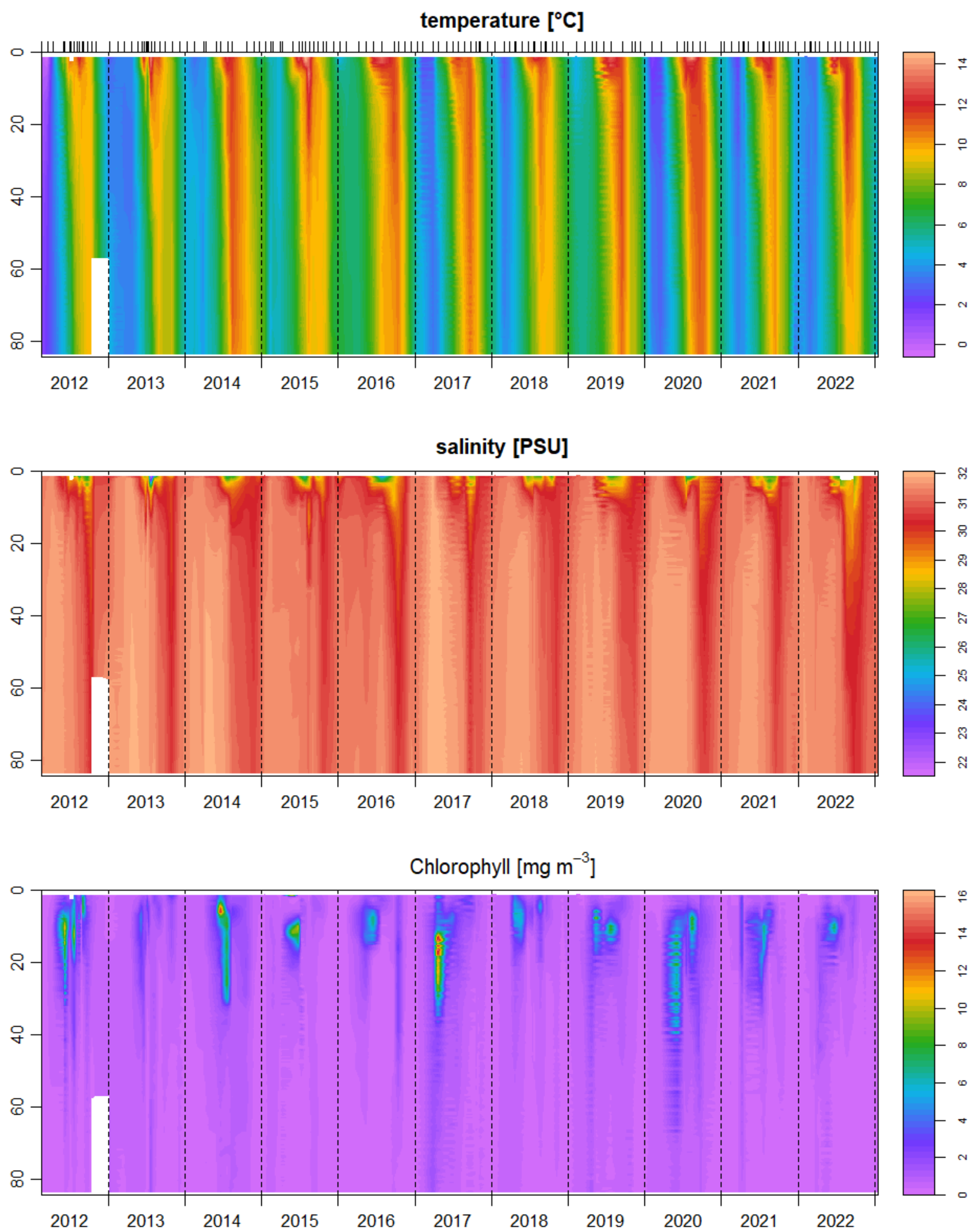


Figure 4. Vertical water column profiles of temperature (top), salinity (middle), and chlorophyll (bottom) over 2021-2022 from the mid-Kachemak Bay conductivity-temperature vs. depth station (Transect 9, station 6).

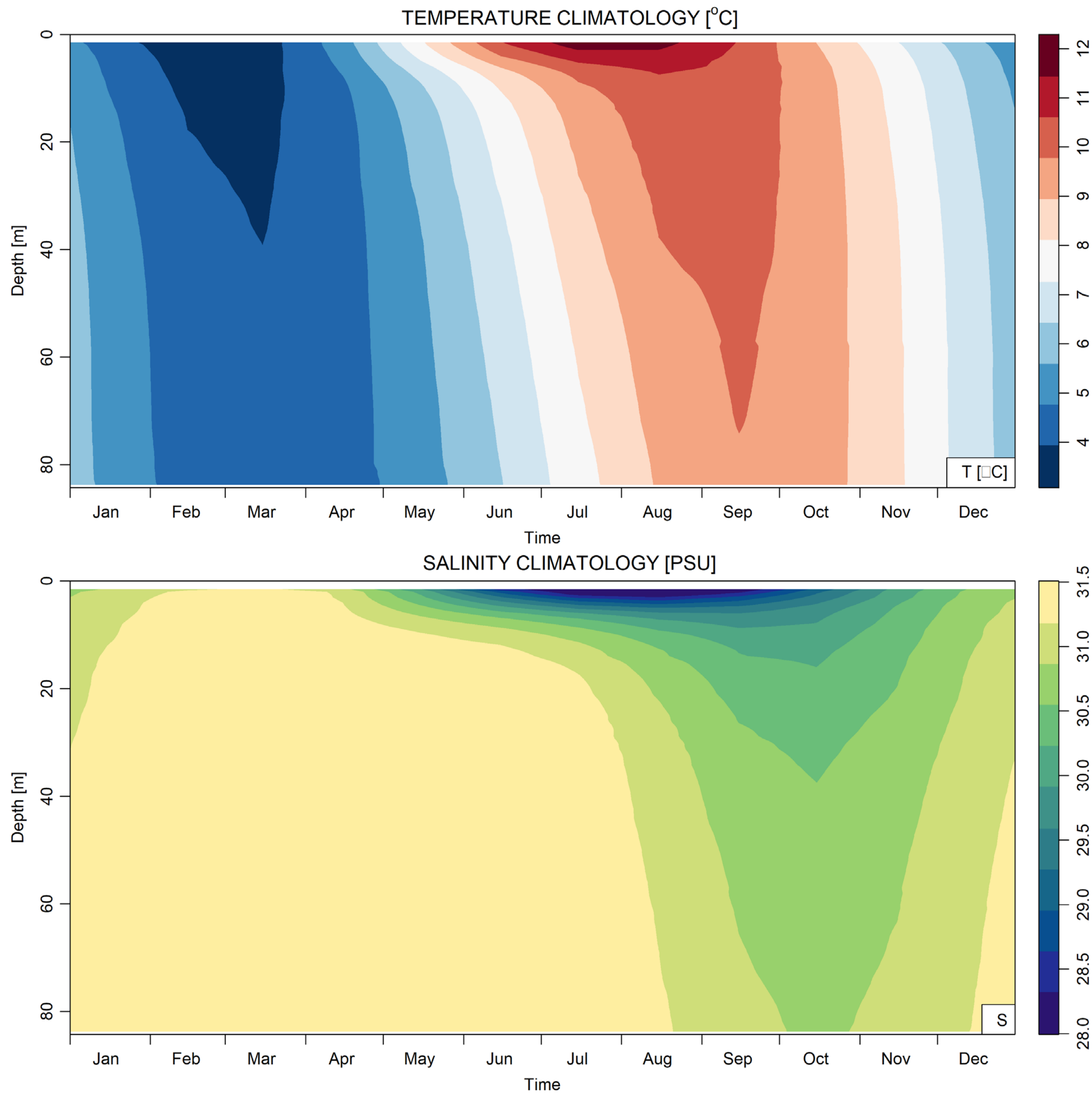


Figure 5. Temperature (top) and salinity (bottom) seasonal water column climatologies for the mid-Kachemak Bay oceanographic station (Transect 9, station 6). The depth-dependent climatologies were calculated from monthly conductivity-temperature vs. depth profiler vertical cast data, collected from 2012-2021.

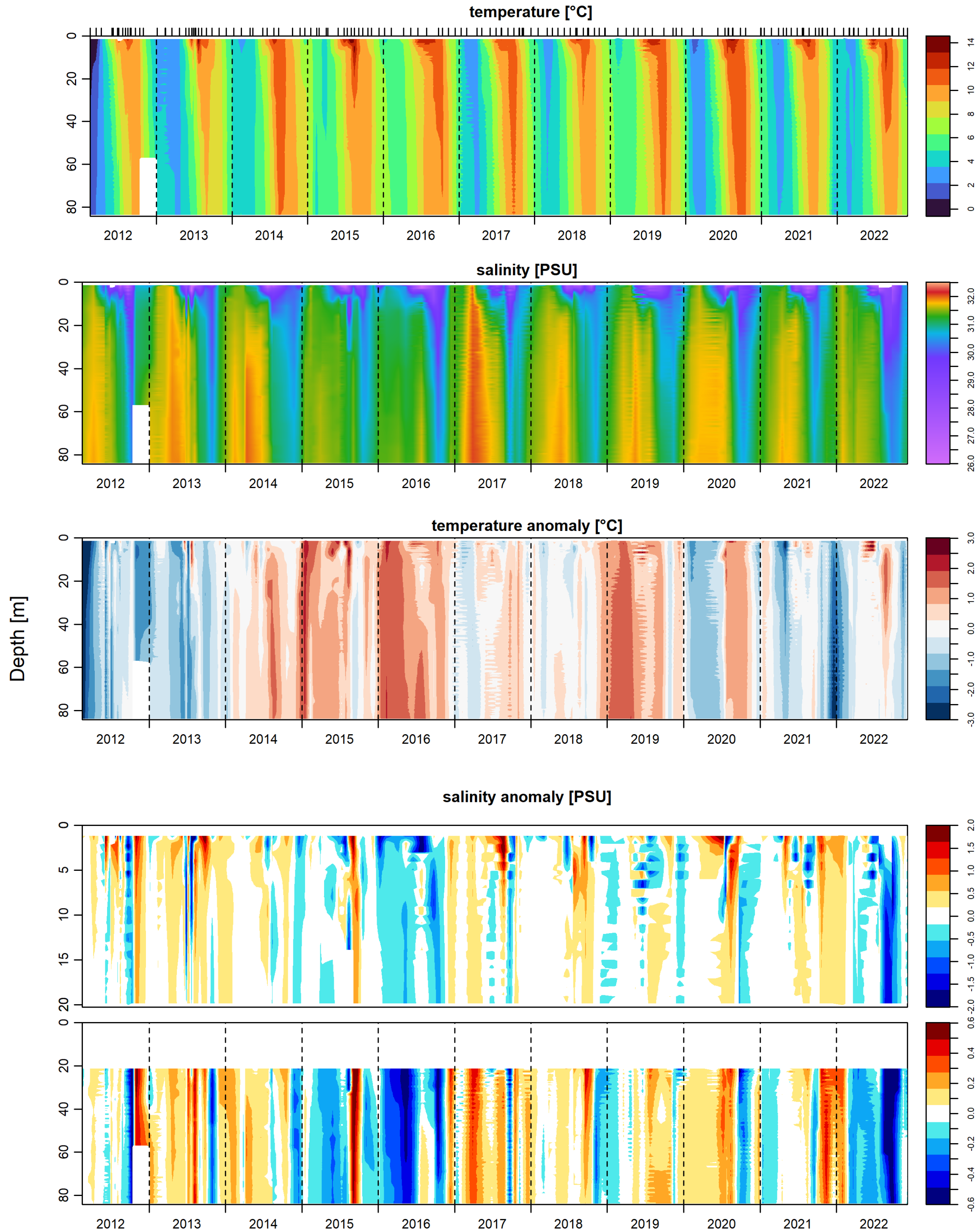
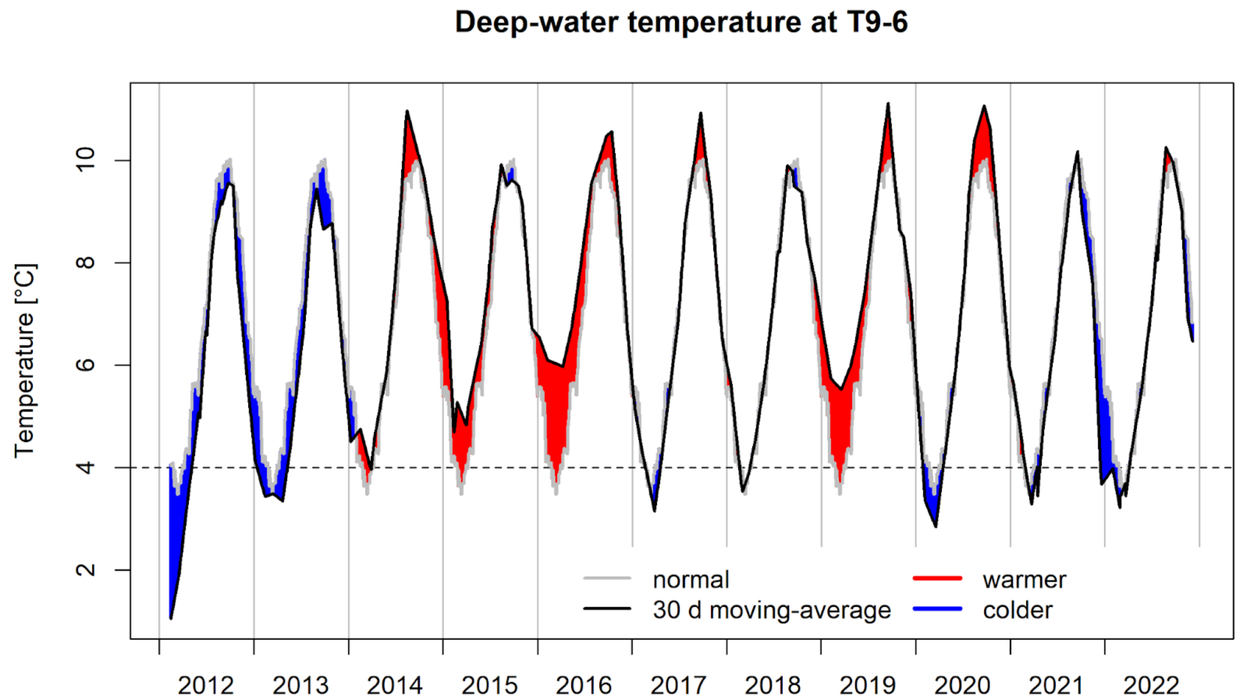


Figure 6. Temperature and salinity profile time series and anomalies center of Kachemak Bay location (Transect 9, station 6). For the salinity anomaly, the surface and deeper layers are shown separately, with different scales.



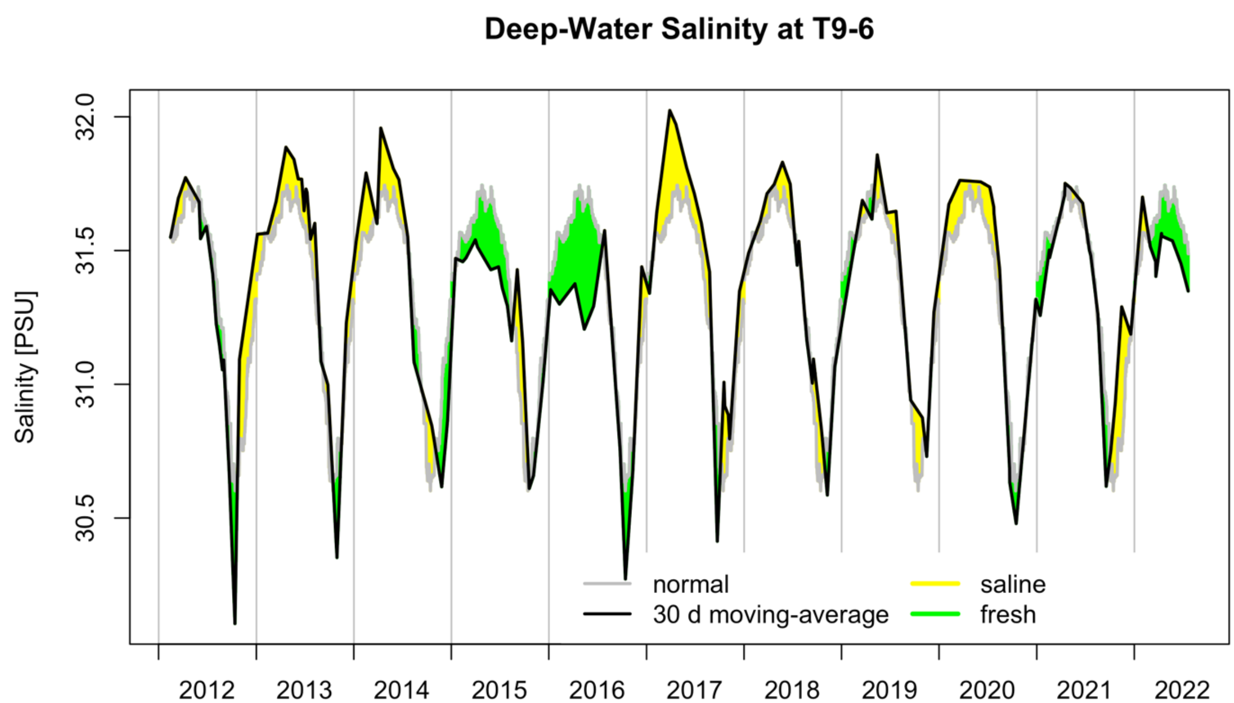
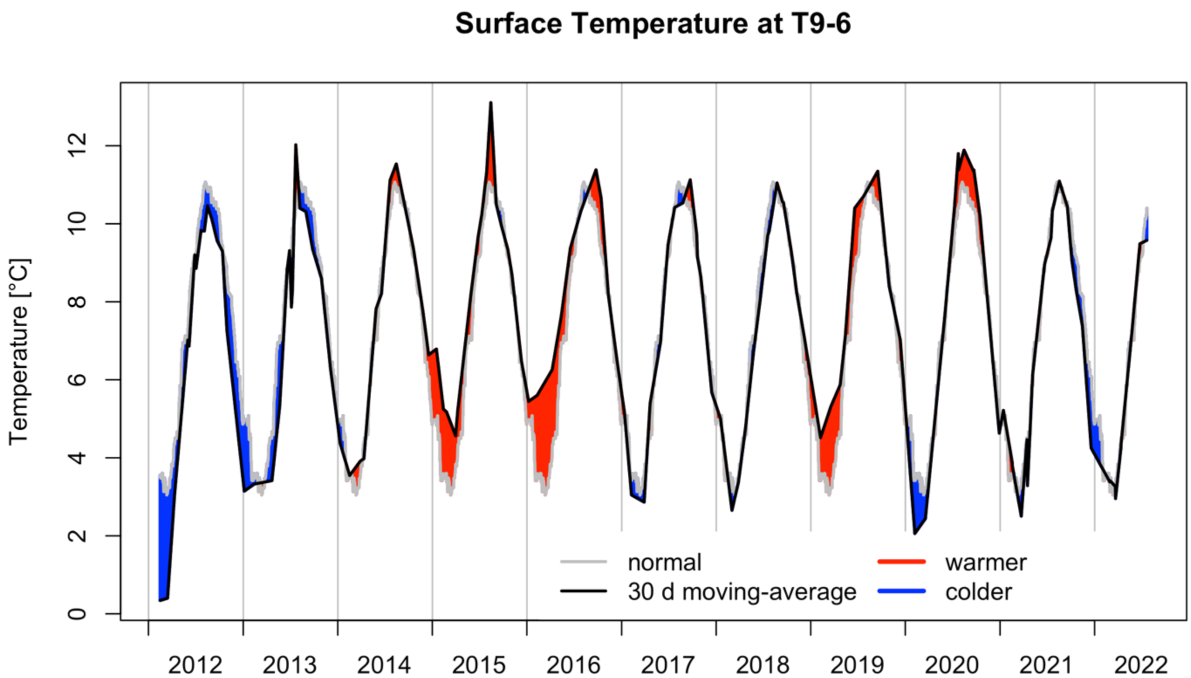


Figure 7. Deep layer temperature (top) and salinity (bottom) at mid-bay station, averaged from 30 m to near bottom depths. Also shown is the anomaly from the long-term seasonal average, with green (yellow) colors indicating fresher (more saline) conditions.



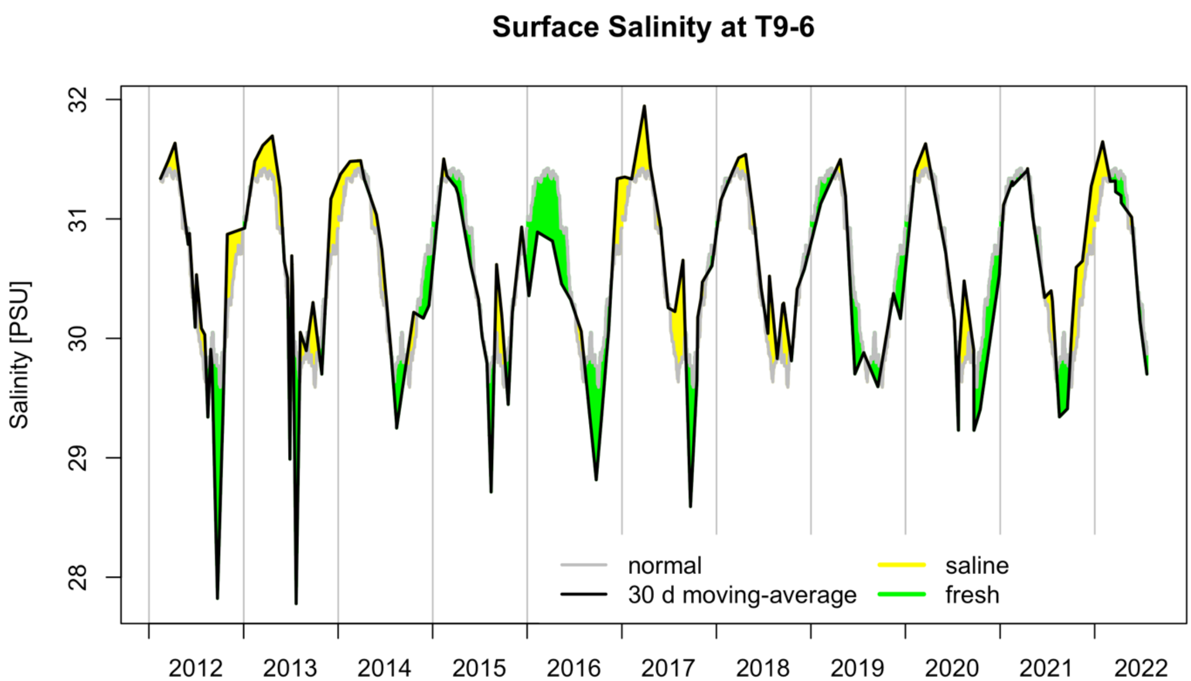


Figure 8. Surface layer temperature (top) and salinity (bottom) at mid-bay station, averaged over the upper 30 m. Also shown is the anomaly from the long-term seasonal average, with green (yellow) colors indicating fresher (more saline) conditions.

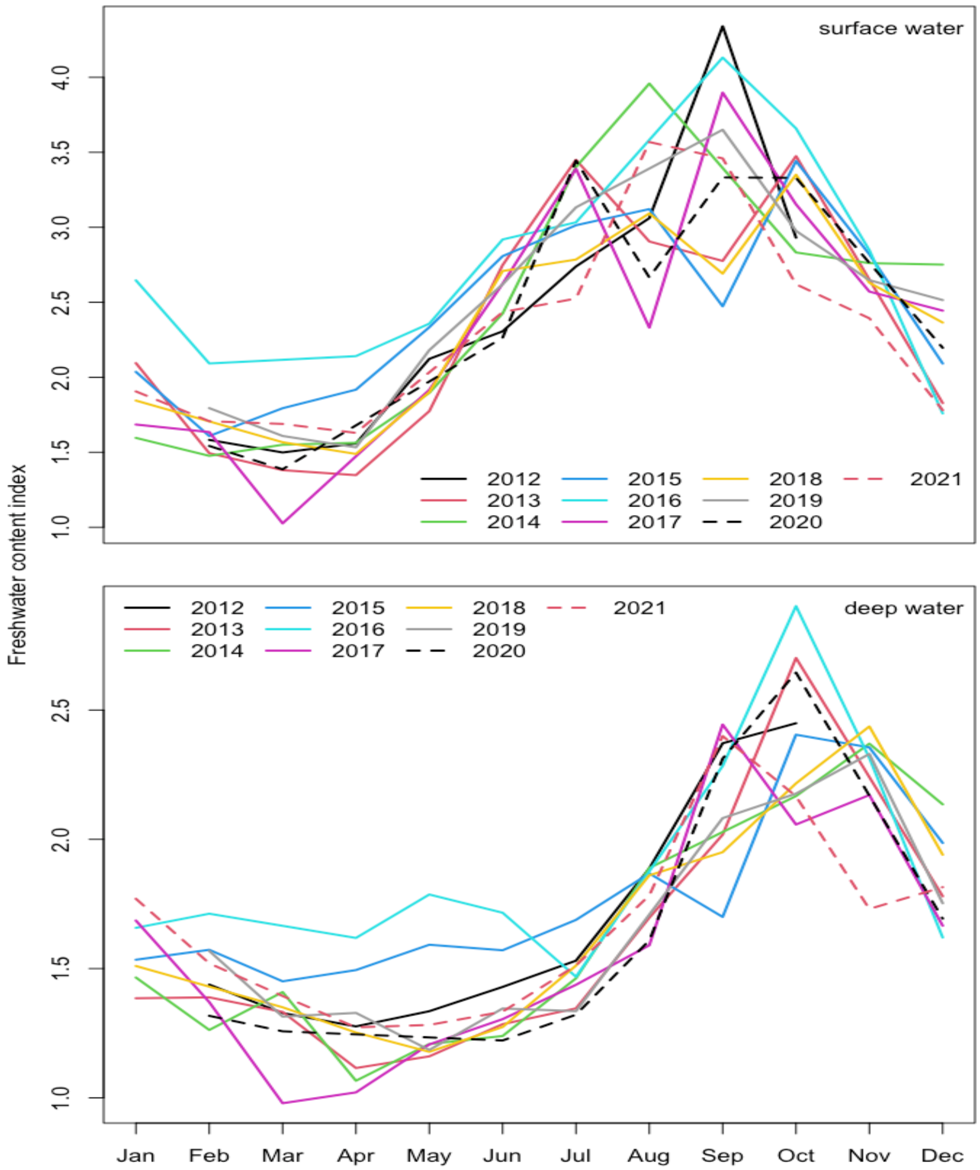


Figure 9. Monthly freshwater content index for mid-Kachemak Bay, 2012-2021. The index is derived from vertical oceanographic profile salinity data collected with one meter vertical resolution at ten stations on the cross-bay transect (Transect 9). Index values are calculated as the average of differences at each point from a reference salinity (33 PSU) for surface (1-15 m, top plot) and deeper (below 20 m, bottom plot) water column layers.

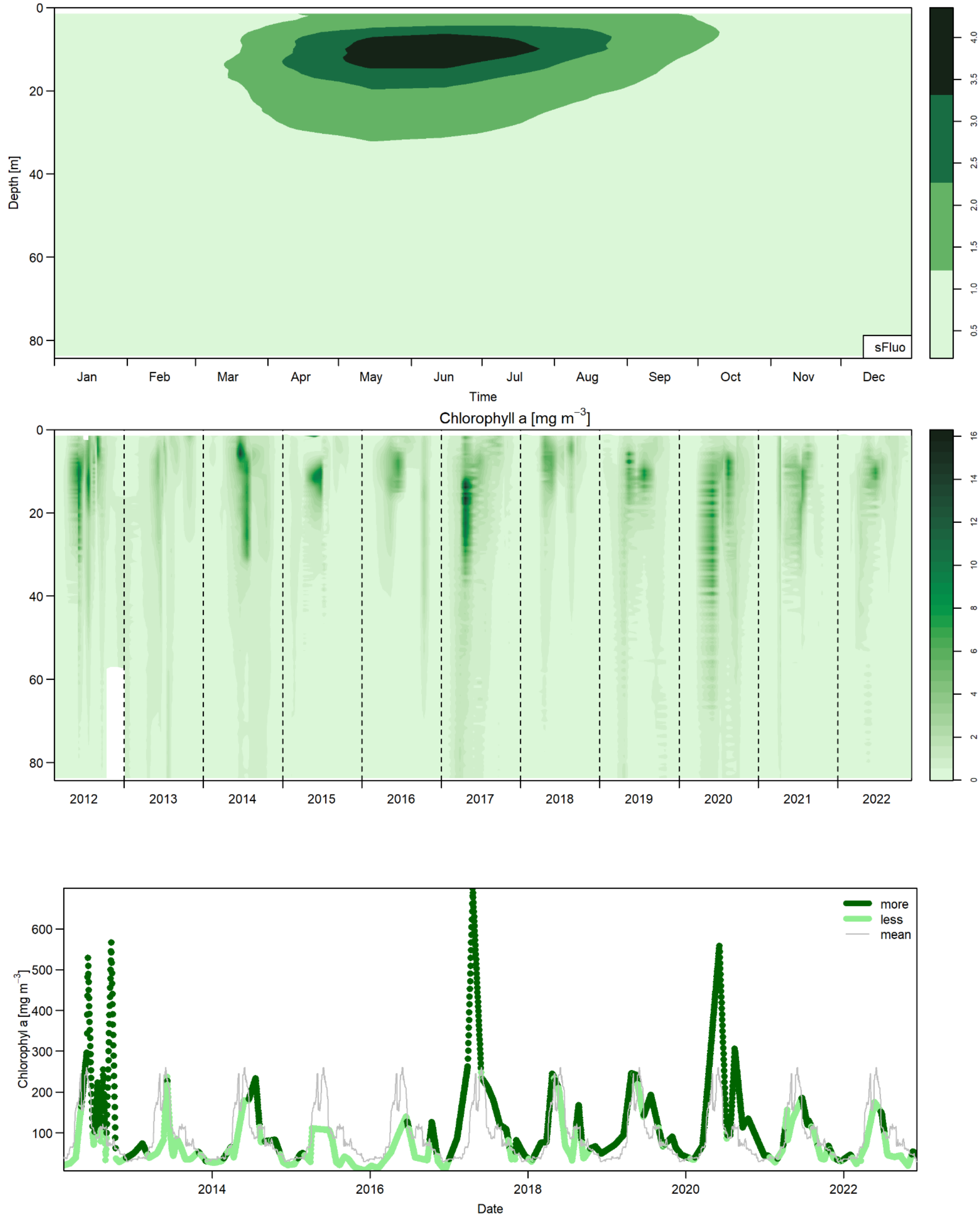


Figure 10. Seasonal climatology (top), section over time (middle), and water-column totals (bottom) of chlorophyll at the mid-Kachemak Bay station (Transect 9, station 6). The bottom panel shows the long-term seasonal mean (light grey) and monthly anomalies when conditions are above (dark green) or below (light green) average.

Along-estuary oceanographic sampling results

Examining seasonal along-estuary patterns from 2017-2021 (examples in Fig. 11), the Kachemak Bay conditions in March months were colder, more saline, and more vertically mixed, with reduced along-estuary oceanographic gradients, relative to other months of the year. March 2017 had lower water column salinities than other years (2018-2021, along-estuary sampling was added in 2017), likely reflecting the end of Pacific marine heatwave freshening in the Gulf of Alaska. The warm 2019 conditions were reflected in slightly warmer March water column temperatures across Kachemak Bay, as well as in early surface freshening and stratification in the inner bay. In July months, both along-estuary and vertical water column patterns had the least interannual variability compared to other times of the year, and relatively large vertical water temperature ranges (~8°C to 12°C). October months also had relatively small interannual temperature variability, with 2020 being the warmest during the study period. However, October salinity conditions varied the most between years, with interannual changes in surface and deep layer salinity values, degree of stratification, and along-estuary gradients. The freshest water column conditions of the year were observed along the bay in September and October, especially at depth, with the surface layer also the deepest in October. The freshest October conditions, in both surface and deep layers, were observed in 2020, and the 2021 survey captured intrusions of both fresh Alaska Coastal Current surface waters and more saline deeper shelf waters into southeast Cook Inlet. In December, water temperatures throughout the water column had relatively high interannual variability, with the coldest water temperatures (>3°C colder than other years) and most vertical mixing observed in 2021. A surface freshwater lens persisted into December in all years except 2021, with most pronounced surface freshening observed in 2018 and 2019. An interesting feature in Kachemak Bay is the consistency of the salinity values (~31.5 PSU) at depth throughout the bay for most months of the year, except September and October. This deep salinity layer (and density stratification) pattern is consistent with persistent intrusions of more saline ocean waters at depth to the head of the bay, reflecting the physical processes of subtidal, estuarine circulation, with subsurface inflow driven by outflows of locally-freshened surface waters.

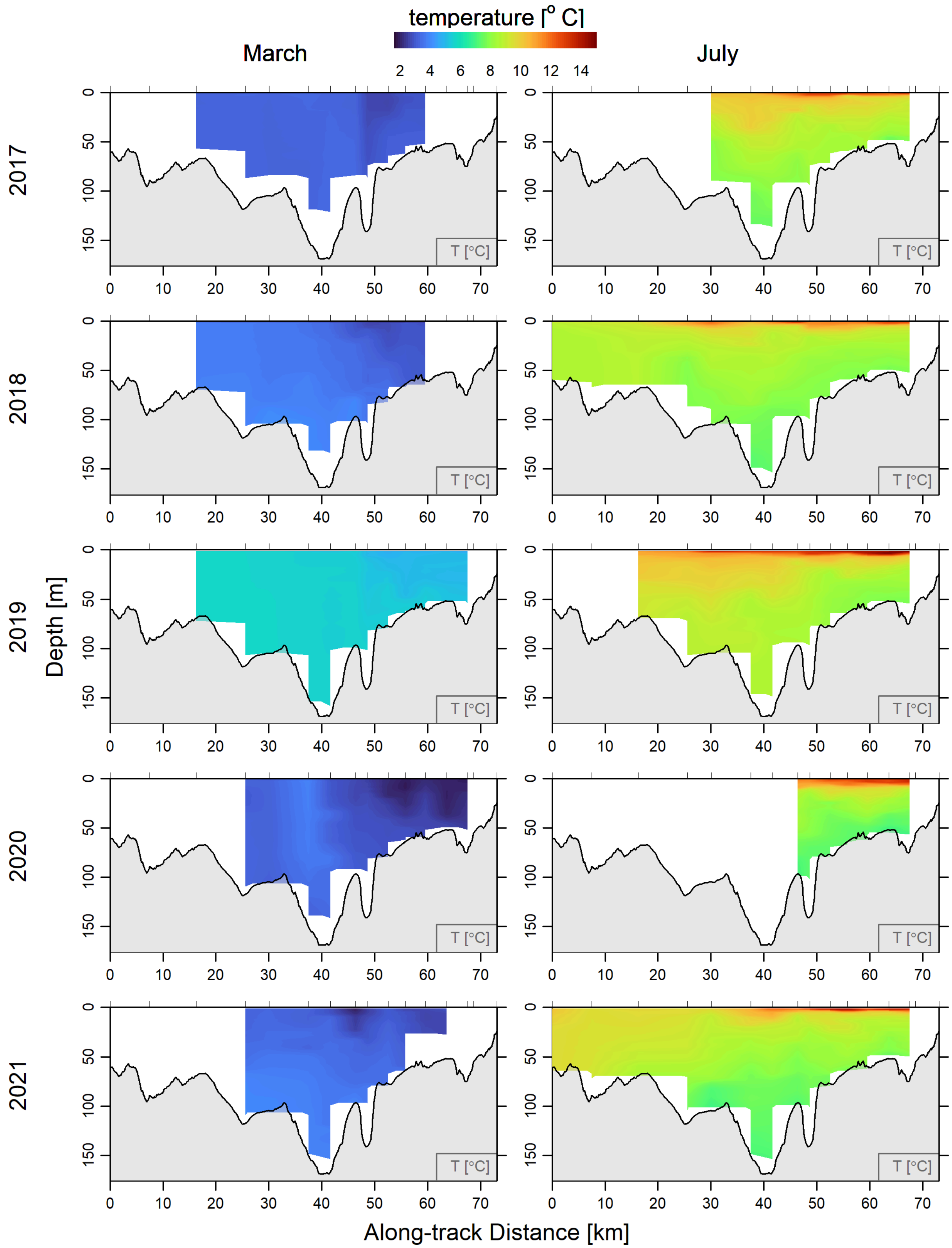


Figure 11. Along-bay vs. depth profiles of temperature for March and July, 2012-2021. Distance is from southeast Cook Inlet to head of Kachemak Bay. Continued on next pages.

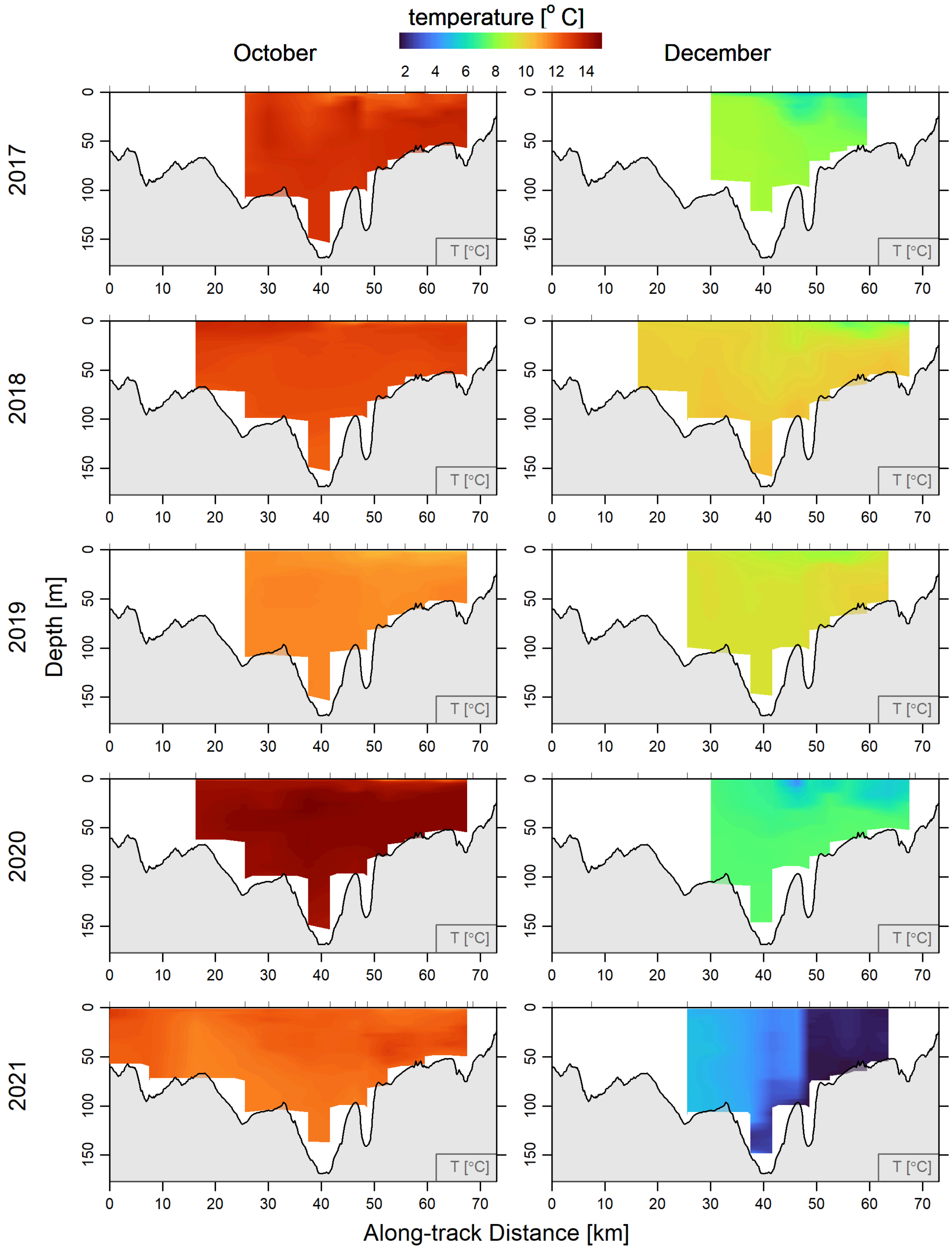


Figure 11 continued. Along-bay temperature profiles for October and December, 2017-2021.

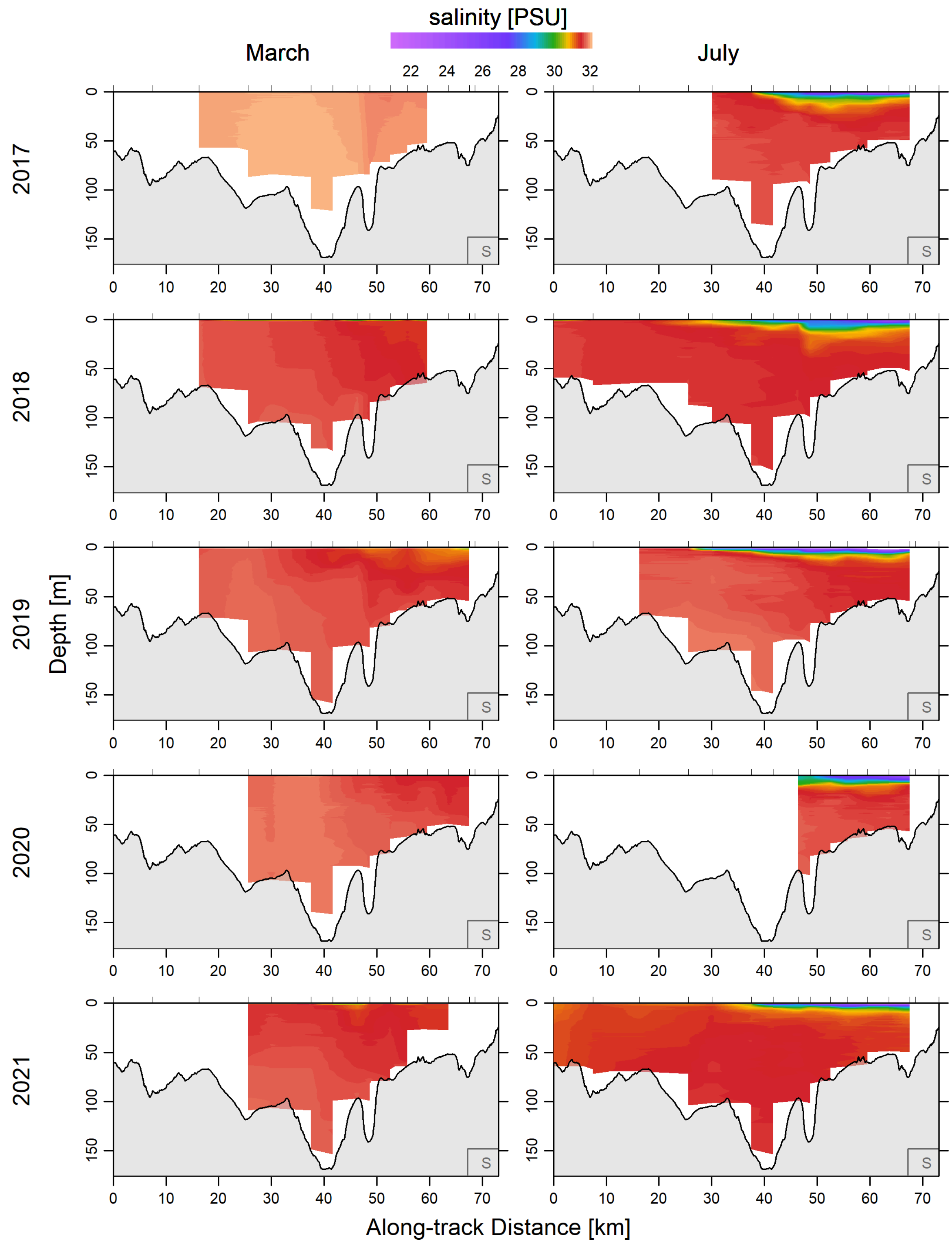


Figure 11 continued. Along-bay salinity profiles for March and July, 2017-2021.

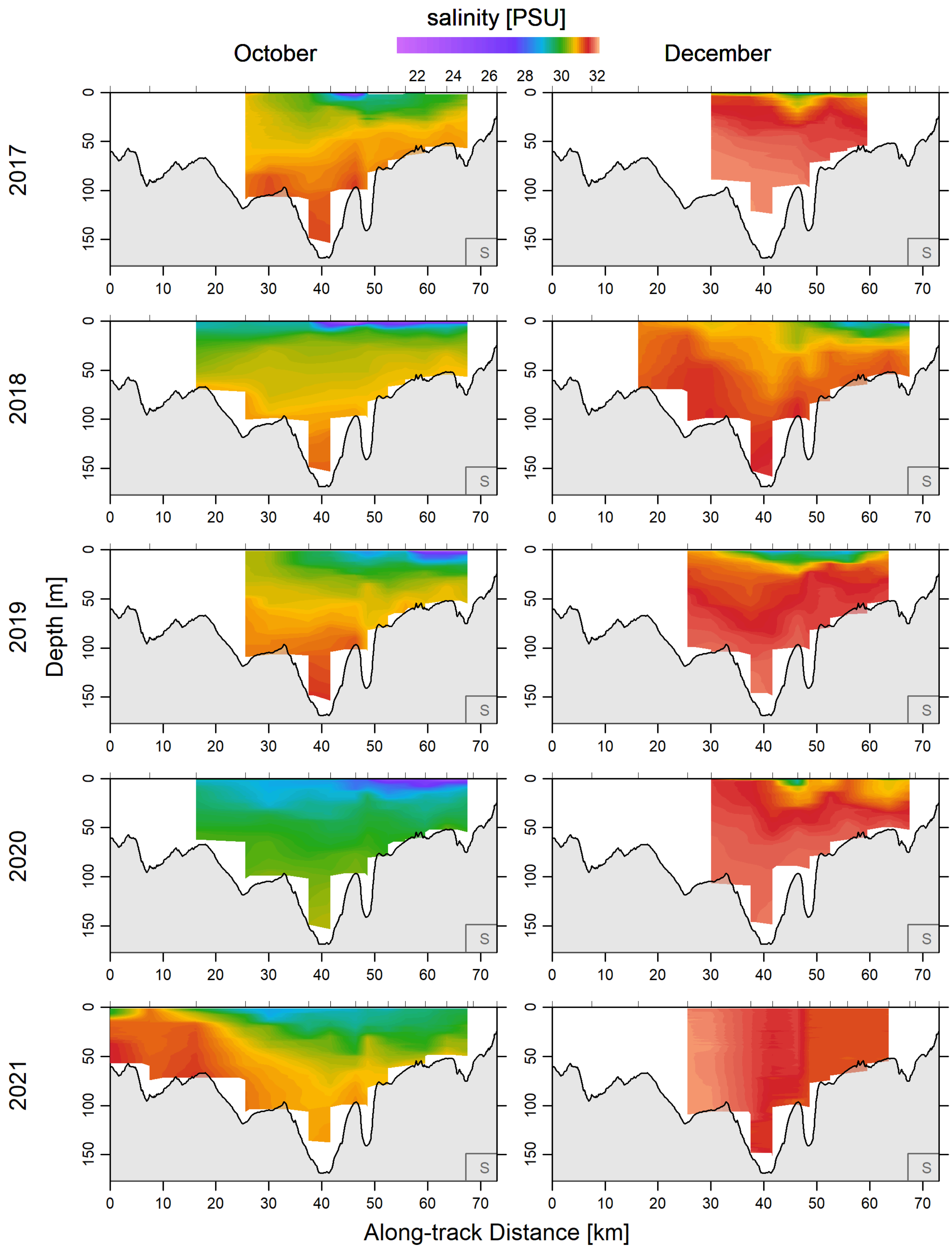


Figure 11 continued. Along-bay salinity profiles for October and December, 2017-2021.

Nutrients

Phosphate and nitrate/nitrite concentrations at Homer and Seldovia harbors were elevated during the winter months and reduced starting in March and through the summer, coinciding with peak chlorophyll concentrations in May from the spring phytoplankton bloom, with nutrients then generally increasing and chlorophyll declining through the rest of the year (Fig. 12). On average, only the Homer station surface waters had nutrient concentrations drop to levels that were limiting for phytoplankton growth and then only for the July samples. Summer nutrient concentrations declined to a lesser degree for Homer station bottom waters and Seldovia station surface and bottom waters, with relatively more nutrient depletion observed at the surface sensor of each station. Winter nutrient and chlorophyll concentrations remained similar at both station locations and sampling depths, with the exception of elevated phosphate concentrations at the Seldovia surface sensor location. These results are consistent with seasonal primary production dynamics and summer water column stratification even at these relatively shallow, near-shore locations. The average seasonal pattern in ammonia concentrations is more complicated, with a consistent peak at all sample locations in February, decline in spring concentrations, with an increase during the summer to peak again in late fall, with variable fall timing between the Homer and Seldovia stations and at different depths (Fig. 12).

The phosphate, nitrate/nitrite, and silica concentrations measured along the axis of Kachemak Bay in 2021, declined in spring and summer months, with timing and at levels similar to nutrient concentration patterns observed at the KBNERR water quality stations. However, low surface water concentrations (at times below detection limits) were observed over a longer period from May to August in the shipboard sampling (Fig. 13). Nutrient concentrations were also consistently higher at depth than at the surface, and these patterns were consistent with seasonal water column stratification and phytoplankton bloom dynamics. Along-estuary differences include a slower decline of spring nitrate/nitrite concentrations at the outer bay, compared to the inner bay, and a faster late summer/fall increase in all nutrient concentrations in the outer bay.

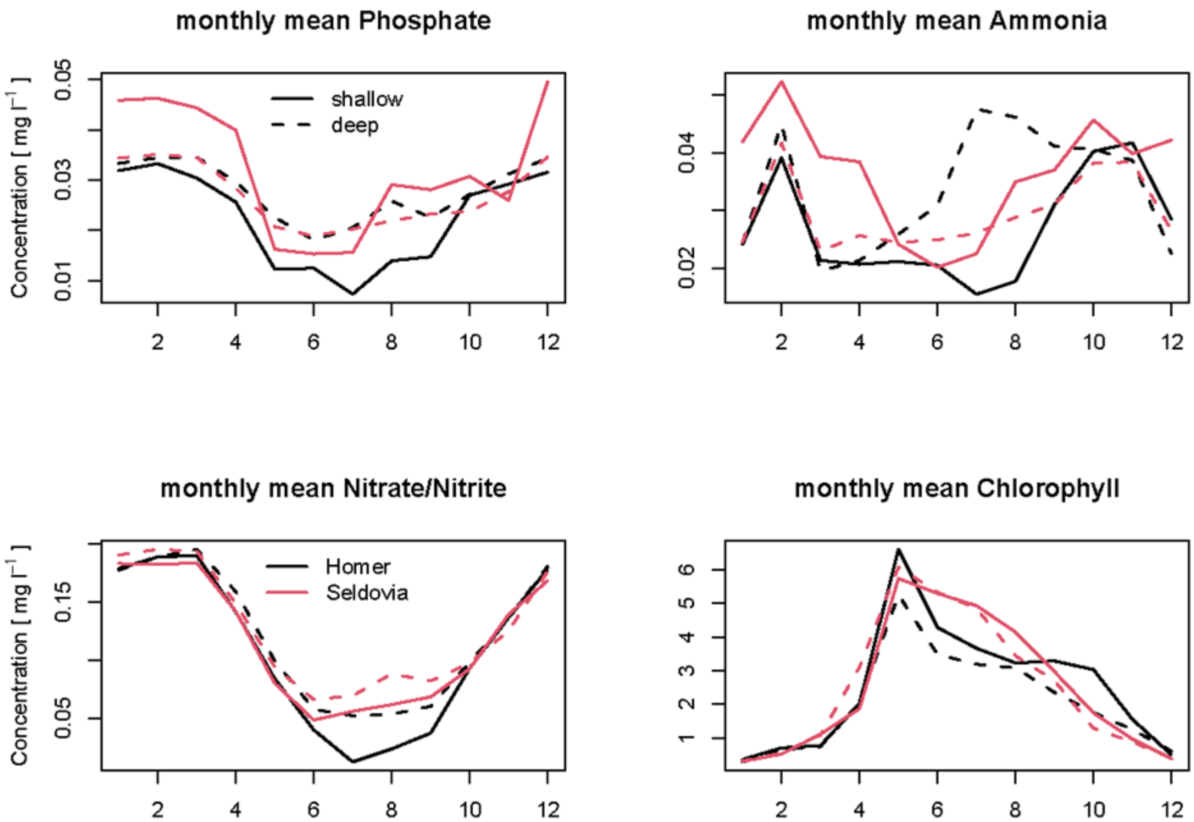


Figure 12. Monthly average concentrations (2002-2021) of macro-nutrients and chlorophyll calculated from analyses of water samples collected monthly near the surface and near the bottom (~7 m) at Kachemak Bay National Estuarine Research Reserve System Wide Monitoring Program sites at the Homer and Seldovia harbors.

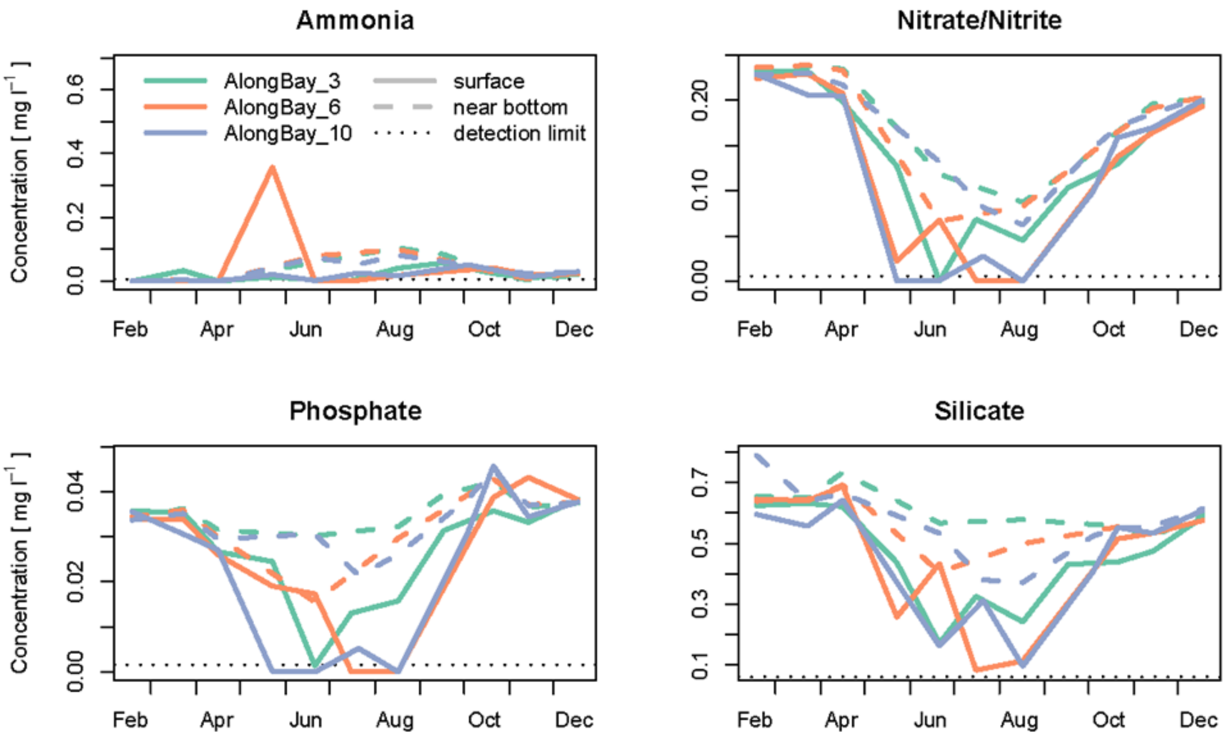


Figure 13. Concentrations of macro-nutrients from monthly surface and near-bottom water sampling in 2021 at three sites in Kachemak Bay. Site locations were along the axis of the bay in the outer-bay (AlongBay-3), mid-bay, (AlongBay-6), and inner bay (AlongBay-10). Sampling began in 2021.

Phytoplankton

In 2017, surface fluorometry samples at each CTD station indicated that phytoplankton abundance numbers and seasonal timing followed typical patterns observed in 2012-2016, with a late spring bloom and peak abundances in June/July (Fig. 14). However, surface sampling did not capture the early, higher chlorophyll concentrations in May/June that were estimated at depth from vertical fluorometer data profiles (Figs. 4, 10). In 2018 phytoplankton abundance remained relatively low, except for a small peak in July, which was consistent with water column data. More typical levels of phytoplankton abundances were observed in 2019, but the bloom timing was later, with peak abundances seen in July and August in both surface and subsurface waters. The delayed 2019 phytoplankton bloom timing was a surprise, given the anomalously warm ocean conditions that year. In 2020 shipboard phytoplankton sampling was not conducted in April, May and June, due to the coronavirus pandemic, and relatively low abundances were observed the rest of the summer. However, shipboard CTD/fluorometer casts were conducted in June 2020 and captured relatively large chlorophyll concentrations below the surface (Fig. 10). In 2021, phytoplankton abundance was very low throughout the spring, summer, and early fall months (Fig. 14), which was consistent with the vertical profile data (Fig. 10). The low 2021 phytoplankton cell counts were corroborated by similar results from KBNERR's phytoplankton monitoring program (not shown), which includes sampling from community monitors at sites throughout Kachemak Bay. As previously described, in 2021 we were able to collect and analyze monthly water samples on our shipboard oceanographic surveys for macro-nutrients (Fig. 13), to complement the long-term KBNERR nutrient sampling at the Seldovia and Homer harbor water quality stations (Fig. 12). The nutrient analyses from surface and near-bottom water samples at plankton monitoring stations in 2021 indicated that nutrients were depleted to below detectable levels in surface waters at mid and inner bay stations during the summer, when the water column was strongly stratified, with reduced levels also observed in deeper waters (Fig. 13). More water column nutrient sampling is needed to know whether the 2021 nutrient conditions were anomalous or not, and to develop robust relationships between nearshore and offshore monitoring results to take more advantage of the long-term KBNERR nutrient monitoring dataset. Typical seasonal patterns in phytoplankton community composition include a spring bloom dominated by diatom species in April/May, followed by a rise in abundance of dinoflagellate species as the diatom bloom declines. However, seasonal changes in community composition varied considerably by location and between years, and our year-round project data are being used to look at these changes in more detail with NCCOS colleagues, in combination with KBNERR phytoplankton monitoring data, other in situ observing data and satellite-based environmental information. During 2012-2021, maximum *Alexandrium* cell concentrations increased with warm water conditions in 2014-2016, decreased with cooler conditions in 2017 and 2018, remained lower than expected in the warmer conditions of 2019 and were also relatively low in 2021, staying well below the 500 cells/L concentrations at which saxitoxin levels are found to become concerning for human shellfish consumption (Fig. 15). 2020 samples were not analyzed for toxic algae due to pandemic-related laboratory access and staffing issues.

Saxitoxins were present in 2019 in both forage fishes and predator fishes, from an NCCOS HAB toxin trophic transfer project in Kachemak Bay/Cook Inlet and southwest Alaska. Toxin concentrations above regulatory limits for safe human consumption were found in Dolly Varden (*Salvelinus malma*), Pacific sand lance (*Ammodytes hexapterus*), and Pacific herring (*Clupea pallasii*) samples (Fig. 16). Sand lance and herring are of particular concern because they were commonly found in the stomachs of predator fish. Predator fish samples were collected for Pacific halibut (*Hippoglossus stenolepis*), pink salmon (*Oncorhynchus gorbuscha*), sockeye salmon (*Oncorhynchus nerka*), coho salmon (*Oncorhynchus kisutch*), and king salmon (*Oncorhynchus tshawytscha*). Toxin levels in halibut tissues did not exceed regulatory limits, but salmon samples showed higher levels of toxin that differed between species and tissue types (Fig. 17). Highest toxin levels were found in king salmon kidneys and red salmon livers, including some samples that exceeded regulatory thresholds (Fig. 17). Samples from fish muscle tissues have so far showed levels of toxin below the regulatory limits, possibly indicating that the fishes are able to metabolize and excrete the toxins without accumulating them in the muscle tissues which are most often consumed by people. Although the organs of these fish are not typically consumed, some people may harvest these organs for certain dishes. The *Alexandrium* abundances observed in the water samples collected in Kachemak Bay/Cook Inlet shipboard surveys remained lower than levels expected to cause paralytic shellfish poisoning, which is consistent with saxitoxin levels in fish that were mostly below the regulatory limit for human consumption. The NCCOS project helped document the presence of HAB toxins in fish, with concurrent oceanography and phytoplankton information from the GWA Cook Inlet oceanography project. However, more frequent sampling is needed to characterize temporal and spatial variability in *Alexandrium* blooms and quantify the timing and degree of saxitoxin transfer into the marine food web.

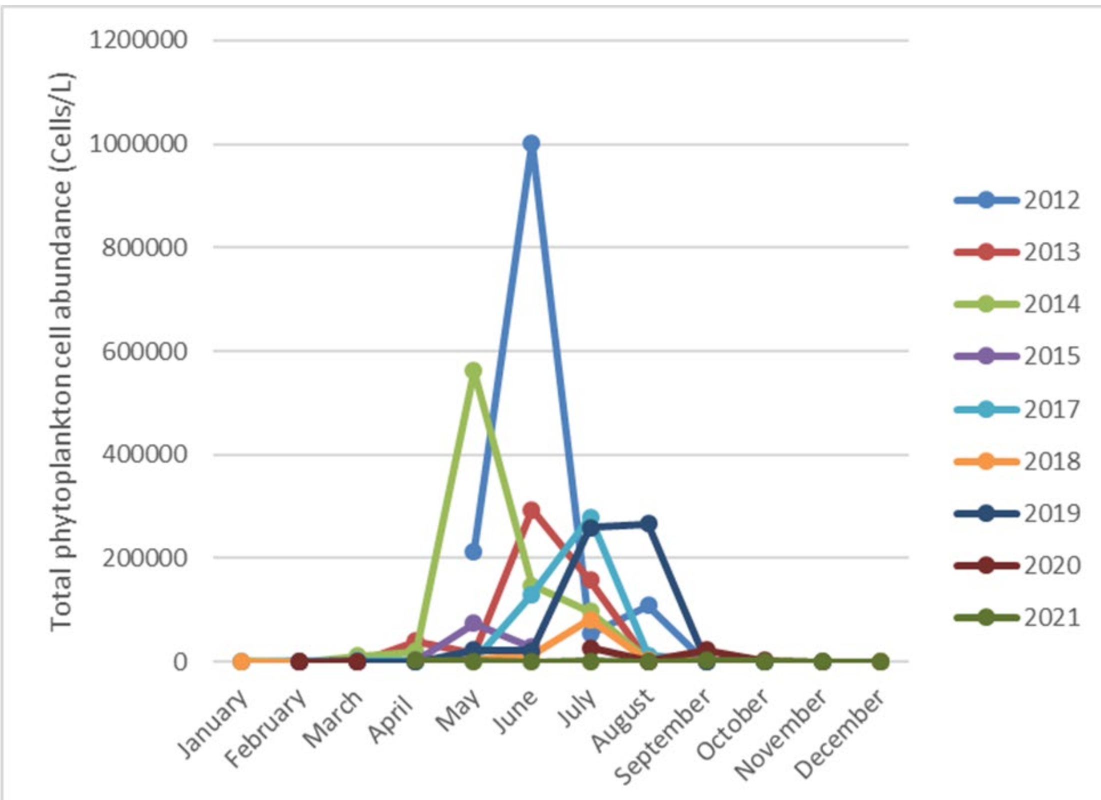


Figure 14. Total phytoplankton cell abundances from monthly sampling at the mid-Kachemak Bay oceanographic sampling station (Transect 9, station 6), color coded by year (2012-2021, except 2016). Cell abundances are shown as estimated cells per liter.

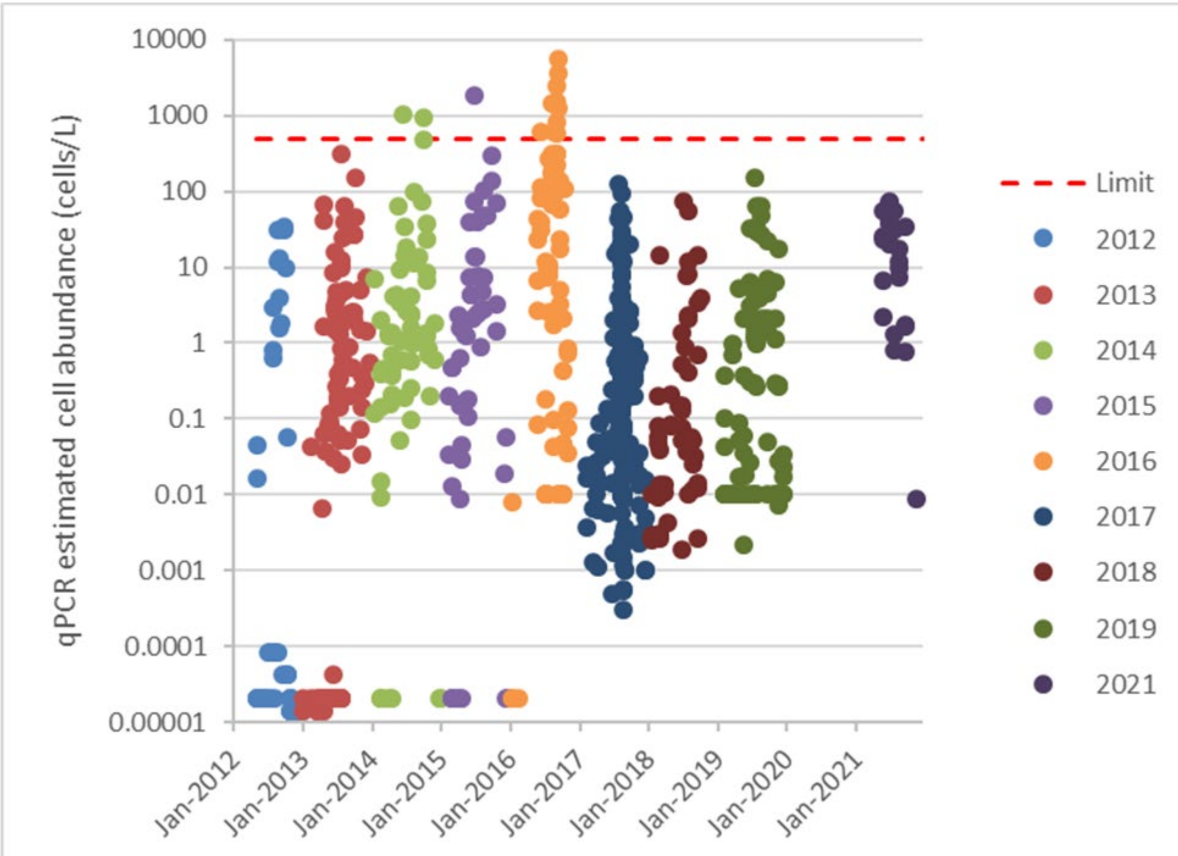


Figure 15. Kachemak Bay Alexandrium abundances, 2012-2021 (2020 samples not analyzed). The y-axis has logarithmic scale of cells/liter. Red dashed line indicates the 500 cells/L concentration, which is a concentration above which paralytic shellfish poisoning toxins can accumulate in shellfish at levels that pose risks to human health.

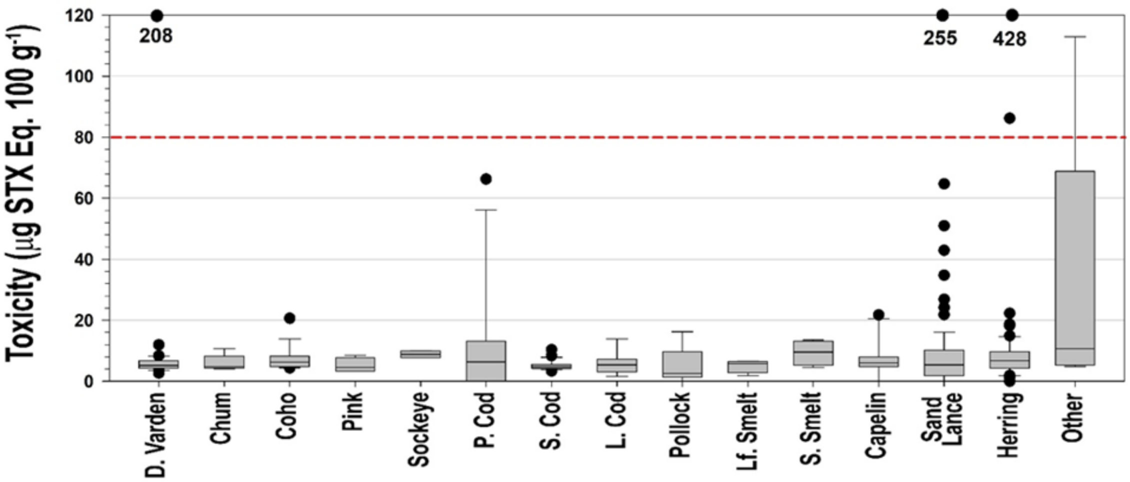


Figure 16. Fish toxicity in samples collected in 2019 from Kachemak Bay and southwestern Alaska. The y-axis shows toxicity in µg per 100 g of tissue. Red dashed line is 80 µg/100 g of tissue, the recommended limit for safe human shellfish consumption. The boxes represent the 25th-75th percentile, the horizontal line in the box is the median, the vertical lines are the 10th-90th percentiles, and the dots are outliers (beyond the 10th-90th percentiles).

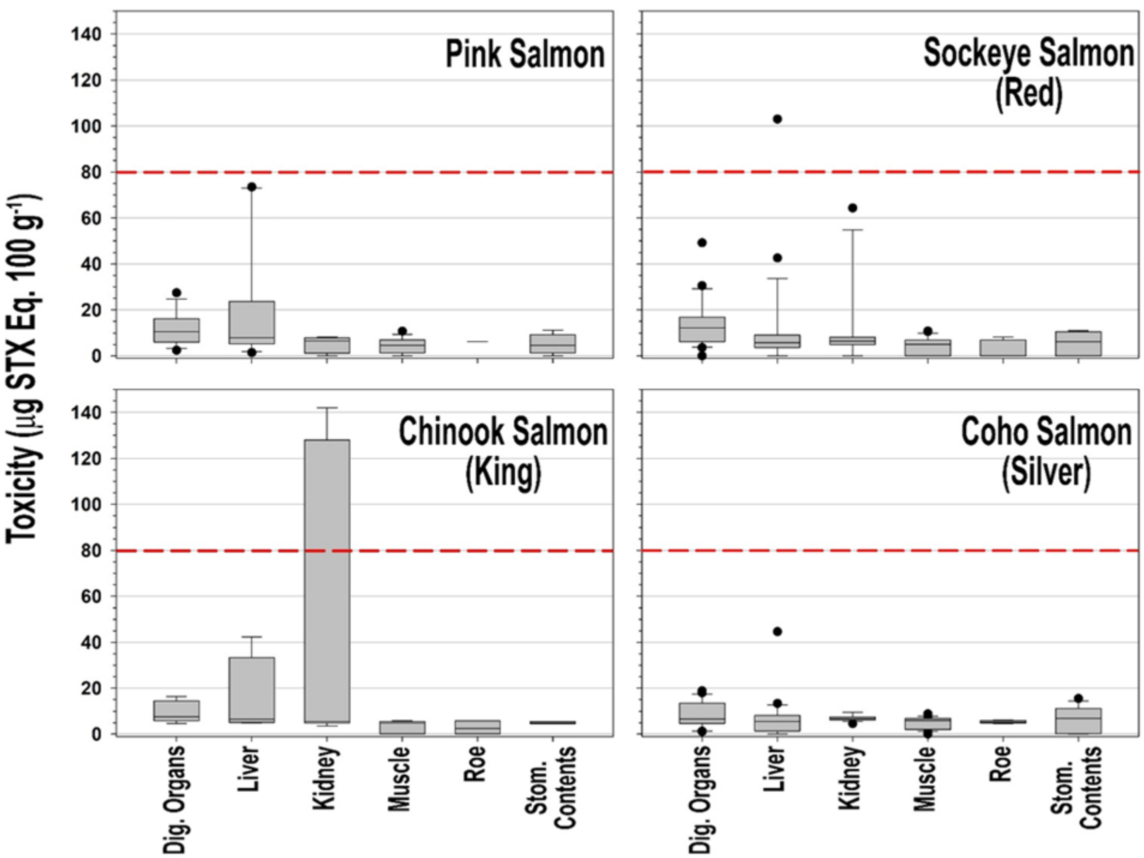


Figure 17. Pacific salmon saxitoxin toxicity in organs and tissues from four species (pink, sockeye, Chinook, coho) in 2019. X-axis shows results for different organs and y-axis shows the toxicity in µg per 100 g of tissue. The red-dashed line is 80 µg/100 g of tissue, the recommended limit for safe human shellfish consumption. The boxes represent the 25^{th}-75^{th} percentile, the horizontal line in the box is the median, the vertical lines are the 10^{th}-90^{th} percentiles, and the dots are outliers (beyond the 10^{th}-90^{th} percentiles).

Zooplankton

The most abundant zooplankton taxa during 2017-2021 (n = 276 samples at select CTD stations) were calanoid copepods (*Pseudocalanus*, *Acartia longiremis)*, barnacle nauplii, jelly fish (*Siphonophora)*, and arrow worms (*Parasagitta elegans)*, similar to what had been observed in 2012-2016. During 2012-2021, peak populations were typically observed in June/July, with considerable interannual variability in both abundance (Fig. 18, note the logarithmic scale) and timing of blooms in different zooplankton taxa. The lowest summer population peak was observed in 2021, with highest seen in 2019 and 2020 (Fig. 18). Using zooplankton and oceanography data from all Kachemak Bay and Cook Inlet project sampling stations from 2012-2018, the seasonal composition and temporal progression of the zooplankton community has been characterized in more detail, along with the zooplankton response to the 2014-2016 Pacific marine heatwave. Results were published in McKinstry et al. (2022), with highlights from that publication including: a) determining a mid-June peak in zooplankton abundance with generalized additive model analysis; b) finding no clear response of lipid-rich calanoid copepods before, during, and after the heatwave; c) identifying five seasonally progressing zooplankton groups from an indicator species analysis of the 88 most common taxa; and d) an earlier appearance of warm water copepod species (typical of the northern California current system) during the anomalously warm heatwave years of 2015/2016, at higher abundances and with much later persistence into the fall than observed in other years. The results also suggested that the warm ocean conditions in the heatwave may have allowed for an overwintering population of warm water copepods in lower Cook Inlet and Kachemak Bay. Based on analysis of 2012-2020 zooplankton data from mid-Kachemak Bay with multivariate method NMDS, which measures similarities in community composition by sample, zooplankton communities cluster in spring and winter, and there is a progression in community composition through summer and fall months (Fig. 19).

DISCUSSION

Gulf of Alaska marine conditions transitioned from the 2014-2016 Pacific marine heatwave to closer to average, but still warm, conditions in 2017-2018, followed by anomalous warming throughout much of 2019, and greater intra-annual seasonal variability in 2020 and 2021, with cold winters and a warm 2020 summer. The persistence of warmer than normal estuary waters during 2014-2020 was documented by decade-long, year-round GWA Kachemak Bay/Cook Inlet oceanography project sampling, and contextualized by over two decades of continuous water quality monitoring in Kachemak Bay. Overall, 2014-2020 was a strikingly persistent period of warmer than average conditions in lower Cook Inlet, as also noted by Litzow et al. (2022) in their examination of the ecosystem effects of 2014-2019 warming in the Gulf of Alaska.

Surface layer (~0-20 m) salinities and stratification are driven by local freshwater input and atmospheric processes, while salinities below the surface layer are much more consistent along the entire bay and reflect intrusions of and climate-driven changes in Alaska Coastal Current waters from the adjacent shelf. Year-round oceanographic observations indicate that a persistent intrusion of more saline ocean waters occurs all the way to the head of Kachemak Bay at depth, which is consistent with estuarine circulation processes driven by significant outflows of locally-freshened surface waters. The intrusions of shelf waters also bring higher nutrients from the Gulf of Alaska into the bay at depth. Deeper subtidal water inflows from the shelf to the lower Inlet are more common in late summer during more stratified water column conditions, and the speed of these subtidal inflows (at 15 m depth) through outer Kachemak Bay can equal the speed of the outgoing ebb tidal current (Holderied pers. comm.).

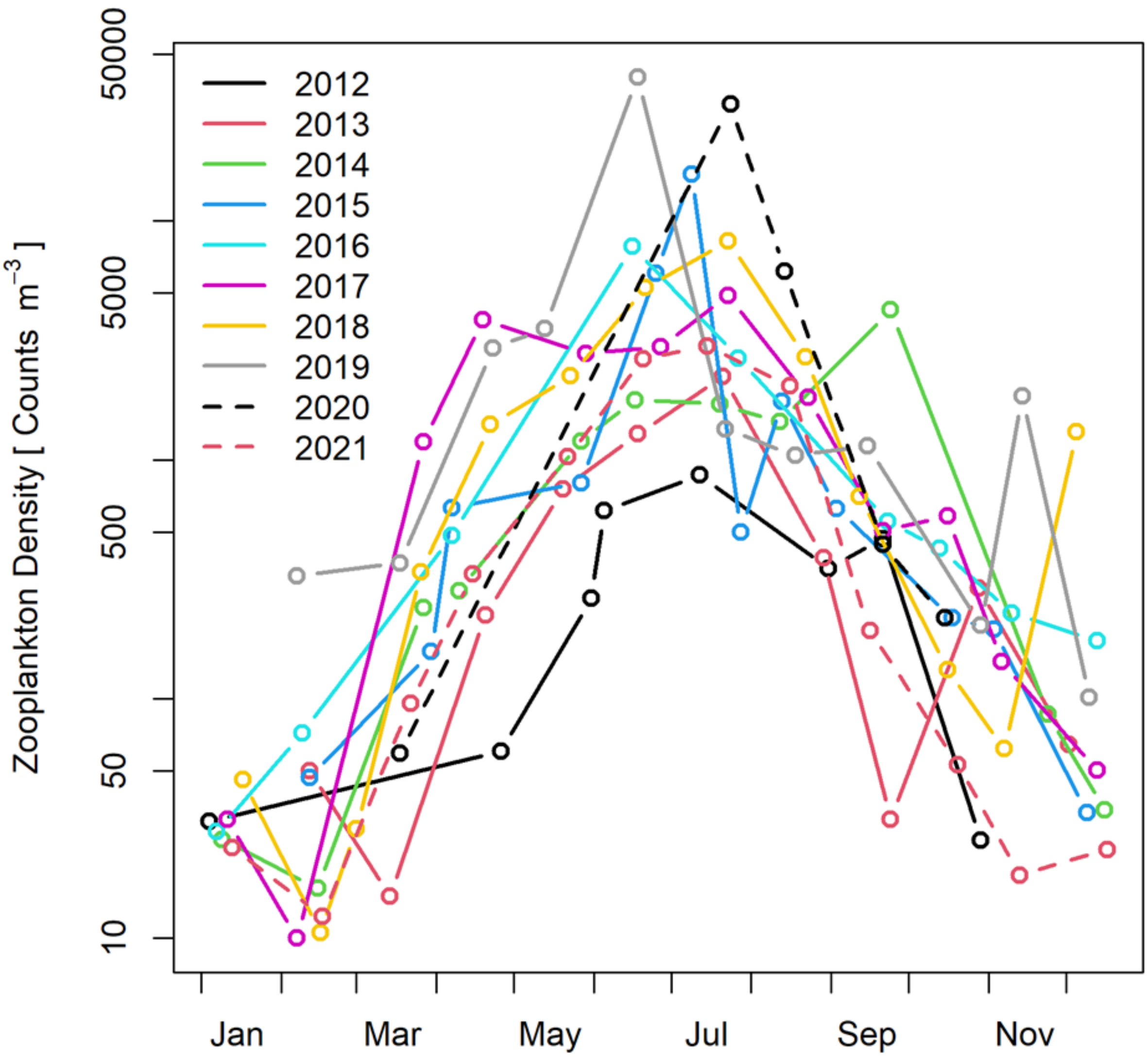


Figure 18. Seasonal and interannual variation in the total zooplankton population (counts of individuals per volume) from monthly sampling in central Kachemak Bay (Transect 9, station 6) from 2012-2020. Note the logarithmic scale on the y-axis.

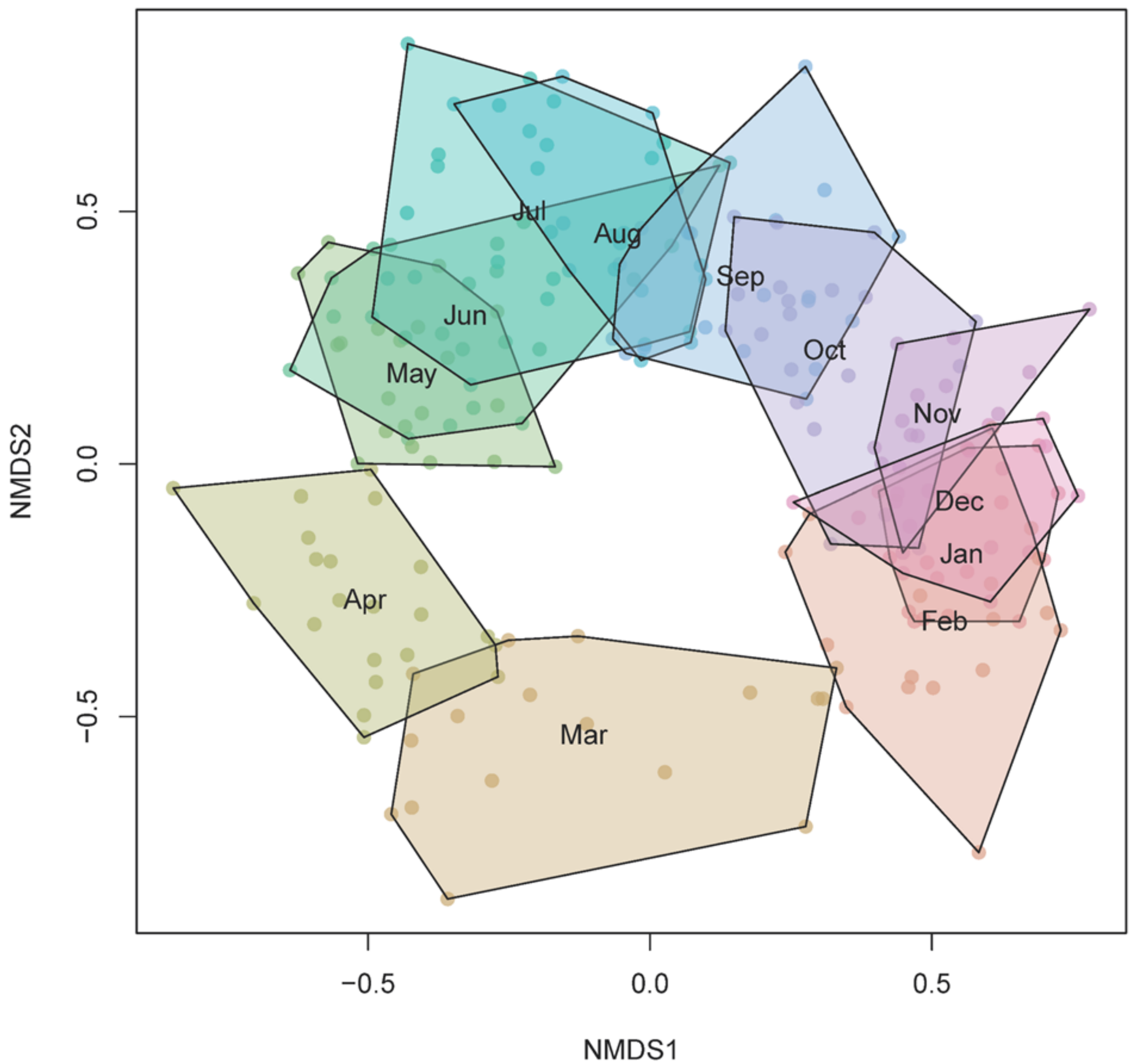


Figure 19. Seasonal cycle of zooplankton community composition, as detected by the first two non-metric multi-dimensional scaling (NMDS) axes. Data was from 2012-2020 monthly plankton and oceanography sampling at a mid-Kachemak Bay station (Transect 9, station 6).

Zooplankton community abundance generally peaked in June in Cook Inlet/Kachemak Bay, with interannual variability in the amount and timing of peak bloom abundance from May to September (McKinstry et al. 2022). While there was not a clear response of cold water calanoid copepod species following the 2014-2016 Pacific heatwave, this may be because ocean conditions, while closer to average, mostly remained on the warm side of normal through the 2018 period of that analysis. The increase of warm water copepod species during the most extreme part of the heat wave may indicate that anomalously warm winter waters during this period allowed for an overwintering population of these species in Kachemak Bay. Zooplankton community composition clustered more consistently in spring and winter months, with a seasonal progression in summer and fall months that varied more between years.

Cook Inlet/Kachemak Bay oceanography and phytoplankton data are being used to better understand climate-driven effects on phytoplankton dynamics, as well as how phytoplankton community composition may affect the initiation and intensity of harmful algal blooms. The phytoplankton community response to broader, climate-driven environmental changes was more variable during 2017-2021, with observations of high chlorophyll concentrations at depth in 2017 and much lower than average summer phytoplankton cell abundance in monthly ship surveys and in separate Kachemak Bay community plankton monitoring in 2020, that remain to be explained. Shipboard phytoplankton sampling was leveraged to monitor for toxic phytoplankton species (*Alexandrium* spp.) that produce the saxitoxins which cause paralytic shellfish poisoning (PSP), with the threat to coastal Alaska communities sadly evidenced by a PSP-related human death in Unalaska in the summer of 2020. Potentially harmful species were present in samples from Kachemak Bay and Cook Inlet throughout the year, but were most common and abundant in warmer months (Vandersea et al. 2018). The absence of *Alexandrium* blooms and PSP events in Cook Inlet/Kachemak Bay during the anomalously warm ocean conditions during 2019 was surprising and highlights the need for more research into and monitoring for factors other than temperature that drive these harmful algal blooms, potentially including phytoplankton community dynamics, nutrient conditions and *Alexandrium* cyst bed distributions.

Cook Inlet and Kachemak Bay ocean monitoring project hypotheses

The 2017-2021 Cook Inlet oceanographic monitoring project was designed to address three hypotheses (*H1-3*) regarding oceanographic and lower trophic marine conditions in this large, productive Gulf of Alaska estuary, as well as to contribute, with other GWA monitoring projects, to addressing a fourth hypothesis (*H4*) for marine conditions across the northern Gulf of Alaska region. As summarized here, all project hypotheses were upheld, though project results did raise additional questions, and suggestions for additional research and data syntheses efforts to address those questions are included below.

H1. Climate variability in the Gulf of Alaska region drives measurable changes in oceanographic conditions in both Cook Inlet and Kachemak Bay, which in turn affect the abundance, composition and phenology of phytoplankton and zooplankton communities within the region. Several climate variations were captured during the study period, especially the 2012-2013 transition from a 6-year period of relatively cold marine conditions to the persistently and extremely warm conditions of the 2014-2016 marine heatwave. Water temperatures were closer to normal conditions, though still warm, in 2017-2018, then much warmer than seasonal averages throughout 2019. Within year oceanographic variability increased in 2020-2021, with rapidly evolving, seasonal climate variations that lasted for several months. Compared to the longer historical perspective provided by KBNERR water quality station monitoring data (2001-present), most of 2014-2020 was warmer than normal, except for some relatively short winter periods. Increases in warm water copepod species abundance were observed during heat wave conditions, along with the longer seasonal persistence of these species into fall months. Phytoplankton species abundance and community composition did not change consistently in response to changing oceanographic conditions, including the response of toxic *Alexandrium* species, which become more abundant during the 2014-2016 heat wave, but not during equally warm conditions in 2019. The results from oceanographic monitoring and biological responses to climate-driven environmental changes in this region have been documented in annual project reports submitted to the EVOSTC and peer-reviewed publications and synthesis reports, including for oceanography (Danielson et al. 2022), toxic phytoplankton (Vandersea et al. 2018, 2019), zooplankton (McKinstry et al. 2022), intertidal ecosystem (Weitzman et al. 2021), and ecosystem response to the 2024-2016 marine heatwave (Walsh et al. 2018, Suryan et al. 2021a, 2021b).

The climate-driven response of the Cook Inlet/Kachemak Bay phytoplankton community during this period was not well explained by correlations with oceanographic variables. Enhanced monitoring of phytoplankton community dynamics and marine nutrient variability on sub-monthly scales would help address these questions, as would additional data syntheses that further integrate and extend results from monitoring on the Gulf of Alaska shelf and oceanic waters (Batten et al. 2022), with monitoring in the Prince William Sound (McKinstry and Campbell, 2018) and Cook Inlet/Kachemak Bay (McKinstry et al. 2022) estuaries.

H2. Gradients in oceanographic conditions and nutrient distributions between the Kachemak Bay estuary and Gulf of Alaska shelf waters are altered by climate variations, and changes in these gradients influence the distribution of plankton and upper trophic species. The along-Kachemak Bay salinity (and density stratification) patterns indicate that there is an ongoing intrusion of more saline ocean waters at depth to the head of the bay, which is consistent with estuarine circulation processes driven by significant outflows of locally-freshened surface waters (Fig. 11). Deeper waters in Kachemak Bay also freshened during the 2014-2016 heat wave, as shelf water salinities decreased from increased freshwater inputs along the coast. Results from 2021 Kachemak Bay nutrient observations (Fig. 13) are consistent with intrusions of deeper, higher nutrient shelf waters from the Gulf of Alaska into Kachemak Bay at depth. Results of climate-driven temperature variability across the northern Gulf of Alaska, including at Cook Inlet/Kachemak Bay oceanographic and nearshore monitoring sites, have been summarized in Danielson et al. (2022), with more details provided in GWA program synthesis reports (Holderied and Weingartner 2015, Danielson et al. 2021). Broadly, these analyses have identified synchronous responses to climate variability across the region in surface waters, with deeper water responses being more sensitive to coastal geomorphology and local physical processes, as illustrated with the Kachemak Bay CTD time series results in this report. One feature of the zooplankton community response to estuary-ocean gradients between Kachemak Bay and Cook

Inlet was a late spring meroplanktonic larvae assemblage that was limited to Kachemak Bay waters in all but one year (McKinstry et al. 2022). However, this difference is likely due to higher invertebrate populations in shallow Kachemak Bay waters, rather than oceanographic gradients.

Future work is needed to extend the integrated temporal and spatial analyses of Gulf of Alaska water temperature done with GWA and other datasets to salinity patterns, climate-driven changes in freshwater inputs, and the effects of physical advective processes on seasonal and interannual variability in water column structure and estuary-shelf exchange. More routine monitoring of Cook Inlet whale populations (currently limited to local whale-watching groups) and seabird populations (last done during the 2012-2016 GWA study period, see Doroff and Holderied 2018) is needed to assess how distributions of these upper trophic marine species respond to changing climate and marine conditions.

H3. Time-series of relative freshwater content, derived from repeated oceanographic sections across Kachemak Bay, provide a useful, integrated index of seasonal and interannual variability in freshwater input for the estuary and lower Cook Inlet region. The monthly freshwater content index, derived from repeated oceanographic sections across the middle of Kachemak Bay, provides a metric for comparison with (1) oceanographic time series measurements from the adjacent shelf, (2) local Kachemak Bay stream observations, and (3) freshwater forcing estimates from precipitation and watershed runoff models. These comparisons are needed to quantify the effects of local (within Kachemak Bay) and remote (Cook Inlet/Gulf of Alaska shelf) forcing on water column oceanography and estuary-shelf water exchanges. A unique opportunity to conduct these analyses comes from serendipitous stream and nearshore ecosystem monitoring that was conducted in Kachemak Bay from 2019-2022, as part of the National Science Foundation-funded, University of Alaska "Fire and Ice" Established Program to Stimulate Competitive Research (EPSCOR) program. Freshwater contributions were quantified by University of Alaska Anchorage researchers (PI: Dr. LeeAnn Munk) for five streams on the south side of Kachemak Bay, with intensive monthly (April-September) nearshore intertidal, zooplankton, and fish monitoring at the same sites by University of Alaska Fairbanks (UAF) researchers (PI: Dr. Brenda Konar) and deployment of drifter buoys to track freshwater plume dispersion. Future work to integrate the GWA and Alaska EPSCoR Fire and Ice datasets would improve understanding of how climate-driven changes in freshwater forcing affect marine conditions and nearshore ecosystems.

H4. Longer-term regional observations will show that the temporal response of oceanographic conditions across estuarine (Prince William Sound; lower Cook Inlet) and shelf waters of the northern Gulf of Alaska remains quasi-synchronous at seasonal and longer time scales, but asynchronous at shorter time scales. The temporal response of northern Gulf of Alaska ocean temperature conditions across synoptic to century-long time scales has been assessed in detail by integrating GWA monitoring and many other datasets (Danielson et al. 2022). These analyses confirmed that thermal variability tended to exhibit synchrony at seasonal and longer time scales across nearshore, coastal and offshore surface waters, and also found that thermal responses in subsurface shelf waters were lagged in time and depended on advective processes. At shorter time scales, surface temperatures varied with local shelf, coastline and estuary geomorphology and locally important physical ocean processes. Biological responses also occurred at different scales, with the responses of rocky intertidal invertebrate and macroalgal communities to environmental drivers over the GWA study period found to be more synchronous during the 2014-2016 heatwave than prior to it, indicating that broad, Gulf-wide climate variations, if sufficiently extreme, can override the more typical sensitivity to local variability in environmental conditions (Weitzman et al. 2021).

More work is needed on similar integrated analyses of the temporal and spatial response of salinity and stratification patterns in the northern Gulf of Alaska, especially to understand climate variations affect exchanges between waters of the Gulf of Alaska shelf and Prince William Sound and Cook Inlet estuaries. The varying temporal response of salinity observed in surface and subsurface Kachemak Bay waters provides one example of asynchronous responses at seasonal time scales.

Project goals and objectives

The broad goals of the Cook Inlet/Kachemak Bay ocean monitoring project were to understand the environmental drivers of variations in nearshore and pelagic species and food webs and contribute to GWA program characterization of the response of northern Gulf of Alaska coastal ecosystems to climate variability and change. The project objectives were summarized at the beginning of this report, with example results provided that outline how they have been successfully achieved over the 2017-2021 GWA study period. The project provided oceanography, nutrient and plankton data and analyses to achieve project goals as part of the GWA program. Specific project goals (*G1-G5*) identified in the 2017-2021 Cook Inlet/Kachemak Bay ocean monitoring project proposal are listed below, with the data and peer-reviewed science publications and reports that have been produced or contributed to for addressing them.

G1. Characterize seasonal and interannual trends and changes in marine conditions for GWA Nearshore component monitoring sites in Kachemak Bay

> Data: Continuous KBNERR water quality station data from Seldovia harbor, Homer harbor, and Bear Cove stations (2012-2021). Monthly CTD profiler temperature, salinity, dissolved oxygen, chlorophyll, turbidity and PAR data from across and along-Kachemak Bay transects (2012-2021).
>
> Publication: Weitzman et al. 2021.

G2. Quantify long-term marine trends and anomalies and identify the response of plankton communities to those physical changes, in order to assess climatic forcings on biological production

Data: Continuous KBNERR water quality station data (2012-2021). Monthly CTD profiler oceanographic data from across and along-Kachemak Bay transects and quarterly CTD oceanographic data in southeast Cook Inlet (2012-2021). Zooplankton and phytoplankton data from seven of the Kachemak Bay and two of the Cook Inlet CTD stations (2012-2021).

Publication: Doroff and Holderied 2018, McKinstry et al. 2022.

G3. Improve characterization of estuary-shelf linkages and how changes in estuary-shelf exchange affect changes in nearshore and pelagic species

Data: Monthly CTD profiler oceanographic data from along-Kachemak Bay transects, extended quarterly to the southeast Cook Inlet entrance (2017-2021). Continuous KBNERR water quality station data (2012-2021).

Publications: Doroff and Holderied 2018, Danielson et al. 2021, Danielson et al. 2022.

G4. Provide information on changing marine conditions needed to assess the effect of climate variations on harmful algal blooms, marine invertebrates, pelagic seabirds, and marine mammals in lower Cook Inlet and Kachemak Bay

Data: Continuous KBNERR water quality station data (2012-2021). Monthly CTD profiler oceanographic data from across and along-Kachemak Bay transects and quarterly CTD oceanographic data in southeast Cook Inlet (2012-2021). Phytoplankton data from seven of the Kachemak Bay and two of the Cook Inlet CTD stations (2012-2021).

Publications: Doroff et al. 2017, Walsh et al. 2018, Vandersea et al. 2018, Bentz et al. 2018, Vandersea et al. 2019, Weitzman et al. 2021, Suryan et al. 2021a, Suryan et al. 2021b.

G5. Assess spatial and temporal variability in oceanographic conditions and marine plankton communities across the northern Gulf of Alaska, including Prince William Sound, shelf waters, and lower Cook Inlet, in collaboration with other GWA Environmental Drivers component projects.

Data: Continuous KBNERR water quality station data (2012-2021). Monthly CTD profiler oceanographic data from across and along-Kachemak Bay transects and quarterly CTD oceanographic data in southeast Cook Inlet (2012-2021).

Publications: Danielson et al. 2021, Danielson et al. 2022, McKinstry et al. 2022.

CONCLUSIONS

During 2017-2021, the Cook Inlet/Kachemak Bay oceanography monitoring project characterized year-round oceanographic and plankton patterns at a sampling frequency that enabled resolution of seasonal and interannual temporal variability and spatial variability over the water column and across the estuary-ocean gradient from the head of Kachemak Bay to the southeast Cook Inlet entrance. Marine conditions in the region were closer to average, though still often warmer than normal, in 2017-2018, following the 2014-2016 Pacific marine heatwave, before more anomalous warming returned for most of 2019. Waters had more intra-annual seasonal variability in 2020 and 2021, with colder than normal winters and a warm 2020 summer, until water temperatures finally returned to average seasonal conditions in 2021. The largest interannual temperature changes occurred in winter months. Salinity observations confirmed patterns seen during 2012-2016, with more frequent variations observed in the surface layer, consistent with forcing from local freshwater and atmospheric processes. Salinities in deeper waters remained relatively consistent along the bay, varied on longer time scales, and had seasonal patterns consistent with intrusions of climate-driven Gulf of Alaska shelf waters. Seasonal evolution of the species composition of the zooplankton community was characterized from monthly sampling data, with heatwave responses in seasonal phenology and increased abundance of warm water species during periods of persistently warm conditions. Conversely, phytoplankton species composition and abundance varied less consistently with seasonal and interannual environmental changes, including the lack of an anticipated Kachemak Bay paralytic shellfish poisoning event during the warm 2019 summer. The results point to a need for monitoring of phytoplankton community dynamics and marine nutrient variability on sub-monthly scales, along with data syntheses that further integrate and extend phytoplankton monitoring results from the Gulf of Alaska shelf, Prince William Sound and Cook Inlet/Kachemak Bay. Oceanographic time series data were used to construct monthly, depth-dependent water column temperature, salinity, chlorophyll, and stratification climatologies, as well as a monthly index for variability in freshwater content in Kachemak Bay waters. The Cook Inlet/Kachemak Bay oceanography project provided time series data and information products on marine conditions and plankton communities for the GWA nearshore component in Kachemak Bay, for support of Federal and state Trustee agency management in the lower Cook Inlet region, and for science outreach to local communities.

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