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

Long-Term Monitoring of Oceanographic Conditions in Cook Inlet/Kachemak Bay to Understand Recovery and Restoration of Injured Near-shore Species

Exxon Valdez Oil Spill Trustee Council Project 16120114-G
Final Report

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Study History: The Cook Inlet/Kachemak Bay oceanographic monitoring project supported by the *Exxon Valdez* Oil Spill Trustee Council from 2012-2016 (Gulf Watch Alaska 16120114-G) has leveraged and expanded several existing physical and biological data time series in the study area. From 2001 to present, oceanographic data (temperature, salinity, dissolved oxygen, turbidity, pH) have been collected at two water quality stations in the Seldovia and Homer harbors, with monthly sampling for nutrients and chlorophyll, as part of the Kachemak Bay National Estuarine Research Reserve System Wide Monitoring Program. From 2012-2016 this project supported deployment of an additional water quality mooring in Bear Cove at the head of Kachemak Bay to improve monitoring of along-estuary oceanographic gradients. Historic water temperature data (1964 to present) from the National Oceanic and Atmospheric Administration National Water Level Observation Network tide gauge station at the Seldovia harbor provide a longer time series for the study area. Previous oceanographic surveys have been conducted on cross-estuary transects in lower Cook Inlet and Kachemak Bay (Okkonen and Howell 2003, Okkonen et al. 2009, and Murphy and Iken 2013) and this current project was designed to repeat sampling along some of those transects to create longer time series for the same locations. The transect numbering scheme was maintained from the earlier surveys to facilitate data comparisons, but since not all previous transects were repeated, the transect numbers in the 2012-2016 project are not sequential. In addition, National Oceanic and Atmospheric Administration Kasitsna Bay Laboratory researchers have conducted small-boat oceanographic sampling in Kachemak Bay since 2011 with support from the National Oceanic and Atmospheric Administration Integrated Ocean Observing System/Alaska Ocean Observing System. The oceanographic time series have been used to provide marine condition information for nearshore ecosystem monitoring conducted annually in Kachemak Bay since 2003 (Konar et al. 2010), which was also part of the Nearshore component of the 2012-2016 Gulf Watch Alaska program. Annual project reports were submitted to the *Exxon Valdez* Oil Spill Trustee Council, and Cook Inlet/Kachemak Bay oceanographic monitoring results were incorporated into the year 3 Gulf Watch Alaska science synthesis report (Holderied and Weingartner 2016).

Abstract: Oceanographic and plankton monitoring has been conducted year-round in lower Cook Inlet and Kachemak Bay from 2012-2016 to assess variability in marine conditions and effects on populations of nearshore and pelagic species injured by the *Exxon Valdez* Oil Spill. A 16-year (2001-2016) time series of nearshore water quality observations in Kachemak Bay and a 5-year (2012-2016) time-series of shipboard oceanographic observations made along repeated transects in lower Cook Inlet (seasonally) and Kachemak Bay (monthly) were used to quantify seasonal and interannual oceanographic variability and along- and across-estuary spatial gradients. Net tows for zooplankton and phytoplankton were conducted on shipboard surveys to identify spatial and temporal patterns in plankton biomass and community composition. The Gulf of Alaska and the Cook

Inlet/Kachemak Bay region experienced a transition from anomalously cold ocean water temperatures in 2012 to persistent warm temperature anomalies in 2014-2016. Biological responses in Cook Inlet and Kachemak Bay included changes in relative abundance of zooplankton species, seabird and sea otter mortality events, increased paralytic shellfish poisoning events, and changes in whale distributions. Opportunistic seabird and marine mammal observations on shipboard surveys found the highest densities of seabirds and sea otters in outer Kachemak Bay and southeast Cook Inlet.

Key words: Cook Inlet, *Exxon Valdez* oil spill, Kachemak Bay, long-term monitoring, oceanography, plankton

Project Data: Data collected under the Cook Inlet/Kachemak Bay oceanographic monitoring project during the 2012-2016 period of the Gulf Watch Alaska long-term monitoring program are published for public access through the Alaska Ocean Observing System (AOOS) Data Portal (http://portal.aoos.org/), following quality control/quality assurance and with associated metadata. The data custodian is

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Project datasets include:

Conductivity-Temperature-Depth (CTD) Profiler Data: Data for 2012-2016 are provided as annual files of processed CTD data in 1-meter vertical depth bins, aggregated from all transects. A zip file is also provided with the raw, hexadecimal format CTD cast data.

Zooplankton Data: Data from 2012-2015 are provided in a single file, with species in all samples identified to lowest possible taxon. Species identification is being conducted for 2016 samples and the data file will be updated when identifications are completed.

Phytoplankton Data: Data for 2012-2015 are provided in a single file with species in all samples identified to lowest possible taxon. Note: In 2016 phytoplankton sampling and analysis was supported under NOAA National Ocean Service, National Centers for Coastal Ocean Science research programs (not EVOSTC) and species-specific identifications and counts were not conducted that year. *Alexandrium* species (cause of paralytic shellfish poisoning) cell concentration time series from 2012-2016 are also provided.

Water Quality Station Data: Oceanography, nutrient and chlorophyll data for 2001-2016 are provided in annual files containing Kachemak Bay National Estuarine Research Reserve (KBNERR) System-Wide Monitoring Program (SWMP) data from the Bear Cove, Homer, and Seldovia stations. These data are also available from the NERR Centralized Data Management Office (CDMO) at http://cdmo.baruch.sc.edu/.

Citation:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The lower Cook Inlet/Kachemak Bay oceanographic monitoring project collected oceanographic and plankton data year-round at high temporal frequency and spatial resolution from 2012 to 2016, to 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 spill-affected 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 the large, highly productive estuary is important because marine conditions that affect biological production, including water temperature, stratification, fresh water runoff, the strength and position of the Alaska Coastal Current, regional modes of climate variability and nutrient conditions, change at a variety of time and space scales.

Oceanographic observations were made throughout the year at nearshore stations in Kachemak Bay, and shipboard oceanography and plankton surveys were conducted monthly (Kachemak Bay) and seasonally (lower Cook Inlet) to capture temporal and spatial patterns in marine conditions across the region. The sampling design provided data to assess variability at seasonal and interannual time scales, with the higher 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 localized areas of persistent convergence and enhanced vertical mixing associated with strong tidal currents moving across steeply sloping bathymetry. Opportunistic seabird and marine mammal observations were also made during shipboard surveys, in collaboration with the U.S. Fish and Wildlife Service (USFWS) Migratory Bird Program.

Continuous oceanographic measurements were made year-round at Kachemak Bay National Estuarine Research Reserve (KBNERR) water quality stations located at the Seldovia and Homer harbors as well as in ice-free months from a buoy near the head of Kachemak Bay at Bear Cove. Multi-sensor YSI (Yellow Springs Instrument) data sondes were deployed at all three sites to collect temperature, salinity, dissolved oxygen, turbidity, fluorescence and pH data. Monthly water samples at the nearshore stations were analyzed for nutrient and chlorophyll concentrations. Shipboard oceanography and plankton surveys were made along repeated transects from 2012-2016, with monthly sampling along a mid-Kachemak Bay transect, and quarterly seasonal sampling along an outer Kachemak Bay and three lower Cook Inlet transects. Monthly surveys were conducted from National Oceanic and Atmospheric Administration (NOAA) Kasitsna Bay Laboratory small boats, with larger vessel charters used to conduct the quarterly surveys. Vertical profiles of oceanographic data were collected with conductivity-temperature vs. depth (CTD) profilers (SeaBird Electronics 19plus) at stations along each transect, including temperature,

conductivity, pressure, dissolved oxygen, turbidity, fluorescence, and photosynthetically-available radiation. Concurrent with the oceanographic observations, zooplankton and phytoplankton net tows were conducted at three of the 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. Vertical zooplankton tows were conducted to 50 m depth with 333 μm bongo nets and surface water samples were collected and filtered through 20 μm nets for phytoplankton measurements. 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. Public access to Cook Inlet project data is available through the Gulf Watch Alaska program website and data portal operated by the Alaska Ocean Observing System (www.gulfwatchalaska.org).

The 5-year time series of shipboard oceanographic data collected as part of this project, in conjunction with the 16-year record of continuous observations from nearshore water quality stations, enabled an initial detailed assessment of seasonal and interannual variability in lower Cook Inlet. The Cook Inlet project provided oceanographic data to support the Kachemak Bay intertidal monitoring project of the Gulf Watch Alaska Nearshore component, as well as for ongoing fish, shellfish, seabird and marine mammal monitoring and management efforts by Trustee agencies in the region, including NOAA, USFWS, Alaska Department of Fish and Game, and Alaska Department of Environmental Conservation. During the 2012-2016 study period, the Gulf of Alaska and the Cook Inlet/Kachemak Bay region experienced a transition from anomalously cold water temperatures in 2012 to persistently warmer than average waters (up to 3 degrees Celsius monthly anomalies) during 2014-2016, particularly during winter months. Warm temperature anomalies were observed throughout the water column and deeper waters in Kachemak Bay also became slightly fresher in 2015 and 2016. An initial regional comparison of water temperature time series between Kachemak Bay, Prince William Sound, and the Gulf of Alaska shelf (GAK1 mooring) for the Gulf Watch Alaska science synthesis report found that temporal patterns were quasi-synchronous across the region at time scales longer than three months, but asynchronous at shorter time scales. Highest densities of seabirds and sea otters were found in outer Kachemak Bay and on the east side of the Cook Inlet entrance region, which are also areas where oceanographic convergences frequently occur. Biological responses in Cook Inlet and Kachemak Bay associated with the Pacific warm anomaly event included changes in relative abundance of zooplankton species, emergence of sea star wasting disease in the Kachemak Bay nearshore ecosystem, seabird and sea otter mortality events, increased paralytic shellfish poisoning events, and changes in whale distributions. Year-round oceanographic observations with high spatial resolution from the Cook Inlet project are being used in ongoing studies to assess the biological response of coastal nearshore and pelagic ecosystem responses to climate variability in the Gulf of Alaska.

INTRODUCTION

The Gulf of Alaska has rich nearshore and pelagic marine ecosystems, with coastal waters that are influenced by fresh water inputs from precipitation, rivers, snow pack, and glacier melt waters, the along-coast Alaska Coastal Current, and upwelling and downwelling associated with winds and complex bathymetry. Mundy and Spies (2005) describe the rich Gulf of Alaska nearshore and pelagic 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 (e.g., El Nino/La Nina, Pacific Decadal Oscillation), and these changes can have significant impacts on marine species in the region (e.g., Speckman et al. 2005). 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 2014-2016 El Nino and Pacific Warm Anomaly event (also known as the "Blob"). 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 (see Mundy and Spies 2005 for one summary), including the match-mismatch hypothesis (Mackas et al. 2007, Anderson and Piatt 1999), 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 in particular, we still lack an adequate understanding of how nearshore and pelagic food webs respond to climate-driven variations in physical processes.

The *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) established a long-term marine ecosystem monitoring program, also known as Gulf Watch Alaska (GWA), 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 monitoring project is part of the Environmental Drivers component of the GWA program. 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 oceanographic monitoring project is providing 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 to evaluate seasonal and interannual variability in marine conditions, changes in the timing of seasonal transitions and spatial gradients in estuarine conditions. The frequent Cook Inlet oceanographic sampling provided a temporal context for other GWA monitoring projects, including the Seward Line (spring/fall oceanographic surveys, project 16120114-J), Continuous Plankton Recorder (~ monthly plankton sampling transects from April to October, project 16120114-A) and Kachemak Bay intertidal monitoring (annual spring sampling, project 16120114-L). By combining oceanographic sampling on the shelf and in the two large estuaries of Prince William Sound and lower Cook Inlet estuary, the GWA program can better distinguish the effects of local (within estuary) and remote (shelf, North Pacific) climate forcing effects on nearshore ecosystems.

The Cook Inlet/Kachemak Bay project provided key information on coastal oceanography, plankton, and nutrient patterns to improve understanding of changes in the populations and distributions of marine species. The project specifically provided data on changing marine conditions to support the GWA Kachemak Bay Nearshore Component monitoring project (16120114-L). Additionally, these oceanographic time-series data support 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 (ADFG) and Alaska Department of Environmental Conservation (ADEC).

The project study area encompasses lower Cook Inlet (south of 60.02 degrees North), including Kachemak Bay, in southcentral Alaska. Lower Cook Inlet and Kachemak Bay have highly diverse marine habitats of rocky intertidal and kelp forests, seagrass beds, salt marshes and rich mudflats that support fish, shellfish, seabird and marine mammal species, including spill-affected species managed by Trustee agencies (NOAA, USFWS, ADFG and ADEC). The maximum tidal ranges of up to 8.7 m across the lower inlet and bay are among the largest in the world. Both Cook Inlet and Kachemak Bay have deeper channels (see shaded bathymetry in Fig. 1) and, particularly in the inlet, bathymetry-linked water convergences and vertical mixing are produced in areas where strong tidal currents move along steeper sea floor slopes. Two areas of strong convergence are found near the Kachemak Bay entrance to the north by Anchor Point and to the south by Point Pogibshi.

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 fresh-water 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 6-km long Homer Spit extends into Kachemak Bay from the northern shoreline and splits the bay into inner and outer bays. The inner bay is influenced more than the outer bay by freshwater inputs. Nearshore monitoring under the international Census of Marine Life program from 2003-2009 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 by the State of Alaska as a critical habitat area under ADFG, as well as by the state and NOAA as the Kachemak Bay National Estuarine Research Reserve (KBNERR). 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.

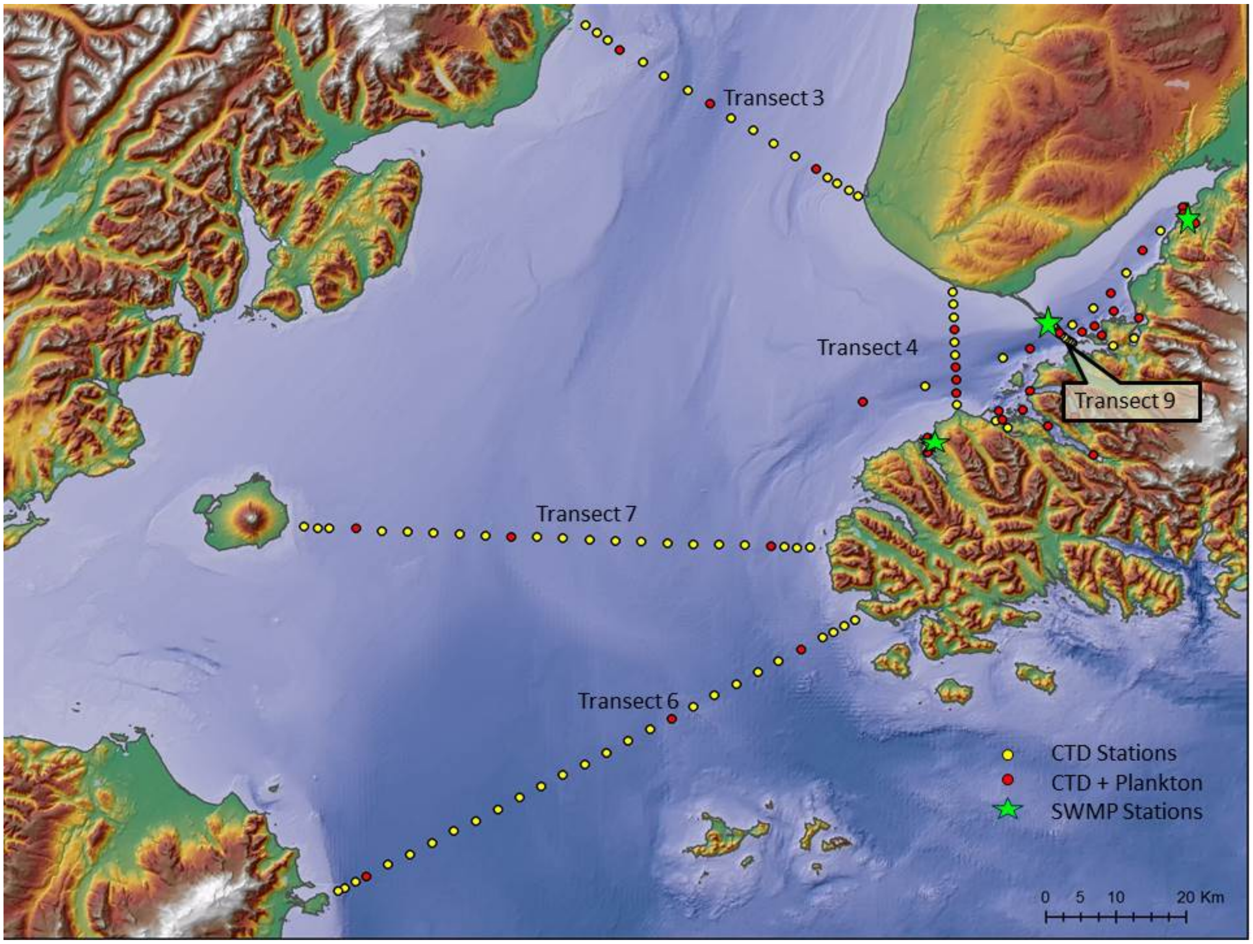


Figure 1. Sampling locations for the lower Cook Inlet and Kachemak Bay monitoring project. KBNERR System-wide Monitoring Program (SWMP) continuous sampling water quality stations are marked with green stars. Repeated shipboard sampling was conducted along five transects, with stations shown for shipboard oceanography (all dots) and phytoplankton and zooplankton sampling (red dots). Transect 9 was sampled monthly and Transects 3, 4, 6, and 7 were sampled seasonally (approximately quarterly) to characterize spring, summer, fall and winter conditions. Along-bay station locations in Kachemak Bay that were surveyed occasionally under non-EVOSTC programs are also shown.

OBJECTIVES

The overall goal of the Cook Inlet/Kachemak Bay oceanographic monitoring project was to collect oceanography and plankton data to help assess the effects of the seasonal and interannual changes in marine conditions on populations of nearshore and pelagic species injured by the spill. In order to provide oceanographic time series with sufficient temporal and spatial resolution to meet project and GWA program objectives, we collected data from three continuously sampling water quality stations in Kachemak Bay and repeated shipboard oceanographic surveys along five transects in Kachemak Bay and lower Cook Inlet (Fig. 1). Sampling included high frequency (continuous and monthly) measurements to assess timing of seasonal changes, as well as detailed spatial sampling across the lower Cook Inlet study area on a quarterly basis to assess estuary-shelf gradients in each season. The four project objectives addressed in the first five years (2012-2016) of the Cook Inlet/Kachemak Bay project are summarized below, with details provided in the Results and Discussion sections of this report:

1. *Examine the short-term variability and track long-term trends in oceanographic and water quality parameters and plankton communities*.

Continuous sampling at three Kachemak Bay water quality monitoring stations (Seldovia, Homer, Bear Cove) and monthly shipboard oceanography and plankton sampling of a mid-Kachemak Bay transect provided data to assess short-term variability in marine conditions. The 16-year time series of oceanographic data from the water quality stations in Seldovia and Homer was used to provide information for longer-term trends.

2. *Provide environmental forcing data for correlation with biological data sets (including Gulf Watch Alaska nearshore monitoring in Kachemak Bay and opportunistic Gulf Watch Alaska seabird and marine mammal monitoring in Cook Inlet/Kachemak Bay)*.

Oceanographic data and anomalies from continuous water quality station measurements in Kachemak Bay, as well oceanography and plankton data from shipboard sampling along two Kachemak Bay transects provided information on changing marine conditions to the Kachemak Bay nearshore sampling project (Iken and Konar, 16120114-L). USFWS observers were hosted for seabird and marine mammal observations on many of the seasonal research cruises in Kachemak Bay and Cook Inlet.

3. *Improve understanding of water mass movement in Kachemak Bay and lower Cook Inlet*.

Monthly small-boat oceanography surveys (2012-2016) along a mid-Kachemak Bay transect across the bay provided a time series of water column data at sufficient frequency to assess seasonal water mass patterns and with detailed cross-bay spatial resolution to identify oceanographic front locations. Quarterly shipboard surveys (2012-2016) along cross-estuary transects in Kachemak Bay (2) and lower Cook Inlet (3) provided water column time series data with detailed spatial resolution to assess seasonal and interannual changes in water mass distributions across the study area.

4. *Determine linkages, and temporal variability in those linkages, between Kachemak Bay/lower Cook Inlet, the northern Gulf of Alaska shelf (Alaska Coastal Current), and Prince William Sound (PWS), using oceanographic data from PWS, the GAK1 mooring, Seward Line and NPRB GOAIERP shipboard sampling along the shelf adjacent to Cook Inlet*.

Continuous measurements at water quality stations in Kachemak Bay (2001-2016) provided oceanographic time series data for comparison with other GWA Environmental Drivers component monitoring projects and other oceanographic time series in the spill-affected region. Kachemak Bay water temperature data were used for an initial assessment of temporal oceanographic linkages across the region for the GWA year 3 science synthesis report, in conjunction with continuous time series data from the GAK1 mooring data (Weingartner and Danielson, GWA project 16120114-P) and in PWS from the NOAA tide gauge station at Cordova (Holderied and Weingartner, 2016).

In addition to meeting the project-specific objectives, the Kachemak Bay/Cook Inlet oceanographic monitoring contributed to the GWA program by addressing the following FY12-16 questions under the FY12-16 Environmental Drivers component:

1. How do oceanographic patterns compare (and co-vary) between different locations in PWS, Gulf of Alaska shelf, and lower Cook Inlet?
2. What are the spatial patterns and timing of ocean stratification that lead to spring and autumn phytoplankton blooms?

METHODS

Water quality station sites

The KBNERR maintains water quality stations at three nearshore sites at Homer harbor, Seldovia harbor and Bear Cove (Fig. 2). The Homer and Seldovia sites are part of the NERR System-Wide Monitoring Program (SWMP). The site locations capture conditions within the outer bay (Seldovia), inner bay (Homer) and near the head of the bay (Bear Cove) to characterize along-estuary conditions. At the Homer and Seldovia sites, there are two multi-sensor instrument packages (YSI sondes) mounted vertically near the surface and near the bottom at each site. The Homer site is located on the north side of Kachemak Bay at the Homer harbor ferry dock (59.60203ºN, 151.40877ºW). The Seldovia site is located on the south side of Kachemak Bay at the Seldovia harbor ferry dock (59.44097ºN, 151.72089ºW), approximately 25 km southwest of the Homer site. Access to Seldovia is by boat or air, because the site is located off the highway system. The Homer surface sonde is only deployed during ice-free months (approximately April-November), but the Seldovia surface sonde and the deep sondes at both locations remain in place year-round. Bear Cove is a sub-bay near the head of Kachemak Bay, and a single surface sonde is deployed on a mooring buoy at the site, approximately one meter below the water surface. The Bear Cove site is located at 59.72620ºN 151.04865ºW and can be accessed only by boat. The mooring is deployed seasonally in ice-free months. Water samples are also collected monthly at the Homer harbor, Seldovia harbor and Bear Cove mooring water quality sites and analyzed for nutrient and chlorophyll concentrations. Water grab samples are collected one meter above the bottom ("deep") and one meter below the surface ("surface") to coincide with the sonde locations.

Shipboard sampling (oceanography, plankton, seabirds, marine mammals)

Shipboard oceanography and plankton sampling was conducted along five transects in lower Cook Inlet and Kachemak Bay, in an area bounded by the following coordinates: 60.0066˚N, - 152.5664˚W; 59.3510˚N, - 153.3015˚W; 58.8651˚N, - 153.2386˚W; 59.4196˚N, - 151.3091˚W; and 59.7421˚N, - 151.0570˚W (Fig. 1). A total of 87 station locations were sampled repeatedly throughout 2012-2016; with 67 stations on three transects in lower Cook Inlet and 20 stations on two transects in Kachemak Bay. Vertical oceanographic profile data was collected at every station (all dots in Fig. 1) and zooplankton and phytoplankton measurements were additionally made at three stations along each transect (red dots in Fig. 1, 15 stations total). Transect 3 is the northernmost transect in lower Cook Inlet and runs northwest from Anchor Point to near the mouth of the Red River south of Tuxedni Bay. Transect 4 is a north-south line in outer Kachemak Bay from Bluff Point to near the mouth of Barabara Creek. Transect 6 is the southernmost Cook Inlet line and runs west from Point Adam to Cape Douglas. Transect 7 is the middle transect in lower Cook Inlet and runs along an east-west line from Flat Island to Augustine Island. Transect 9 crosses the middle of Kachemak Bay from the end of the Homer Spit to Mckeon Flat, which is also the line that separates the inner and outer areas of the bay. Along-Kachemak Bay oceanographic sampling also took place during the 2012-2016 study period from the bay entrance to near the head of the bay at Bear Cove (Fig. 1), under separate NOAA National Ocean Service (NOS) National Centers for Coastal Ocean Science (NCCOS) and Alaska Ocean Observing System (AOOS) research programs. Along-bay sampling results are not discussed in this report, but the results helped inform development of revised project sampling designs for the next five years. Along-Kachemak Bay surveys will be routinely conducted under the GWA 2017-2021 program to further improve characterization of estuary-shelf oceanographic gradients and linkages between those patterns and seabird and marine mammal distributions. Table 1 summarizes the sampling frequency, locations and observation types for shipboard surveys during the 2012-2016 study period.

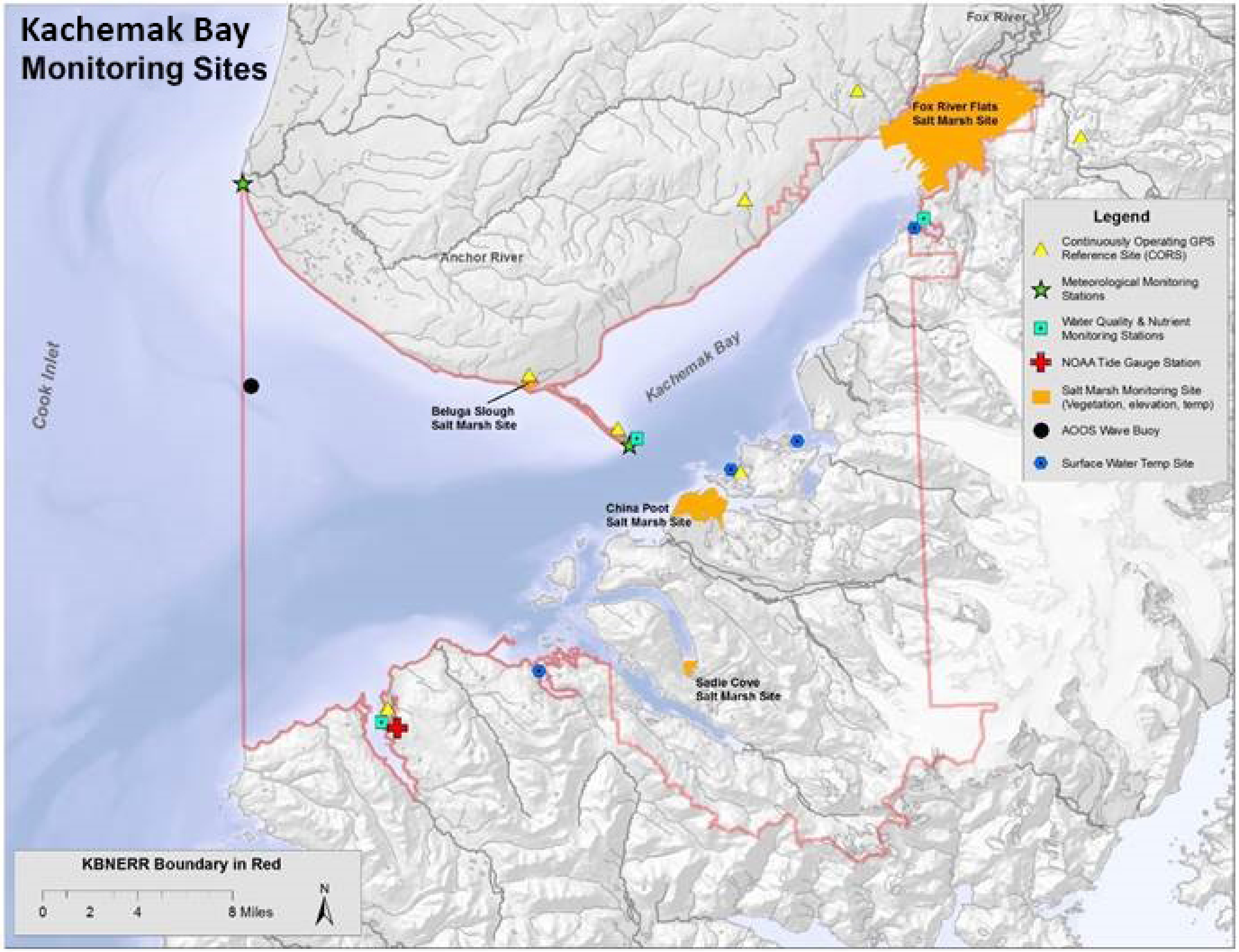


Figure 2. Locations of KBNERR long-term monitoring sites for water quality and nutrient monitoring (green squares) at Seldovia harbor, Homer harbor and Bear Cove, and the meteorological observation site (green star) at Homer Harbor. Also shown are observation types and locations for other routine oceanographic monitoring conducted in Kachemak Bay under non-EVOSTC programs.

Table 1. Number of repeated shipboard sampling stations on Cook Inlet/Kachemak Bay transects during the FY12-17 study period. The sampling events are organized by date (year and month on left), type of data (at top), and transect (columns under each data type at top). The number of stations is also summed for each transect and year (row at end of each year).

		CTD					**ZOOPLANKTON**					**PHYTOPLANKTON**					**WATER SAMPLES**				
		Transect No.					Transect No.					Transect No.					Transect No.				
Month	Year	3	4	6	7	9	3	4	6	7	9	3	4	6	7	9	3	4	6	7	9
February	2012					10															
March	2012					10															
April	2012					20					4					2	1	1	1	3	
May	2012	16	30	27	18	20	3	3	3	3	6	3	1	3	3	11	1	9	1	3	1
June	2012		20			33		7			6		5			6		2	2	2	1
July	2012	16	10	28	12	31	3	3	3	2	3	3	3	3	2	3	4	2	3	2	
August	2012		10			41					3		3								
September	2012					58					3					9					
October	2012	16	10	28	17	20	1		3	3	3	1		3	3	6		1	5	4	
	Σ=	**48**	**80**	**83**	**47**	**243**	**7**	**13**	**9**	**8**	**28**	**7**	**12**	**9**	**8**	**37**	**6**	**15**	**12**	**14**	**2**
January	2013					10					3					3					
February	2013		10			11		3			3		3			3		2			
March	2013					10					3					2					2
April	2013	16	10	23	24	10	3	3	3	3	3	3	3	3	3	2	2	1	4	3	1
May	2013					10					3					3					4
June	2013		10			20					3		3			6					1
July	2013	16	10	28	23	10	3	3	3	3	3	3	3	3	3	3			4	4	
August	2013					10					3					3					
September	2013					10					3					3					
October	2013		10			10		4			3		7			9					4
November	2013	16		20		1	3		3			3		3							
December	2013					10					3					3					

		CTD					**ZOOPLANKTON**					**PHYTOPLANKTON**					**WATER SAMPLES**				
		Transect No.					Transect No.					Transect No.					Transect No.				
	Σ=	**48**	**50**	**71**	**47**	**122**	**9**	**13**	**9**	**6**	**33**	**9**	**19**	**9**	**6**	**40**	**2**	**3**	**8**	**7**	**12**
January	2014					10					3					3					
February	2014	16	10		12	10	3	3		3	3	3	3		3	4					
March	2014					10					5					3					
April	2014	16	10	28	23	10	3	3	3	3	3	3	3	3	3	3					
May	2014					11					3					3					1
June	2014					11					3					3					
July	2014	17	10	28	22	12	3	4	7	6	3	3	3	3	3	3	2	2	6	0	1
August	2014		10			10		3			2		3			3					
September	2014					10					3					3					
October	2014	16	10	22	22	10	3	3	3	3	3	3	3	3	3	3	2	2	4	2	2
November	2014					10					3					2					
December	2014					10					3					3					
	Σ=	**65**	**50**	**78**	**79**	**124**	**12**	**16**	**13**	**15**	**37**	**12**	**15**	**9**	**12**	**36**	**4**	**4**	**10**	**2**	**4**
January	2015					10															
February	2015	16	11	28	17	12	3	3	3	3	3	3	3	3	3	3	1		1		
March	2015					10					3					3					
April	2015	16	10	10	17	10	3	3	2	3	3	3	3	2	2	3				1	
May	2015					10					3					3					
June	2015					10					3					2					
July	2015					12					3					3					
August	2015		10			20					3		2			5					
September	2015		10			10		3			3		3			3		3			3
October	2015	17	11			11	3	4			3	3	4			3	4	5			4

		CTD					**ZOOPLANKTON**					**PHYTOPLANKTON**					**WATER SAMPLES**				
		Transect No.					Transect No.					Transect No.					Transect No.				
December	2015		10			10		3			3		3			3					
	Σ=	**49**	**62**	**38**	**34**	**125**	**9**	**16**	**5**	**6**	**30**	**9**	**18**	**5**	**5**	**31**	**5**	**8**	**1**	**1**	**7**
January	2016					10					4					2					
February	2016	16	10	26	23	10	3	3	3	3	3	3	3	3	3	3	3	4	6	6	4
March	2016	16	10	20		10	4	6	5		3	3	3	3		3	4	4	4		3
April	2016		1		1	10		1		1	3		1		1	3		2		2	3
May	2016					10					3					3					3
June	2016		10			10		3			3		3			3		4			4
July	2016	17		30	23		3		3	3		3		3	3		4		4	4	
August	2016					11					3					3					4
September	2016		10			10		3			3		3			3		4			4
October	2016					9					3					3					4
	Σ=	**49**	**41**	**76**	**47**	**90**	**10**	**16**	**11**	**7**	**28**	**9**	**13**	**9**	**7**	**26**	**11**	**18**	**14**	**12**	**29**
January	2017					10					3					3					4
	Σ=	**0**	**0**	**0**	**0**	**10**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**3**					**4**

Standard Operating Procedures

Oceanographic and plankton sampling methods, including instrument calibration, data collection, sample processing, and quality control/quality assurance (QA/QC), were conducted in accordance with the project sampling protocols (available on the GWA Ocean Workspace). The sampling procedures outlined in the original project proposal and in the sampling protocol were used throughout the 2012-2016 study period and are summarized below for each type of observation in the Cook Inlet/Kachemak Bay project.

Water quality monitoring

At the Homer and Seldovia water quality stations, two YSI 6000 series multi-parameter water quality monitors (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. Details are available at the NOAA National Estuarine Research Reserve System (NERRS) Centralized Data Management Office (CDMO) website (http://cdmo.baruch.sc.edu/) and in the project sampling protocol document. 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 min sampling intervals.

Deployment data were uploaded from the YSI sonde and pre- and post-deployment data were removed. The 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.

Nutrient and chlorophyll measurements were made from monthly water grab samples collected at two depths (near-surface and near-bottom) at the Homer and Seldovia water quality stations. Unless delayed by weather, all grab samples from both stations were taken within a 24-hour period and close to high tide, to best assess stratification conditions. The Homer station can be accessed year around by vehicle, but sampling at Seldovia and Bear Cove, which requires boat or air access, was occasionally limited by weather conditions. At each station, two replicate samples are collected using a triggered vertical Niskin bottle at depths of one meter from the surface and one meter from the bottom. All samples are transferred to wide-mouth Nalgene sample bottles that were previously acid washed in

10% hydrochloric acid (HCL), rinsed three times with distilled-deionized water, dried and followed by rinsing 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 hrs and 30 min. 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. Chorophyll-a 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 also maintained routine monitoring of weather conditions from 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 are being used to provide information on local atmospheric forcing conditions in conjunction with oceanography and nearshore GWA monitoring projects in Kachemak Bay. Additional information on the meteorological datasets can be found at the NERRS CDMO website.

Shipboard oceanography and plankton surveys

Shipboard oceanography and plankton surveys were made along five repeated transects in Kachemak Bay and lower Cook Inlet (Fig. 1) from February 2012 to January 2017 (Table 1). The mid-Kachemak Bay transect (Transect 9) was sampled monthly and transects in lower Cook Inlet (Transects 3, 6, and 7) and outer Kachemak Bay (Transect 4) were sampled quarterly, with additional opportunistic surveys made along Transect 4. Monthly Kachemak Bay surveys were conducted from NOAA/NCCOS Kasitsna Bay Laboratory (KBL) small boats, with larger vessels chartered for the quarterly Cook Inlet surveys. Station spacing was designed to capture detailed spatial gradients, with approximately 400 m spacing on the mid-Kachemak Bay transect and one nautical mile (1852 m) spacing on the outer bay transect. On the Cook Inlet transects, stations were spaced one nautical mile (1852 m) apart near shore and two nautical miles (3704 m) apart off shore to capture nearshore oceanographic gradients associated with sloping bathymetry. Transect and station locations are consistent those used previously by Okkenon et al. (2009) and Murphy and Iken (2013) in lower Cook Inlet and Kachemak Bay. Due to adverse and abruptly changing weather and sea state conditions in Cook Inlet, it was not always possible to complete sampling of all transects or all stations along a given transect. For safe CTD deployment and effective data collection, sampling conditions were limited to wind speeds less than 25 knots and wave heights less than six feet.

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 (Fig. 1), at a nominal drop rate of 1 meter/second. Two SBE 19plus CTDs, provided by the NOAA KBL and KBNERR, were used for the project. The KBL CTD included a SBE 43 dissolved oxygen sensor, WETLabs combined chlorophyll fluorometer/turbidity sensor (ECO-FL-NTU(RT)), and Li-Cor PAR sensor. The KBNERR CTD included a SBE 43 dissolved oxygen sensor, Li-Cor PAR sensor, WETLabs fluorometer and a WETLabs transmissometer. The 19plus CTDs and ancillary instruments were sent to SeaBird Electronics for routine calibration of the temperature, conductivity, pressure and dissolved oxygen sensors, with calibrations of other sensors done by the respective instrument manufacturers.

Data processing only used data from the CTD downcast, because the sensors are located near the bottom of CTD and water flow is disturbed by the instruments and cage on the upcast. CTD cast data were processed with standard SBE algorithms in the SBE data processing software package (*http://www.seabird.com/software*). Raw hexadecimal format files were downloaded from the CTD and processed by NOAA KBL researchers with the following steps: 1) converted to text format; 2) filtered to adjust response times of the temperature and pressure sensors; 3) aligned to adjust the temperature and conductivity data for small vertical differences in sensor locations; 4) edited to remove data with pressure reversals (during upcast or temporary ascents during the cast) and flag potentially spurious data; 5) derived parameters were calculated (e.g., depth, density); and 6) data were averaged to 1m depth bins. Data points that were flagged by the SBE processing software as missing or outlier values were removed from the processed dataset. 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.

After data processing and QA/QC, all the individual CTD cast data files (1 m binned data) were aggregated into one file for each year (text file with comma separated value format), organized by transect number and sampling date. For initial analysis, Ocean Data Viewer software was used to create along-transect versus depth contour plots of oceanographic variables (temperature, salinity, density, and chlorophyll (from fluorescence)) for each sampling event date and transect. Time series contour plots (time vs. depth) were also produced for selected individual stations from each transect for the 2012-2016 period. Examples of both products are provided in the Results section of this report and are available to GWA researchers on the GWA Ocean Workspace for the entire time series.

Zooplankton sampling

Zooplankton were collected at three repeated stations along each shipboard survey transect in Kachemak Bay and lower Cook Inlet (Fig. 1). Sampling was conducted with vertical tows of a bongo style zooplankton net with a 60 cm mouth diameter and 333 μm mesh (Aquatic Research Instruments, Hope, ID). To calculate sample volume, a mechanical flow meter (General Oceanics) was attached to the frame of one of the two bongo nets. Zooplankton samples were taken from the cod end in the net that did not have the flow meter attached. The net was towed vertically from 50 m to the surface at each plankton station or to near-bottom for stations with shallower depths. A tow rate of approximately 0.5 m/s was used for the tows, which equated to a nominal sample volume of 14.2 m^3 for a 50 m depth station. Preserved zooplankton samples were identified and enumerated to lowest taxonomic classification possible by Dr. Rob Campbell at the Prince William Sound Science Center in Cordova, Alaska.

Phytoplankton sampling

Phytoplankton monitoring efforts were primarily conducted under NOAA/NCCOS research programs, but EVOSTC-funded ship time was leveraged to increase the spatial coverage of phytoplankton sampling across the study area. Surface water samples were collected at each plankton station (locations shown as red dots in Fig. 1) on all the shipboard surveys and more frequently (weekly in summer months) from the NOAA KBL dock. Seawater samples were collected from the dock or boat using a bucket with volumetric markings to quantify the amount of water filtered. Seawater was then poured through a 20µm 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, under NOAA/NCCOS funded research programs, harmful algal bloom 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).

Seabird and marine mammal observations

NOAA KBL and KBNERR researchers coordinated with the Dr. Kathy Kuletz at USFWS to place seabird observers on 14 project research cruises from 2012 through 2016. A single observer collected survey data from the bridge of the vessel and surveyed while the vessel was on oceanographic transects and in transit between transects during daylight hours, using a 300 m strip transect. Flying birds were recorded at ~ 1 min intervals (depending on ship speed) and birds on the water or foraging were recorded continuously, using standard protocols (Kuletz et al. 2008). Marine mammals were recorded using the seabird protocol, thus the densities for marine mammals are not to be used for other than distributional inference. Seabird and marine mammal observations were entered directly into a laptop computer linked to a hand-held GPS using dLOG software (Ford 2004). To calculate densities (birds/km^2), the transects were divided into approximately 3-km segments, with the centroid used to assign a latitude and longitude for each sample. Seabird densities were compared for east and west portions of lower Cook Inlet (divided approximately at longitude 152° W). Seasons were defined as winter (December-February), spring (March-May), summer (June-August) and fall (September-November). All processing and analysis was completed using R v. 3.3.2 (R Development Core Team 2016).

RESULTS

Under the Cook Inlet/Kachemak Bay monitoring project, year-round environmental data were collected from 2012-2016 to provide oceanographic information at high-frequency to assess seasonal and annual variability in marine conditions, with detailed spatial resolution to characterize estuary-shelf water gradients. Selected oceanographic and biological results are presented below from the time series of water quality station observations, shipboard oceanography and plankton surveys, and opportunistic surveys of marine birds and mammals conducted in Kachemak Bay and lower Cook Inlet. All data files from the project are publicly available on the GWA data portal (www.gulfwatchalaska.org) and additional data visualization products (e.g., oceanographic contour plots for all transect surveys, marine species distribution maps) are available on the GWA Ocean Workspace for use by other GWA program researchers, Trustee agency staff and other collaborators.

Oceanography results

Water quality monitoring at Seldovia, Homer and Bear Cove stations provided continuous oceanographic time series of estuarine conditions across Kachemak Bay. Monthly averaged values for near-surface water temperature, salinity, dissolved oxygen, chlorophyll fluorescence, and turbidity at all three sites from 2012-2016 are shown in Figure 3 and summary statistics from the near-surface observations at all three sites are provided in Table 2. Water temperature patterns at all three sites had similar timing in seasonal transitions, with summer warming occurring later at Seldovia in some years. Lowest winter surface water temperatures were observed at the Homer site, with highest summer temperatures found at the Bear Cove site. Water salinity was most variable and lowest near the head of Kachemak Bay at Bear Cove and least variable at the Seldovia site, reflecting greater amounts of freshwater input near the head of the bay and in the inner bay. Near-surface dissolved oxygen concentrations were relatively consistent across all three sites, with higher values in spring and lower values in the fall. Chlorophyll concentrations (from fluorescence) exhibited seasonal pattern expected for spring phytoplankton blooms, with peak values in late spring and early summer at the Seldovia and Bear Cove sites. Monthly average turbidity patterns were more variable between years and sites, which may reflect differing patterns in freshwater runoff across the bay, but additional analyses are needed to more fully examine linkages between turbidity and meteorological data at time scales shorter than a month.

Since the near-surface sondes were removed from the Homer harbor and Bear Cove water quality sites in winter due to ice, the longest and most consistent water quality data sets were available from the Seldovia harbor site and those data were used to investigate temporal oceanographic patterns in more detail. Figure 4 shows monthly averages and anomalies for temperature and salinity from the deeper of the two sondes at the Seldovia water quality station, which has an average depth of approximately 8 m. During the 2012-2016 study period, the Cook Inlet/Kachemak Bay region experienced a transition from anomalously cold water temperatures in 2012 to persistent warm temperature anomalies starting in late 2013 and lasting through 2014-2016. The observed warming was part of a large scale warming event across the Gulf of Alaska and northeast Pacific Ocean known as the “Pacific Warm Anomaly” event or “Blob”. The transition to warm temperature anomalies occurred in late fall 2013/early winter 2014, which was slightly earlier than when the warming transition was observed for shelf waters at the GAK1 mooring (Fig. 4). Warmest anomalies were observed in the winters of 2014-2015 and 2015-2016, with monthly averaged anomalies of 3° C above the 2005-2014 monthly average at the Seldovia SWMP station (Fig. 4). Seasonally, salinity decreases in spring through late summer with freshwater inputs from precipitation, snowpack melt and glacier melt. Fall salinity conditions are more variable, depending on storm tracks and precipitation events. Average salinities typically increase in winter as colder temperatures change precipitation from rain to snow and reduce freshwater input, but the warmer winters in 2014-2016 were also reflected in fresher monthly anomalies for that period (Fig. 4).

To illustrate typical water column structure in summer months, Figure 5 provides an example from July 2014 of contours of temperature, salinity, density and chlorophyll (derived from fluorescence) for the mid-Kachemak Bay survey line (Transect 9). Overall, waters in Kachemak Bay were typically vertically stratified from April to November, with density stratification driven primarily by buoyancy forcing from freshwater input and estuarine circulation. The water column typically has a two layer structure, as shown in Figure 5, with a relatively shallow (5-20 m), fresher upper layer with salinity values that vary across the bay, and a larger lower layer with higher salinity values that are relatively consistent with depth and across the entire bay (~31 PSU).

To investigate interannual variability, time series of vertical oceanographic profiles were constructed for individual station locations. Figure 6 provides an example of time series from February 2012 to December 2016 for both temperature and salinity profiles from monthly sampling at the middle station along the mid-Kachemak Bay survey line (Transect 9, station 6). The transition to warmer water temperatures starting in late 2013 and early 2014 is dramatic, with much warmer surface temperatures observed in the summers of 2014, 2015 and 2016. The cold winter water temperatures in 2012 (marked with blue circle) were not seen in subsequent winters and 2015-2016 winter temperatures were much warmer than normal throughout the water column (red circle). Surface salinities were lowest in late summer and early fall, with freshest conditions in 2012 and 2013, but deeper waters freshened in 2015-2016 (purple circle), which may reflect the influence of freshening in Alaska Coastal Current water that then entered the deeper portions of the bay.

The transition to warmer conditions was also evident in lower Cook Inlet surveys, as illustrated in Figure 7 by a comparison between spring, summer and winter surveys in 2012 and 2014 along the Cook Inlet entrance line (Transect 6) and time series plots of profiles from a station on Transect 6 and a station in the middle of the Anchor Point line (Transect 3). Water temperatures reached 13°C in summer 2016 throughout the water column at the mid-Transect 3 station and in the upper 10 m at the southeast Cook Inlet entrance station, which is extremely warm for this region.

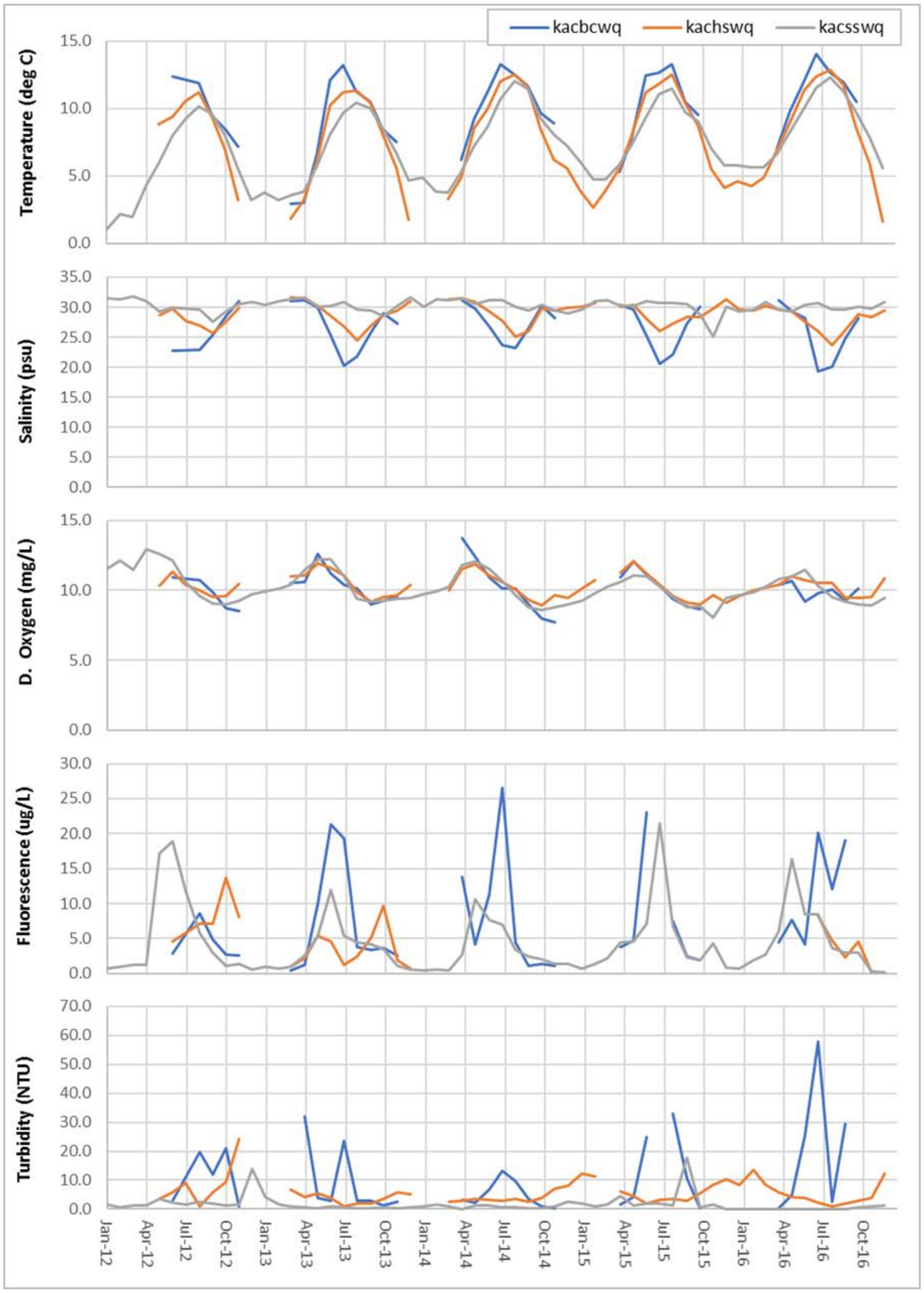
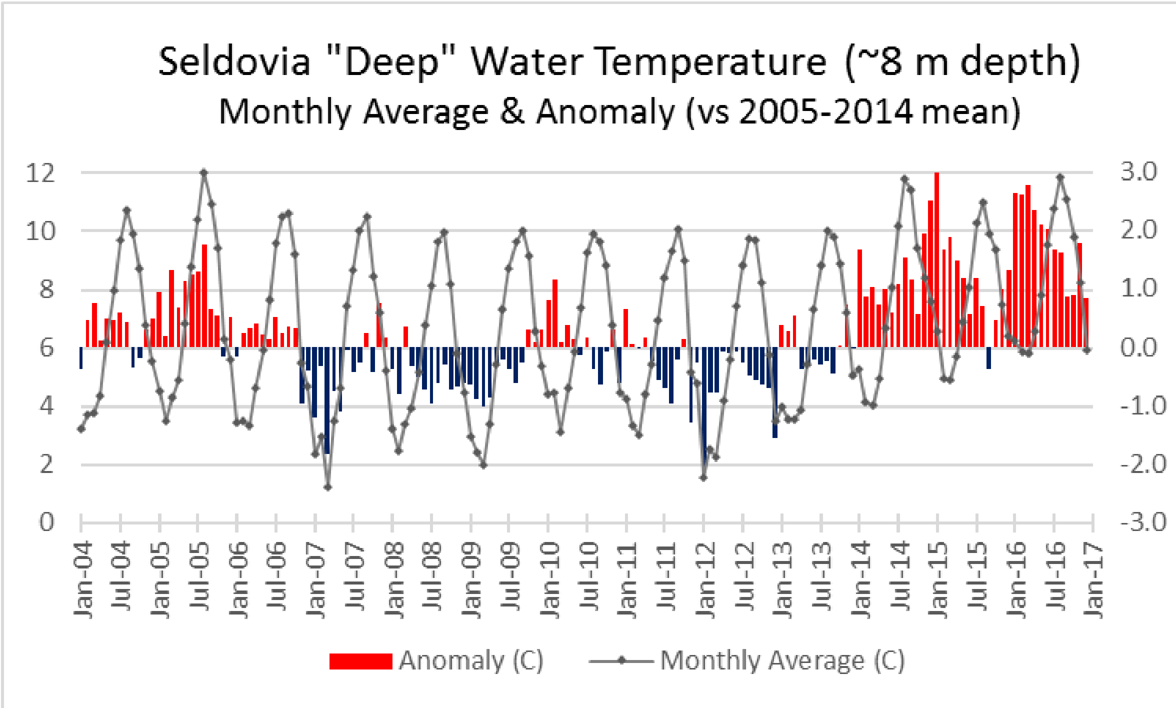


Figure 3. Monthly-averaged environmental data calculated from data recorded at near-surface sensors at KBNERR monitoring stations in Seldovia (kacsswq, grey line), Homer (kachswq, orange line), and Bear Cove (kacbcwq, blue line) during 2012 – 2016. These data are collected at 1 m below the water surface as part of the NERR SWMP.



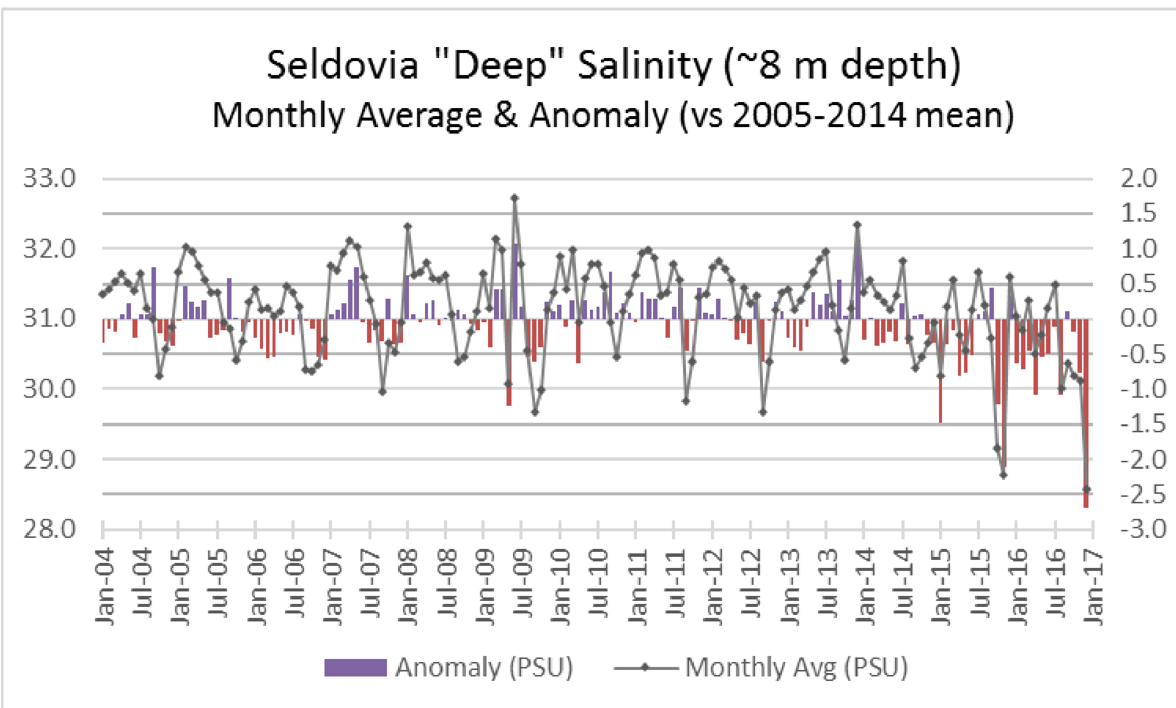


Figure 4. Monthly average (lines) and monthly anomaly (colored bars) for temperature (top) and salinity (bottom) calculated from near-bottom sensor data collected at the Seldovia SWMP water quality station during 2004 – 2016. The monthly anomalies were calculated against a 2005-2014 monthly climatology for comparison with other GWA datasets. Positive/negative anomalies are shown for temperature (red/blue) and salinity (purple/maroon).

Table 2. Summary statistics from the near-surface sensors at KBNERR monitoring stations in Seldovia, Homer, and Bear Cove during 2012-2016. Data were collected from YSI sondes located 1 m below the sea surface.

		2012				2013				2014				2015				2016*			
	Deployment →	01/01 - 12/31				01/01 - 12/31				03/3 - 12/31				01/1 - 11/23				01/01 - 9/30			
Site	Parameter	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var
Seldovia	Temp (deg C)	-0.17-11.3	5.8	3.19	10.15	1.7-12.4	6.7	2.73	7.46	2.9-12.6	7.9	2.72	7.41	2.4-13.1	7.9	2.42	5.88	5.0-13.7	8.6	42.68	7.2
	Salinity (psu)	20.9-32.2	30.3	1.49	2.21	23.7-31.2	30.4	1.37	1.87	25.8-32.1	30.4	1.11	1.23	26.7-31.6	30.4	0.87	0.76	26.6-31.6	29.9	0.93	0.87
	DO (mg/L)	8.6-14.9	10.8	1.52	2.34	8.5-13.3	10.3	1.23	1.5	8.2-13.5	10.1	1.28	1.64	8.5-12.3	9.9	0.85	0.74	8.5-12.5	10.2	0.82	0.68
	Turbidity (NTU)	0-34.6	2.9	4.83	23.3	0-19.26	0.98	2.07	4.28	0-4.9	1	0.93	0.87	0-35.3	2.1	3.7	13.72	0-0	0	0	0
	Fluorescence (ug/L)	0.2-47.4	5.05	7.96	63.47	0.3-23.5	0.98	3.07	9.49	0-28.7	3.11	3.59	12.9	0.5-26.3	4	4.17	17.4	0.1-26.3	5.2	4.64	21.52

		2012				2013				2014				2015				2016*			
	Deployment →	05/31 - 11/14				03/11 - 12/03				03/03 - 12/31				01/1 - 12/22				01/22 - 9/30			
Site	Parameter	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var
Homer	Temp (deg C)	2.3-12.2	8.9	2.44	5.98	0-13.9	7.7	3.49	12.19	2.7-19.7	8.3	3.18	10.11	-0.16 - 13.9	7.7	3.57	12.76	3.4-14.7	9	3.39	11.53
	Salinity (psu)	20.5-31.2	27.8	2.35	5.53	17-58.6	29.1	2.68	7.23	20.3-31.8	29.1	2.4	5.77	19.5-32.5	28.8	2.01	4.02	19.4-30.9	27.8	2.54	6.47
	DO (mg/L)	8.8-12.1	10.2	0.75	0.56	8.6-10.6	10.6	1.11	1.24	8.34-14.1	10.2	1.08	1.17	6-14.4	10.1	1.19	1.42	8.1-12	10.3	0.66	0.44
	Turbidity (NTU)	0-46.5	8.7	10.72	114.94	0-57.8	4.1	5.07	25.71	1.1-42.8	4.1	4.29	18.4	0.9-42.5	9.7	60.88	34.34	0-37.7	5.1	6.79	46.11
	Fluorescence (ug/L)	1.1-38.4	7.7	8.75	76.5	0.4-32.5	4.1	4.99	24.93	NA	NA	NA	NA	NA	NA	NA	NA	0.1-11.9	3.9	3.45	11.87

		2012				2013				2014				2015				2016*			
	Deployment →	07/23 - 11/07				03/29 - 11/05				04/21 - 11/03				04/03 - 10/14				04/21 - 06/02			
Site	Parameter	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var	Range	Mean	Std. Dev	Var
Bear Cove	Temp (deg C)	6.7-14.3	9.9	1.86	3.47	0.9-16.1	9.2	3.53	12.48	5.6-16.3	10.9	2.1	4.43	4.8-15.6	10.4	2.95	8.72	6.5-12.9	9.3	2.1	4.41
	Salinity (psu)	15.4-31.0	25.7	3.49	12.24	14.6-31.8	26.3	4.51	20.4	16.7-31.6	26.9	3.42	11.71	14.3-31.56	26.2	4.23	17.93	29.9-31.6	29.7	1.5	2.25
	DO (mg/L)	8.1-11.3	9.7	0.98	0.98	7.4-15.6	10.4	1.34	1.79	7.3-15.3	10.2	1.73	3.02	7.6-14.4	10.3	1.28	1.63	8.7-12.2	10.5	0.91	0.84
	Turbidity (NTU)	0.3-38.1	7.1	8.02	64.31	0-31.5	4.1	5.75	33.13	0-27.7	4.9	4.78	22.84	0.0-52.5	14.5	14.09	198.66	0.1-33.0	4.5	7.08	50.13
	Fluorescence (ug/L)	1.6-18.6	4.5	2.7	7.31	0.13-38.7	7.1	9.39	88.09	0.7-46.2	5.9	7.83	61.36	0.9-40.17	6.9	7.96	63.41	2.6-17.1	6.7	3.26	10.61

* 2016 data does not include complete time series due to processing lag

Mid-Kachemak Bay Transect (T9): 21 July 2014

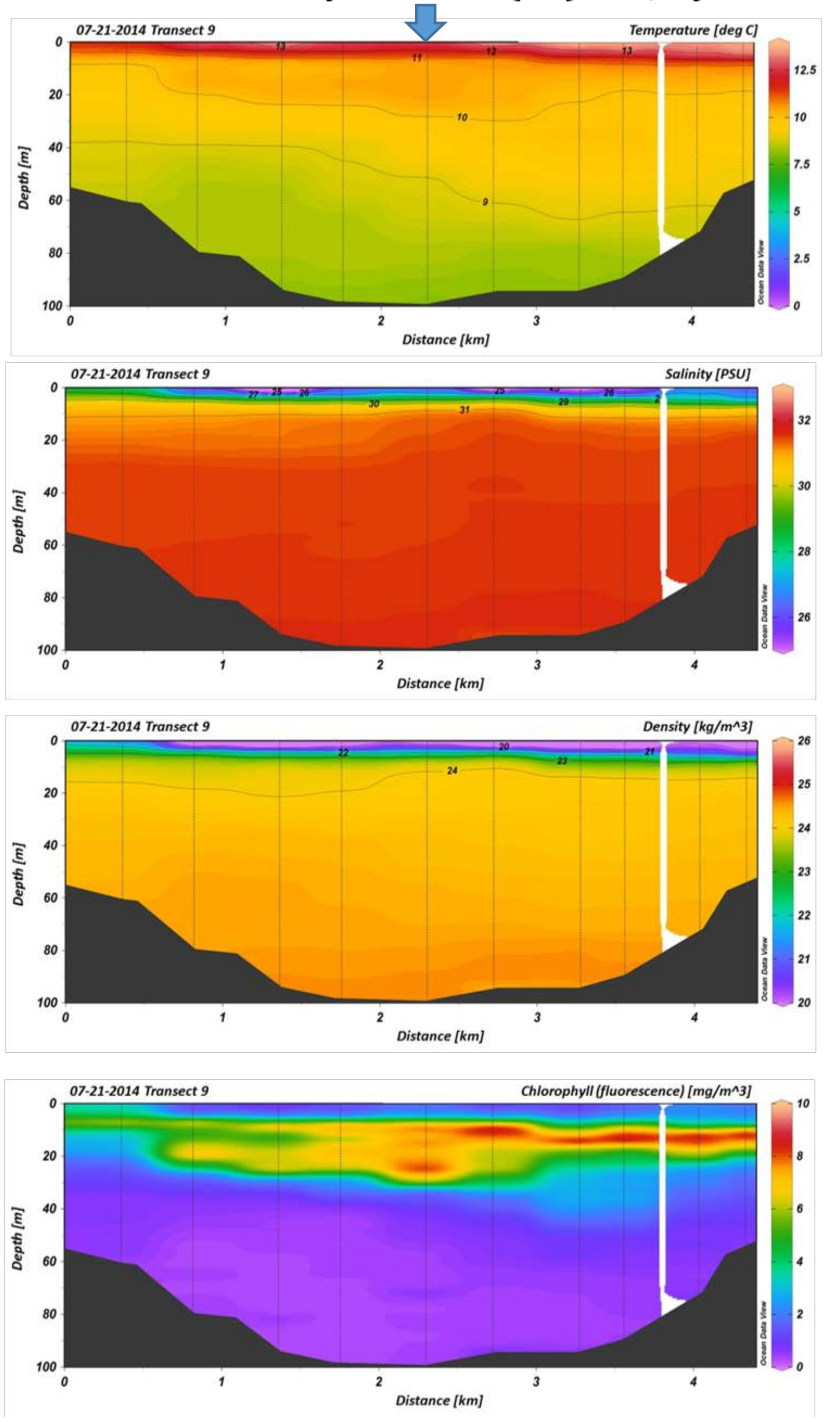


Figure 5. Contour plots of temperature, salinity, density and chlorophyll (fluorescence) for the mid-Kachemak Bay transect (Transect 9) from 21 July 2014 survey. View is looking into Kachemak Bay, dashed lines indicate station locations and arrow at top indicates the location of stations 9-6.

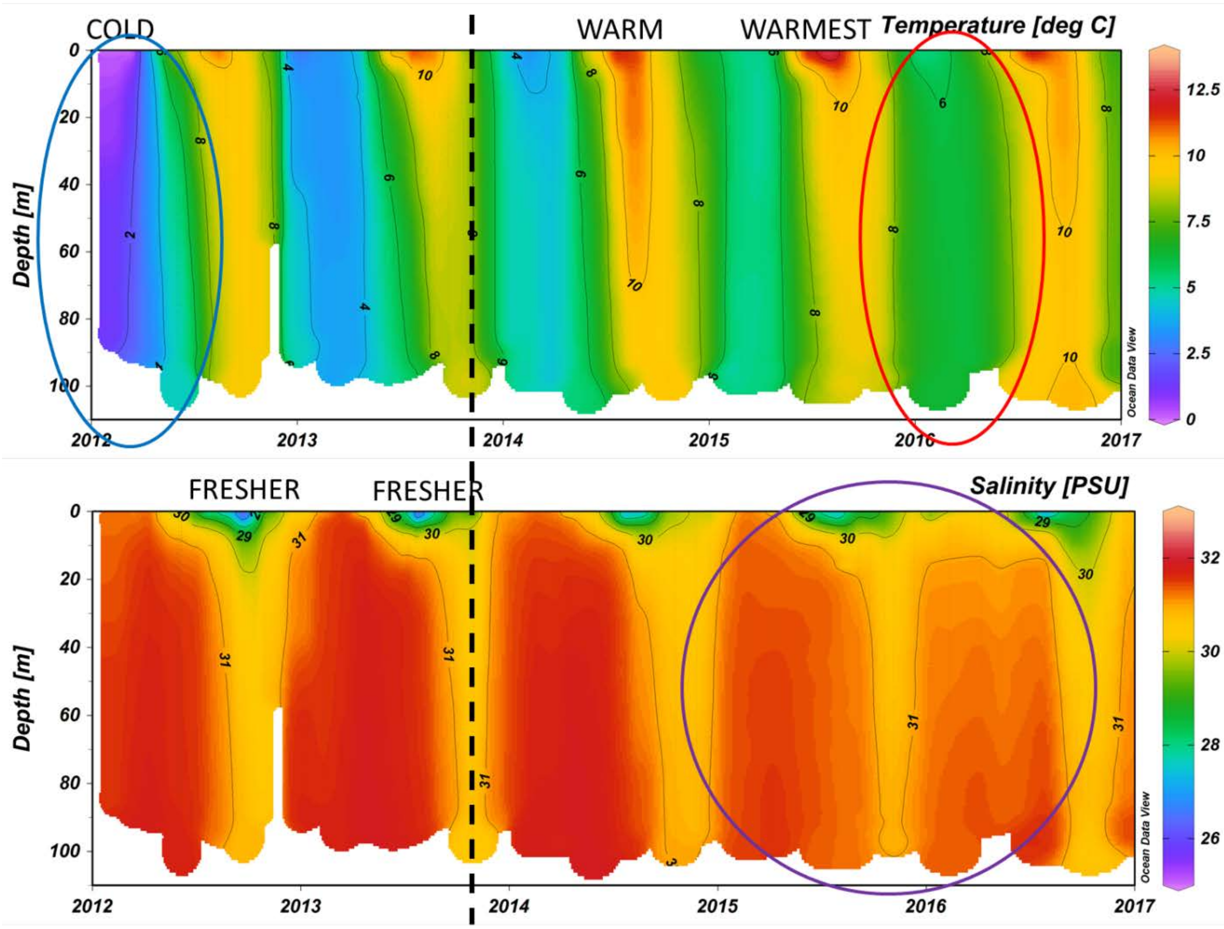


Figure 6. Time series of vertical profiles of water column temperature (top, degrees C) and salinity (bottom, PSU) from 2012-2016 collected from monthly CTD casts at a mid-Kachemak Bay station (station 9-6). The dashed black line marks the transition to warmer conditions in late 2013, with warmer than average temperatures observed throughout the water column in 2014-2016. Circled areas are described in the text.

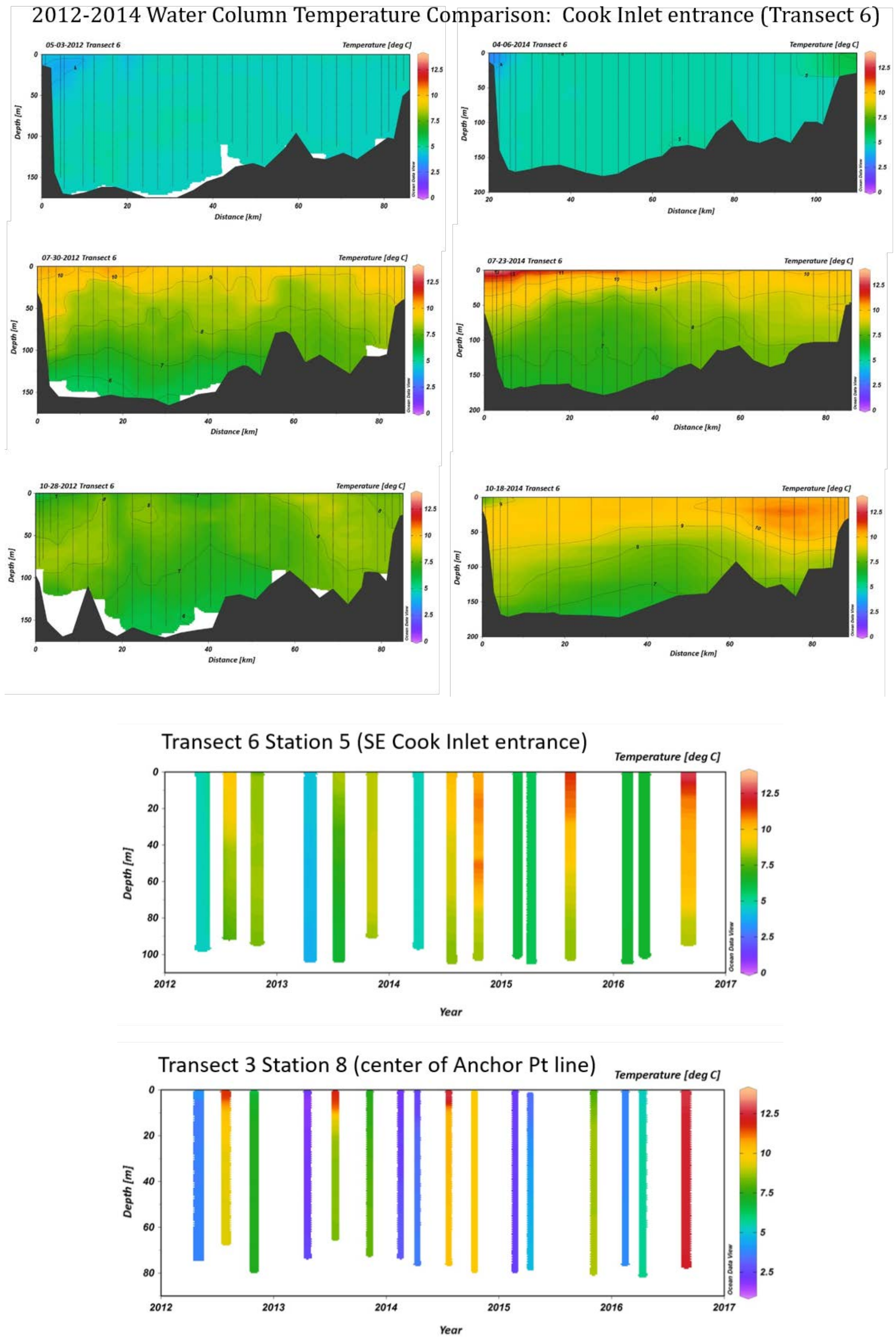


Figure 7. Time series of oceanographic profiles from across the Cook Inlet entrance in 2012 and 2014 (top panel) and for 2012-2016 from stations on the southeast side of Cook Inlet (middle) and in the center of the Anchor Point transect in Cook Inlet (top).

The oceanography surveys were designed to assess seasonal and interannual variability in along-estuary oceanographic conditions, with detailed resolutions of cross-estuary spatial patterns. Monthly sampling along the mid-Kachemak Bay transect (Transect 9) also provided data to assess changes in seasonal timing between years as shown in Figure 6. Contour plots of water temperature, salinity, density and chlorophyll fluorescence (e.g. Fig. 5) have been generated for all the shipboard sampling transect and provided on the GWA Ocean Workspace for use by other researchers. The primary oceanographic features for each shipboard survey transect are summarized here:

Kachemak Bay, Transect 9: The mid-bay transect runs north-south from the Homer Spit at the boundary between inner and outer Kachemak Bay. There is a tendency for surface inflow on the south side and strong surface outflow on the north side near the end of the spit. Surface waters on this transect are strongly influenced by freshwater input from glacial rivers at the head and along the south side of the inner bay. The surface freshwater patterns vary seasonally in response to precipitation events and with the fortnightly tidal cycles.

Kachemak Bay, Transect 4: The outer Kachemak Bay transect runs north-south between Bluff Point and Barabara Point. The outer bay has a variable, counter-clockwise gyre circulation pattern and the structure and strength of the gyre influences surface water connections between Kachemak Bay, lower Cook Inlet and the Gulf of Alaska. The transect crosses a deep channel and surface convergences frequently occur over the Archimandritof shoals to the north of the channel.

Lower Cook Inlet, Transect 3: This is the northern transect in the lower inlet and runs from Anchor Point northwest to Red River. An area of persistent, bathymetrically-linked surface convergences, vertical mixing and tide rips is found near Anchor Point along the east end of the transect. The northwest side of the transect is strongly influenced by fresh water inputs from upper Cook Inlet and this is the study transect where conditions are most frequently vertically mixed and horizontally stratified across the estuary.

Lower Cook Inlet, Transect 7: This transect runs east-west in the middle of the lower inlet from Flat Island to Augustine Island in Kamishak Bay. Oceanographic conditions are influenced periodically by inflowing water from the Alaska Coastal Current, as well as by freshwater buoyancy forcing from upper Cook Inlet on the west side. Sea states and surface currents are also influenced frequently by strong winds associated with Gulf of Alaska storms and with gap winds across Kamishak Bay through the mountains on the west side of the inlet.

Lower Cook Inlet, Transect 6: This is the southern transect in the lower inlet and runs across the Cook Inlet entrance from Point Adam west to Cape Douglas on the Alaska Peninsula. The deepest waters along all the study transects are found in the deep channel on the west side of Transect 6 (185 m). Oceanographic conditions are influenced primarily by exchanges with the Alaska Coastal Current and fresh water buoyancy forcing from upper Cook Inlet rivers at the westernmost portions of the transect by Cape Douglas. Sea states and surface currents are influenced frequently by strong winds associated with Gulf of Alaska storms and with gap winds through the mountains on the west side of the inlet

Zooplankton monitoring

Cumulatively, 215 discrete zooplankton samples from shipboard surveys in 2012-2015 were analyzed through January 2017 by GWA researchers at the Prince William Sound Science Center, which resulted in the identification of species from 168 taxa across 12 phyla. Sample identification and data analyses for samples collected in project year 2016 will be completed in the GWA FY17-21 program, in collaboration with S. Batten, R. Campbell, and C. McKinstry of the GWA Environmental Drivers component. A subset of the data analyses from 2012-2014 surveys are summarized here, to show results across a range of environmental conditions, with 2012 an anomalously cool year, 2013 closer to average; and 2014 an anomalously warm year.

For initial analyses, we utilized only most frequently observed taxa (present in > 5% of samples) in multivariate analyses of these data. Abundance data were transformed [log(n + 1)] to stabilize variance (Keister and Peterson 2003). Using Ward's agglomerative method, a hierarchical cluster analysis (HCA) produced distinct groups based on species assemblage. These groups were used in the Indicator Species Analysis (ISA; Dufrene and Legendre 1997) to examine which species were indicative of each group. We summarized each transect in a stacked histogram of the relative proportion of zooplankton species category by sampling date (Figs. 8, 9 and 10); rare or intermittent categories (≤ 1% across most sampling periods) were combined in the "other" category.

Copepods were the primary zooplankton category with two taxa represented in >90% of the samples; the genus *Pseudocalanus spp.*, and *Acartia longiremis* were the types of copepod present in the study area throughout the sampling period. *Calanus marshallae* was present in the study area but rare and *Neocalanus plumchrus* was more common in the lower Cook Inlet Transects 6 and 7 during 2013 and 2014 (Fig. 11). The chaetognath *Parasagitta elegans,* a small arrow worm that preys on copepods, were commonly found at all transects. Barnacle larvae were most common in Kachemak Bay and to a lesser extent at Transect 3 stations in lower Cook Inlet in the spring. Jellyfish were more frequently encountered in our samples during fall of 2014 at all transects sampled.

Analyses of zooplankton indicator species from 2012-2014 for all sampling areas combined indicate early spring periods were characterized by ostracods, cumacea, and the copepod *Scolechithricella minor* ($p < 0.05$). Late spring months were primarily identified by the concurrent presence of all three species of *Neocalanus* in more than 60% of samples ($p < 0.05$); fish eggs were also an important factor of this group. The summer period included one copepod, *Tortanus discaudatus*, as the defining species ($p < 0.05$). Species that categorized the late fall were dominated by copepods including *Mesocalanus tenuicornis*, *Calanus pacificus*, and *Clausocalanus* sp. ($p < 0.05$). Taxonomic groups from Kachemak Bay Transects (4 and 9) were defined by meroplanktonic larvae such as barnacle cyprids, shrimp and crab zoea ($p < 0.05$) in the summer time.

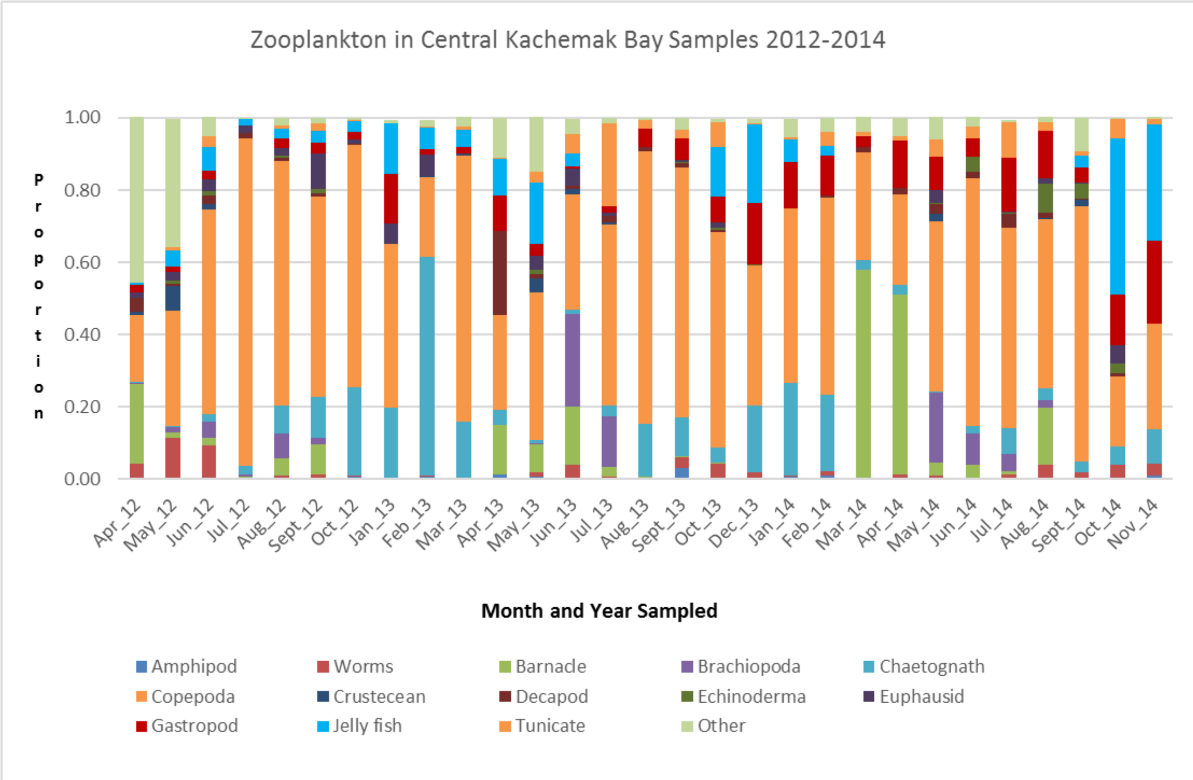


Figure 8. Proportion of zooplankton species categories in central Kachemak Bay samples collected on shipboard surveys along Transect 9 during 2012-2014. Data were combined from all three plankton stations (9-1, 9-6, 9-10) for each survey. Rare or intermittent categories (≤ 1% across most sampling periods) were combined as "Other".

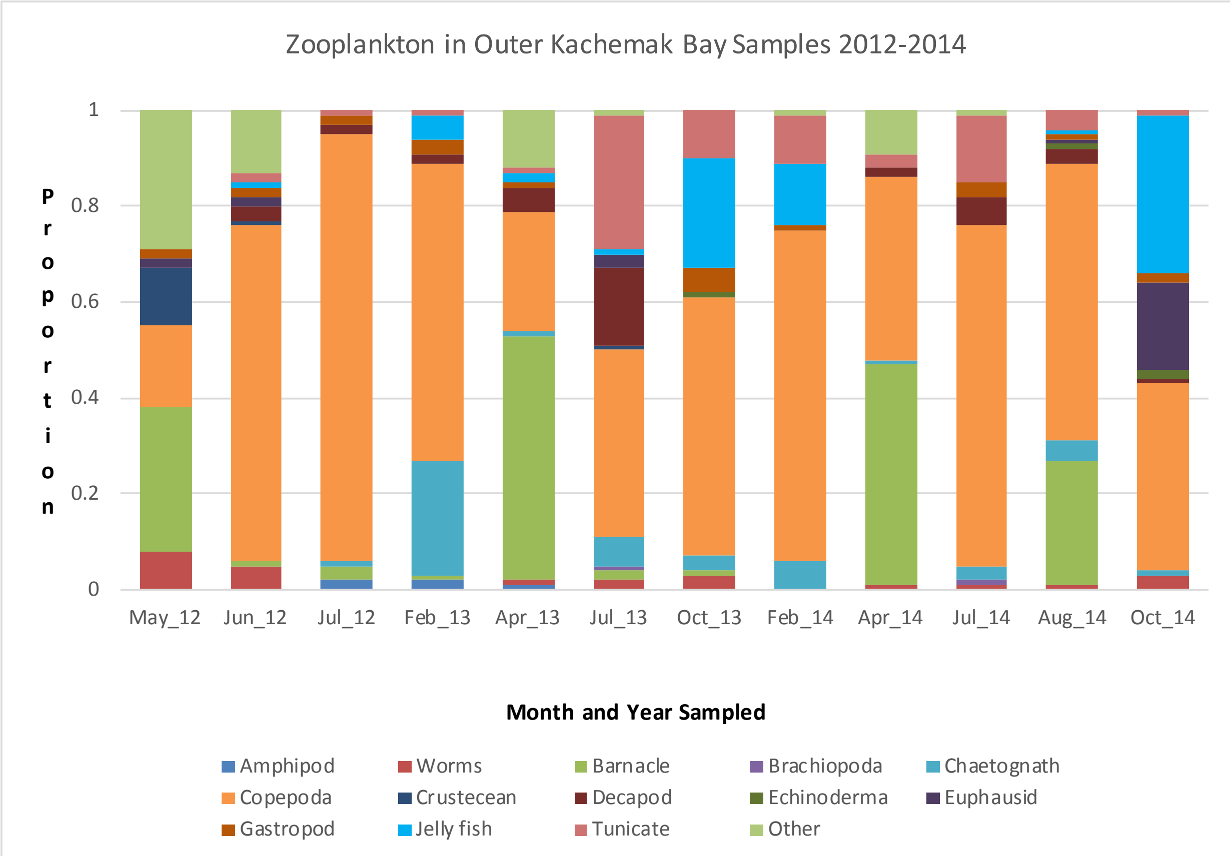


Figure 9. Proportion of zooplankton species categories in outer Kachemak Bay samples collected on shipboard surveys along Transect 4 (combined from stations 4-2, 4-4 and 4-7) during 2012-2014. Rare or intermittent categories (≤ 1% across most sampling periods) were combined as "Other". Sampling frequency was quarterly with an additional survey in June 2012.

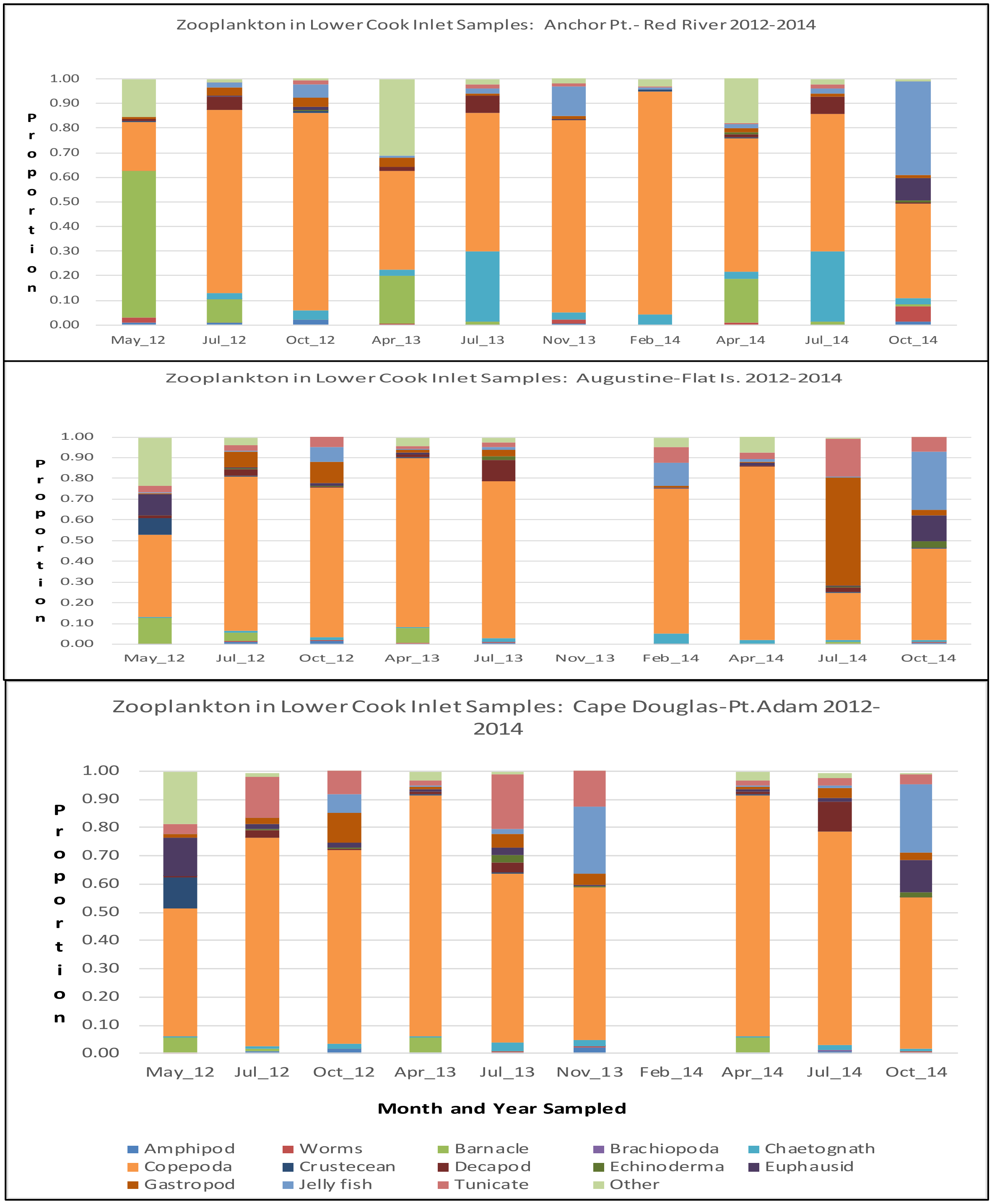


Figure 10. Proportion of zooplankton species categories in lower Cook Inlet samples collected during 2012-2014 from combined plankton stations on shipboard surveys (north to south) along Transect 3 (top – Anchor Pt to Red River), Transect 7 (middle – Flat Island to Augustine Volcano), and Transect 6 (bottom – Pt. Adam to Cape Douglas). Rare or intermittent categories (≤ 1% across most sampling periods) were combined as “Other”.

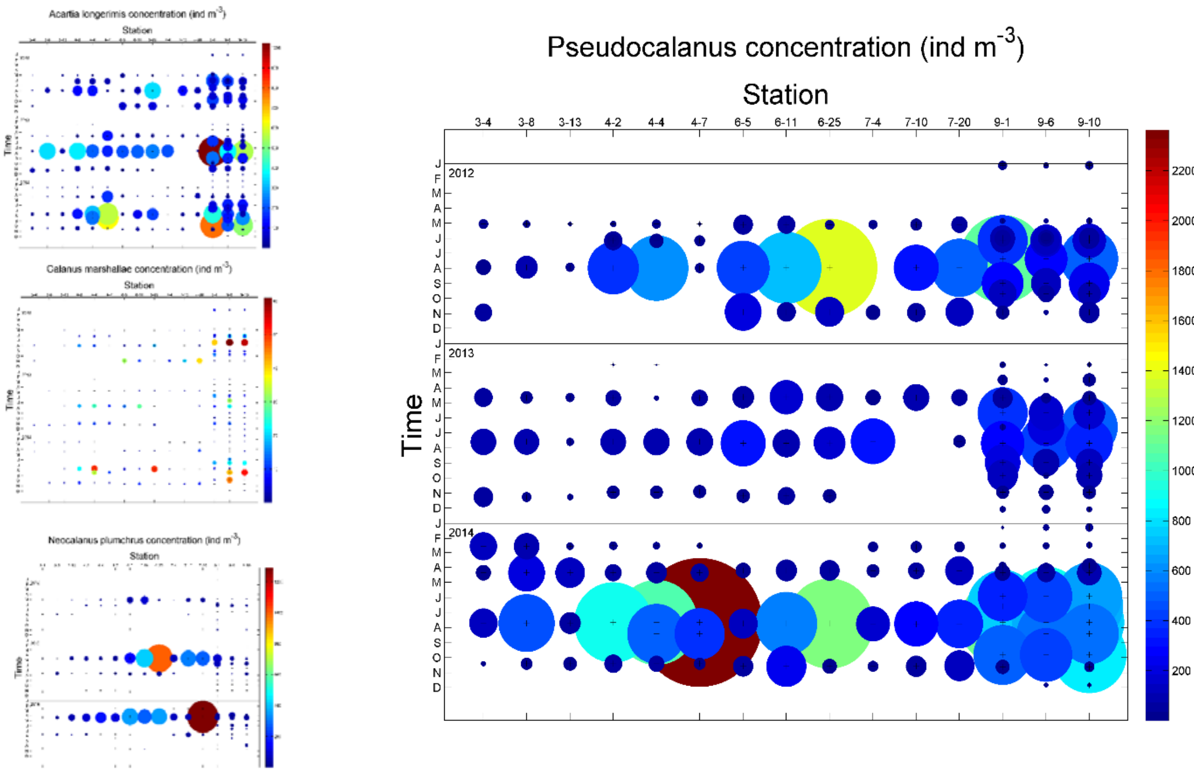


Figure 11. Proportional copepod abundance for species of interest in the Gulf of Alaska *Pseudocalanus* spp. *Acartia longerimis*, *Calanus marshallae* and *Neocalanus plumchrus* concentrations (individuals m-3) observed during 2012-2014 at stations (numbers on x-axis) across the study area. Both the size and color of the dots are proportional to copepod abundance. Station numbers identify transects in Kachemak Bay (Transects 4 and 9) and lower Cook Inlet (Transects 3, 6, and 7), with plankton sampled at three stations on each transect. Mid-Kachemak Bay stations (Transect 9) are sampled monthly, while other transects are sampled quarterly.

Phytoplankton monitoring

Our results show that the samples from these transects are generally dominated by diatoms, usually *Chaetoceros spp.,* except for a few fall samples that were dominated by dinoflagellates (Figs. 12 and 13). Spring and summer samples also showed high abundances of diatoms, including *Pseudo-nitzschia spp, Rhizosolenia* spp., and *Thalassiosira* spp. There were no apparent patterns of abundances among years or transects. The samples from the KBL were collected more often and so the results are not as variable, but show the same general pattern as the other transect samples (Fig. 14). The KBL samples are dominated by diatoms, usually *Chaetoceros* spp., with low abundances of dinoflagellates seen throughout the year. Total cell abundances of dinoflagellates and diatoms were also plotted (Fig. 14) and show the same general pattern among years with a spring bloom of diatoms beginning in late April or early May, peaking in July, and continuing through August when numbers begin to decline. From November through March, phytoplankton cell abundances for all transects and at the KBL dock decline to or near zero.

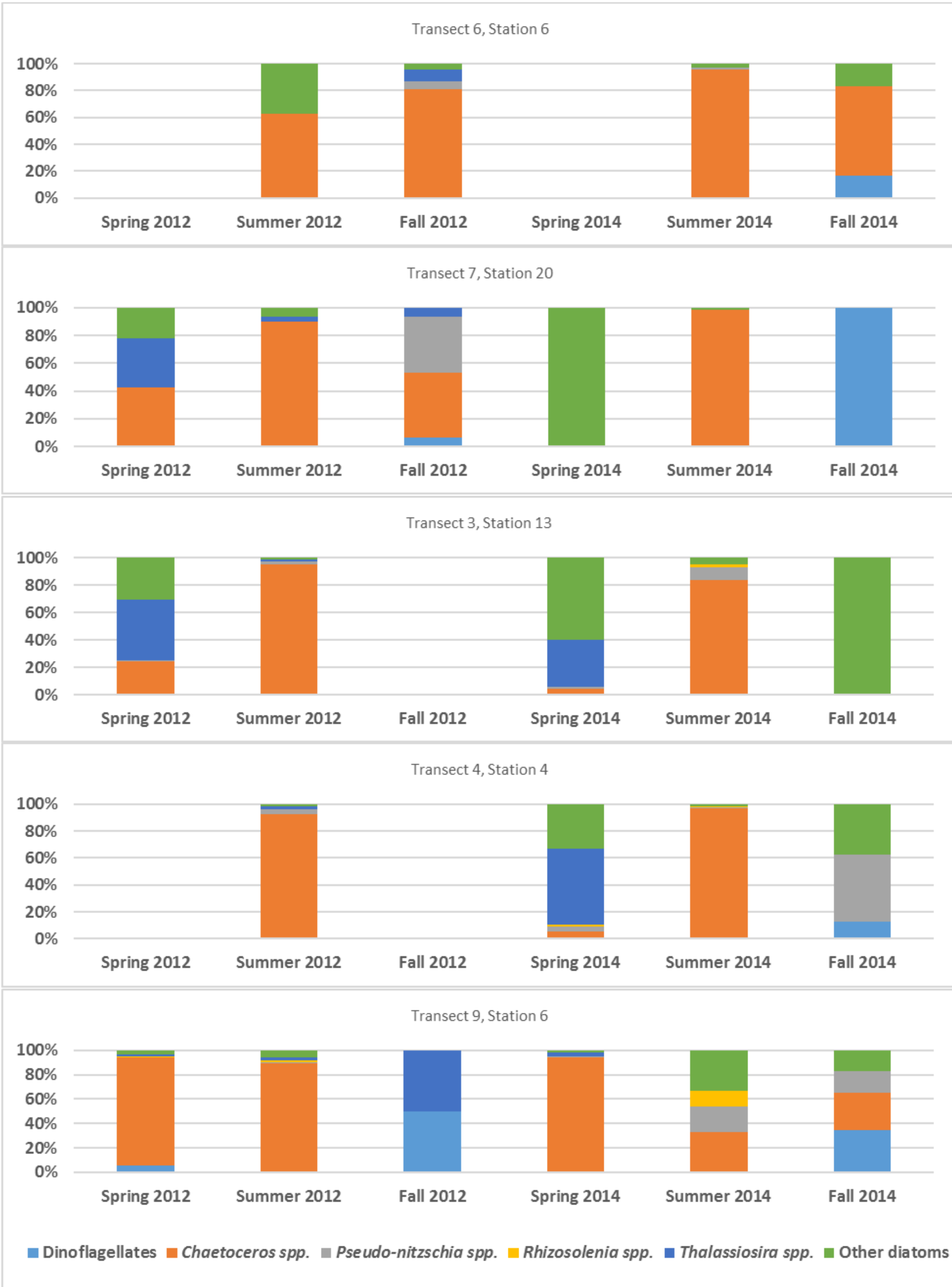


Figure 12. Taxonomic composition of Kachemak Bay and Cook Inlet phytoplankton samples from Transects 3, 4, 6, 7, and 9 for 2012 and 2014. Winter samples were excluded due to low cell abundances. Taxa were grouped into 6 categories: Dinoflagellates, *Chaetoceros* spp. (diatom), *Pseudo-nitzschia* spp. (diatom), *Rhizosolenia* spp. (diatom), *Thalassiosira* spp. (diatom), and "Other diatoms". Compositions are shown as a percentage of total cell abundance.

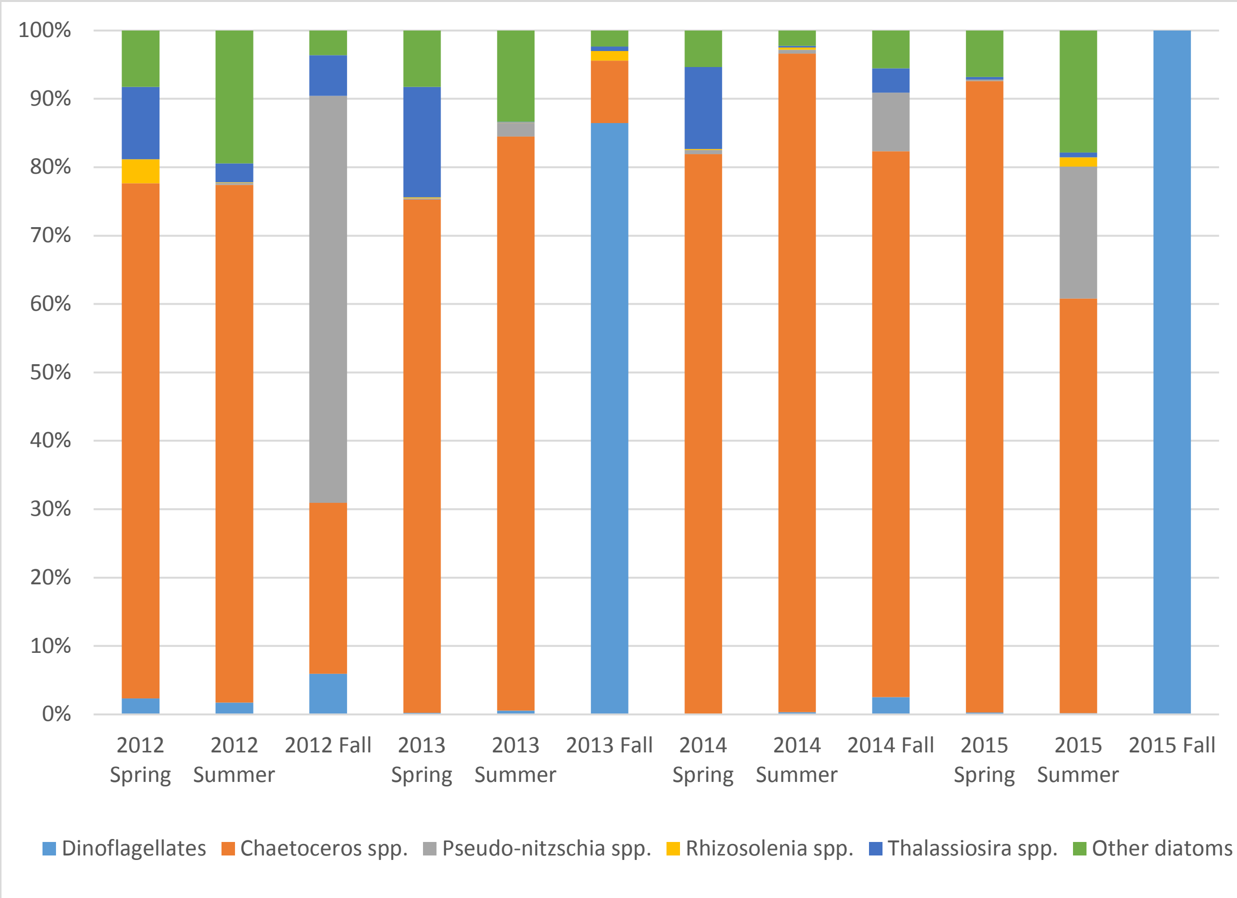


Figure 13. Graphs showing the taxonomic composition of phytoplankton samples from the Kasitsna Bay Laboratory. Winter samples were excluded because of low abundances of cells. For this analysis taxa were grouped into 6 categories: Dinoflagellates, *Chaetoceros* spp. (diatom), *Pseudo-nitzschia* spp. (diatom), *Rhizosolenia* spp. (diatom), *Thalassiosira* spp. (diatom), and "Other diatoms". Compositions for taxa are shown as a percentage of total cell abundance.

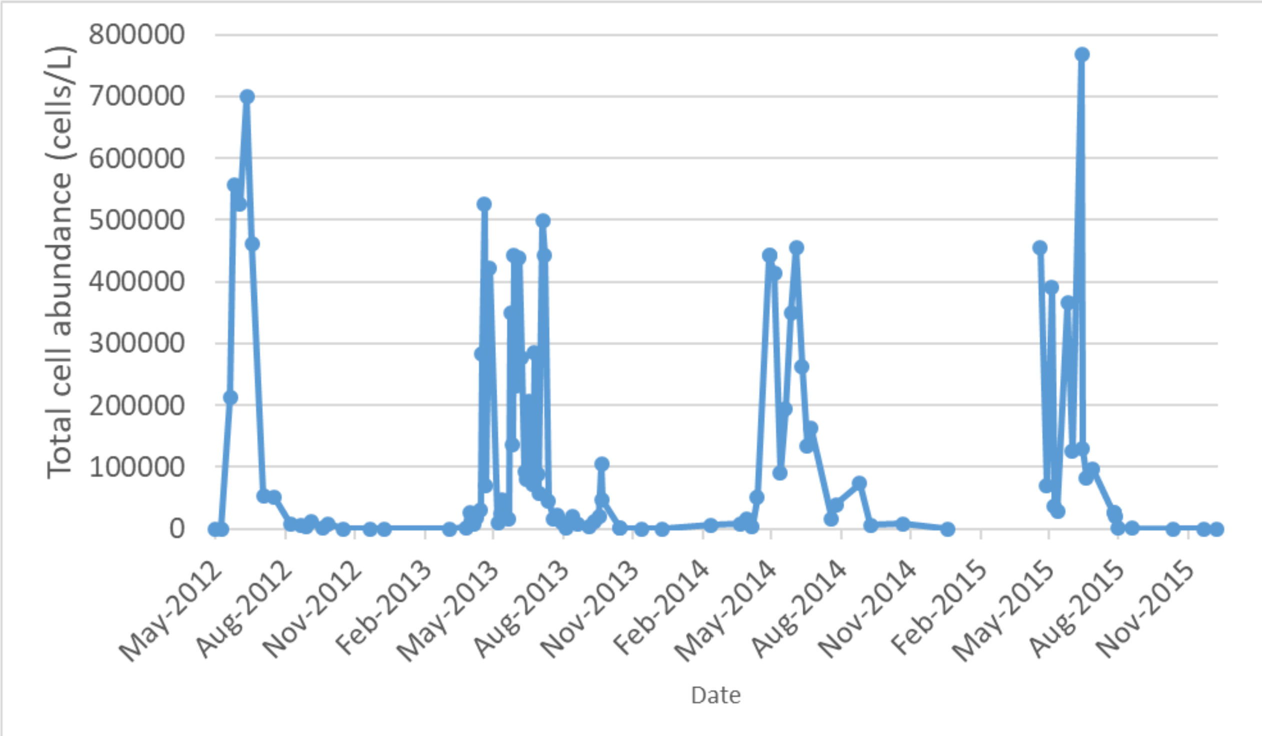


Figure 14. Graph showing total phytoplankton cell abundance from samples collected at the Kasitsna Bay Laboratory dock from May 2012 through December 2015.

Seabird/marine mammal observations

USFWS observers conducted 1434 km of at-sea transects in lower Cook Inlet and Kachemak Bay during the 2012-2016 study period (Fig. 15). Total seabird densities ranged from 9.9 birds km^{-2} in fall to 20.6 birds km^{-2} in summer (Table 3), although relative abundance of species varied seasonally (Table 4). Marine bird densities were generally higher on the east side of lower Cook Inlet (Table 3), especially in the nearshore waters of outer Kachemak Bay, except for a winter aggregation of scoters near Kamishak Bay on the west side (Fig. 16). The five most common marine birds observed (Table 4) were white-winged scoter (*Melanitta fusca*; winter), common murre (*Uria aalge*; year round), black-legged kittiwake (*Rissa tridactyla*; summer), red-necked phalarope (*Phalaropus lobatus*; spring), and sooty shearwater (*Ardenna grisea*; summer and fall). High densities of seabirds on the east side of lower Cook Inlet (Fig. 16) coincide with inflowing oceanic water from the northern Gulf of Alaska. This pattern has been observed previously, for seabirds as well as for forage fish and oceanographic patterns (Speckman et al. 2005), but seasonal aspects have not yet been examined. Sea otters were the most abundant and widespread marine mammal recorded during USFWS surveys (Table 5), with highest densities on the north side of outer Kachemak Bay (Fig. 17).

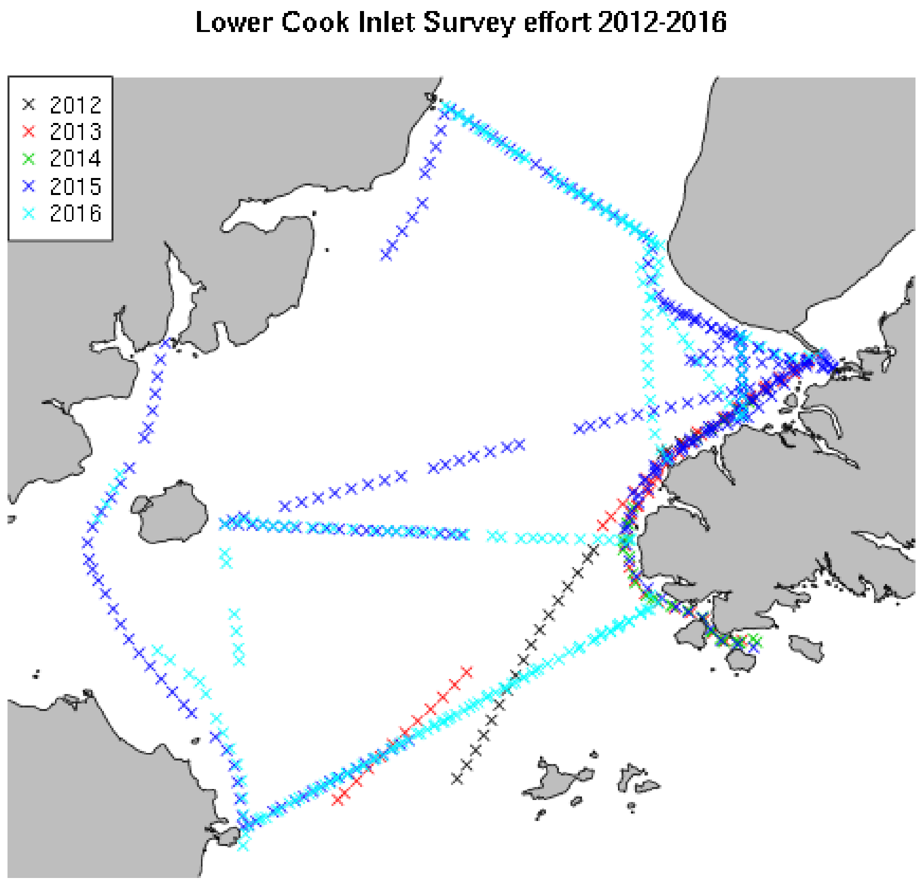


Figure 15. Marine bird and mammal transects, 2012–2016, conducted by USFWS observers on NOAA KBL/KBNERR shipboard surveys in lower Cook Inlet and Kachemak Bay.

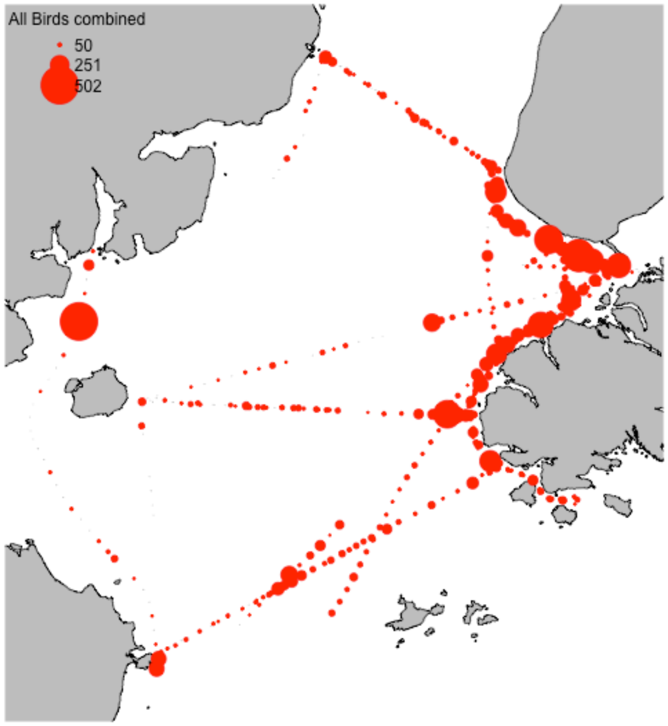


Figure 16. Total marine bird distribution (birds km^{-2}) for all lower Cook Inlet and Kachemak Bay surveys combined, 2012—2016.

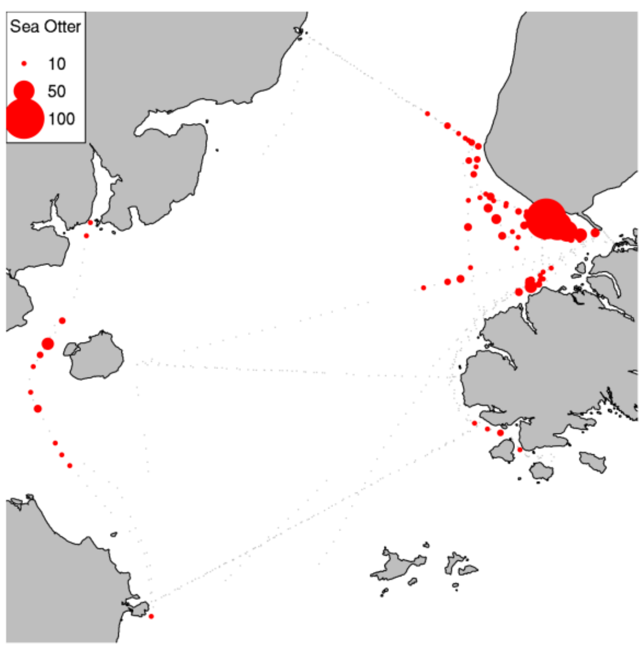


Figure 17. Distribution of sea otters recorded by USFWS observers during all lower Cook Inlet and Kachemak Bay surveys, 2012–2016.

Table 3. Total marine bird densities (birds km^{-2}) for eastern and western portions of lower Cook Inlet and the ratio between east and west by season (2012–2016).

Season	**Mean**	**West**	**East**	**Ratio**
Winter	19.5	7.9	31.0	3.9
Spring	18.0	18.1	17.8	1
Summer	20.6	11.8	29.3	2.5
Fall	9.9	9.1	10.7	1.2

Table 4. Average densities (birds km^{-2}) of marine birds in lower Cook Inlet by season, 2012-2016. Birds are ordered from most to least abundant in yearly average density.

Species	Winter	Spring	Summer	Fall	Year
White-winged Scoter	12.08	3.06	0	0.16	3.83
Common Murre	1.5	3.4	1.58	1.74	2.05
Black-legged Kittiwake	0.03	1.29	4.25	2.11	1.92
Red-necked Phalarope	0	5.24	0	0.28	1.38
Sooty Shearwater	0	0.01	3.72	1.23	1.24
Unidentified Dark Shearwater	0	0.73	2.63	1.58	1.24
Northern Fulmar	0.38	0.07	2.08	1.31	0.96
Glaucous-winged Gull	1.43	1.32	0.29	0.19	0.81
Horned Puffin	0.01	0.02	1.83	0.17	0.51
Pigeon Guillemot	1	0.48	0.39	0	0.47
Tufted Puffin	0	0.19	0.31	0.78	0.32
Fork-tailed Storm-Petrel	0	0.18	0.63	0.22	0.26
Pelagic Cormorant	0.19	0.36	0	0.02	0.14
Marbled Murrelet	0.05	0.28	0.11	0.04	0.12
Northern Pintail	0	0.33	0	0	0.08
Short-tailed Shearwater	0	0.01	0.1	0.22	0.08
Mew Gull	0.16	0.04	0.03	0	0.06
Brachyramphus Murrelet	0.04	0.16	0	0	0.05
Pacific Loon	0	0.13	0	0.07	0.05

Species	Winter	Spring	Summer	Fall	Year
Parakeet Auklet	0	0	0	0.16	0.04
Common Loon	0.03	0.09	0.04	0	0.04
Harlequin Duck	0.11	0.03	0	0	0.03
Herring Gull	0.04	0.01	0.01	0.06	0.03
Common Eider	0.09	0	0	0	0.02
Long-tailed Duck	0.09	0	0	0	0.02
Pomarine Jaeger	0	0	0.02	0.04	0.02
Parasitic Jaeger	0	0.01	0.04	0.01	0.01
Ancient Murrelet	0	0	0.06	0	0.01
Surf Scoter	0.01	0.04	0	0	0.01
Red-breasted Merganser	0	0.05	0	0	0.01
Kittlitz's Murrelet	0	0.01	0.02	0	0.01
Cassin's Auklet	0.02	0	0.01	0	0.01
Rhinoceros Auklet	0	0	0	0.02	0.01
Red-faced Cormorant	0.01	0.01	0	0	0
Double-crested Cormorant	0	0.01	0	0	0
Glaucous-winged x Herring Gull	0	0	0.01	0	0
Thick-billed Murre	0.01	0	0	0	0

Table 5. Marine mammal counts by USFWS observers on lower Cook Inlet surveys, by season. On-transect counts were within the 300 m survey strip, and off-transect counts were outside the 300 m survey strip. Note that these are raw counts, and effort was not consistent across seasons, 2012-2016.

Species	Spring	Summer	Fall	Winter	Total
On Transect					
Sea Otter	225	53	56	163	497
Harbor Seal	0	10	0	4	14
Dall’s Porpoise	0	3	7	0	10
Harbor Porpoise	0	1	0	4	5

Species	Spring	Summer	Fall	Winter	Total
Humpback Whale	0	2	0	0	2
Killer Whale	0	1	6	0	7
Unid. Whale	2	0	0	0	2
Off Transect					
Sea Otter	64	16	34	180	294
Dall's Porpoise	0	2	9	0	11
Unid. Whale	1	8	0	0	9
Humpback Whale	1	1	0	0	2
Minke Whale	0	2	0	0	2
Harbor Seal	0	0	0	1	1
Harbor Porpoise	0	0	0	1	1
Fin Whale	0	1	0	0	1
Unid. Seal	0	0	1	0	1

DISCUSSION

Oceanography

Seasonal and interannual changes in marine conditions have been characterized with high cross-estuary spatial resolution in Kachemak Bay and Cook Inlet from 2012-2016, with examples of cross-estuary and temporal variability at sites across the region provided in the Results section of this report. Continuous sampling at three water quality stations along the estuarine gradient in Kachemak Bay and monthly sampling along the mid-Kachemak Bay transect line provided oceanographic and plankton data needed to assess short-term variability and track long-term trends (project Objective 1), as illustrated in Figures 3 and 4 and Table 2. Monthly averages and anomalies for water temperature and salinity calculated from the water quality station data (Fig. 4) have been provided to GWA nearshore component researchers (Iken and Konar, GWA project 16120114-L) to help explain interannual changes at Kachemak Bay monitoring sites (project Objective 2). The monthly shipboard sampling in mid-Kachemak Bay and quarterly sampling in lower Cook Inlet provided sufficient information to assess seasonal and interannual changes in water mass patterns (Fig. 6 and 7), as well as changes in seasonal timing between years (Fig. 6), addressing project Objective 3. Detailed cross-estuary spatial resolution also allowed identification of oceanographic fronts and regions of persistent vertical mixing (for example, see Figs. 5 and 7). Due to the large amount of data produced under this project, the water station and CTD cast data provided on the public data portal have been supplemented with cross-estuary contour plots (similar to Fig. 5), that were generated for all shipboard sampling transects and provided on the GWA Workspace for use by other GWA researchers and Trustee agency staff (project Objective 2). Oceanographic linkages across the GWA study area (project Objective 4) were initially examined by comparing water temperature data from Kachemak Bay, the GAK1 mooring and a NOAA tide gauge sensor at Cordova harbor in Prince William Sound (Holderied and Weingartner, 2016).

The lower Cook Inlet and Kachemak Bay long-term oceanographic monitoring during 2012-2016 captured the transition in the Gulf of Alaska from relatively cold conditions in 2012 to anomalously warm marine conditions starting in late 2013 and continuing to present (Figs. 4, 6 and 7). In addition to the persistent warm temperatures, we also observed a freshening of waters at the deeper Seldovia station sonde (Fig. 4) and in Kachemak Bay waters below the pycnocline (Fig. 6) for 2014-2016, which is also consistent with observations of freshening conditions at the GAK 1 mooring during this same time period (Weingartner and Danielson, 2018). Interestingly, the detailed seasonal patterns in salinity sampled in Kachemak Bay (Fig. 6) showed that surface waters were fresher in 2012 and 2013 than they were in the warmer 2014-2016 period. The results indicate that surface waters appear to respond more to local inputs of freshwater than to region-wide interannual changes in freshwater input, while deeper waters in the bay (below the primary pycnocline) respond more to region-wide seasonal and interannual patterns and similarly to the response of shelf waters observed at the GAK1 mooring.

The detailed information on seasonal transitions and changes in timing from year to year provided by the monthly shipboard sampling, as well as from the water quality stations, have consistently been the most frequently used information for our own analyses, as well as the most requested information by other researchers. Given the utility of higher-frequency information for understanding biological changes in plankton and upper trophic species, the project sampling design for the next five-year GWA program includes monthly sampling of along-Kachemak Bay oceanographic gradients to provide higher temporal resolution of along-estuary, as well as cross-estuary gradients. An analysis of oceanographic variability across the northern Gulf of Alaska region for the GWA science synthesis report showed that temperature patterns in Kachemak Bay are largely coherent with the patterns observed at the GAK1 mooring and in Prince William Sound at time scales longer than three months (Holderied and Weingartner, 2016). The identification of consistently cooler and more saline water in outer Kachemak Bay, relative to near-surface waters at the GAK1 mooring (see monthly climatology in Fig. 18), was an unexpected result and needs further examination to assess potential biological implications. We are currently working with researchers from the GWA Environmental Drivers and Nearshore Component to extend the regional oceanographic comparison across the entire 2012-2016 study period and include continuous temperature data from nearshore monitoring sites in Kachemak Bay, Kenai Fjords and Katmai (noting that mooring and intertidal sensor data are available after sensors are recovered during spring field surveys).

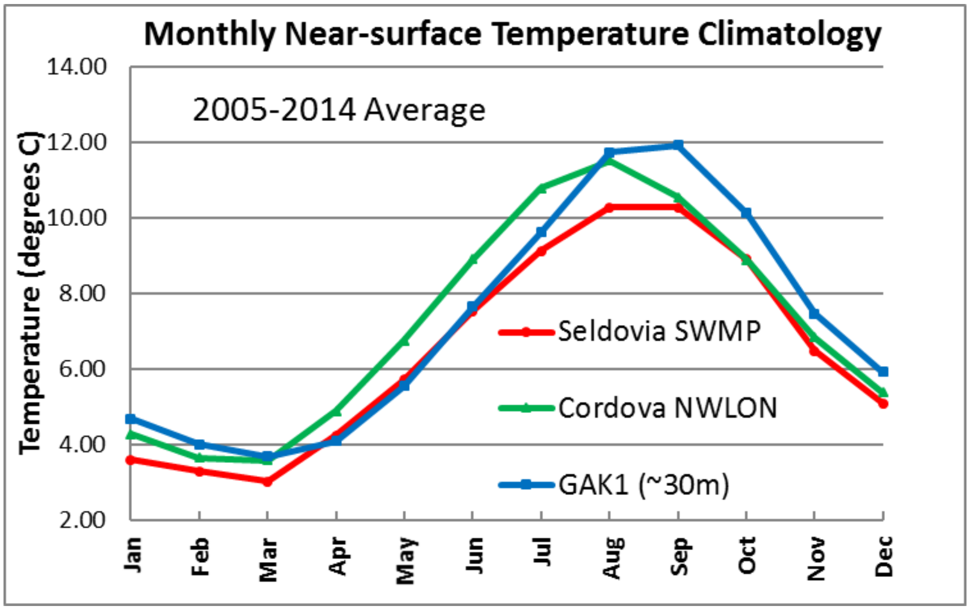


Figure 18. Monthly climatology of near surface water temperature calculated from continuous oceanographic observations made from 2005-2014 at the Seldovia Harbor SWMP station in Kachemak Bay, the NOAA tide gauge (in the National Water Level Observing Network) at Cordova Harbor in Prince William Sound and the GAK1 mooring. Adapted from Holderied and Weingartner, 2016.

Zooplankton and phytoplankton

Zooplankton species composition in Cook Inlet and Kachemak Bay was dominated by copepods in the majority of surveys, with barnacles and jellyfish occasionally becoming the dominant species (Figs. 8, 9, 10). Copepod species also varied in abundance between relatively cold (2012) and warm (2014) years (Fig. 11), with warm water species abundance increasing with the region-wide increases in temperature. Additional analyses of zooplankton data are being conducted in collaboration with other researchers in the GWA Environmental Drivers component to assess how the interannual changes in ocean temperatures during 2012-2016 influenced zooplankton species abundance and observed taxonomic grouping across the GWA study region. We note that zooplankton laboratory analyses for species composition for 2016 samples are to be completed in 2017 and reported with FY17-21 GWA program annual project reports. Continued analyses of zooplankton taxonomic groups by sampling year in combination with phytoplankton and chlorophyll data, when completed, will provide better information on marine plankton bloom structure in Kachemak Bay. Pairing the physical environmental data collected during this study, particularly the detailed horizontal and vertical seasonal water mass structure, with the zooplankton taxonomic groupings will help inform patterns of species occurrence with respect to ocean circulation patterns for the region.

For phytoplankton, the transition from cooler to warmer conditions did not have a significant effect on overall species composition, but did result in large increases in concentrations of toxic algae species and paralytic shellfish poisoning events in Kachemak Bay in 2015 and 2016. These were the first paralytic shellfish poisoning events in Kachemak Bay in over a decade and resulted in oyster farm closures in both 2015 and 2016. Analyses of changes in phytoplankton species composition over time showed a consistent pattern of domination of sample abundances by diatoms, in particular *Chaetoceros* spp., beginning in spring and extending to early fall for all transects and years. Despite significant (~2 degrees C) increases in mean monthly sea surface temperatures in the bay and lower Cook Inlet between 2012 and 2014, phytoplankton species community composition (Figs. 12 and 13) and cell abundance (Fig. 14) did not change discernably over that period. This result indicates that other factors, such as nutrients or grazing, are likely to be limiting factors for total phytoplankton cell abundances and standing biomass. During the FY17-21 GWA program, we plan to more closely examine both the role of nutrients in phytoplankton bloom dynamics and more subtle changes in the response of phytoplankton community composition to interannual changes in oceanographic conditions.

Seabirds and marine mammals

USFWS researchers were hosted on shipboard cruises to provide biological data on spill-affected species coincident with the physical oceanography and plankton observations (project Objective 2). Surveys of marine birds and mammals in the lower Cook Inlet and outer Kachemak Bay provided data on the occurrence, relative densities of, and seasonal species in this region. Of the most common species, only murres and kittiwakes commonly breed within the study area (Piatt 2002); seasonal survey results provided an indication of the attraction of the area to migrating birds. While warm temperatures persisted from 2014 to 2016, the biological response was most noticeable in Kachemak Bay in 2015, with extensive seabird and sea otter mortalities (see Konar et al. 2018). The spatial and temporal scale of our opportunistic marine bird and mammal surveys were not resolved enough to adequately document the local response to the warm event. However, based on informal observations by project investigators, other local researchers and water taxi operators, 2015 was also unusual for the large and perhaps unprecedented numbers (>50 at one time) of actively feeding humpback whales observed in Kachemak Bay from late summer into November. The whale sightings coincided with persistent observations of herring (likely age 0 based on size, but also older year classes) in the summer of 2015 reported by local fishermen, water taxi operators and researchers. Marine bird and mammal mortality events observed in 2015 did not continue into 2016 even though some of the warmest winter temperature anomalies occurred over the 2015-2016 winter. The marine bird and mammal survey data collected in collaboration with this project helps establish a coarse seasonal presence for species in our sampling region but more dedicated research on the linkages among marine bird and mammal populations, their food resources, storm events, and potential marine biotoxin events is needed to understand the biological responses in this system.

CONCLUSIONS

The Gulf of Alaska experienced a transition from anomalously cold water temperatures in 2012 to persistent warm temperature anomalies in 2014-2016, as part of the Pacific Warm Anomaly ("Blob") and El Nino climate events. Warmer than average water temperatures were observed in Kachemak Bay starting in late 2013 and persisting through 2016, with the strongest monthly average temperature anomalies observed in winter 2015-2016. Anomalously warm waters were also observed at all lower Cook Inlet sampling locations in 2014-2016. Seasonal and interannual changes in surface salinities appear to be most influenced by precipitation events and the amount of snow and timing of spring warming, rather than the warm anomaly. However, in deeper waters below the pycnocline and at the Seldovia harbor water quality station, low salinity anomalies (freshening) were observed in 2014-2016, which is consistent with the freshening of Alaska Coastal Current waters observed at the GAK 1 mooring. Overall phytoplankton species composition did not change significantly during the study, but interannual changes in seasonal phytoplankton bloom timing were observed, along with increasing blooms of toxic *Alexandrium* species in Kachemak Bay in 2014, 2015 and 2016, and with paralytic shellfish poisoning events in 2015 and 2016. The relative abundance of zooplankton species changed with warmer ocean waters and 2015 saw dramatic biological responses in Kachemak Bay and Cook Inlet, which included seabird and sea otter mortality events and changes in whale distributions. Over the study period, highest densities of seabirds and sea otters were found in outer Kachemak Bay and on the east side of the Cook Inlet entrance region. The GWA monitoring program captured detailed oceanographic and biological changes associated with the unprecedented 2014-2016 Pacific marine heat wave, which is the type of ecosystem response to changing marine conditions that the program was designed to capture. Results from FY12-16 GWA monitoring in lower Cook Inlet and Kachemak Bay were also used to modify the FY17-21 project design, with an increase in along-bay sampling frequency to better characterize estuary-shelf oceanographic gradients and areas of high biological productivity in the study area.

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