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

The Seward Line: Marine ecosystem monitoring in the Northern Gulf of Alaska

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

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Study History: Begun in fall 1997 as part of the joint National Oceanic and Atmospheric Administration and National Science Foundation's Global Ocean Ecosystems Dynamics program, the Seward Line has become the most comprehensive long-term multidisciplinary marine sampling program in the coastal Gulf of Alaska, monitoring changes in the oceanography of a region that is critical to Alaska's commercial and subsistence fisheries, and tourism economies. From 1998 to 2004, conditions along the Seward Line were sampled on 6-7 cruises per year spanning from March to December. When field studies ended in December 2004, the North Pacific Research Board continued to fund the program, reducing its scope to a cruise each May and September, with a focus along the Seward Line and the main passageways in western Prince William Sound. In 2010, the Alaska Ocean Observing System began to also provide financial support for the Seward Line observations. During 2011-2013, the Seward Line was embedded within the North Pacific Research Board's Gulf of Alaska Integrated Ecosystem Research Program, which added determination of microzooplankton analyses to many cruises. With the addition of *Exxon Valdez* Oil Spill Trustee Council support through Gulf Watch Alaska in 2012, (Project 16120114-J) and elevation of the Seward Line to a Long-Term Monitoring program by North Pacific Research Board during the summer of 2014, the Seward Line had secured a stable funding base. In 2018 the Seward Line became part of the National Science Foundation's Long-term Ecological Research program. The Northern Gulf of Alaska Long-Term Ecological Research allowed expansion of the sampling domain, the addition of a summer cruise, and provided funds for additional measurements and personnel (scientists, students, and staff) as well as access to larger vessels on some cruises.

Abstract: Gulf of Alaska waters undergo year-to-year variability in the physical environment superimposed on longer-term cycles and long-term trends. These variations influence ocean chemistry and propagate through the food web's lower trophic levels, ultimately influencing fish, seabirds, and marine mammals. The Seward Line program monitors the changes in physics, chemistry, and lower trophic levels (i.e., plankton) to describe the current state and natural variability inherent in this ecosystem, which is at risk of significant anthropogenic impact. Our observations are the basis for critical indices of ecosystem status that help us understand key aspects of stability and change in upper ecosystem components over short and long timescales. During the 2017-2021 study years, the Gulf of Alaska physical and lower trophic level metrics slowly returned to a normal state following the extremes of the 2014-2016 marine heatwave, with response delayed by additional heatwave conditions during 2019. The spring phytoplankton bloom responds strongly to heatwave events with altered timing, reduced biomass, and smaller-sized species. With the Seward Line now having 25 years of observations, we can show that for zooplankton the state of the Pacific Decadal Oscillation corresponds to broad changes in community composition. Upper trophic level predators, such as seabirds, also show long-term trends that are taxa specific.

Key words: Biological, chemical, Gulf of Alaska, marine mammals, nutrients, oceanography, physical, phytoplankton, Prince William Sound, seabirds, Seward Line, zooplankton.

Project Data: Data exist in three major groups: ocean physics, nutrients and chlorophyll, and species-resolved zooplankton catches. Seabird data is reported on the GWA pelagic component.

There are no limitations on the use of the data; however, it is requested that the authors be cited for any subsequent publications that reference this dataset. It is strongly recommended that careful attention be paid to the contents of the metadata file associated with these data to evaluate data set limitations or intended use. Data are stored in a comma-delimited CSV format.

All data reside online (or will within 2 years of collection) and are publicly available through several locations, primarily from the Gulf of Alaska data portal and published with DataONE at the links below:

> https://portal.aoos.org/gulf-of-alaska.php#metadata/e25fe1f2-1c98-44f6-856f-5d61c87c0384/project
>
> https://search.dataone.org/portals/NGALTER/About-the-Data-Catalog

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.

Citation:

Hopcroft, R. R., S. L. Danielson, S. L. Strom, and K. Kuletz. 2023. The Seward Line: Marine ecosystem monitoring in the Northern Gulf of Alaska, 2017-2021. Long-term Monitoring Program (Gulf of Alaska) Final Report, (*Exxon Valdez* Oil Spill Trustee Council Project 21120114-L), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

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EXECUTIVE SUMMARY

The Seward Line program has sampled the physical, chemical, and biological properties along a 150 mile-long transect from the mouth of Resurrection Bay, Alaska to offshore waters using ships for 25 years. Principal tools include electronic packages that profile the physical properties of the water column (e.g., temperature and salinity), bottles that sample discrete depths for measuring water chemistry (e.g., nutrients) and single-celled organisms (i.e., phytoplankton and microzooplankton), nets that sample the multicellular meso- and macro-zooplankton, and observers that census seabirds and marine mammals. Its major objectives are to monitor the state of these ecosystem components, describe their variability, and understand the relationships among them to thereby improve our understanding and management of this highly productive habitat.

Long time-series are required before meaningful patterns or trends begin to emerge. For physical and lower trophic level studies after the unprecedented marine heatwaves in 2014-2016 and 2019, many metrics appear to have return to their pre-heatwave state. Twenty-five years of observations are now allowing us to disentangle broader-scale temporal patterns that were not apparent previously.

INTRODUCTION

Long time-series are required for scientists to identify secular change (and infer cause) in the face of substantial year-to-year variability. Like other regions, the North Pacific undergoes significant interannual variability, driven partially by variations in basin- or global-scale phenomena (e.g., El Niño, the Pacific Decadal Oscillation). Longer-term variations referred to as "regime shifts" have occurred in the past and will likely occur again. These are expressed as fundamental shifts in ecosystem structure and function, such as the 1976 regime shift that resulted in a switch within the Gulf of Alaska (GOA) from a shrimp-dominated fishery to one dominated by pollock, salmon, and halibut (Anderson and Piatt 1999). Long-term observations are also critical to describe the current state, and natural variability inherent in an ecosystem at risk of significant anthropogenic impact such as occurred during the *Exxon Valdez* oil spill. Given the potential for such profound impacts, the Seward Line provides these critical observations on the current state of the northern Gulf of Alaska (NGA) ecosystem.

Inherent in the concept of any long-term observation program is the ability to assess effects of climate variation. Beyond this long-term aspect, the Seward Line sampling program is designed to capture the major gradients in lower tropic level production as estimated from broad-scale analyses of satellite ocean color imagery (assumed to represent phytoplankton production gradients). This design allows us to investigate the mechanisms by which variations in physical and chemical conditions translate into changes in the composition and abundance of organisms in the planktonic food web, and how apex predators, such as seabirds, integrate and reflect these changes. The first-order driver of production variability is the intense environmental seasonality of the system (Brickley and Thomas 2004, Waite and Mueter 2013). Our cruises span the major spring-late summer gradient in this seasonality, while retaining a focus on important periods for the life cycles of various zooplankton species. The early May period was selected to capture the peak productivity associated with the spring bloom. The consistent timing of the May cruise has allowed us to look at phenology shifts (e.g., Mackas et al. 2012) in the large *Neocalanus* spp. copepods that dominate the spring zooplankton biomass (Coyle et al. 2019). The September cruise captures the end of the low productivity oceanographic summer, when smaller phyto- and zooplankton dominate, and precedes the stormy fall overturn. Changes in the microzooplankton community are likely to accompany this seasonal gradient, as hinted at in earlier work showing, for example, higher abundances of dinoflagellates in summer compared to spring (Strom et al. 2007, Strom and Fredrickson 2008).

Dominant spatial gradients in the coastal GOA are the east-west contrast and the cross-shelf zonation (Brickley and Thomas 2004, Waite and Mueter 2013). The Seward Line station layout is explicitly designed to capture the important cross-shelf divisions (described above), as well as incorporating Prince William Sound (PWS) as a largely enclosed, estuarine “end member” of this coastal continuum. Mating biological observations (e.g., plankton community composition) directly to physical and chemical sampling allows us to define these zones according to their oceanographic properties rather than fixed geographic coordinates (Coyle and Pinchuk 2003, 2005). This is crucial in a region where variations in cross-shelf transport, down- or upwelling intensity, and mesoscale eddy activity can shift frontal boundaries rapidly (Stabeno et al. 2004). Multi-decadal observation of the coastal GOA is required for broad-scale atmospheric indices such as the Pacific Decadal Oscillation to emerge, while shorter-term events such as the El Niño Southern Oscillation may have less predictable impacts (Stabeno et al. 2004). Most recently, a warm-water anomaly referred to as “the Blob” has had far ranging impacts in the GOA (Arimitsu et al. 2021, Danielson et al. 2022, Suryan et al. 2021). Ultimately, the Seward Line observations help us understand how environmental effects (i.e., oceanographic conditions and their variability) relate to higher-order emergent ecological properties such as spatial and temporal coherence of communities, resilience, and diversity (Beaugrand et al. 2010, Wiltshire et al. 2008).

OBJECTIVES

The scientific purpose of this project is to develop an understanding of the marine ecosystem response to climate variability and provide baselines against which to assess anthropogenic influences on the GOA ecosystem. Toward this end, the Seward Line cruises on the NGA shelf determine the physical-chemical structure, phytoplankton biomass and size composition, and the distribution and abundance of zooplankton, along with their seasonal and interannual variations.

Some of the data are compared with historical data sets whereas other data sets are a more recent product of our continuing sampling effort.

Specifically, the objectives for cruises each May and September are:

1. Determine thermohaline, velocity, and nutrient structure of the Seward Line across the GOA shelf, and at stations throughout PWS (Fig. 1).
2. Determine phytoplankton (chlorophyll) biomass and size distribution.
3. Determine the distribution and abundance of metazooplankton.
4. Determine the distribution and abundance of microzooplankton (starting in 2014).
5. Opportunistically, determine rates of growth and egg production of selected key zooplankton species.
6. Support determination of carbonate chemistry (i.e., ocean acidification).
7. Determine distribution and composition of seabirds (and marine mammals) along the Seward Line, PWS and Kenai coastline.
8. Provide at-sea experience for graduate and undergraduate students.

Objectives 4, 5, 6 & 8 are primarily supported through other consortium funding, while 7 has costs shared between Gulf Watch Alaska and the consortium. Consequently, this report focuses on Objectives 1, 2, 3, and 7 which were largely supported by *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) funds, while the other objectives are covered in lesser detail. Additional detail for Objective 7 is provided in the final report for project 21120014-M.

METHODS

Project design and conceptual approach

Core program: The Seward Line Program consists of 13 primary and 9 secondary stations along the Seward Line and 4 stations in western PWS. These are sampled in May and early September typically from either National Science Foundation (NSF) vessel *R/V Sikuliaq* or the U. S. Fish and Wildlife Service (USFWS) vessel *R/V Tiglax* (Fig. 1). Beginning in 2014, we added an additional two stations to the offshore end of the Seward Line to improve coverage of the oceanic ‘end member’ of this coastal ecosystem.

Oceanographic sampling methodology has remained stable since sampling began in the fall of 1997 (Weingartner et al. 2002), although the logistics of vessel availability (*R/V Tiglax*) has pushed summer sampling from mid-August to early/mid-September. All hydrographic and bottle-based sampling is conducted during the day, as well as collection of the smaller zooplankton species that do not migrate vertically, and do not avoid nets. Seabird and mammal observations are made during station transits. At night, sampling is conducted for the larger and

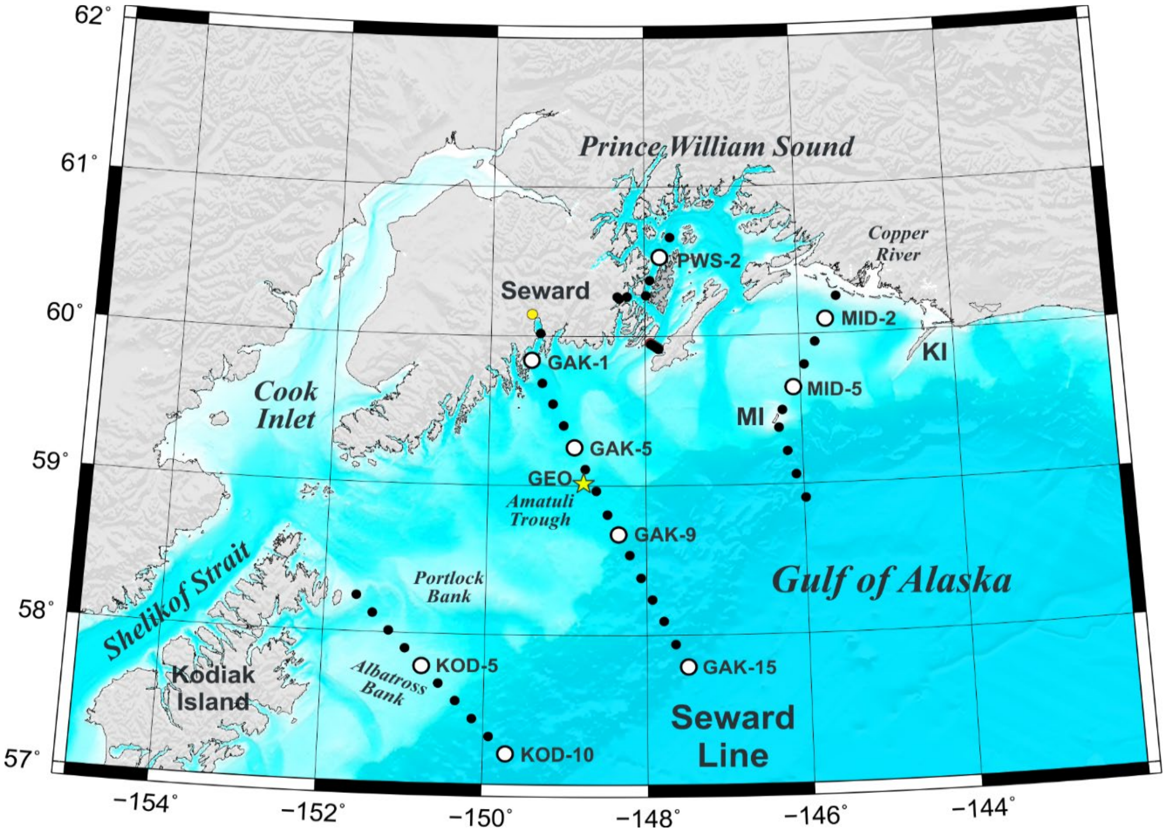

Figure 1. The Seward Line's primary stations, embedded within the Northern Gulf of Alaska-Long-Term Ecological Research (LTER) program. Open circles indicate intensive stations, black circles indicate regular stations. Yellow star shows position of LTER mooring. Yellow circle indicates the location of Seward.

more mobile zooplankton, many of which can only be sampled efficiently during their daily migration toward the surface under the cover of darkness. Although this protocol results in some backtracking along the transect line, it ensures that all data can be employed in analysis without biases arising from diel cycles and avoids the need for sailing with duplicative personnel to staff day/night sampling teams. At present, there are no autonomous or remote sensing technologies that allow sufficient sampling of the biological components of this program – they can only be adequately assessed by vessel-based observations. Nonetheless, the Seward Line program provides the opportunity for testing and validating any such technologies as they become available.

Hydrography and nutrients

Each station includes high-resolution vertical profiling of water properties (including temperature, salinity, chlorophyll *a* fluorescence, photosynthetically active radiation (PAR), beam transmission, dissolved oxygen) to within 5 m of the bottom using a Seabird 911Plus conductivity-temperature-depth (CTD) with dual temperature, conductivity and oxygen sensors. Dissolved inorganic nutrients (phosphate, silicic acid, nitrate, nitrite, ammonium) and carbonate chemistry (a.k.a., “Ocean Acidification” parameters) are collected from rosette (Niskin) bottles that sample at 10 m depth intervals in the upper 50 m, and at irregularly spaced but consistent depths to the bottom. Oxygen samples are collected from rosette bottles for calibration of high-resolution sensors. Oxygen is measured according to specifications set forth by the World Ocean Circulation Experiment (WOCE; Gordon et al. 1993). Nutrient samples are collected, filtered (0.4 µm), frozen at -40 or -80°C, and transported to the University of Alaska Fairbanks Nutrient Analytical Facility, where analyses are carried out based on protocols described in the GO-SHIP Repeat Hydrography Nutrient Manual (Baker et al. 2020) using a QuAAtro39 continuous segmented flow analyzer (Seal Analytical). These state-of-the-art protocols ensure high-precision, accurate analyses of nutrients in seawater.

The physical and chemical data are used to quantify the seasonal, interannual, and along- and cross-shelf distributions of water masses and their variability. Interdecadal time scales are also addressed through use of ship-based gridded sea surface temperature compilations (e.g., Huang et al. 2017), upwelling indices, the Pacific Decadal Oscillation (and other atmospheric indices), oceanographic buoy data, and the EVOSTC-supported continuous measurements at GAK-1 (EVOSTC project 21120114-I). Although limited to surface observations, satellite sensor data (ocean color, surface altimetry and sea surface temperature) is used to place our shipboard data in broader spatial and temporal contexts (Appendix 1). These data, combined with atmospheric and oceanographic model reanalysis hindcasts, can help characterize aspects of the system that we do not directly measure. This holistic approach to interpreting the physical environment is critical to extrapolating our shipboard measurements and enabling a physics-to-birds-and-mammals understanding of the GOA ecosystem.

Chlorophyll

Chlorophyll *a* is the most widely used index of phytoplankton biomass, and one of the few biological parameters that can be sensed in situ or remotely by satellites. Chlorophyll a is sampled at all stations and analyzed at sea as a measure of phytoplankton biomass and as a means to calibrate in vivo fluorescence sensors on the CTD package. We coordinate sampling depths with water column chemistry measurements (i.e., at 10 m intervals in the upper 50 m). Samples are collected with the rosette on up-casts and filtered at low vacuum through 20 µm pore-size polycarbonate filters and onto glass fiber filters (0.7 µm effective pore size) to estimate phytoplankton biomass partitioning into ≥20 and <20 µm size classes. Previous work has shown that these two size classes respond to different sets of environmental conditions and have different fates in the coastal GOA food web (Strom et al. 2007, 2010). In the past, chlorophyll samples were stored frozen for post-cruise fluorometric analysis (Parsons et al. 1984). Subsequent concerns about degradation of pigments by this approach (Wasmund and Topp 2006) have resulted in the extraction process commencing immediately after filtration and fluorometry conducted on shipboard since 2014.

Phytoplankton and microzooplankton

Determination of phyto- and microzooplankton composition and biomass provides information on the functioning of the ecosystem, and responses to environmental forcing. Knowledge of phytoplankton composition allows us to relate physical processes (mixing, light availability) and nutrient supplies to the nature of the production response. Large chain diatoms may be particularly important in connecting pelagic production with the benthos. Large heterotrophic dinoflagellates can respond strongly to diatom blooms; their biomass indicates potential grazing impact of microzooplankton on diatom blooms, a major trophic transfer pathway in coastal GOA waters sampled so far (Strom et al. 2001, 2006, 2007). Large microzooplankters are also important prey for the crustacean zooplankton (Liu et al. 2005, 2008). A scarcity of large microzooplankton indicates a highly recycled food web with relatively less export to benthos or larger pelagic species. In general, knowledge of phyto- and microzooplankton composition and biomass is essential for evaluating the food web structure and potential trophic transfer efficiency of the region.

Phytoplankton community composition (primarily diatom and dinoflagellate identification) is assessed using inverted light microscopy of formalin-fixed samples. Acid Lugol's fixation and inverted light microscopy (Sherr and Sherr 1993) are used to identify, count, and size all microzooplankton ≥15 µm in size (using a semi-automated digitizing system, Roff and Hopcroft 1986). Biomass is estimated from microzooplankton cell volumes using published conversion factors (Strom et al. 2006, 2007). The ≥15 µm size class of microzooplankton can be directly consumed by mesozooplankton. All phytoplankton and microzooplankton sampling was confined to the same surface mixed layer (50 m and above) as employed for chlorophyll determination.

Primary production

Intermittent point measurement of primary production using both stable and radioisotopes over the past two decades have highlighted that the intense day-to-day (and within day) variability in solar irradiance due to cloud cover is a major driver of production rate variability (Strom et al. 2010). Primary production is currently measured at one PWS and four Seward Line stations per cruise, representing a gradient from nearshore to offshore (oceanic) waters. Water is collected from 6 depths per station and incubated on deck at light levels (fractions of surface irradiance) corresponding to those at collection depth. Uptake of 13C from labeled sodium bicarbonate (an inorganic carbon source) into particulate matter over 24 h allows calculation of the production rate (µgC liter^{-1} d^{-1}); depth integration of these data yields the water column production rate (mgC m^{-2} d^{-1}).

Ocean color as observed by satellites offers appropriate time frames over which to estimate relative productivity. Through appropriate interpolation and averaging of pixels, it is possible to construct weekly, monthly, or seasonal values of chlorophyll which over these longer periods tend to correlate with the magnitude of primary production. Here we generated 8-day mean chlorophyll concentrations from MODIS Aqua for a 100 km wide swath centered along the

Seward Line. These data were further averaged to yield a “spring” (April-June) and summer (July-August) value, for which anomalies were calculated over the life of this satellite (2003-present).

Metazooplankton

Metazoan zooplankton represent the key linkage between production by single-celled organisms, and larger organisms such as fish, seabirds and marine mammals. Although typically considered as a single unit, the term encompasses a wide array and vast size range of species for which no one piece of sampling equipment can suffice. To address this challenge, our sampling uses three different types of plankton nets. During daytime, mesozooplankton samples are collected with a Quad net consisting of 25 cm diameter nets of 2.6 m length equipped with General Oceanics flowmeters. A pair of these nets is constructed of 150 µm mesh and samples small, primarily early copepodid stages of calanoids (e.g., Coyle and Pinchuk 2003, 2005), while nauplii and the smallest copepodid stages of neritic species are sampled with a pair of nets equipped with 50 µm mesh (not generally processed). Quad net tows are made from 100 m to the surface at the 13 primary stations along the Seward Line, and at all PWS stations. During night-time, a 0.25-m^2 Hydrobios Multinet system with 0.5 mm mesh nets is fished to assess larger meso/macro-zooplankton and micronekton, such as euphausiids that are important components in the diet of many fish, seabirds and marine mammals. The Multinet is equipped with one drogue net plus five nets that can be programmed to open and close at specific depths, or opened and closed electronically from the deck if a conducting cable is available. Depth, flow meter counts, and volume filtered are recorded at 1 second intervals. The Multinet is fished at each of the 13 primary Seward Line stations (Fig. 1), plus the 10-12 stations within PWS. At each station, 5 samples are collected at 20 m depth intervals from 100 m depth to the surface. As time permits, additional Multinet collections are made to 600 m at GAK13 and PWS2 to assess over-wintering populations of Neocalanus spp. in 5 layers: 600-400 m, 400-300 m, 300-200 m, 200-100 m, and 100-0 m. All zooplankton samples are preserved in 5-10% formalin and stained with Rose Bengal for later analysis to the lowest taxonomic category possible.

During traditional taxonomic processing, all larger organisms (primarily shrimp and jelly fish) are removed and enumerated, and the sample is repeatedly split using a Folsom splitter until the smallest subsample contains about 100 specimens of the most abundant taxa. The most abundant taxa are identified, copepodites staged, measured, enumerated, and weighed, with each larger subsample examined for the larger, less abundant taxa. Blotted wet weights of all specimens of each taxon and stage are taken on each sample with ±1 µg Cahn Electrobalance until weights stabilize, after which point the wet weight biomass is estimated using mean wet weight. Wet weights on euphausiids, shrimp and other larger taxa are always measured and recorded individually for each sample. Beginning in 2018, length-weight relationships were established for most taxa and wet-weights are predicted from length. Typically, at least 400-600 organisms are recorded per net-sample. The data are uploaded to a Microsoft Access database for sorting and analysis. Long-term patterns and trends are typically performed on power-transformed data (typically power 0.15). Analysis to date indicates the Multinet collections are consistent with those obtained using a 1.0 m^2 MOCNESS during the Global Ocean Ecosystems Dynamics program years (1998-2004).

Seabirds and mammals

The Seward Line design (spring and fall seasons, cross-shelf) provides an opportunity to examine seabird and marine mammal responses to seasonal changes and the cross-shelf gradient of physical and biological parameters. The spring survey occurs just prior to or at the beginning of the breeding period and the fall survey occurs when birds must prepare for harsh winter conditions or long migrations.

Seabird and marine mammal surveys were conducted when the vessel was underway, including transits between sampling stations and sampling lines, and when towing underway instrument packages. A single observer conducted surveys from the bridge or flying bridge using a modified line-transect protocol. The observer searched an area within a 300 m, 90° arc from the bow to the beam, using hand-held 10x binoculars when necessary. Observations were recorded using four distance bins: 0–50 m, 51–100 m, 101–200 m, and 201–300 m. Observations of rare birds or large flocks, or marine mammals observed outside of the sampling window were recorded as "off-transect". Observations were recorded directly into a laptop computer using software Dlogv3 (R. G. Ford Consulting, Portland, Oregon) which logged the geographic coordinates of each sighting, as well as the track line and environmental conditions at 20 sec intervals. Data were processed by subdividing survey transects into 3-km segments.

RESULTS

Physics

In order to focus our attention on the habitat experienced by the sampled plankton, the following analyses consider averages over the upper 100 m of the water column - the depth to which zooplankton vertical net tows often collect samples. We also restrict our analyses to GAK-1 through GAK-13 because the stations GAK-14 and GAK-15 on the lower continental slope were not sampled in the earlier years of the program.

During spring, we observe on average a relatively narrow half-degree range (5.5 to 6.0 °C) of 0-100 m temperatures across Seward Line stations GAK-1 to GAK-13 (Fig. 2). In contrast, the mean temperatures over this depth range in September exceeds two degrees (7.7 to 9.9 °C; Fig. 2), with nearshore temperatures usually significantly warmer than offshore waters (Fig. 3). The sign of the temperature gradient changes over the intervening months: nearshore waters are typically cooler than offshore waters in spring but warmer than offshore waters in fall (Fig. 3). In all months the coastal salinities are lower than salinities found offshore. The range of salinity across the Seward Line in May is typically between 31.5 to 32.6; in September the cross-shelf

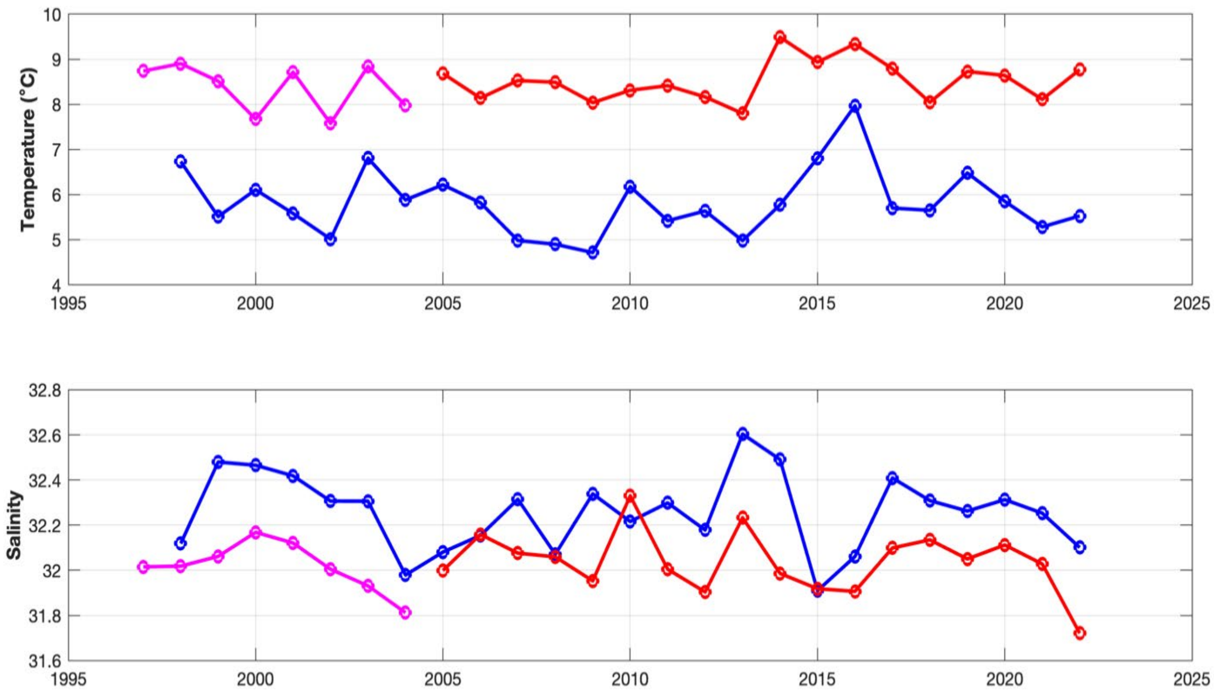

Figure 2. Mean 0-100 m upper water column temperature (top) and salinity (bottom) computed across Seward Line stations GAK-1 through GAK-13 for May (blue), September (red) and October (magenta).

salinity range more than doubles in magnitude (range 30.3 to 32.6), reflecting accumulation of freshwater in the coastal zone over the course of the summer (Fig. 2).

Warmest springs occurred in 1998, 2003, 2015-16, and 2019, and these generally correspond to warmer Septembers, although September 2014, 2017, and 2022 were also notably warm (Figs. 2 and 3). The vertical and horizontal structure of heat and haline anomalies (Fig. 4) exhibit appreciable patchiness, showing that surface anomalies often do not well reflect conditions at depth. Notably cooler springs occurred in 2002, 2007-3009 and 2013 (Janout et al. 2010). Cool Septembers and Octobers occurred in 2000, 2002, 2013 and 2019. Warm May conditions are often associated with low salinity conditions ($r^2 = 0.25$, $p = 0.04$).

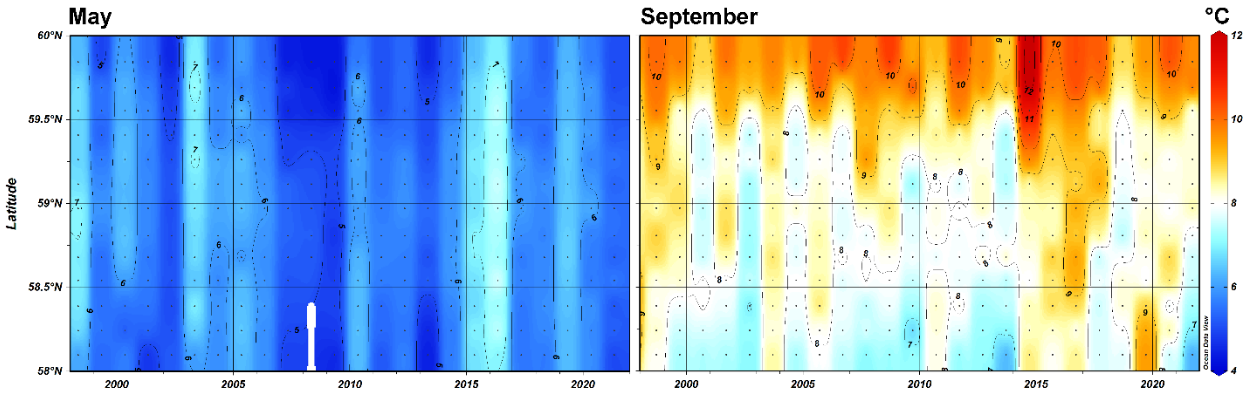

Figure 3. Average water temperatures in the upper 100 m along the Seward Line during May and September, 1998-2021.

Due to memory in the system and potential unidentified mechanistic linkages, Seward Line thermal anomalies in May can provide an indication of likely conditions four months later in September. Regression analyses show that mean May upper water column temperature on the Seward Line provides a significant leading predictor of the September temperature anomaly ($r^2 = 0.38$, $p = 0.006$). In contrast, the mean May salinity is only weakly related to the September salinity ($p = 0.07$). Neither temperature nor salinity in the month of September is a predictor of following May conditions.

An examination of summer season changes (May to September) in temperature and salinity (Fig. 5) shows that in most years (12 of 17) the change in upper water column heat content corresponds to a predictable change in upper water column salinity. Five other years, however,

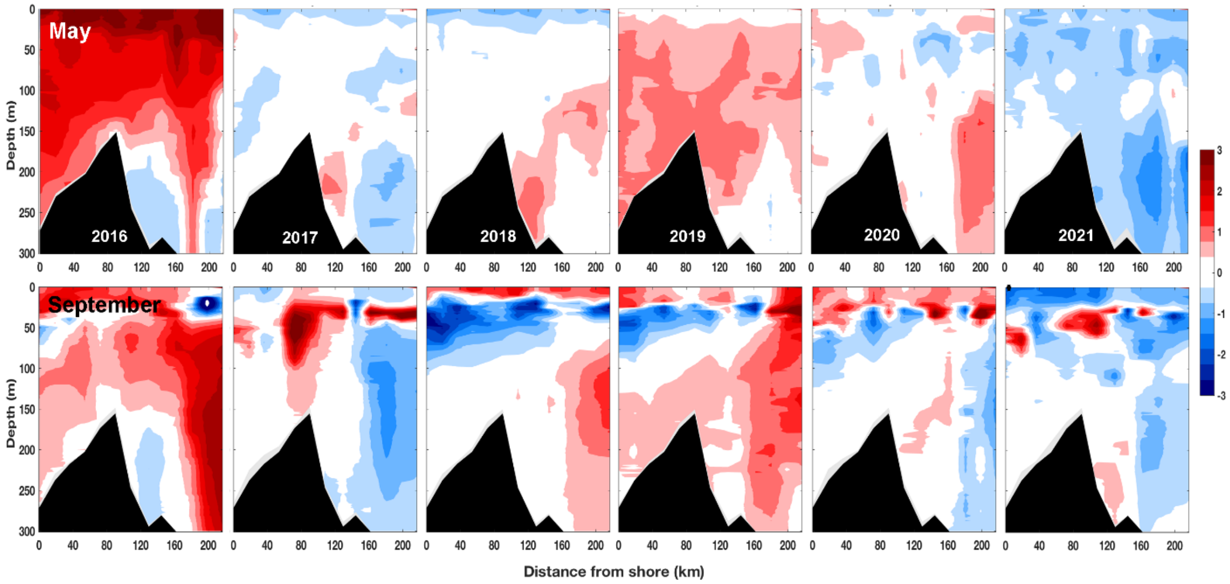

Figure 4. Water temperature anomalies (°C - color bar) along the Seward Line during May and September for the prior six study years.

appear as outliers to this relation. These include the Pacific marine heatwave (PMW) years of 2014, 2016, and 2019 and cool phase years of 2010 and 2013. Four of these five years exhibited the smallest (out of all 17 years 2005-2022) warming from May to September, while the other year (2013) exhibited the largest decline in salinity and was an important transitional year into the 2014-2016 PMH.

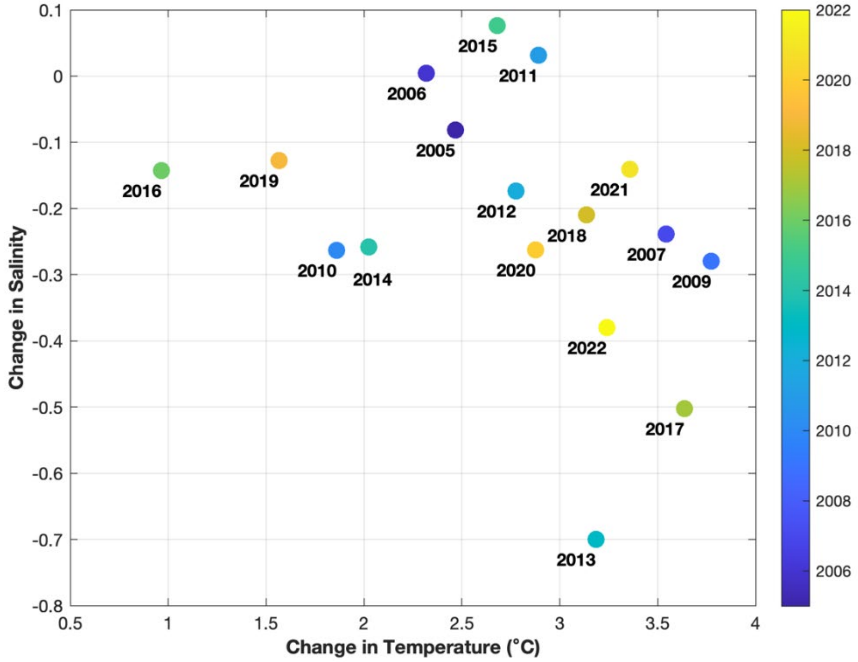

Figure 5. May to September change in Salinity as a function of the change in temperature over the same time frame. All data points based on averages over 0-100 m depth and across GAK-1 through GAK-13 on the Seward Line.

Macronutrients

In general, macronutrient concentrations in surface waters reflect the seasonal progression of their input and utilization. Nutrient recharge occurs in winter due to storms mixing nutrient-rich subsurface waters into the surface, prevailing downwelling conditions advecting nutrient-rich offshore waters onto the shelf, and the limited biological uptake during winter's light limiting conditions. The observed concentrations in the surface mixed layer during May (Fig. 6) reflect the extent to which the nutrients have been utilized by the spring phytoplankton community and provide clues about the timing and strength of the spring bloom in any given year. May nutrient concentrations also demonstrate how the bloom clearly peaks at different times in different cross-shelf regions. The silicic acid drawdown in spring indicates sustained diatom production, during the spring bloom, and as the season progresses the depletion of nitrate and phosphate contribute to a shift in community composition by summer. Nitrate can be depleted over much of the shelf into summer, and a community of small cells is maintained by recycled ammonia and phosphate. However, enhanced freshwater input in summer and fall brings along silicic acid, resulting in relatively elevated concentrations of silicic acid in surface waters of the inner shelf. The convoluted nature of the Gulf of Alaska shelf allows for regions where tidal mixing, subsurface flows and/or storms can provide intermittent nutrient input that contributes to summer and fall production. Nutrient concentrations in fall reflect the degree to which the onset of fall storms are able to break stratification, enhance surface mix layer depth, and increase nutrient inventories.

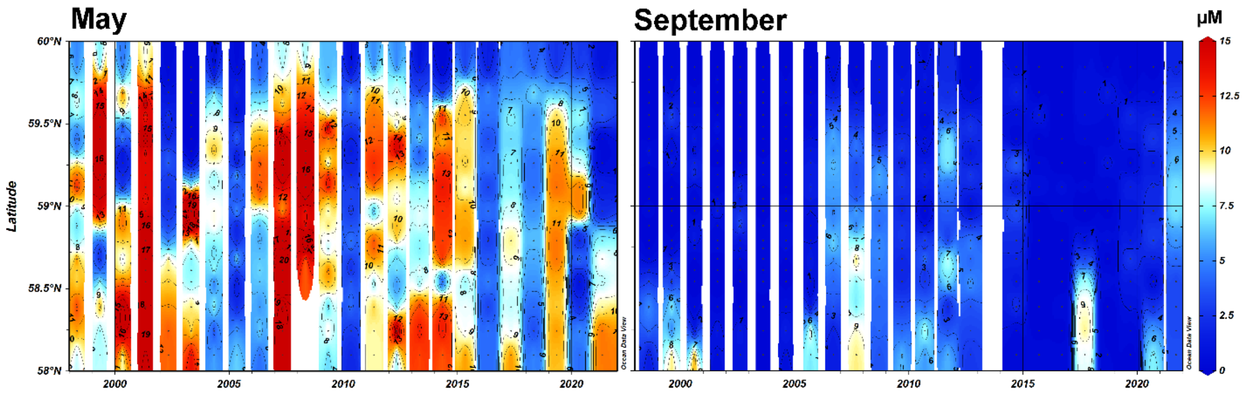

Figure 6. Nitrate concentration in near-surface (<10m) waters of the Seward Line during May (left) and September (right).

Phytoplankton (chlorophyll) and primary production

Phytoplankton measurements during early May target the period of typically highest chlorophyll concentration over the shelf (based on remote sensing data), when phytoplankton growth outpaces grazing pressure and sinking losses. September measurements can capture the late summer community, when nutrients are limiting and biomass is low, or can give insights into the period of fall wind mixing, surface nutrient replenishment, and associated (minor) fall diatom bloom.

The past 5 years have seen a maturation of the phyto- and microzooplankton time series, allowing us a decadal-scale perspective that is providing new science insights and predictive tools. A major recent effort has been the development of 25-year chlorophyll-a time series from historic Seward Line and PWS data. This effort involved reconciling dozens of different data sets collected by several different investigators over the years; time-series analysis and use for model validation are on-going. In a related effort, chlorophyll-a data from Seward Line cruises has been combined with estimates of spring bloom magnitude from remote sensing to create a predictive ‘phytoplankton size index’ The size composition of the Seward Line continental shelf phytoplankton community during early May is linearly related to the ultimate magnitude of the overall spring bloom (Fig. 7). The unusually large 2021 spring bloom is apparent in the time series and was the subject of a “one pager” provided to the North Pacific Research Board that year. The size index for spring 2022 predicts one of the largest cumulative blooms in the time series (Fig. 8). This size index has been incorporated into the National Oceanic and Atmospheric

Administration's early season Preview of Ecological and Economic Conditions (PEEC) review, as well as the annual Gulf of Alaska Ecosystem Status Report. Recently the 25-year time series of PWS chlorophyll a data have also been compiled and is being used to parameterize and validate food web models for PWS.

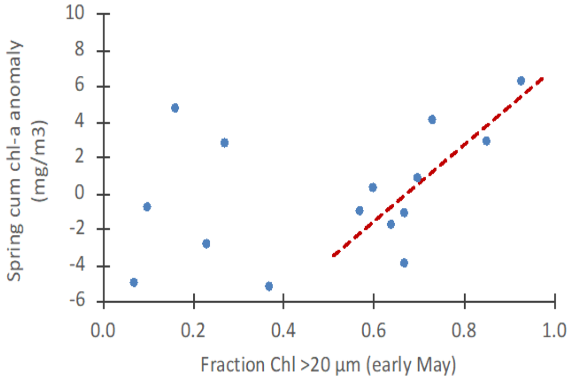

Figure 7. Phytoplankton size index (average fraction of chlorophyll-a [chl-a] in large cells on Seward Line shelf, early May) predicts ultimate magnitude of Northern Gulf of Alaska spring bloom (shown as cumulative April–June chl-a anomaly) when size index >0.5 (dashed red line; $r^2=0.61$*).*

Primary production data are painting a picture of an ecosystem alternately regulated by light and nutrients. (Note that production measurements during 2020 were severely curtailed by COVID-19 restrictions on cruise length and personnel). From our growing database of stable isotope-based daily productivity estimates, we have been able to establish robust predictive relationships with environmental variables. In spring and fall, water column primary production is a first-order function of chlorophyll a biomass, albeit with interannual shifts in the slope of the relationship, particularly in spring (Fig. 9). Summer (not funded by EVOSTC) represents a two-layer system: production in the deep (subsurface) chlorophyll maximum layer is a function of light, while in the surface mixed layer production relates linearly to biomass and inversely to concentrations of recycled nutrients (ammonium, phosphate).

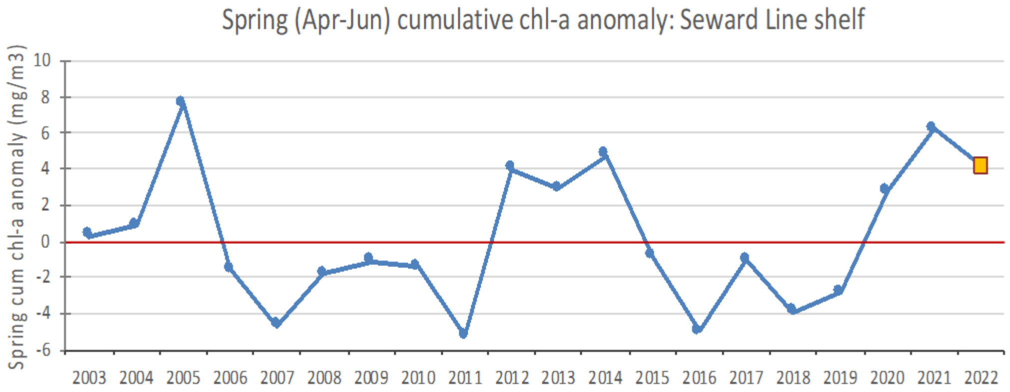

Figure 8. Time series of spring bloom magnitude, from remote sensing, as cumulative chlorophyll-a (chl-a) anomaly; yellow square shows that predicted 2022 spring bloom magnitude is one of the largest in the time series.

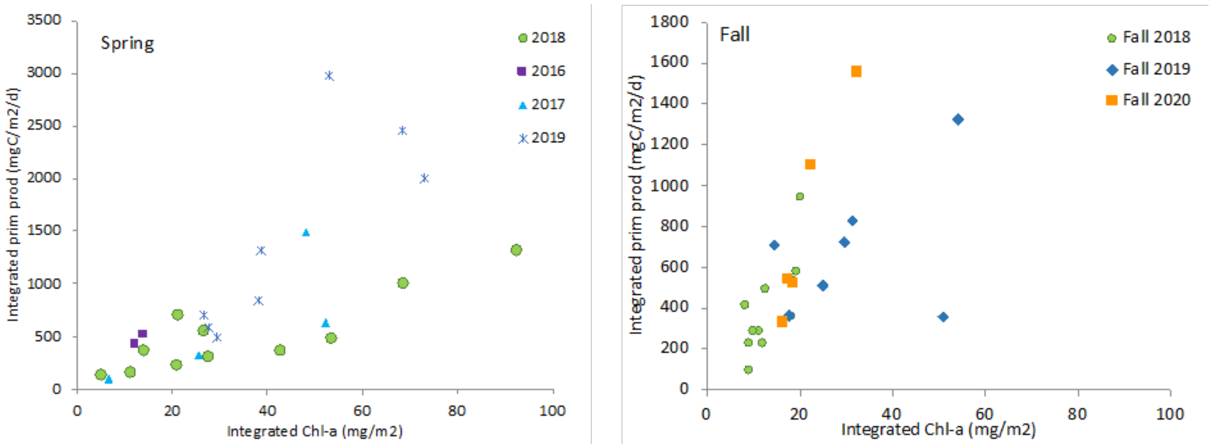

Figure 9. Integrated primary production from Seward Line, Prince William Sound, and other Northern Gulf of Alaska shelf stations during recent years in spring (early May) and fall (early-mid September). In spring and fall primary production is a first-order function of chlorophyll-a biomass, with the slope of the relationship showing interannual variation. For the entire data set, mgC fixed [mg chl-a]$^{-1}$ d^{-1} = 22 for spring, 18 for fall. Primary production was not measured in spring 2020; 2021 samples have been processed and data are currently being analyzed.

Microzooplankton

Our growing time series shows the unusually high microzooplankton biomass associated with the massive spring 2021 diatom bloom (Fig. 10A), in the context of an 11-year time series. As for chlorophyll-a, during the past year we have undertaken a reanalysis of this entire time series. Informed by findings from our recent North Pacific Research Board-supported project on mixotrophy in the NGA, we have been able to extract known, morphologically distinct mixotrophic taxa from our historic data set (derived from Lugol's iodine fixed samples). These taxa play a key role in the ecosystem, acting simultaneously as primary producers and consumers, and buffering the ecosystem response to environmental variability. As one example, the chloroplast-retaining ciliate *Mesodinium* spp. is one of the most abundant mixotrophs in the NGA ecosystem, where it can contribute >50% of total ciliate biomass (Fig. 10B). Our time series shows the near disappearance of *Mesodinium* during the 2014-16 PMH, followed by a recovery to levels higher than those seen prior to the heatwave.

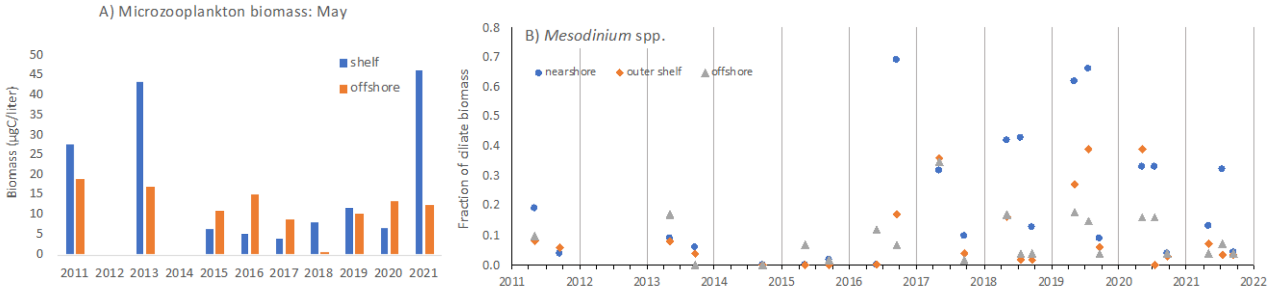

Figure 10. Selected results from microzooplankton time series and reanalysis. A) Time series of total microzooplankton biomass on the Seward Line in early May, showing high levels on the shelf during the massive spring 2021 diatom bloom. Values are averages from 10-m samples at 3-5 stations in each zone. B) Mixotrophic ciliate Mesodinium spp. is a key player in the 'microzooplankton' community. This ciliate specializes in long-term retention of cryptophyte chloroplasts and can comprise >50% of total ciliate biomass. Mesodinium spp. tends to be especially important nearshore (blue symbols) and in the spring and summer. Mesodinium appears to have increased in the ecosystem following the profound 2014-16 marine heatwave.

Metazooplankton

The metazoan zooplankton community on the GOA shelf consists of over 200 holoplanktonic species, of which about 3 dozen contribute the majority of the abundance and biomass. The major suspension feeding groups captured by the 500-µm nets are the calanoid copepods and euphausiids, while the cnidarians (jellyfish and kin) and chaetognaths (arrow worms) are the major planktonic predators. The PMH had relatively little impact on the abundance of the large copepods that dominate the spring copepods community (Fig. 11), although their biomass increased because warmer temperatures accelerated their development (leading to sampling of larger-than-normal individuals). Spring copepod biomass remained elevated post PMH, but declined during 2019, then rebounded. Euphausiids biomass was low during the PMH, particularly within PWS (not shown), but recovered subsequent to the PMH.

In contrast, years with where warm waters persist into September have a marked increase in less lipid-rich, warm-water California Current species (Fig. 12). The abundance of warm water calanoid copepod species (Fig. 13) during fall is highly correlated (r^2=0.5) to the Pacific Decadal Oscillation during prior months. In most years, euphausiid biomass increases between our spring and September surveys.

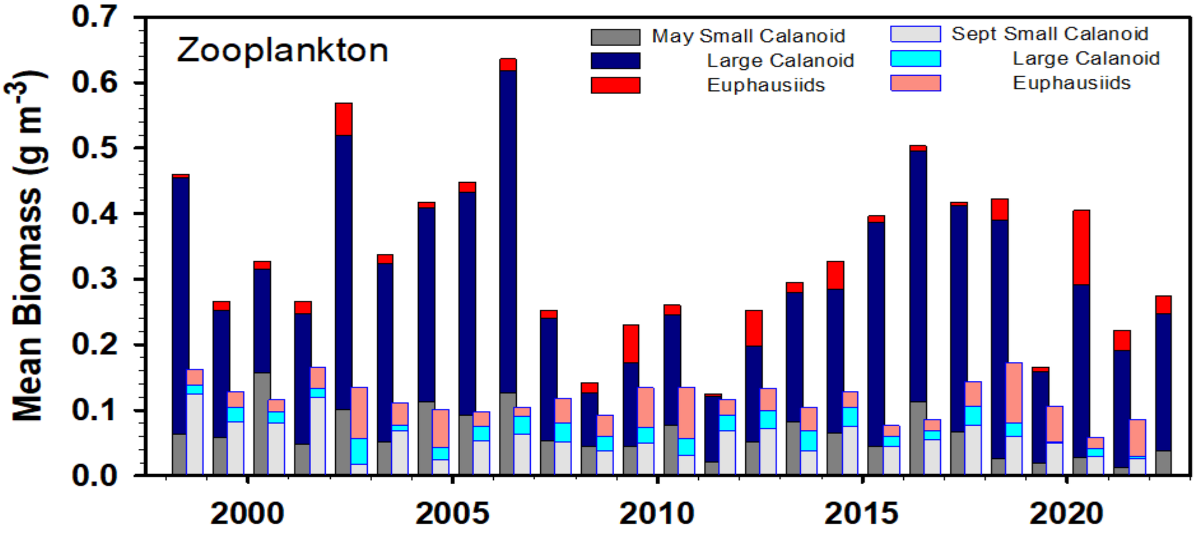

Figure 11. Average wet-weight biomass of major "grazing" zooplankton groups along the Seward Line during May 1998-2022. Note 2020-2022 is preliminary for euphausiids.

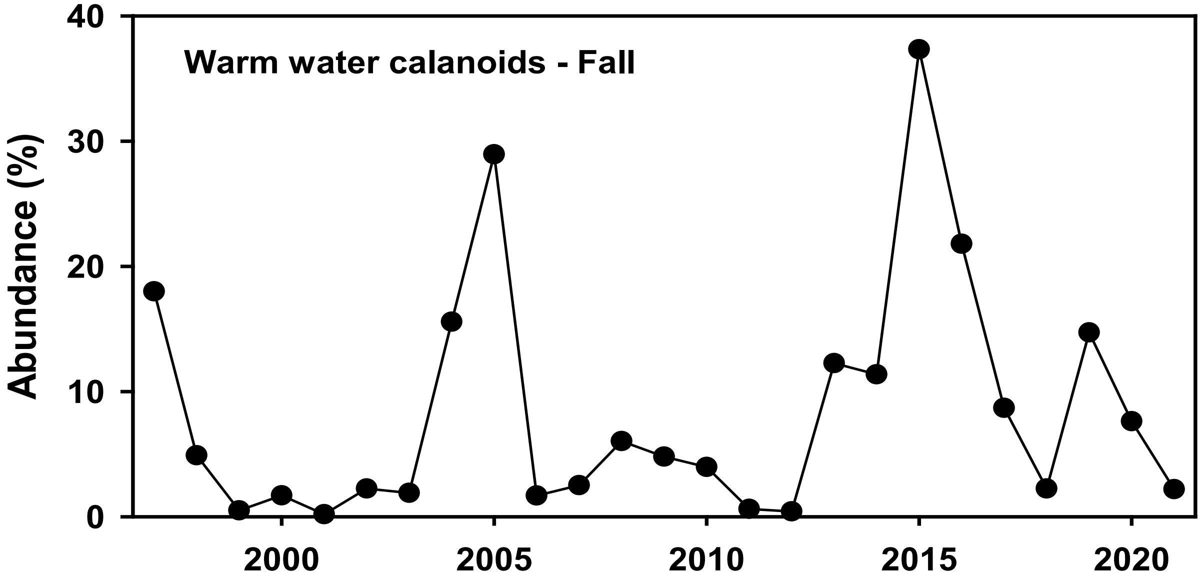

Figure 12. Percentage of calanoid copepod community abundance contributed by warm-water species as by 150µm-nets along the Seward Line during August/September 1998-2021.

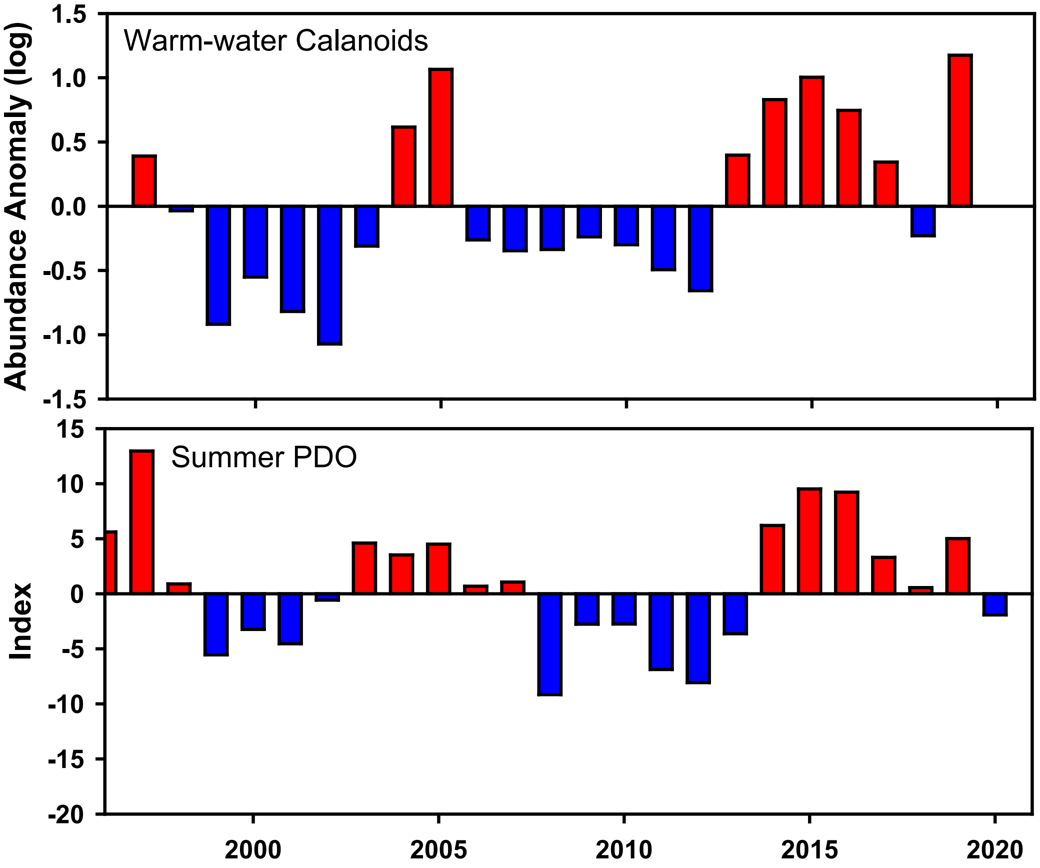

Figure 13. Abundance anomaly of warm-water calanoid copepods along the Seward Line compared to the Pacific Decadal Oscillation (PDO) for the preceding six months; both are highly correlated (r^2=0.51).

Seabirds and marine mammals

Survey effort during 2017–2021 covered 5219 km during spring (April–May), and 5448 km during fall (September; Fig. 14). No seabird observations occurred during spring 2020 due to COVID-19 restrictions. During 2017–2022 spring and fall cruises we observed 77 species of marine birds and 13 species of marine mammals, with extralimital records including southerly species such as the temperate/tropical Risso's dolphin (*Grampus griseus*) and the tropical red-footed booby (*Sula sula*). Species showed distinct spatial and seasonal abundance patterns (Fig. 15). For example, during 2017–2021, common murres (*Uria aalge*) were most abundant within ~ 60 km of breeding colonies during April–May (pre-breeding), while in September (post-breeding) they were more widely dispersed, with concentrations east of Kodiak and in the Copper River plume.

Our surveys build off earlier efforts that began in 1998, and we collaborated with prior investigators to integrate the full spring Seward Line seabird time-series (Fig. 16; Cushing et al.

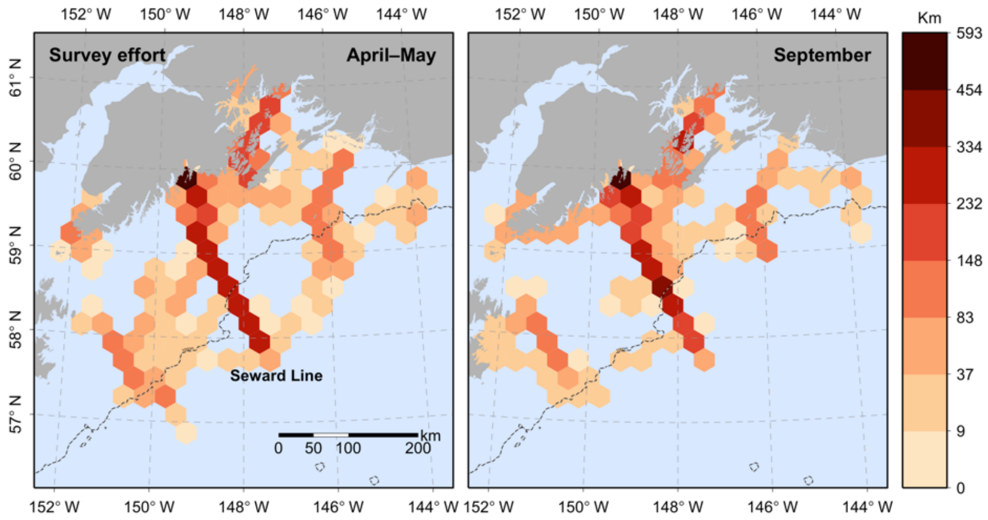

Figure 14. Densities (birds km^{-2}) of selected seabird taxa during 2014–2022, April–May and September cruises. Note that different scales are used for the four seabird taxa.

2023). This time period includes a series of predominantly colder years (2007–2013), followed by the 2014–2016 PMH, allowing examination of the responses of diverse seabird taxa to changing conditions. Seabird responses to shifts between cold and warm conditions have varied among taxa. Tubenoses (e.g., albatrosses, storm-petrels, fulmars, shearwaters) were associated with warm conditions, with higher abundance and increased use of the middle shelf during 2015–2018. In contrast, alcids (e.g., murres, puffins, guillemots, murrelets) and gulls (e.g.,

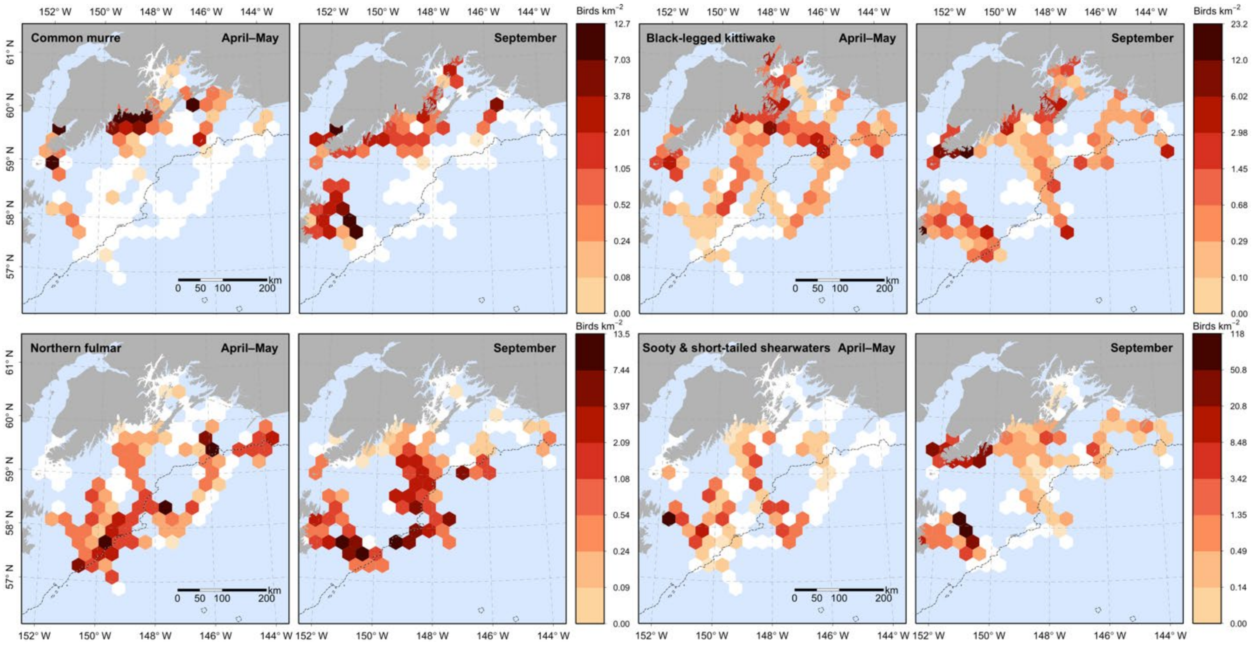

Figure 15. Seabird survey effort (linear km) during 2014–2022, April–May and September cruises.

kittiwakes, glaucous-winged gulls) concentrated inshore during and after the heatwave (Fig. 16). Since the heatwave, abundance of alcids and gulls has remained low during spring. Temporal patterns of seabirds differed between spring and fall, especially for alcids. Abundance of tubenoses during fall was variable and includes species that breed in the North Pacific (e.g., northern fulmar, *Fulmarus glacialis*), the tropical Pacific (albatrosses), and the southern hemisphere (shearwaters). The largest influxes of Buller's shearwaters (*Ardenna bulleri*) occurred during fall in warm years such as 2014, 2015 and 2019.

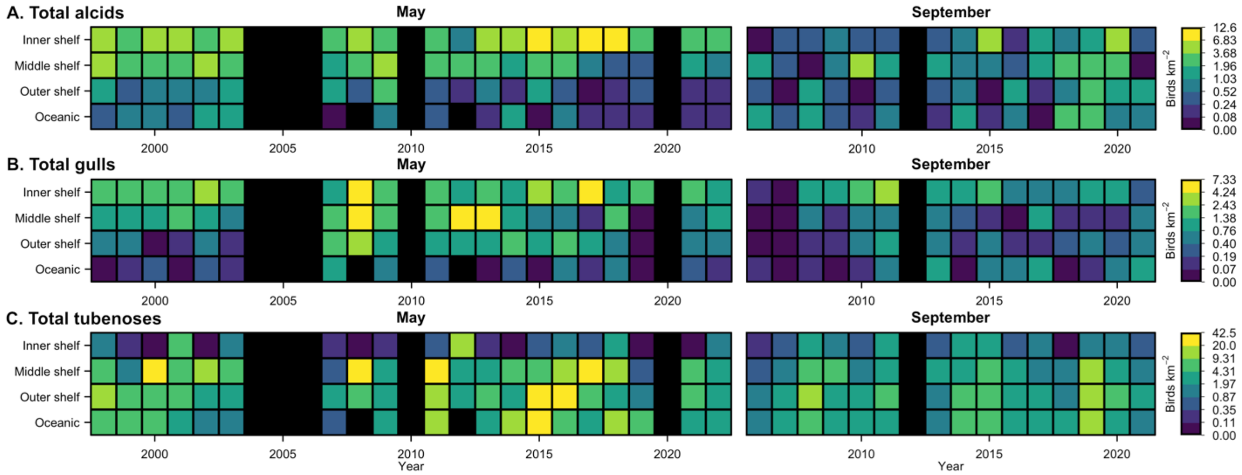

Figure 16. Mean densities (birds/km^2) of major seabird taxonomic groups within domains along the Seward Line. For each year, transects within 10 km Seward Line stations GAK-1–GAK-13 were used to calculate station-centered mean densities; these values were then averaged within each of 4 domains. Note that different scales are used for the three seabird groups. Black indicates no seabird surveys were conducted. Data credits: May 1998–2000: R. H. Day, ABR, Inc.—Environmental Research and Services; May 2001–2003: L. de Sousa, University Alaska Fairbanks; May 2007–2022 and September 2006–2021: K. Kuletz, U. S. Fish and Wildlife Service.

Distributional patterns differed among marine mammal species (Fig. 17). The most abundant Odontocete, Dall's porpoise (*Phocoenoides dalli*), was widely distributed, while harbor porpoises (*Phocoena phocoena*) were primarily coastal. Sperm whales (*Physeter microcephalus*) occurred in shelf-break and slope habitats, and in deep waters within PWS. Killer whales (*Orcinus orca*) were most abundant in PWS, along the Kenai coastline, and east of Kodiak. Fin whales (*Balaenoptera physalus*) were the predominant baleen whale observed over shelf and oceanic waters, while humpback whales (*Megaptera novaeangliae*) were near the coast, near Middleton Island, and east of Kodiak. Common minke whales (*Balaenoptera acutorostrata*) were most frequently over the inner shelf. Northern fur seals (*Callorhinus ursinus*) occurred widely over shelf and oceanic habitats, mainly during spring. Steller sea lions (*Eumetopias jubatus*), harbor seals (*Phoca vitulina*), and sea otters (*Enhydra lutris*) favored coastal waters.

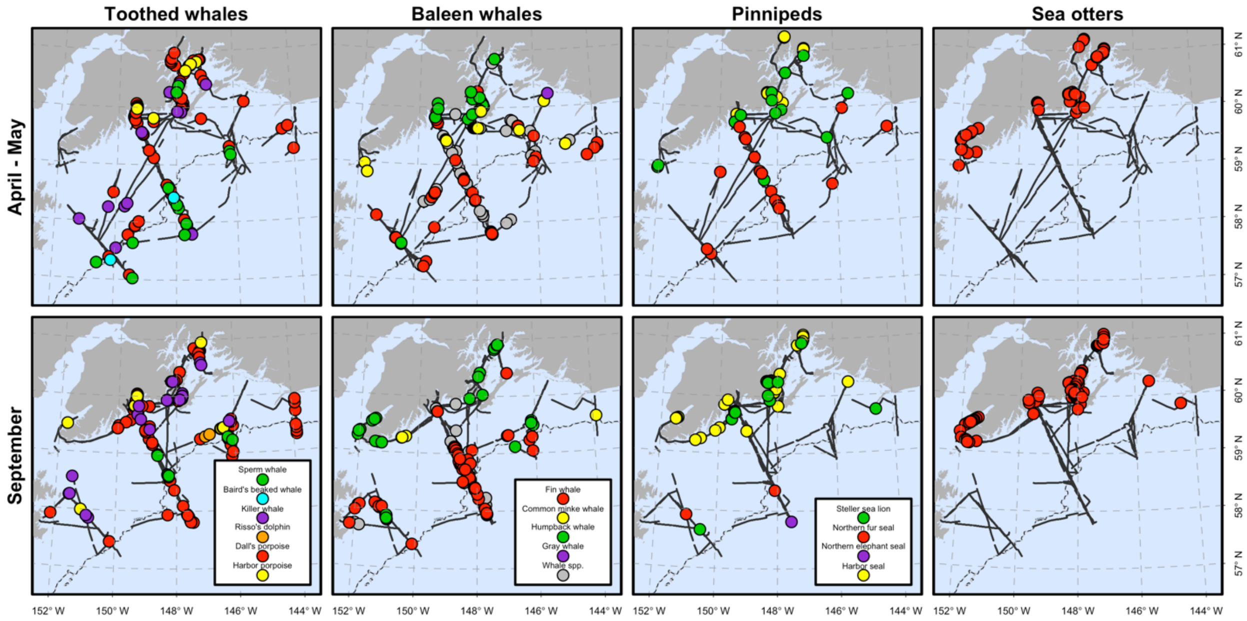

Figure 17. Distribution of marine mammals during 2014–2022, April–May and September cruises. Black lines represent survey locations.

DISCUSSION

Physics

The coastal GOA is experiencing long-term warming and surface freshening (Danielson et al. 2022); along with increasing salinity at depth, these trends are increasing the intensity of stratification (Royer and Grosch 2006, Kelley 2015) and decreasing depth of the mixed layer (Ducklow et al. 2022). The Seward Line program was well-positioned to document and study the 2014-16 PMH and the both the "blob" El Niño events within it (Litzow et al. 2020, Arimitsu et al. 2021, Suryan et al. 2021). By 2017, many physical parameters had returned to near their long-term means, although 2019 again emerged as an anomalously warm year. Cooling during that fall was rapid, returned the system to more normal conditions. While satellites provide valuable assessment of surface water temperatures at Gulf-wide scales, they can be a poor predictor of temperatures at depth and in nearshore environments, thus only direct measurements of physical properties through the water column can provide the information on long-term changes and their mechanisms.

The integrated upper water column temperature in May provides a significant predictor of thermal conditions in August, thus we can expect that the intervening months also likely reflect the thermal anomalies with similar magnitude and sign. This useful finding provides basis for classification of a single growing season as either "warm" or "cool" relative to the long-term average. To the extent that thermal conditions regulate metabolic rates, a simple index of temperature anomaly in May provides an ecologically useful metric when considering ecosystem dynamics and species-specific impacts.

The magnitude of warming of the upper water column over the course of the summer provides some indication of the likely change in shelf salinity during this time, but a handful of years fall off the “normal” relation that most years follow. This observation requires further analysis because determining the mechanistic links between the two may engender new insights into the workings of the GOA continental shelf.

Nutrients

The warming and freshening trends in the Gulf of Alaska will enhance stratification of surface waters leading to reduced mixing of the upper ocean as more energy will be needed to break down the enhanced stratification. Thus, this expected water column structure will result in reduced nutrient input during the summer and fall with repercussions to the phytoplankton community composition, and export production. The extent to which enhanced input of fresh water could contribute to river plume turbulence and mixing of the inner shelf with a concomitant input of subsurface nutrients is something that requires further study.

Phytoplankton (chlorophyll) and primary production

While chlorophyll concentrations were persistently low during heatwave springs, our data are showing that variations in the phytoplankton carbon:chlorophyll ratio partially compensate for such apparent biomass differences. Perhaps the major and most significant effect of the heatwaves, on the whole-community level, is the change in phytoplankton community size composition. The large diatom cells and chains that characterize a ‘typical’ subarctic spring were scarce during the heatwaves, replaced by a community of small flagellates. Size is a primary determinate of phytoplankton fate, in terms of the transfer of production to planktonic grazers (microzooplankton, microzooplankton) versus sinking losses, so these size composition effects have major implications for both pelagic and benthic consumer communities.

Microzooplankton

Microzooplankton showed major declines during spring of 2014-16 heatwave years, in parallel with declines in large phytoplankton. Returns to normal biomass levels were rapid and declines were not evident during the shorter heatwave of 2019. The community composition was affected by the heatwave on both general (ciliates versus flagellates) and species-specific levels; there is some evidence that microzooplankton species composition shifts have persisted to the present day, a hypothesis that we are currently exploring.

Metazooplankton

Spring copepod biomass remained elevated post PMH, but declined during 2019, then rebounded. Euphausiid biomass was low during the PMH, particularly within PWS (not shown), but recovered subsequent to the PMH. The Seward Line program and other studies have documented a change in the summer zooplankton communities associated with warmer years. During the 2014-2016 heatwave, the contribution of smaller, less lipid-rich California Current species reached a peak level, and there was poor survival of forage fish (Zador and Yasumiishi 2017) and commercial species (Rogers et al. 2021). The reduction in prey consequently forced many seabirds inshore where food was likely more abundant, although major seabird mortality still occurred in some species (Piatt et al. 2020; see next section). With a 25-year record of observations we can now show that the abundance of warm water species during fall is highly correlated (r^2=0.5) to the Pacific Decadal Oscillation during prior months (Ducklow et al. 2022), confirming prior conjecture that their prevalence arose from increased northward advection/survival during warm years. In fact, even the spring zooplankton community can be correlated to intensity of the Pacific Decadal Oscillation. We propose that changes in wind intensity promote greater wintertime downwelling in the positive Pacific Decadal Oscillation phase, transporting more *Neocalanus* copepods onto the shelf where growth and survival are enhanced compared to animals that spend more of their lives offshore in oceanic waters.

Seabirds and marine mammals

Movement of piscivorous seabirds such as gulls and murres into coastal waters during the heatwave was probably caused by a reduction in their prey on the continental shelf (Arimitsu et al. 2021). The heatwave has been associated with shifts in forage fish populations and changes in the diets of alcids and gulls in the NGA (Arimitsu et al. 2021, Suryan et al. 2021), and alcids and gulls exhibited multiple years of reproductive failures, and murres experienced mass starvation (Piatt et al. 2020, Schoen et al. 2022). Similar to our observations during the heatwave, black-legged kittiwakes breeding at Middleton Island reduced their use of the shelf near that island (Osborne et al. 2020), where capelin consistently had occurred in prior years (McGowan et al. 2020), and instead foraged farther from their colony, often near the coast of the mainland or the outer islands of PWS. Since the heatwave, abundance of alcids and gulls has remained low on the shelf during spring, suggesting that they have not fully recovered from these food-web disruptions. Long-term observations are critical in providing the context of such unusual events (Cushing et al. 2023).

CONCLUSIONS

Although the coastal GOA is experiencing long-term warming, surface freshening and increased stratification, the last five years have seen a return to the pre-heatwave state for many of our physical and lower trophic-level biological metrics. Warming conditions inhibit nutrient exchange and thereby reduce phytoplankton primary production, biomass, and cell size. Community composition of micro-, meso-, and macrozooplankton is also typically altered by climate forcing, particularly during summer and fall. Upper trophic level species such as seabirds similarly respond to changes in their prey base. Nonetheless, the system appears capable of recovery from extreme events such as the PMH.

ACKNOWLEDGEMENTS

We thank the members of our funding consortium (Alaska Ocean Observing System, *Exxon Valdez* Oil Spill Trustee Council, National Science Foundation, North Pacific Research Board) for making this work possible. We thank captains and crews of the *R/V Alpha Helix*, *R/V Tiglax* and *R/V Sikuliaq* for keeping us safe at sea. We thank our staff and students for assistance at sea and the hard work in the lab to generate this data. Finally, we thank numerous colleagues not on the author list for their valuable contribution over the past 25 years.

These findings and conclusions presented by the author(s) are their own and do not necessarily reflect the views or position of the *Exxon Valdez* Oil Spill Trustee Council.

LITERATURE CITED

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

Arimitsu, M., J. Piatt, S. Hatch, R. Suryan, S. Batten, M. Bishop, R. Campbell, H. Coletti, D. Cushing, K. Gorman, R. Hopcroft, K. Kuletz, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, S. W. Pegau, A. Schaefer, S. Schoen, J. Straley, and V. von Biela. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology 27:1859-1878.

Beaugrand, G., M. Edwards, and L. Legendre. 2010. Marine biodiversity, ecosystem functioning, and carbon cycles. Proceedings of the National Academy of Science 107:10120-10124.

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

Coyle, K. O., A. J. Hermann, and R. R. Hopcroft. 2019. Modeled spatial-temporal distribution of production, chlorophyll, iron and nitrate on the northern Gulf of Alaska shelf relative to field observations. Deep-Sea Research II 165:163-191.

Coyle, K. O., and A. I. Pinchuk. 2003. Annual cycle of zooplankton abundance, biomass and production on the northern Gulf of Alaska shelf, October 1997 through October 2000. Fisheries Oceanography 12:227-251.

Coyle, K. O., and A. I. Pinchuk. 2005. Seasonal cross-shelf distribution of zooplankton taxa on the northern Gulf of Alaska shelf relative to water mass properties, species depth preferences and vertical migration behavior. Deep-Sea Research II 52:217-245.

Cushing D. A., K. J. Kuletz, L. Sousa, R. H. Day, S. L. Danielson, E. A. Labunski, and R. R. Hopcroft. 2023. Differential response of seabird species to warm- and cold-water events in a heterogenous cross-shelf environment in the Gulf of Alaska. Marine Ecology Progress Series :HEATav2. https://doi.org/10.3354/meps14239.

Danielson, S. L., T. D. Hennon, D. H. Monson, R. M. Suryan, R. W. Campbell, S. Baird, K. Holderied, and T. J. Weingartner. 2022. Temperature variations in the northern Gulf of Alaska across synoptic to century-long time scales. Deep Sea Research II 203:105155. https://doi.org/https://doi.org/10.1016/j.dsr2.2022.105155.

Ducklow, H. W., M. Cimino, K. O. Dunton, R. R. Hopcroft, R. Ji, A. Miller, and H. M. Sosik. 2022. Marine coastal pelagic ecosystem responses to climate variability and change. Bioscience 72:827-850.

Gordon, C., A. A. Jennings, and J. M. Krest. 1993. A suggested protocol for continuous flow automated analysis of seawater nutrients (phosphate, nitrate, nitrite, and silicic acid) in the WOCE Hydrographic Program and the Joint Global Ocean Fluxes Study. Oregon State University College of Oceanography, Descriptive Chemical Oceanography Group Technical Report 93-1.

Huang, B., P. W. Thorne, V. F. Banzon, T. Boyer, G. Chepurin, J. H. Lawrimore, M. J. Menne, T. M. Smith, R. S. Vose, and H-M Zhang. 2017. Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons. Journal of Climate 30:8179-8205.

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

Litzow, M. A., M. E. Hunsicker, E. J. Ward, S. C. Anderson, J. Gao, S. G. Zador, S. Batten, S. C. Dressel, J. Duffy-Anderson, E. Fergusson, R. R. Hopcroft, B. J. Laurel, and R. O'Malley. 2020. Evaluating ecosystem change as Gulf of Alaska temperature exceeds the limits of preindustrial variability. Progress in Oceanography 186:102393.

Liu, H., M. J. Dagg, J. M. Napp, and R. Sato. 2008. Mesozooplankton grazing in the coastal Gulf of Alaska: *Neocalanus* spp. vs. other mesozooplankton. ICES Journal of Marine Science 65:351-360.

Liu, H., M. J. Dagg, and S. Strom. 2005. Grazing by the calanoid copepod *Neocalanus cristatus* on the microbial food web in the coastal Gulf of Alaska. Journal of Plankton Research 27:647-662.

Mackas, D. L., W. Greve, M. Edwards, S. Chiba, K. Tadokoro, D. Eloire, M. G. Mazzocchi, S. Batten, A. J. Richardson, C. Johnson, E. Head, A. Conversi, and T. Peluso. 2012. Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology. Progress in Oceanography 97-100:31-62.

McGowan, D. W., E. D. Goldstein, M. L. Arimitsu, A. L. Deary, O. Ormseth, A. De Robertis, J. K. Horne, L. A. Rogers, W. T. Wilson, K. O. Coyle, K. Holderied, J. F. Piatt, W. T. Stockhausen, and S. Zador. 2020. Spatial and temporal dynamics of Pacific capelin *Mallotus catervarius* in the Gulf of Alaska: implications for ecosystem-based fisheries management. Marine Ecology Progress Series 637:117–140.

Osborne, I. W., P. S. O'Hara, S. Whelan, P. Zandbergen, S. A. Hatch, and K. H. Elliott. 2020 Breeding seabirds increase foraging range in response to an extreme marine heatwave. Marine Ecology Progress Series 646:161–173.

Piatt, J. F., J. K. Parrish, H. M. Renner, S. J. Schoen, T. T. Jones, M. L. Arimitsu, K. J. Kuletz, B. Bodenstein , M. Garcia-Reyes , R. S. Duerr, R. M. Corcoran, R. S. A. Kaler, G. J. McChesney, R. T. Golightly, H. A. Coletti, R. M. Suryan, H. K. Burgess, J. Lindsey, K. Lindquist , P. M. Warzybok, J. Jahncke, J. Roletto, and W. J. Sydeman. 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. PLoS ONE 15:e0226087.

Roff, J. C., and R. R. Hopcroft. 1986. High precision microcomputer based measuring system for ecological research. Canadian Journal of Fisheries and Aquatic Science 43:2044-2048.

Schoen, S. K., M. L. Arimitsu, C. E. Marsteller, and J. F. Piatt. 2022. Lingering impacts of the 2014–2016 northeast Pacific marine heatwave on seabird demography in Cook Inlet. Alaska. Marine Ecology Progress :HEATav1. https://doi.org/10.3354/meps14177.

Sherr, E. B., and B. F. Sherr. 1993. Preservation and storage of samples for enumeration of heterotrophic protists. Pages 213-227 *in* P. F. Kemp, B. F. Sherr, E. B. Sherr and J. J. Cole, editors. Current Methods in Aquatic Microbial Ecology. Lewis Publishers, New York, New York, USA.

Stabeno, P. J., N. A. Bond, A. J. Hermann, N. N. Kachel, C. W. Mordy, and J. E. Overland. 2004. Meteorology and oceanography of the northern Gulf of Alaska. Continental Shelf Research 24:859-897.

Strom, S. L., M. A. Brainard, J. L. Holmes, and M. B. Olson. 2001. Phytoplankton blooms are strongly impacted by microzooplankton grazing in coastal North Pacific waters. Marine Biology 138:355-368.

Strom, S. L., and K. A. Fredrickson. 2008. Intense stratification leads to phytoplankton nutrient limitation and reduced microzooplankton grazing in the southeastern Bering Sea. Deep-Sea Research II 55:1761-1774.

Strom, S. L., E. L. Macri, and K. A. Fredrickson. 2010. Light limitation of summer primary production in the coastal Gulf of Alaska: physiological and environmental causes. Marine Ecology Progress Series 402:45-57.

Strom, S. L., E. L. Macri, and M. B. Olson. 2007. Microzooplankton grazing in the coastal Gulf of Alaska: Variations in top-down control of phytoplankton. Limnology Oceanography 52:1480-1494.

Strom, S. L., M. B. Olson, E. L. Macri, and C. W. Mordy. 2006. Cross-shelf gradients in phytoplankton community structure, nutrient utilization, and growth rate in the coastal Gulf of Alaska. Marine Ecology Progress Series 328:75-92.

Suryan, R. M., M. L. Arimitsu, H. A. Coletti, R. R. Hopcroft, M. R. Lindeberg, S. J. Barbeaux, S. D. Batten, W. J. Burt, M. A. Bishop, J. L. Bodkin, R. Brenner, R. W. Campbell, D. A. Cushing, S. L. Danielson, M. W. Dorn, B. Drummond, D. Esler, T. Gelatt, D. H. Hanselman, S. A. Hatch, S. Haught, K. Holderied, K. Iken, D. B. Irons, A. B. Kettle, D. G. Kimmel, B. Konar, K. J. Kuletz, B. J. Laurel, J. M. Maniscalco, C. Matkin, C. A. E. McKinstry, D. H. Monson, J. R. Moran, D. Olsen, W. A. Palsson, W. S. Pegau, J. F. Piatt, L. A. Rogers, N. A. Rojek, A. Schaefer, I. B. Spies, J. M. Straley, S. L. Strom, K. L. Sweeney, M. Szymkowiak, B. P. Weitzman, E. M. Yasumiishi, and S. G. Zador. 2021. Ecosystem response persists after a prolonged marine heatwave. Scientific Reports 11:6235.

Waite, J. N., and F. J. Mueter. 2013. Spatial and temporal variability of chlorophyll-a concentrations in the coastal Gulf of Alaska, 1998-2011, using cloud-free reconstructions of SeaWiFS and MODIS-Aqua data. Progress in Oceanography 116:179-192.

Weingartner, T. J., K. O. Coyle, B. Finney, R. R. Hopcroft, T. E. Whitledge, R. D. Brodeur, M. Dagg, E. Farley, D. Haidvogel, L. Haldorson, A. I. Hermann, S. Hinckley, J. Napp, P. J. Stabeno, T. C. Kline, C. M. Lee, E. Lessard, T. C. Royer, and S. L. Strom. 2002. The Northeast Pacific GLOBEC program: coastal Gulf of Alaska. Oceanography 15:48-63.

Wiltshire, K. H., A. M. Malzahn, K. Wirtz, W. Greve, S. Janisch, P. Mangelsdorf, B. F. J. Manly, and M. Boersma. 2008. Resilience of North Sea phytoplankton spring bloom dynamics: An analysis of long-term data at Helgoland Roads. Limnology Oceanography 53:1294-1302.

Zador, S., and E. M. Yasumiishi. 2017. Ecosystem Considerations 2017 Status of the Gulf of Alaska Marine Ecosystem. NOAA National Marine Fisheries Service, Seattle, Washington, USA.

OTHER REFERENCES

This section includes peer reviewed publications, EVOSTC reports and other significant report contributions, publicly available datasets associated with this project, and popular articles about the project.

Publications

Arimitsu, M., J. Piatt, S. Hatch, R. Suryan, S. Batten, M.A. Bishop, R. Campbell, H. Coletti, D. Cushing, K. Gorman, R. **Hopcroft**, K. **Kuletz**, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, W.S. Pegau, A. Schaeffer, S. Schoen, J. Straley, and V. von Biela. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.15556.

Arimitsu, M. L., J. F. Piatt, J. T. Thorson, K. **Kuletz**, G. Drew, S. K. Schoen, D. A. Cushing, C. Kroeger, and W. J. Sydeman. 2023. Joint spatiotemporal models to predict seabird densities at sea. Frontiers in Marine Science. *In Press*.

Batten, S. D., D. E. Raitsos, S. L. Danielson, R. **Hopcroft**, K. Coyle, and A. McQuatters-Gollop. 2017. Interannual variability in lower trophic levels on the Alaskan Shelf. Deep Sea Research Part II: Topical Studies in Oceanography 147:58-68. https://doi.org/10.1016/j.dsr2.2017.04.023.

Campbell, R. W. 2018. Hydrographic trends in Prince William Sound, Alaska, 1960–2016. Deep Sea Research Part II: Topical Studies in Oceanography 147:43-57. https://doi.org/10.1016/j.dsr2.2017.08.014.

Cieslak, M. C., A. M. Castelfranco, V. Roncalli, P. H. Lenz, and D. K. Hartline. 2020. t-Distributed Stochastic Neighbor Embedding (t-SNE): A tool for eco-physiological transcriptomic analysis. Marine genomics 51:100723. https://doi.org/10.1016/j.margen.2019.100723

Coyle, K. O., A. J. Hermann, and R. R. **Hopcroft**. 2019. Modeled spatial-temporal distribution of productivity, chlorophyll, iron and nitrate on the northern Gulf of Alaska shelf relative to field observations. Deep Sea Research Part II: Topical Studies in Oceanography. 165:163–191 https://doi.org/10.1016/j.dsr2.2019.05.006.

Cushing D. A., K. J. **Kuletz**, L. Sousa, R. H. Day, S. L. Danielson, E. A. Labunski, and R. R. **Hopcroft**. 2023. Differential response of seabird species to warm- and cold-water events in a heterogenous cross-shelf environment in the Gulf of Alaska. Marine Ecology Progress Series. *In Press*.

Cushing, D. A., D. D. Roby, and D. B. Irons. 2018. Patterns of distribution, abundance, and change over time in a subarctic marine bird community. Deep Sea Research Part II: Topical Studies in Oceanography 147:148-163. https://doi.org/10.1016/j.dsr2.2017.07.012.

Danielson, S. L., T. D. Hennon, D. H. Monson, R. M. Suryan, R. W. Campbell, S. Baird, K. Holderied, and T. J. Weingartner. (2022). Temperature variations in the northern Gulf of

Alaska across synoptic to century-long time scales. Deep Sea Research Part II: Topical Studies in Oceanography 203:105155. https://doi.org/https://doi.org/10.1016/j.dsr2.2022.105155.

Danielson, S. L., D. F. Hill, K. S. Hedstrom, J. Beamer, and E. Curchitser. 2020. Demonstrating a high-resolution Gulf of Alaska ocean circulation model forced across the coastal interface by high-resolution terrestrial hydrological models. Journal of Geophysical Research: Oceans 125(8), e2019JC015724. https://doi.org/10.1029/2019JC015724.

Doyle, M. J., S. L. Strom, K. O. Coyle, A. J. Hermann, C. Ladd, A. C. Matarese, S. K. Shotwell, and R. R. **Hopcroft**. 2019. Early life history phenology among Gulf of Alaska fish species: Strategies, synchronies, and sensitivities. Deep-Sea Research Part II 165:41-73. https://doi.org/10.1016/j.dsr2.2019.06.005.

Ducklow, H., M. Cimino, K. H. Dunton, W. R. Fraser, R. R. **Hopcroft**, R. Ji, A. J. Miller, M. D. Ohman, and H. M. Sosik. 2022. Marine pelagic ecosystem responses to climate variability and change. BioScience 72:827–850. https://doi.org/https://doi.org/10.1093/biosci/biac050.

Hauri, C., R. Pages, A. M. P. McDonnell, M. F. Stuecker, S. L. Danielson, K. Hedstrom, B. Irving, C. Schultz, and S. C. Doney. 2021. Modulation of ocean acidification by decadal climate variability in the Gulf of Alaska. Communications Earth & Environment 2:191. https://doi.org/10.1038/s43247-021-00254-z.

Hauri, C., C. Schultz, K. Hedstrom, S. Danielson, B. Irving, S. C. Doney, R. Dussin, E. N. Curchitser, D. F. Hill, and C. A. Stock. 2020. A regional hindcast model simulating ecosystem dynamics, inorganic carbon chemistry, and ocean acidification in the Gulf of Alaska. Biogeosciences 17:3837–3857. https://doi.org/https://doi.org/10.5194/bg-17-3837-2020.

Kandel, A., and A. Aguilar-Islas. 2021. Spatial and temporal variability of dissolved aluminum and manganese in surface waters of the northern Gulf of Alaska. Deep Sea Research Part II: Topical Studies in Oceanography 104952. https://doi.org/10.1016/j.dsr2.2021.104952.

Lenz, P. H., and V. Roncalli. 2019. Diapause within the context of life-history strategies in Calanid copepods (Calanoida: Crustacea). The Biological Bulletin 237:170-179. https://doi.org/10.1086/705160.

Litzow, M., M. E. Hunsicker, E. J. Ward, S. C. Anderson, J. Gao, S. G. Zador, S. Batten, S. C. Dressel, J. Duffy-Anderson, E. Fergusson, R. **Hopcroft**, B. J. Laurel, and R. O'Malley. 2020. Evaluating ecosystem change as Gulf of Alaska temperature exceeds the limits of preindustrial variability. Progress in Oceanography 186:102393. https://doi.org/10.1016/j.pocean.2020.102393.

Ormseth, O. A., M. M. Baker, R. R. **Hopcroft**, C. Ladd, C. W. Mordy, J. H. Moss, F. J. Mueter, S. K. Shotwell, and S. L. Strom. 2019. Introduction to understanding ecosystem processes in the Gulf of Alaska, volume 2. Deep Sea Research Part II: Topical Studies in Oceanography 165:1-6. https://doi.org/10.1016/j.dsr2.2019.06.019.

Roncalli, V., M. C. Cieslak, S. A. Sommer, R. R. **Hopcroft**, and P. H. Lenz. 2018. De novo transcriptome assembly of the calanoid copepod *Neocalanus flemingeri*: A new resource for emergence from diapause. Marine Genomics 37:114–119. https://doi.org/10.1016/j.margen.2017.09.002.

Roncalli, V., M. C. Cieslak, M. Germano, R. R. **Hopcroft**, and P. H. Lenz. 2019. Regional heterogeneity impacts gene expression in the subarctic zooplankter *Neocalanus flemingeri* in the northern Gulf of Alaska. Communications Biology 2:1-13. https://doi.org/10.1038/s42003-019-0565-5.

Roncalli, V., M. C. Cieslak, R. R. **Hopcroft**, and P. H. Lenz. 2020. Capital breeding in a diapausing copepod: A transcriptomics analysis. Frontiers in Marine Science 7. https://doi.org/10.3389/fmars.2020.00056.

Roncalli, V., J. Niestroy, M. C. Cieslak, A. M. Castelfranco, R. R. **Hopcroft**, and P. H. Lenz. 2022. Physiological acclimatization in high-latitude zooplankton. Molecular Ecology, 31:1753–1765. https://doi.org/10.1111/mec.16354.

Roncalli, V., S. A. Sommer, M. C. Cieslak, C. Clarke, R. R. **Hopcroft**, and P. H. Lenz. 2018. Physiological characterization of the emergence from diapause: A transcriptomics approach. Scientific Reports 8(1). https://doi.org/10.1038/s41598-018-30873-0.

Siedlecki, S. A., D. J. Pilcher, A. J. Hermann, K. Coyle, and J. Mathis. 2017. The importance of freshwater to spatial variability of aragonite saturation state in the Gulf of Alaska. Journal of Geophysical Research: Oceans 122:8482–8502. https://doi.org/10.1002/2017JC012791.

Strom, S. L., K. A. Fredrickson, and K. J. Bright. 2019. Microzooplankton in the coastal Gulf of Alaska: Regional, seasonal and interannual variations. Deep Sea Research Part II: Topical Studies in Oceanography 165:192–202. https://doi.org/10.1016/j.dsr2.2018.07.012.

Suryan, R. M., M. L. Arimitsu, H. A. Coletti, R. R. **Hopcroft**, M. R. Lindeberg, S. J. Barbeaux, S. D. Batten, W. J. Burt, M. A. Bishop, J. L. Bodkin, R. Brenner, R. W. Campbell, D. A. Cushing, S. L. Danielson, M. W. Dorn, B. Drummond, D. Esler, T. Gelatt, D. H. Hanselman, S. A. Hatch, S. Haught, K. Holderied, K. Iken, D. B. Irons, A. B. Kettle, D. G. Kimmel, B. Konar, K. J. **Kuletz**, B. J. Laurel, J. M. Maniscalco, C. Matkin, C. A. E. McKinstry, D. H. Monson, J. R. Moran, D. Olsen, W. A. Palsson, W. S. Pegau, J. F.

Piatt, L. A. Rogers, N. A. Rojek, A. Schaefer, I. B. Spies, J. M. Straley, S. L. Strom, K. L. Sweeney, M. Szymkowiak, B. P. Weitzman, E. M. Yasumiishi, and S. G. Zador. 2021. Ecosystem response persists after a prolonged marine heatwave. Scientific Reports 11:1–17. https://www.nature.com/articles/s41598-021-83818-5.

Turner, J. S., J. L. Pretty, and A. M. P. McDonnell. 2017. Marine particles in the Gulf of Alaska shelf system: Spatial patterns and size distributions from in situ optics. Continental Shelf Research 145:13-20. https://doi.org/10.1016/j.csr.2017.07.002.

Reports

Arimitsu, M., D. Cushing, B. Drummond, S. Hatch, T. Jones, R. Kaler, E. Labunski, J. Lindsey, J. F. Piatt, H. Renner, and S. Whelan. 2022. Seabird Synthesis. In Feris B. E. and S. Zador, eds. Ecosystem Status Report 2022: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska, 99501. https://www.fisheries.noaa.gov/resource/data/ecosystem-status-report-2022-gulf-alaska.

Arimitsu, M., D. Cushing, B. Drummond, S. Hatch, T. Jones, J. F. Piatt, and H. Renner. 2021. Seabird Synthesis. In Feris B. E. and S. Zador, eds. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 1007 West Third, Suite 400, Anchorage, Alaska, 99501. https://apps-afsc.fisheries.noaa.gov/refm/docs/2021/GOAecosys.pdf.

Arimitsu, M., J. Piatt, R. Suryan, S. Batten, M. A. Bishop, H. Coletti, D. Cushing, K. Gorman, S. Hatch, S. Haught, R. R. **Hopcroft**, K.J. **Kuletz**, C. Marsteller, D. McGowan J. Moran, S. Pegau, A. Schaefer, S. Schoen, J. Straley, and V. R. von Biela. 2020. Chapter 3 Reduced quality and synchronous collapse of forage species disrupts trophic transfer during a prolonged marine heatwave. In M. R. Suryan, M. R. Lindeberg, and D. R. Aderhold, eds. The Pacific Marine Heatwave: Monitoring During a Major Perturbation in the Gulf of Alaska. Gulf Watch Alaska Long-Term Monitoring Program Draft Synthesis Report (*Exxon Valdez* Oil Spill Trustee Council Program 19120114). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. http://gulfwatchalaska.org/wp-content/uploads/2021/05/GWA_Science_Synthesis_Report_Final_2021.pdf.

Suryan, R. M., M. Arimitsu, H. Coletti, R. R. **Hopcroft**, M. R. Lindeberg, S. Batten, M. A. Bishop, R. Brenner, R. Campbell, D. Cushing, S. Danielson, D. Esler, T. Gelatt, S. Hatch, S. Haught, K. Holderied, K. Iken, D. Irons, D. Kimmel, B. Konar, K. **Kuletz**, B. Laurel, J. M. Maniscalco, C. Matkin, C. McKinstry, D. Monson, J. Moran, D. Olsen, S. Pegau, J. Piatt, L. Rogers, A. Schaefer, J. Straley, K. Sweeney, M. Szymkowiak, B. Weitzman, J. Bodkin, and S. Zador. 2020. Chapter 4 Ecosystem response to a prolonged marine heatwave in the Gulf of Alaska. *In* M.R. Suryan, M.R. Lindeberg, and D.R. Aderhold, editors. The Pacific Marine Heatwave: Monitoring During a Major Perturbation in the

Gulf of Alaska. Gulf Watch Alaska Long-Term Monitoring Program Draft Synthesis Report (*Exxon Valdez* Oil Spill Trustee Council Program 19120114). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. http://gulfwatchalaska.org/wp-content/uploads/2021/05/GWA_Science_Synthesis_Report_Final_2021.pdf.

Publicly available datasets

Kuletz, K., D. Cushing, and E. Labunski. 2020. Marine bird survey observation and density data from Northern Gulf of Alaska LTER cruises, 2018–2020. Research Workspace. Dataset. doi:10.24431/rw1k45w.

Kuletz, K. 2020. Seward Line and Lower Cook Inlet marine bird survey data, 2006–2017, Gulf Watch Alaska Pelagic Component. Research Workspace. Dataset. doi: 10.24431/rw1k21l, version: 10.24431_rw1k21l_2020_6_17_201714.

LTER Data Portal: https://search.dataone.org/portals/NGALTER/About-the-Data-Catalog.

Scientific presentations

Aguilar-Islas, A. M. 2020. The Northern Gulf of Alaska Long Term Ecological Research Site: Nutrient dynamics across the shelf from Kayak to Kodiak islands. Invited presentation. University of South Florida, Tampa, Florida.

Aguilar-Islas, A., M. R. Kaufman, and S. Strom. 2020. Nutrient dynamics and their influence in the Northern Gulf of Alaska (ME34E-0212). Poster presentation. Ocean Sciences Meeting, San Diego, California, February.

Arimitsu, M. 2022. Changes in marine predator and prey populations in the Northern Gulf of Alaska: Gulf Watch Alaska Pelagic Update 2021. Poster presentation. Alaska Marine Science Symposium, Virtual, January.

Arimitsu, M., M. A. Bishop, D. Cushing, S. Hatch, B. Helfin, R. Kaler, K. **Kuletz**, et al. 2018. Changes in marine predator and prey populations in the aftermath of the North Pacific Heat Wave: Gulf Watch Alaska Pelagic update 2017. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Arimitsu, M., M. A. Bishop, D. Cushing, S. Hatch, B. Helfin, R. Kaler, K. **Kuletz**, et al. 2018. Changes in marine predator and prey populations in the aftermath of the North Pacific Heat Wave: Gulf Watch Alaska Pelagic update 2017. Poster presentation. Annual meeting of the Pacific Seabird Group, La Paz, Mexico, February.

Arimitsu, M., M. A. Bishop, D. Cushing, S. Hatch, R. Kaler, K. **Kuletz**, et al. 2020. Changes in marine predator and prey populations in the Northern Gulf of Alaska: Gulf Watch Alaska

pelagic update 2019. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Arimitsu, M. L., S. Paitt, S. Hatch, R. Suryan, S. Batten, M. A. Bishop, et al. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Arimitsu, M., J. Thorson, J. Piatt, G. Drew, K. Kuletz, W. Sydeman, et al. 2021. Spatio-temporal modeling provides VAST possibilities for analysis of at-sea survey data. Oral presentation. Annual meeting of the Pacific Seabird Group, Virtual, February.

Block, L. 2022. Exploring zooplankton community shifts in the Northern Gulf of Alaska using a new analysis approach to maintain taxonomic and spatiotemporal complexity. Poster presentation. Alaska Marine Science Symposium, Virtual, January.

Block, L. 2022. A new approach for exploring spatiotemporal patterns and community shifts in zooplankton data. Poster presentation. Ocean Sciences Meeting, Virtual, March.

Brydie, A., and S. L. Danielson. 2020. Copper River discharges in the Northern Gulf of Alaska: freshwater distribution and evolution during the July 2019 freshet (CP24F-1195). Poster presentation. Ocean Sciences Meeting, San Diego, California, February.

Burt, W., R. **Hopcroft**, S. Danielson, and S. Strom. 2020. Quantifying phytoplankton biomass and productivity at unprecedented spatial scales in the Northern Gulf of Alaska LTER Program using ship-board optical measurements. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January. Retrieved from https://nga.lternet.edu/presentations/2020/Burt_2020_AMSS_Quantifying_Phytoplankton.pdf

Burt, W., R. R. **Hopcroft**, S. Strom, and S. L. Danielson. 2020. Use of ship-board optical measurements to quantify plankton biomass and productivity across multiple trophic levels in the Northern Gulf of Alaska LTER program (OB24C-0479). Poster presentation. Ocean Sciences Meeting, San Diego, California, February. Retrieved from https://nga.lternet.edu/presentations/2020/Burt_2020_OSM_Quantifying_Phytoplankton.pdf

Busse, H., J. Fiechter, and S. Strom. 2020. Grazing rates of mixotrophic nano- and dinoflagellates in the Northern Gulf of Alaska in response to gradients in light, inorganic nutrients, and prey availabilities (ME14D-0054). Poster presentation. Ocean Sciences Meeting, San Diego, California, February. Retrieved from https://nga.lternet.edu/presentations/2020/Busse_2020_OSM_Mixotrophy.pdf

Cohen, J. 2022. Investigating the impact of marine heatwaves on phytoplankton community composition in the Gulf of Alaska. Oral presentation. Alaska Marine Science Symposium, Virtual, Anchorage, Alaska, January.

Coleman, D. 2022. Lipid accumulation in Neocalanus copepods in the Northern Gulf of Alaska (NGA). Oral presentation. Alaska Marine Science Symposium, Virtual, Anchorage, Alaska, January.

Coleman, D. 2022. Lipid accumulation in Neocalanus copepods in the Northern Gulf of Alaska (NGA). Oral presentation. Ocean Sciences Meeting, Virtual, March.

Coleman, D., and R. **Hopcroft**. 2021. Habitat utilization by diapausing copepods in the Northern Gulf of Alaska. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Collins, E. 2018. Microbial community structure in Prince William Sound. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Coyle, K. O., A. J. Hermann, and R. R. **Hopcroft**. 2018. Modeled spatial-temporal distribution of production and biomass relative to field observations in the northern Gulf of Alaska (RS41A-02). Oral presentation. 2018 Ocean Sciences Meeting, Portland, Oregon, February.

Cushing, D. 2022. Two decades of spring seabird observations along the Seward Line, Gulf of Alaska. Oral presentation. Alaska Marine Science Symposium, Virtual, January.

Cushing, D., K. **Kuletz**, R. R. **Hopcroft**, S. L. Danielson, and E. Labunski. 2017. Shifts in cross-shelf distribution of seabirds in the northern Gulf of Alaska under different temperature regimes, 2007-2015. Poster presentation. Pacific Seabird Group Meeting, Tacoma, Washington, February.

Cushing, D., K. **Kuletz**, E. Labunski, and R. **Hopcroft**. 2019. Seabird studies during the Northern Gulf of Alaska Long Term Ecological Research Program. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Cushing, D., E. Labunski, and K. Kuletz. 2021. Summer tourists: The rare, amazing, and out-of-their-range visitors observed during seabird surveys in the Northern Gulf of Alaska. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Danielson, S. L. 2018. It is a finescale line: Acrobat observations from along the Gulf of Alaska hydrographic tightrope (A-F055). Poster presentation. LTER All Scientists' Meeting, Pacific Grove, California, October.

Dias, B. S. 2022. Impact of marine heatwaves on Pacific herring and Prince William Sound marine ecosystem. Oral presentation. Alaska Marine Science Symposium, Virtual, Alaska, January.

Dias, B. 2022. Effects of marine heatwaves persistence in Prince William Sound herring. Oral presentation. Ocean Sciences Meeting 2022, Virtual, February.

Dias, B. 2022, June. Prince William Sound marine ecosystem under different heatwave scenarios. Oral presentation. Ecosystem Studies of Subarctic and Arctic Seas (ESSAS) Annual Science Meeting, Seattle, Washington, June.

Fredrickson, K., H. Busse, D. Walker-Phelan, C. Mazur, and S. Strom, S. 2020. Unexpected Importance of the Smallest Phytoplankton in the Northern Gulf of Alaska Ecosystem. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hauri, C. 2022, January. Modulation of ocean acidification by decadal climate variability in the Gulf of Alaska. Oral presentation. Alaska Marine Science Symposium, Virtual, Anchorage, Alaska, January.

Hauri, C., and S. C. Doney. 2021. Freshwater inputs change ocean acidification impacts on nearshore biogeochemistry in the Gulf of Alaska. Oral presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hauri, C., K. Hedstrom, C. Schultz, S. Danielson, J. Beamer, S. C. Doney, et al. 2019. Influence of Ocean Acidification and Climate Change on the Biogeochemistry in the Gulf of Alaska: A Regional Modeling Study. Plenary presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hauri, C., C. Schultz, K. Hedstrom, J. Beamer, S. L. Danielson, S. C. Doney, et al. 2018. Influence of ocean acidification and climate change on the biogeochemistry of the Gulf of Alaska (HE13A-06). Oral presentation. 2018 Ocean Sciences Meeting, Portland, Oregon, February.

Hernandez, A., and R. R. **Hopcroft**. 2020. The effects of environmental changes in the Northern Gulf of Alaska on the synthesis of lipid in *N. flemingeri* and *N. plumchrus* from 2018 to 2019 (ED34D-3692). Poster presentation. Ocean Sciences Meeting, San Diego, California, February.

Hill, D. 2022. Improved freshwater runoff estimates for Alaska - a project update. Poster presentation. Alaska Marine Science Symposium, Virtual, Anchorage, Alaska, January.

Hopcroft, R. R. 2017. Oceanography in the northern Gulf of Alaska: the Seward Line. Public lecture presentation. Osher Lifelong Learning Institute, Fairbanks, Alaska, December.

Hopcroft, R. R. 2018. The Seward Line - 2017. Poster presented at the Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hopcroft, R., A. Aguilar-Islas, S. Danielson, J. Fiechter, A. McDonnell, and S. Strom. 2019. The Northern Gulf of Alaska LTER: results from the first year. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hopcroft, R. R., K. O. Coyle, S. L. Danielson, and S. L. Strom. 2017. Three in a row: continued warm conditions along the Gulf of Alaska's Seward Line. Oral presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hopcroft, R. R., K. O. Coyle, S. L. Danielson, and S. L. Strom. 2017. Twenty years of observations along the Gulf of Alaska's Seward Line: impact of continued warm conditions. Invited presentation. Kodiak Area Marine Science Symposium, Kodiak, Alaska, April.

Hopcroft, R. R., and D. J. Lindsay. 2018. Gelatinous zooplankton in Alaskan waters: from nets to ROVs. Invited presentation. PICES Annual Meeting, Yokohama, Japan, October.

Hopcroft, R. R., S. L. Strom, A. M. Aguilar-Islas, S. L. Danielson, and J. Fiechter, J. 2018. The Northern Gulf of Alaska Long-term Ecological Research Program. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Hopcroft, R. R., S. Strom, A. M. Aguilar-Islas, S. L. Danielson, and J. Fiechter. 2018. A new Long-term Ecological Research (LTER) site in the Northern Gulf of Alaska. Poster presentation. PICES Annual Meeting, Yokohama, Japan, October. Retrieved from https://meetings.pices.int/publications/book-of-abstracts/2018-PICES-Book-of-Abstracts.pdf

Kandel, A., and A. Aguilar-Islas. 2020, February. Temporal variability of dissolved aluminum and manganese in the Northern Gulf of Alaska (CT44C-1017). Poster presentation. Ocean Sciences Meeting, San Diego, CA, February. Retrieved from https://nga.lternet.edu/presentations/2020/Kandel_2020_OSM_Aluminium_Manganese.pdf

Kuletz, K., D. Cushing, R. R. **Hopcroft**, S. L. Danielson, and E. Labunski. 2017. Running hot and cold: shifts in seabird distribution in the Northern Gulf of Alaska under different temperature regimes, based on Seward Line surveys, 2007-2015. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Kuletz, K., D. Cushing, and E. Labunski. 2021. Short-tailed shearwater timing and movement through Alaska's seas, based on at-sea surveys, 2007-2019. Oral presentation. Annual meeting of the Pacific Seabird Group, virtual, February.

Kuletz, K., B. Hoover, D. Cushing, J. Santora, W. Sydeman, R. R. **Hopcroft**, R. R., et al. 2019. Seabird distribution relative to biophysical oceanographic properties in North Pacific ecosystems. Oral presentation. Annual meeting of the Pacific Seabird Group, Lihue, Kuai, Hawaii, March. Retrieved from https://pacificseabirdgroup.org/annual-meeting/annual-meetings-archive/

Kuletz, K., R. R. **Hopcroft**, S. L. Danielson, J. Santora, W. Sydeman, B. Hoover, and D. Cushing. 2018. Seabird distribution relative to biophysical oceanographic properties in North Pacific ecosystems (A-F048). Poster presentation. 2018 LTER All Scientists' Meeting, Pacific Grove, California, October. Retrieved from https://lternet.edu/stories/poster-sessions-at-the-2018-all-scientists-meeting/

Lenz, P. H. 2017. Ecophysiology of marine copepods in a cyclical and changing environment. Invited presentation. Institute of Marine Science, University Alaska Fairbanks, Fairbanks, Alaska, September.

Lenz, P., M. Cieslak, A. M. Castelfranco, D. K. Hartline, and V. Roncalli. 2021. Environmental transcriptomics of seasonal dormancy in a sub-arctic copepod, a key crustacean zooplankter at the base of the metazoan food web. Invited presentation. National Center for Genome Analysis Support Genomics Research webinar series, Zoom, March. Retrieved from https://www.youtube.com/watch?v=e4NXDd-uy3U

Lenz, P. H., V. Roncalli, M. C. Cieslak, S. A. Matthews, C. Clarke-Hopcroft, and R. R. **Hopcroft**. 2017. Emergence from diapause in Neocalanus flemingeri females: physiological and morphological progression. Oral presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Lenz, P. H., V. Roncalli, M. C. Cieslak, S. A. Matthews, D. K. Hartline, and A. E. Christie. 2017. Adventures in transcriptomics. Oral presentation. Aquatic Sciences Meeting (ASLO), Honolulu, HI, March.

Lenz, P. H., V. Roncalli, D. K. Hartline, M. Germano, M. C. Cieslak, S. L. Strom, and R. R. **Hopcroft**. 2018, January. The physiological ecology of the calanid copepod, *Neocalanus flemingeri* in the northern Gulf of Alaska. Oral presentation and poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Lindeberg, M., K. Holderied, D. Aderhold, K. Hoffman, M. Arimitsu, B. Ballachey, et al. 2017. Gulf Watch Alaska: Results from five years of ecosystem monitoring in the Northern Gulf of Alaska. Presented at the Alaska Marine Science Symposium, Anchorage, Alaska, January.

Lowin, B., S. Strom, and W. Burt. 2021. Phytoplankton dynamics across hydrographic fronts and mesoscale features: Preliminary results from the new NGA-LTER Ocean Optics

Program. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January. Retrieved from https://nga.lternet.edu/presentations/2021/Lowin_2021_AMSS_Phytoplankton_Dynamics.pdf

Matthews, S. A., V. Roncalli, M. C. Cieslak, D. K. Hartline, A. E. Christie, and P. H. Lenz. 2017. The transcriptome of *Labidocera madurae*: Evaluation of the quality and depth of a de novo assembly (Abstract ID: 29119). Poster presentation. Aquatic Sciences Meeting (ASLO), Honolulu, HI, March.

Mayer, K., C. Clarke-Hopcroft, and R. R. **Hopcroft**. 2020. Spatial and temporal patterns of zooplankton species in the Gulf of Alaska as revealed by image analysis (ED34D-3695). Poster presentation. Ocean Sciences Meeting, San Diego, CA, February. Retrieved from https://nga.lternet.edu/presentations/2020/Mayer_2020_OSM_Image_Analysis.pdf

Mazur, C., S. Strom, and A. Aguilar-Islas. 2020. Comparing the bioavailability of a natural and synthetic iron source: Do past experiments accurately model diatom growth in response to episodic iron addition? (OB34G-0636). Poster presentation. Ocean Sciences Meeting, San Diego, CA, February. Retrieved from https://nga.lternet.edu/presentations/2020/Mazur_2020_OSM_Do_Past_Experiments.pdf

Mendoza Islas, H., and R. **Hopcroft**. 2020. Abundance and distributions of gelatinous zooplankton in the Northern Gulf of Alaska. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Mendoza Islas, H. M., and R. R. **Hopcroft**. 2020. First year pollock and their zooplankton predators in the Gulf of Alaska. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Mendoza Islas, H. M., and R. R. **Hopcroft**. 2020. Abundance and distributions of gelatinous zooplankton in the Northern Gulf of Alaska (ME34E-0208). Poster presentation. 2020 Ocean Sciences Meeting, San Diego, CA, February.

Monacci, N. M., J. N. Cross, and J. T. Mathis. 2018. Ocean acidification observations along the Seward Line: 2008-2017. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Monell, K., V. Roncalli, P. H. Lenz, and R. R. **Hopcroft**. 2020. Characterization of cell division during early oogenesis in copepod females emerging from diapause (ME14D-0049). Poster presentation. 2020 Ocean Sciences Meeting, San Diego, CA, February.

Monson, D., K. Holderied, R. Campbell, S. L. Danielson, R. R. Hopcroft, B. Ballachey, et al. 2018. Congruence of intertidal and pelagic water and air temperatures during an anomalously warm period in the northern Gulf of Alaska; the "Blob" washes ashore. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Norgaard, A. 2022. Inorganic carbon dynamics at the Gulf of Alaska ecosystem observatory. Poster presentation. Alaska Marine Science Symposium, Virtual, January.

O'Daly, S. 2022. The role of zooplankton in determining carbon export in the Gulf of Alaska. Oral presentation. Alaska Marine Science Symposium, Virtual, January.

O'Daly, S., S. Strom, and A. M. P. McDonnell. 2020. Particulate carbon flux, flux attenuation, and export efficiency in the summer of 2019 across the Northern Gulf of Alaska shelf. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

O'Hara, M. 2022. Cryptophyte distribution and mixotrophy in the Northern Gulf of Alaska. Poster presentation. Alaska Marine Science Symposium, Virtual, January.

O'Hara, M. 2022. Cryptophyte distribution and mixotrophy in the Subarctic Pacific Ocean. Poster presentation. Ocean Sciences Meeting, Virtual, February.

Ortega, E. 2022. Temporal and spatial variability of particulate metals in the Northern Gulf of Alaska. Oral presentation. Ocean Sciences Meeting, Virtual, March.

Pages, R. 2022. Long-term trends and compound events of ocean deoxygenation and acidification in the Gulf of Alaska. Oral presentation. Alaska Marine Science Symposium, Virtual, January.

Pages, R. 2022. Long-term trends and compound events of ocean deoxygenation and acidification in the Gulf of Alaska. Oral presentation. Ocean Sciences Meeting, Virtual, March.

Piatt, J. F., J. K. Parrish, H. M. Renner, S. K. Schoen, T. T. Jones, M. L. Arimitsu, K. J. Kuletz, B. Bodenstein, M. García-Reyes, R. S. Duerr, R. M. Corcoran, R. S. A. Kaler, G. J. McChesney, R. T. Golightly, H. A. Coletti, R. M. Suryan, H. K. Burgess, J. Lindsey, K. Lindquist, P. M. Warzybok, J. Jahncke, J. Roletto, and W. J. Sydeman. 2018. Unprecedented scale of seabird mortality in the NE Pacific during the 2015-2016 marine heatwave. Plenary presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Reister, I. 2022. Fate of the Copper River plume. Poster presentation. Alaska Marine Science Symposium, Virtual, January.

Reister, I. 2022. Fate of the Copper River plume. Poster presentation. Ocean Sciences Meeting, Virtual, March.

Reister, I., and S. Danielson. 2021. Freshwater in the Northern Gulf of Alaska Marine Environment. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Roncalli, V. 2017. The ecophysiology of a marine organism - a transcriptomic approach to diapause emergence. Invited presentation. Institut de Recerca de la Biodiversitat, University of Barcelona, Barcelona, Spain, July.

Roncalli, V. 2018. Physiological ecology of the calanoid *Neocalanus flemingeri* in the Gulf of Alaska. Invited presentation.presentation. Pacific Biosciences Research Center, University Hawaii Manoa, Honolulu, HI, February.

Roncalli, V., M. Cieslak, A. M. Castelfranco, R. **Hopcroft**, D. K. Hartline, and P. Lenz. 2021. From suspended animation to fully active: Post-diapause transcriptomic restart in a high latitude zooplankter. Oral presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Roncalli, V., M. Cieslak, R. R. **Hopcroft**, and P. H. Lenz. 2019. Environmental heterogeneity in the Northern Gulf of Alaska impacts physiological status in the copepod, *Neocalanus flemingeri*. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Roncalli, V., M. C. Cieslak, P. H. Lenz, and R. R. **Hopcroft**. 2020. Energy allocation in a diapausing copepod: a transcriptomics analysis (ME12A-01). Oral presentation. Ocean Sciences Meeting, San Diego, CA, February.

Roncalli, V., M. C. Cieslak, S. A. Matthews, C. Clarke-Hopcroft, R. R. **Hopcroft**, and P. H. Lenz. 2017. Physiological changes in *Neocalanus flemingeri* females during the transition from diapause to reproduction (Abstract ID: 29198). Oral presentation presentation. Aquatic Sciences Meeting (ASLO), Honolulu, HI March.

Roncalli, V., M. C. Cieslak, S. A. Sommer, C. Clarke, P. H. Lenz, and R. R. **Hopcroft**. 2017. Transcriptomic changes in *Neocalanus flemingeri* from diapause emergence to egg production. Oral presentation. 13th International Conference on Copepoda, Los Angeles, CA, July.

Roncalli, V., D. K. Hartline, M. Germano, M. C. Cieslak, S. L. Strom, R. R. **Hopcroft**, and P. H. Lenz. 2018. Consequences of regional heterogeneity on the physiology of a calanoid copepod, **Neocalanus flemingeri** in the northern Gulf of Alaska (RS41A-06). Oral presentation. Ocean Sciences Meeting, Portland, OR, February.

Smoot, C., K. Coyle, and R. **Hopcroft**. 2020. Warm-water zooplankton in the Northern Gulf of Alaska: Observations from the Seward Line. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Stidham, E. 2021. Seasonal abundance and biomass of pelagic tunicates and snails in the Gulf of Alaska and Prince William Sound. Poster presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Stidham, E. 2022. Two-decades of observations on pelagic tunicates and pelagic snails in the Northern Gulf of Alaska (NGA). Poster presentation. Alaska Marine Science Symposium, Virtual, January.

Stidham, E. 2022. Two-decades of observations on pelagic tunicates and pelagic snails in the Northern Gulf of Alaska (NGA). Oral presentation. Ocean Sciences Meeting, Virtual, March.

Strom, S. 2019. Mixotrophy in the Gulf of Alaska: Abundant plant-animal cells have major implications for ecology and biogeochemistry. Plenary presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Strom, S. L., and R. R. **Hopcroft**. 2018. Planktonic communities in the coastal Gulf of Alaska: strong dichotomies in structure and function (RS41A-03). Oral presentation. Ocean Sciences Meeting, Portland, Oregon, February.

Strom, S., R. R. **Hopcroft**, A. M. Aguilar-Islas, S. L. Danielson, and J. Fiechter. 2019. Resilience amidst a sea of change: the Northern Gulf of Alaska LTER program. Keynote Presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Strom, S. L., R. R. **Hopcroft**, A. M. Aguilar-Islas, S. L. Danielson, J. Fiechter, A. M. P. McDonnell, and M. Sigman. 2018. The Northern Gulf of Alaska (NGA) LTER: Resilience amidst a sea of change (A-K114). Poster presentation. LTER All Scientists' Meeting, Pacific Grove, California, March. Retrieved from https://lternet.edu/stories/poster-sessions-at-the-2018-all-scientists-meeting/

Strom, S. L., R. R. **Hopcroft**, K. O. Coyle, and S. L. Danielson. 2017. Three in a row: continued warm conditions along the Gulf of Alaska's Seward Line. Oral presentation. Aquatic Sciences Meeting (ASLO), Honolulu, Hawa'ii, March.

Suitos, J. 2017. Genetic comparison between Prince William Sound and Alaska Coastal Current populations of a zooplankton species, the copepod *Neocalanus flemingeri*. Oral presentation. Undergraduate Research and Creative Work Symposium, University of Hawaii Manoa, Honolulu, Hawa'ii, May.

Suryan, R., M. Arimitsu, H. Coletti, R. **Hopcroft**, M. Lindeberg, S. Batten, J. Bodkin, M. A. Bishop, R. Campbell, D. Cushing, S. Danielson, D. Esler, S. Hatch, S. Haught, K. Holdereid, K. Iken, D. Irons, R. Kaler, B. Konar, K. Kuletz, C. Matkin, C. McKinstry, D. Monson, J. Moran, D. Olsen, S. Pegau, J. Piatt, A. Schaefer, J. Straley B. Weitzman. 2021. Ecosystem response to a prolonged marine heatwave in the Gulf of Alaska:

Seabirds are the tip of the iceberg. Oral presentation. Third World Seabird Conference, Virtual, October.

Suryan, R., M. Lindeberg, M. Arimitsu, H. Coletti, R. **Hopcroft**, D. Aderhold, and K. Hoffman. 2020. Ecosystem response to a prolonged marine heatwave in the Gulf of Alaska: Perspectives from Gulf Watch Alaska. Plenary presentation. Alaska Marine Science Symposium, Anchorage, Alaska, January.

Suryan, R. M., S. G. Zador, M. Lindeberg, D. Aderhold, J. Moran, Y. Arimitsu, J. Piatt, J. Moran, J. Straley, H. Coletti, D. Monson, T. Dean, R. Hopcroft, S. Batten, S. Danielson, B. Laurel. 2018. Ecosystem variability and connectivity in the Gulf of Alaska following another major ecosystem perturbation. Oral presentation. PICES Annual Meeting, Yokohama, Japan.

Theses and dissertations

Busse, H. 2021. Mixotrophy by phytoflagellates in the Northern Gulf of Alaska: Impacts of physico-chemical characteristics and prey concentration on feeding by photosynthetic nano- and dinoflagellates. Western Washington University, Bellingham, Washington. https://cedar.wwu.edu/wwuet/1005.

Kandel, A. R. Y. 2020 Spatial and temporal variability of dissolved aluminum and manganese in surface waters of the Northern Gulf of Alaska, United States. University of Alaska Fairbanks abgerufen am 23.07.2021, https://www.proquest.com/docview/2476549380/abstract/CD792F466B734239PQ/1.

Mendoza-Islas, H. 2020. Abundance, composition and distribution of predatory gelatinous zooplankton in the Northern Gulf of Alaska. University of Alaska Fairbanks https://search.proquest.com/docview/2447028430.

Monell, K. J. 2020. Characterization of cell division in the tissues of the calanoid copepod, *Neocalanus flemingeri* from diapause through early oogenesis. University of Hawai'i at Manoa, abgerufen am 23.07.2021, http://scholarspace.manoa.hawaii.edu/handle/10125/73356.

Mazur, C. M. 2020 Comparing the bioavailability of a natural and synthetic iron source: do past experiments accurately model phytoplankton response to episodic iron addition? Western Washington University, Bellingham, Washington https://cedar.wwu.edu/wwuet/966/.

Pretty, J. L. 2019. Particles in the Pacific: how productivity and zooplankton relate to particles in the deep sea. University of Alaska Fairbanks https://scholarworks.alaska.edu/handle/11122/10529.

Outreach

Cushing, D. A. 2019. Seabirds and the Northern Gulf of Alaska Long Term Ecological Research Program. Guest Speaker, Eagle River High School Oceanography Classes (grades 10–12), Eagle River, Alaska.

Cushing, D., E. Labunski, and K. Kuletz. 2022. Summer tourists: The rare, amazing, and out-of-their-range visitors observed during seabird surveys in the northern Gulf of Alaska. Poster presentation. Pratt Museum Exhibit, Kachemak Bay Shorebird Festival, Homer, Alaska.