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Long-term monitoring and integrated research – Understanding ecosystem processes in the Gulf of Alaska

1. Introduction

This is the third installment in a series of special issues in Deep Sea Research II (DSR II): Topical Studies in Oceanography, dedicated to understanding ecosystem processes in the Gulf of Alaska. The first special issue, DSR II volume 1 (Dickson and Baker, 2016), focused on physical processes from initial outcomes of the Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP). The second, DSR II volume 2 (Ormseth et al., 2019), showcased biological research and final results of the GOAIERP synthesis phase. This third special issue is a compilation of research reflected in several distinct programs focused on ecosystem research in the Gulf of Alaska. The volume presents new findings from the final synthesis phase of the GOAIERP and complementary work from several other large multidisciplinary programs in the Gulf of Alaska: The *Exxon Valdez* Oil Spill Trustee Council's (EVOSTC's) long-term programs, Gulf Watch Alaska (GWA) and Herring and Research Monitoring (HRM), and the National Science Foundation's Northern Gulf of Alaska Long-Term Ecological Research program (NGA LTER). These large integrated ecosystem research programs were established to better understand the changing dynamics of the Gulf of Alaska and effects on ecosystem processes and populations of subsistence, commercial, and recreationally important species and coastal communities.

Some of the oldest and most comprehensive marine ecosystem monitoring programs were established in the Gulf of Alaska following the environmental disaster of the *Exxon Valdez* oil spill more than 30 years ago (Spies et al., 1996). The international Global Oceans Ecosystem Dynamics (GLOBEC) program (Fogarty and Powell, 2002) identified the coastal Gulf of Alaska as one of three regions of interest in the U.S. and created the Gulf of Alaska GLOBEC program from 1997 to 2004 (Batchelder et al., 2005). As a result, these research and monitoring programs have provided an unparalleled data repository that has supported important research to assess ecosystem status, ecosystem interactions, and ecosystem responses to perturbation. These programs generally fall within the northern Gulf of Alaska from southeastern Alaska to the Kodiak Archipelago (Fig. 1) and are described in greater detail below.\

1.1. Gulf of Alaska Integrated Ecosystem Research Program

GOAIERP was one of several integrated ecosystem research projects (IERP) in Alaska funded by the North Pacific Research Board (NPRB). This research was conducted to understand the marine environment and its influence on variability in recruitment of five commercially and ecologically valuable fish stocks (Dickson and Baker, 2016). The first phase of GOAIERP research was conducted from 2010 to 2014 and products of this phase included a suite of *in situ* observations from integrated ecosystem surveys, laboratory experiments of physical thresholds for fish condition, and high resolution regional oceanographic, planktonic, and habitat distribution models (Dickson and Baker, 2016). The second phase of the GOAIERP was a synthesis phase occurring from 2014 to 2018 and designed to integrate new data from collaborating programs and further address system connectivity, highlight primary ecosystem drivers, and synthesize the various large-scale and local-scale process study programs in the Gulf of Alaska (GOA). At the synthesis phase, the research results were applied to inform resource management.

The GOAIERP was motivated by a foundational hypothesis that the main determinant of year-class strength for GOA groundfishes is early life survival. It was proposed that this is regulated in space and time by climate-driven variability, offshore and nearshore habitat quality, larval and juvenile transport, and settlement to suitable demersal habitat. This program explored the idea that survival of an individual fish, from the time it is spawned to recruitment, is controlled by the complex and variable biophysical environment encountered during egg and larval drift stages prior to reaching habitat suitable for juvenile settlement. The program sampled the environment and developed models exploring these interactions and transport processes. Since successful recruitment may depend on many interrelated factors affecting individual fish along their transport pathways, sampling, analysis, and modeling explored how physical processes (e.g. freshwater runoff, mixing and stratification, water temperature, and wind speed and direction) influence transport pathways during the first year of life.

An essential feature of the GOAIERP was its comprehensive spatial scope, multidisciplinary approach, and integrative structure. A collaborative research approach was applied, including explicit focus on separate trophic levels (lower, middle, upper) and model development. Integrated physical, chemical, and biological oceanographic sampling was conducted along a sampling grid, spanning the eastern, central, and western GOA (Ormseth et al., 2019). Ecosystem surveys were conducted at inshore and offshore sites and field surveys were complemented by laboratory analysis of food habits and energetic condition, and physiological experiments. Results were used to develop species-specific individual-based models (IBMs) to predict recruitment variability under various environmental scenarios (Gibson et al., 2022). Discussions were held throughout the program to coordinate research design, data collection, analysis, and interpretation to promote the integration of results and an enhanced understanding of ecosystem dynamics.

The synthesis phase welcomed fishery managers to the conversation

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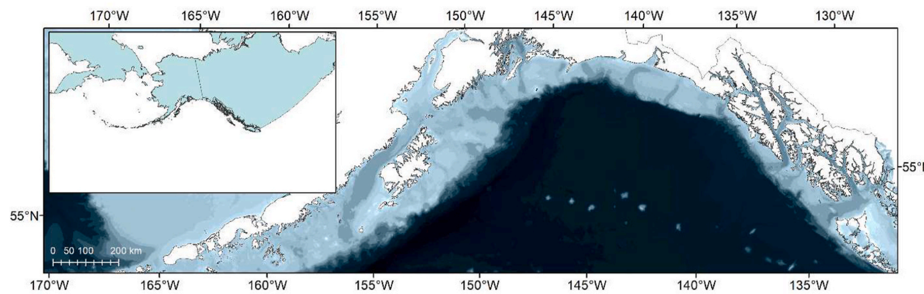

Fig. 1. Main Map: Gulf of Alaska. Map shows general sampling area used by the programs represented in this special issue. Inner Map: North Pacific.

to transition the results of the basic research to application in resource management. For example, NOAA's Ecosystem Status Reports are intended to provide the North Pacific Fishery Management Council (NPFMC), including its Scientific and Statistical Committee and Advisory Panel, with information on ecosystem status and trends (Ferriss and Zador, 2021). GOAIERP research provided justification for generating separate indicators for the Eastern GOA and Western GOA. The synthesis also facilitated the development of an ecosystem and socioeconomic profile (ESP) framework that is described in more detail in section 2.3 below.

1.2. Gulf Watch Alaska

The GWA program began in 2012 as a long-term ecosystem monitoring program funded by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) and guided by their restoration plan (EVOSTC, 1994). The purpose of this long-term program is to improve our understanding of how changing environmental conditions affect GOA ecosystems and the long-term status of resources injured by the *Exxon Valdez* oil spill (EVOSTC, 1994, 2010). This includes nearshore and offshore ecosystems in the spill affected region, from Prince William Sound to lower Cook Inlet and portions of the Katmai coast.

GWA is a multi-disciplinary integrated program with the overall goal of sustaining and building on long-term ecosystem monitoring information (Aderhold et al., 2018; McCammon et al., 2018). The program is designed around three major ecosystem components: Environmental drivers, pelagic ecosystems, and nearshore ecosystems. Projects within these components monitor metrics encompassing oceanographic conditions and productivity; forage fish, marine bird, and whale populations; and nearshore vertebrate predators, benthic invertebrates, and macroalgae. Many of these projects curate and continue decades long datasets, some well before the 1989 spill, providing an ability to examine spatial and temporal variability in the physical and biological environments. These time series are a valuable source for ecosystem indicators included in NOAA's Ecosystem Status Reports.

GWA is also a multi-agency and organization program with the goal of providing science synthesis products to resource managers and the public. There have been more than 100 peer-reviewed publications over the last decade by GWA scientists, including a DSR II special issue (Aderhold et al., 2018) and this issue. Synthesis publications highlighted the recent Pacific marine heat wave between 2014 and 16 and associated ecosystem level impacts (Arimitsu et al., 2021; Danielson et al., 2022; Suryan et al., 2021; Weitzman et al., 2021). Through the GWA program, these types of publications have provided invaluable information to resource managers and the scientific community that is not achievable by individual short-term projects.

1.3. Herring research and monitoring

The HRM program also began in 2012 and was funded by the EVOSTC. Through a public process and development of an Integrated Herring Restoration Plan (EVOSTC, 2008) a Prince William Sound (PWS) Herring Survey Program was initiated in 2009 and evolved into the current long-term HRM program.

Pacific herring (*Clupea pallasii*) are an ecologically important forage fish in the GOA (Szymon et al., 2021) and the PWS population is still considered an injured resource from the *Exxon Valdez* oil spill. The PWS herring fishery has been below the management threshold of 22,000 metric tons since 1998 and no commercial fishery has occurred since then. No definitive answer has been identified for the collapse of this fishery but several factors are thought to be limiting recovery, including predation, changes in ocean conditions, competition for food, and disease.

The HRM program is designed to provide a greater understanding of the factors affecting the recovery of PWS herring populations at an ecosystem level through a mix of process studies and monitoring projects (Pegau and Aderhold, 2021). The program strives to improve predictive models of herring stocks (modified age-structure-analyses) and targeted hypotheses on their life-history, age-0 herring overwintering condition, disease dynamics, and adult movements inside and outside of the PWS. In all, the EVOSTC has funded over 100 projects investigating this key ecosystem resource to better understand its recovery and ability to adapt to environmental perturbations. The HRM program has led to many contributions to the scientific community and recent synthesis publications (Hershberger et al., 2021; McGowan et al., 2021; Muradian et al., 2017; Sewall et al., 2019).

1.4. Northern Gulf of Alaska Long-Term Ecological Research

The NGA LTER program began in 2018 funded by the National Science Foundation (Hopcroft et al., 2017). This program continues and expands a long and rich history of sustained oceanographic data collection by the University of Alaska Fairbanks. This research is centered around the GOA Seward Line and GAK1 mooring, with over 50 years of sampling, and expands 150 miles east and west to include oceanographic sampling lines off the Copper River delta and Kodiak Island, respectively. The expanded NGA LTER sampling region provides enhanced offshore biophysical oceanographic data on a spatial scale that matches and greatly compliments GWA long-term monitoring. The NGA LTER program joins a network of 28 National Science Foundation LTER locations nationwide with a mission to provide scientists, policy makers, and society with knowledge and predictive understanding necessary to conserve, protect, and manage the nation's ecosystems, their biodiversity, and the services they provide.

The NGA LTER program goals are to investigate the features, mechanisms, and processes that drive northern GOA ecosystem production and foster its resilience. Topics of interest include temperature/salinity structure, spring bloom production, hot spots of high summer primary and secondary production, trophic match/mismatch between producers and consumers, and structure and composition of biological communities. These goals and topics of interest are being addressed through tri-annual across-shelf surveys between spring and fall and the deployment of multi-instrument moorings for year-round observations. Process studies at select stations target specific mechanistic questions and modeling efforts incorporate physical and biogeochemical observations for testing hypotheses on ecosystem variability and resilience. Recent NGA LTER publications highlight the Pacific marine heatwave, biophysical oceanography, and modeling results (Coyle et al., 2019; Danielson et al., 2020, 2022; Hauri et al., 2020; Kandel and Aguilar-Islas, 2022; Roncalli et al., 2022).

In summary, these large marine ecosystem programs and the trio of DSR II special issues establish a significant foundation of research to inform ecological interactions, resource management, and community impacts in the GOA, in the context of recent marine heatwaves and accelerating environmental change. Much of the research presented in this volume derives from these programs and provides important information on specific habitats, interactions and life history stages, particularly in the nearshore.

1.5. Gulf of Alaska research overview

1.5.1. Oceanography and the North Pacific marine heatwave

The GOA is a large, coastal ocean system that features an along shore current, the Alaska Coastal Current (ACC), that is driven by winds and freshwater runoff (Royer, 1981a, b; Stabeno et al., 2004; Weingartner et al., 2005). The ACC moves along the coastal zone to the southwest and features eddies, upwelling, and flux in the surface Ekman layer (Mordy et al., 2019; Stabeno et al., 2004) all of which enhance primary production despite persistent downwelling conditions. As described, the GOA recently experienced the multi-year Pacific marine heatwave (PMH) from 2014 to 2016 (Bond et al., 2015; Di Lorenzo and Mantua, 2016). The PMH was widespread and caused multiple changes to manifest across the ecosystem (Barbeaux et al., 2020; Suryan et al., 2021). Several papers in this volume seek to place the impact of this marine heatwave and subsequent smaller events in a broader context from the perspective of both physical and biological oceanography.

Danielson et al. (2022) uses a variety of data sources to provide insight into the thermal variability of the northern GOA. The goal was to examine the long-term trends in temperature, placing the PMH in a broader temporal context and understand how different regions of the GOA responded to PMH. Overall, the study shows that the PMH was variable in its impacts along the shelf and consists of multiple processes interacting. For example, GOA coastal surface water warmed in concert with offshore waters through 2013, but deep inner shelf waters had a delayed response. In contrast, offshore waters cooled from 2014 to 2016 despite ongoing warming on the shelf. The authors also found that the rate of warming has intensified when examining the past 50 years compared to the past 120 years. Warming also impacts the amount of freshwater input the GOA receives (Hill et al., 2015) and Kandel and Aguilar-Islas (2022) examine dissolved manganese (Mn) and aluminum (Al) concentrations along the GOA shelf which may act as proxies for iron (Fe), a limiting nutrient for primary production in the northern Pacific Ocean (Fiechter et al., 2009; Martin and Fitzwater, 1988). Seasonal patterns in dissolved Mn and Al had a distinct cycle linked to glacial melt and runoff. Spatially, strong cross-shelf gradients were observed, and the ACC restricted water with higher dissolved metal concentrations closer to the nearshore (Kandel and Aguilar-Islas, 2022). These results suggest that as warming persists, different regions of the shelf will warm at different rates and that primary productivity may be impacted by change in dissolved metal input related to glacial melt.

The oceanographic changes during the PMH resulted in declines in overall plankton productivity that have been linked to effects at higher trophic levels, e.g. the die-offs of common murres observed 2015 to 2017 (Piatt et al., 2020). Batten et al. (2022) found that plankton taxonomic richness was reduced along Continuous Plankton Recorder sampling routes overall and species that are commonly found in warmer waters were more prevalent during the PMH. Interestingly, they found increased abundances of zooplankton, in particular pteropods and copepods, during the PMH which they attributed to reduced predation pressure from forage fish. While zooplankton numbers were higher during the PMH, Batten et al. (2022) point out that larger, lipid-rich zooplankton were reduced, as also noted by Ashlock et al. (2021), leading the authors to conclude that the benefits of warmer water on zooplankton growth and abundance for some species were offset by the overall reduction in zooplankton quality. At a finer spatial scale, McKinstry et al. (2022) focused on the lower Cook Inlet zooplankton community response to the PMH. A phenological change was detected, with earlier arrival of both meroplankton and warmer water species during the PMH. In contrast to Batten et al. (2022), larger, lipid-rich species of zooplankton showed no evident decline in abundance, which the authors suggest shows inshore populations of these species may be more resilient to warming. Also interesting was evidence that taxa typically found in warmer waters appeared to overwinter in Kachemak Bay, perhaps representing the establishment of local populations of species more commonly found to the south. These results show that warming effects on the plankton may vary widely both temporally and spatially in the northern GOA. The studies also highlight that the dynamic nature of the GOA complicates the prediction of ecosystem response to warming.

1.6. Nearshore environments and fish communities

The GOA is highly variable in habitat and conditions with a narrow continental shelf, steep continental slope, well-defined straits and channels, and numerous inshore embayments; many areas, especially the nearshore, are not accessible with standard sampling approaches (Baker et al., 2019). Targeted sampling provides an opportunity to collect important information on specific habitats, interactions, and life history stages (Grüss et al., 2021). The GOA nearshore environment is a particularly biologically rich and productive ecosystem due to complex and unique coastal features and habitats. Ocean waters along thousands of kilometers of rugged coastline, large-scale embayments and fjords are mixed with freshwater from thousands of rivers and glaciers (Lindeberg and Johnson, 2015). Complex bathymetry, estuaries, eelgrass meadows, and kelp forests provide essential habitat for numerous fish species, many of which are managed for commercial fisheries (NPFMC, 2020). However, there remains a lack of information for these nearshore environments and understanding how they will respond to warming climate conditions. Several studies in this issue are filling this gap and advancing our knowledge of these northern latitude habitats.

Siegert et al. (2022) and McCabe and Konar (2022) explored GOA's nearshore environments facing increased stress from global warming. Siegert et al. (2022) investigated how hydrographic conditions influence trophic structure in high latitude rocky intertidal systems by comparing two areas in lower Cook Inlet with differing hydrological inputs, one glacial (Kamishak Bay) and the other oceanic (Kachemak Bay). Food web structure was compared by using trophic metrics based on the distribution of shared taxa in isotopically derived (δ 13 C and δ 15 N) trophic niche space. They found glacially influenced rocky intertidal systems had better trophic stability than those with oceanic influence, but that macroalgae was a more important food source than particulate organic matter in both areas. McCabe and Konar (2022) examined rocky intertidal community structure, recruitment of key organisms, and environmental correlates in northern and southern regions of the GOA. In general, findings were that larger watersheds with more glacial coverage and river discharge resulted in more primary producers and less filter feeders. This pattern was more apparent in Kachemak Bay, the northern region with oceanic influence. These studies show glacially influenced intertidal habitats have better trophic stability than those with oceanic influence but future warming could cause some changes to their species composition.

Two papers in this issue focused on fishes and their use of dynamic nearshore habitats, a poorly understood and often overlooked area of research in the GOA. Budge et al. (2022) examined the trophic interactions of several juvenile fishes in the nearshore GOA using fatty acid and stable isotope markers to evaluate foraging ecology and the potential for competition among age-0 fish species. For western GOA, both indicated that Pacific cod (*Gadus microcephalus*) and saffron cod (*Eleginus gracillis*) usually shared similar diets, potentially leading to competition for resources. There was also evidence in the west that Pacific cod and walleye pollock (*Gadus chalcogrammus*) both relied on calanoid copepods during the summer. Juvenile Pacific sand lance (*Ammodytes hexapterus*) and herring were much smaller than the other species and had diets that contrasted with all other species. In east and west GOA, rockfish (*Sebastes* spp.) were present in two distinct size classes with the smaller size feeding at a lower trophic level than all other fish species in the study and greenling and rockfish typically consumed prey with a very different lipid source than the other juvenile fish. In general, they found a complex relationship within the nearshore fish communities in the east and west showing substantial variation across bays, seasons and subareas. To better understand relationships between physicochemical factors and fish community structure within high-latitude estuarine systems, Guo et al. (2022) conducted systematic beach seining at multiple river mouth sites in a macro-tidal estuary located in the northern GOA (Kachemak Bay). Their results showed the combined effects of site and sampling month best explained variability in the fish community. For example, juvenile Pacific herring were associated with more turbid, less saline conditions, while saffron cod were associated with less turbid, more saline conditions. Pacific sand lance were good indicators of both inner bay and high current sites. Overall, their findings point to broader scale coastal shifts as potential mechanisms driving changes in community structure within similar systems in this region.

1.7. Fisheries and management applications

The GOA ecosystem produces high value commercial groundfish fisheries that are managed by the North Pacific Fishery Management Council (NPFMC). The NPFMC is supporting efforts toward ecosystem-based fisheries management (Zador et al., 2017). One of the avenues for providing ecosystem science to the NPFMC is through an annual Ecosystem Status Report (Ferriss et al., 2021). These reports provide and summarize ecosystem indicators to better understand connections between ecosystem research and fishery management. Research and monitoring programs provide vital information for these reports producing long-term time series, syntheses, and models for management applications. Several papers in this issue are focused on ecosystem-based fisheries management and informing decision makers.

In southeastern GOA, Surma et al. (2022) investigated Pacific herring as a key forage fish and prey species for predators. Mass- and energy-balanced ecosystem models were developed in Ecopath and Ecosim. Results showed Supportive Role to Fishery (SURF) index values from mass-balanced models lay below the threshold required to designate herring as a key forage fish but values from an energy-balanced model supported the key status of herring. In energy-balanced models, impacts of herring depletion on predators were stronger and more numerous suggesting that the high energy content of herring enhances its importance to predators. Interestingly, simulation results also demonstrated positive impacts of herring depletion on two zooplankton groups due to release from predation pressure. The authors concluded that Pacific herring status as a key forage fish is dependent on their energy content relative to other forage fishes.

The Pacific herring fishery in PWS has remained closed since 1994. Gray et al. (2022) examined the theory that piscivorous groundfish could be a major hindrance to the recovery of this herring population. Groundfish collections for stomach contents were made during winter when juvenile herring energy levels decrease, reducing their ability to avoid predators. Pacific cod showed strong evidence of seasonality in herring consumption and notably more adult herring than other piscivores. Big skate (*Beringraja binoculata*) consumed herring ages 3+ and younger. Walleye pollock was a major consumer of age-0 herring. As groundfish body size increased, all three species consumed larger, age-2+ pollock, suggesting pollock presence mediates herring overwintering mortality and that pollock cannibalism is an important dietary pathway in PWS. These results identify key groundfish consumers of herring and offer novel insight into the importance of pollock as a forage fish in PWS.

With juvenile recruitment hypothesized to be a key factor controlling groundfish abundance, Gibson et al. (2022) details a series of modeling approaches used to assess the effect of environmental variability on transport and success of groundfish early life stages from spawning to settlement. Analyses determined that connectivity between spawning areas and nursery sites explained significant amounts of variability in recruitment of certain species, but not more than half of the recruitment variability for any one species. Modeling studies also suggested that the eastern and western GOA are substantially different with respect to their contribution to important spawning and nursery area habitat. Overall, the GOAIERP modeling effort was useful, not only in better understanding groundfish recruitment, but also as a case study in model development. This case study provides guidance on how to direct models to better understand, hindcast, and predict stock status and trends. It also highlights the value that modeling can add to a field program and fisheries management planning.

To quantitatively include ecosystem indicators into fisheries stock assessments, Shotwell et al. (2022) used GOAIERP's data synthesis of five commercially and ecologically valuable groundfish species to propose a direct avenue for a new ecosystem and socioeconomic profile (ESP) framework. The ESP framework permits identification of mechanistic relationships and tests ecosystem linkages within the stock assessment process. Authors initially developed life history narratives for each species, sablefish (*Anoplopoma fimbria*), pollock, Pacific cod, arrowtooth flounder (*Atheresthes stomias*), and Pacific ocean perch (*Sebastes alutus*), to identify critical ecosystem processes that could impact survival of each species. Habitat distribution models, seasonal phenology, and energy allocation strategies were then used to align ecosystem information at a spatial and temporal scale relevant to a stock and create informed indicators that can then be related to a stock assessment parameter of interest, such as recruitment. This type of integration ensures that identified ecosystem linkages are evaluated concurrently with the stock assessment and ultimately transferred to fishery managers in an efficient and effective format for informing management decisions.

Coastal community outreach and engagement is also critically important to ecosystem-based fisheries management. Rosellon-Druker et al. (2022) used a small-scale integrated ecosystem assessment and a socio-ecological conceptual model for sablefish in the fishing community of Sitka, Alaska. Models were developed from participatory focus groups, including stakeholders, and literature reviews to identify ecosystem attributes driving sablefish abundance. A qualitative network model was assembled so perturbations of individual components could be assessed mathematically. Simulations tested different biophysical scenarios, while evaluating trade-offs across ecological and human dimension components. Results showed adult (large and small size) and juvenile sablefish responded similarly to most biophysical conditions. Human dimension components responded negatively to tested scenarios. These results suggest a need for management strategies that differentiate between small and large adults, particularly if current sablefish stock assessment trends persist, such as the lack of older fish contributing to spawning biomass and uncertainties in estimates of year-class strength.

2. Conclusion

The GOA is a complex and dynamic ecosystem from which we continue to gather information and knowledge. Over the past two decades, we have benefited from numerous long-term monitoring programs, ecosystem surveys, and collaborative research programs developed and implemented to better understand this marine ecosystem. These programs strategically standardized surveys, curated time-series, and produced integrated syntheses and models allowing for ecosystem level information. Findings from these efforts have provided considerable new insights into the GOA's physical system, localized processes, and potential impacts of perturbations related to global warming and marine heatwaves. The design and vision of these integrated ecosystem programs has pushed our knowledge of the GOA further and toward more effective ecosystem-based resource management.

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References

Aderhold, D.A., Esler, D., Heintz, R.A., Hopcroft, R.R., Lindeberg, M.R., Pegau, W.S., 2018. Spatial and temporal ecological variability in the northern Gulf of Alaska: what have we learned since the *Exxon Valdez* oil spill? Deep-Sea Res. II. 147, 1–202. https://doi.org/10.1016/j.dsr2.2017.11.015.

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

Ashlock, L., García-Reyes, M., Gentemann, C., Batten, S., Sydeman, W., 2021. Temperature and patterns of occurrence and abundance of key Copepod taxa in the Northeast Pacific. Front. Mar. Sci. 8 https://doi.org/10.3389/fmars.2021.670795.

Baker, M.R., Palsson, W.A., Zimmermann, M., Rooper, C.N., 2019. Model of trawlable area using benthic terrain and oceanographic variables - informing survey design and habitat maps in the Gulf of Alaska. Fish. Oceanogr. 1–29. https://doi.org/10.1111/fog.12442, 00.

Barbeaux, S.J., Holsman, K.K., Zador, S., 2020. Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod fishery. Front. Mar. Sci. 20 (7), 703.

Batchelder, H.P., Strub, P.T., Lessard, E.J., Weingartner, T.J., 2005. US GLOBEC biological and physical studies of plankton, fish and higher trophic level production, distribution, and variability in the northeast Pacific. Deep-Sea Res. II. 52, 1–2. https://doi.org/10.1016/j.dsr2.2004.10.001.

Batten, S.D., Ostle, C., Hélaouët, P., Walne, A.W., 2022. Responses of Gulf of Alaska plankton communities to a marine heat wave. Special issue. Deep-Sea Res. II. 195, 105002 https://doi.org/10.1016/j.dsr2.2021.105002.

Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett. 42, 3414–3420. https://doi.org/10.1002/2015GL063306.

Budge, S.M., Wang, S.W., Ormseth, O.A., Rand, K.M., 2022. Foraging ecology of nearshore fishes in the Gulf of Alaska. Special issue. Deep-Sea Res. II. 195, 105013 https://doi.org/10.1016/j.dsr2.2021.105013.

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

Danielson, S., Hennon, T.D., Monson, D.H., Suryan, R.M., Campbell, R.W., Baird, S.J., Holderied, K., Weingartner, T.J., 2022. Thermal Variability in the Northern Gulf of Alaska across Years of Marine Heatwaves and Cold Spells. Special Issue, II. Deep-Sea Res, p. 195 xxxxxx.

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

Dickson, M.S., Baker, M.R., 2016. Introduction to the North Pacific research board Gulf of Alaska integrated ecosystem research program (GOAIERP), Volume I. Special issue. Deep Sea Res. II. 132, 1–5. https://doi.org/10.1016/j.dsr2.2016.08.005.

Di Lorenzo, E., Mantua, N., 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nat. Clim. Change 6, 1042–1047. https://doi.org/10.1038/nclimate3082.

Exxon Valdez Oil Spill Trustee Council (EVOSTC),, 1994. *Exxon Valdez* Oil Spill Restoration Plan. November. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, AK available online. http://www.evostc.state.ak.us/.

Exxon Valdez Oil Spill Trustee Council (EVOSTC), 2008. Draft Integrated Herring Restoration Plan. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, AK available online. http://www.evostc.state.ak.us/.

Exxon Valdez Oil Spill Trustee Council (EVOSTC), 2010. *Exxon Valdez* Oil Spill Restoration Plan: 2010 Update of Injured Resources and Services. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, AK available online. http://www.evostc.state.ak.us/static/PDFs/2010IRSUpdate.pdf.

Ferriss, B.E., Zador, S., 2021. Ecosystem Status Report 2021: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, 1007. North Pacific Fishery Management Council. West Third, Suite 400, Anchorage, Alaska 99501.

Fiechter, J., Moore, A.M., Edwards, C.A., Bruland, K.W., Di Lorenzo, E., Lewis, C.V.W., Powell, T.M., Curchitser, E.N., Hedstrom, K., 2009. Modeling iron limitation of primary production in the coastal Gulf of Alaska. Deep-Sea Res. II. 56, 2503–2519. https://doi.org/10.1016/j.dsr2.2009.02.010.

Fogarty, M.J., Powell, T.M., 2002. An overview of the US GLOBEC program. Oceanography 15 (2), 4–12. https://doi.org/10.5670/oceanog.2002.17.

Gibson, G.A., Baker, M.R., Stockhausen, W.T., Hinckley, S., Parada, C., Aydin, K., Coyle, K.O., Hermann, A.J., Hurst, T.P., Punt, A.E., 2022. Modeling in an integrated ecosystem research framework to explore recruitment in Gulf of Alaska groundfish – Applications to management and lessons learned. Special issue, Deep-Sea Res. II. 195, 105048 https://doi.org/10.1016/j.dsr2.2022.105048.

Gray, B.P., Bishop, M.A., Powers, S., 2022. Winter variability in the diets of groundfish inhabiting a subarctic sound with a focus on Pacific herring and walleye pollock piscivory. Special issue, Deep-Sea Res. II. 195, 104984 https://doi.org/10.1016/j.dsr2.2021.104984.

Grüss, A., Pirtle, J.L., Thorson, J.T., Lindeberg, M.R., Neff, A.D., Lewis, S.G., Essington, T. E., 2021. Modeling nearshore fish habitats using Alaska as a regional case study. Fish. Res. 238, 105905.

Guo, C., Konar, B., Gorman, K., Walker, C., 2022. Environmental factors important to high-latitude nearshore estuarine fish community structure. Special issue. Deep-Sea Res. II. 195, 105109 https://doi.org/10.1016/j.dsr2.2022.105109.

Hauri, C., Schultz, C., Hedstrom, K., Danielson, S., Irving, B., Doney, S.C., Dussin, R., Curchitser, E.N., Hill, D.F., Stock, C.A., 2020. A regional hindcast model simulating ecosystem dynamics, inorganic carbon chemistry, and ocean acidification in the Gulf of Alaska. Biogeosciences 17 (14), 3837–3857. https://doi.org/10.5194/bg-17-3837-2020.

Hershberger, P.K., Meyers, T.R., Gregg, J.L., Groner, M.L., Hall, S.A., Jayasekera, H.T., MacKenzie, A.H., Neat, A.S., Piatt, E.N., Garver, K.A., 2021. Annual Recurrences of Viral Hemorrhagic Septicemia Epizootics in Age-0 Pacific Herring. *Clupea pallasii* Valenciennes. https://doi.org/10.3390/ani11082426, 1847, Animals. 11. 2426.

Hill, D.F., Bruhis, N., Calos, S.E., Arendt, A., Beamer, J., 2015. Spatial and temporal variability of freshwater discharge into the Gulf of Alaska. J. Geophys. Res.: Oceans 120, 634–646. https://doi.org/10.1002/2014JC010395.

Hopcroft, R.R., Aguilar-Islas, A.M., Danielson, S.L., Fiechter, J., Strom, S.L., 2017. Northern Gulf of Alaska long term ecological research (NGA LTER) program. Proposal to the National science foundation. Available online. https://nga.lternet.edu/.

Kandel, A., Aguilar-Islas, A., 2022. Spatial and temporal variability of dissolved aluminum and manganese in surface waters of the northern Gulf of Alaska. Special issue. Deep-Sea Res. II. 195, 104952 https://doi.org/10.1016/j.dsr2.2021.104952.

Lindeberg, M.R., Johnson, S.W., 2015. Our Living Oceans: Habitat. Status of the Habitat of U.S. Living Marine Resources, first ed. U.S. Dept. Commer. NOAA Tech. Memo. NMFS- F/SPO-75, p. 30. Alaska Chapter.

McCabe, M.K., Konar, B., 2022. Influence of environmental attributes on intertidal community structure in glacial estuaries. Special issue. Deep-Sea Res. II. 195, 104986 https://doi.org/10.1016/j.dsr2.2021.104986.

McCammon, M., Hoffman, K., Holderied, K., Aderhold, D.R., Neher, T.H., 2018. Long-term Monitoring of Marine Conditions and Injured Resources and Services. *Exxon Valdez* Oil Spill Long-Term Monitoring Program (Gulf Watch Alaska) Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 16120114). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. Available online. http://www.evostc.state.ak.us/.

McGowan, D.W., Branch, T.A., Haught, S., Scheuerell, M.D., 2021. Multi-decadal shifts in the distribution and timing of Pacific herring (*Clupea pallasii*) spawning in Prince William Sound, Alaska. Can. J. Fish. Aquat. Sci. 78 (11), 1611–1627. https://doi.org/10.1139/cjfas-2021-0047.

McKinstry, C.A.E., Campbell, R.W., Holderied, K., 2022. Influence of the 2014–2016 marine heatwave on seasonal zooplankton community structure and abundance in the lower Cook Inlet, Alaska. Special issue. Deep-Sea Res. II. 195, 105012 https://doi.org/10.1016/j.dsr2.2021.105012.

Martin, J.H., Fitzwater, S.E., 1988. Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. Nature 331, 341–343. https://doi.org/10.1038/331341a0.

Mordy, C.W., Stabeno, P.J., Kachel, N.B., Kachel, D., Ladd, C., Zimmermann, M., Hermann, A.J., Coyle, K.O., Doyle, M.J., 2019. Patterns of flow in the canyons of the northern Gulf of Alaska. Special issue. Deep-Sea Res. II. 165, 203–220. https://doi.org/10.1016/j.dsr2.2019.03.009.

Muradian, M.L., Branch, T.A., Moffitt, S.D., Hulson, P., 2017. Bayesian stock assessment of Pacific herring in Prince William sound Alaska. PLoS One 12. https://doi.org/10.1371/journal.pone.0172153.

North Pacific Fishery Management Council (NPFMC), 2020. Fishery Management Plan for Groundfish of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK, p. 364.

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

Pegau, S.W., Aderhold, D.R., 2021. Herring Research and Monitoring Synthesis. Synthesis Report (*Exxon Valdez* Oil Spill Trustee Council Restoration Project 14120111).

Exxon Valdez Oil Spill Trustee Council, Anchorage, Alaska. Available online. http://www.evostc.state.ak.us/.

Piatt, J.F., Parrish, J.K., Renner, H.M., Schoen, S.K., Jones, T.T., Arimitsu, M.L., Kuletz, K.J., Bodenstein, B., Garcia-Reyes, M., Duerr, R.S., Corcoran, R.M., 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. PLoS One 15 (1). https://doi.org/10.1371/journal.pone.0226087.

Roncalli, V., Niestroy, J., Cieslak, M.C., Castelfranco, A.M., Hopcroft, R.R., Lenz, P.H., 2022. Physiological acclimatization in high-latitude zooplankton. Mol. Ecol. 31 (6), 1753–1765. https://doi.org/10.1111/mec.16354.

Rosellon-Druker, J., Szymkowiak, M., Aydin, K.Y., Cunningham, C.J., Fergusson, E.A., Kasperski, S., Kruse, G.H., Moss, J.H., Rhodes-Reese, M., Shotwell, K.S., Spooner, E., Yasumiishi, E.M., 2022. Participatory place-based integrated ecosystem assessment in Sitka, Alaska: constructing and operationalizing a socio-ecological conceptual model for sablefish (*Anoplopoma fimbria*). Special issue. Deep-Sea Res. II. 195, 104912 https://doi.org/10.1016/j.dsr2.2020.104912.

Royer, T.C., 1981a. Baroclinic transport in the Gulf of Alaska. 1. Seasonal variations of the Alaska current. J. Mar. Res. 39, 239–250.

Royer, T.C., 1981b. Baroclinic transport in the Gulf of Alaska. 2. A fresh water driven coastal current. J. Mar. Res. 39, 251–266.

Sewall, F., Norcross, B., Vollenweider, J., Heintz, R., 2019. Growth, energy storage, and feeding patterns reveal winter mortality risks for juvenile Pacific herring in Prince William Sound, Alaska, USA. Mar. Ecol. Prog. Ser. 623, 195–208. https://doi.org/10.3354/meps13013.

Shotwell, S.K., Pirtle, J.L., Watson, J.T., Deary, A.L., Doyle, M.J., Barbeaux, S.J., Dorn, M. W., Gibson, G.A., Goldstein, E.D., Hanselman, D.H., Hermann, A.J., Hulson, P.J.F., Laurel, B.J., Moss, J.H., Ormseth, O.A., Robinson, D., Rogers, L.A., Rooper, C.N., Spies, I., Strasburger, W.W., Suryan, R.M., Vollenweider, J.J., 2022. Synthesizing integrated ecosystem research to create informed stock-specific indicators for next generation stock assessments. Special issue. Deep-Sea Res. II. 195, 105070 https://doi.org/10.1016/j.dsr2.2022.105070.

Siegert, D., Konar, B., Lindeberg, M.R., Sauupe, S., Iken, K., 2022. Trophic structure of key taxa in rocky intertidal communities in two contrasting high-latitude environments. Special issue, Deep-Sea Res. II. 195, 105050 https://doi.org/10.1016/j.dsr2.2022.105050.

Spies, R.B., Rice, S.D., Wolfe, D.A., Wright, B.A., 1996. The effects of the *Exxon Valdez* oil spill on the Alaskan coastal environment, pp 1-16. In: Wolfe, Wright (Ed.), *Exxon Valdez* Oil Spill Symposium (Rice, Spies, 18. American Fisheries Society Bethesda, Maryland, pp. 1–16.

Stabeno, P.J., Bond, N.A., Hermann, A.J., Kachel, N.B., Mordy, C.W., Overland, J.E., 2004. Meteorology and oceanography of the Northern Gulf of Alaska. Continent. Shelf Res. 24, 859–897. https://doi.org/10.1016/j.csr.2004.02.007.

Surma, S., Pakhomov, E.A., Pitcher, T.J., 2022. Pacific herring (*Clupea pallasii*) as a key forage fish in the southeastern Gulf of Alaska. Special issue. Deep-Sea Res. II. 195, 105001 https://doi.org/10.1016/j.dsr2.2021.105001.

Suryan, R.M., Arimitsu, M.L., Coletti, H.A., Hopcroft, R.R., Lindeberg, M.R., Barbeaux, S. J., Batten, S.D., Burt, W.J., Bishop, M.A., Bodkin, J.L., Brenner, R.E., Campbell, R.W., Cushing, D.A., Danielson, S.L., Dorn, M.W., Drummond, B., Esler, D., Gelatt, T., Hanselman, D.H., Hatch, S.A., Haught, S., Holderied, K., Iken, K., Iron, D.B., Kettle, A.B., Kimmel, D.G., Konar, B., Kuletz, K.J., Laurel, B.J., Maniscalco, J.M., Matkin, C., McKinstry, C.A.E., Monson, D.H., Moran, J.R., Olsen, D., Palsson, W.A., Pegau, W.S., Piatt, J.F., Rogers, L.A., Rojek, N.A., Schaefer, A., Spies, I.B., Straley, J. M., Strom, S.L., Sweeney, K.L., Szymkowiak, M., Weitzman, B.P., Yasumiishi, E.M., Zador, S.G., 2021. Ecosystem response persists after a prolonged marine heatwave. Sci. Rep. 11, 6235. https://doi.org/10.1038/s41598-021-83818-5.

Szymon, S., Pakhomov, E.A., Pitcher, T.J., 2021. Pacific herring (Clupea pallasii) as a key forage fish in the southeastern Gulf of Alaska. Deep-Sea Res. II 105001. https://doi.org/10.1016/j.dsr2.2021.105001.

Weingartner, T.J., Danielson, S.L., Royer, T.C., 2005. Freshwater variability and predictability in the Alaska coastal current. Deep-Sea Res. II. 52, 169–191. https://doi.org/10.1016/j.dsr2.2004.09.030.

Weitzman, B., Konar, B., Iken, K., Coletti, H., Monson, D., Suryan, R.M., Dean, T., Hondolero, D., Lindeberg, M.R., 2021. Changes in rocky intertidal community structure during a marine heatwave in the northern Gulf of Alaska. Front. Mar. Sci. 8 https://doi.org/10.3389/fmars.2021.556820.

Zador, S.G., Holsman, K.K., Aydin, K.Y., Gaichas, S.K., 2017. Ecosystem considerations in Alaska: the value of qualitative assessments. ICES J. Mar. Sci. 74 (1), 421–430. https://doi.org/10.1093/icesjms/fsw144.

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