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Introduction to understanding ecosystem processes in the gulf of Alaska, volume 2

The Gulf of Alaska (GOA) marine ecosystem is complex, supporting abundant plant and animal populations, human coastal communities and commercial activities. This is the second special issue intended to showcase research conducted as part of the GOA Integrated Ecosystem Research Program (IERP), a large multidisciplinary ecological study funded by the North Pacific Research Board (NPRB) and the National Oceanic and Atmospheric Administration (NOAA; a complete description of the GOAIERP, including the final reports, is available at www.nprb.org/gulf-of-alaska-project). The main goal of the program was to examine the influence of ecosystem processes on survival, from egg stage to young-of-the-year (YOY), in five species of commercially-valuable marine groundfish: arrowtooth flounder *Atheresthes stomias*, Pacific cod *Gadus macrocephalus*, Pacific Ocean perch *Sebastes alutus* (POP), sablefish *Anoplopoma fimbria*, and walleye pollock *Gadus chalcogrammus*. The GOAIERP was guided by three overarching hypotheses:

1) The gauntlet: The primary determinant of year-class strength for marine groundfishes in the GOA is early life survival. This is regulated in space and time by climate-driven variability in a biophysical gauntlet comprising offshore and nearshore habitat quality, larval and juvenile transport, and settlement into suitable demersal habitat.
2) Regional comparison: The physical and biological mechanisms that determine annual survival of juvenile groundfishes and forage fishes differ in the eastern and western GOA regions.
3) Interactions: Interactions among species (including predation and competition) are influenced by the abundance and distribution of individual species and by their habitat requirements, which vary with life stage and season.

To accomplish this goal the program brought together researchers from a wide variety of scientific disciplines to design and carry out a highly integrated study. The program was structured as four separate but interconnected groups of investigators. Three of the components focused on separate parts of the ecosystem: physical, chemical, and biological oceanography were the domain of the Lower Trophic Level (LTL) group; the Middle Trophic Level (MTL) component focused on forage fishes and the inshore environment; the Upper Trophic Level (UTL) group investigated fishes, seabirds, and marine mammals and their roles as predators and competitors. The three trophic-level components were intended to be primarily observational, conducting field surveys and process studies, but also included retrospective analyses. The fourth group, Modeling, created linked systems of computer models that paralleled the conceptual framework of the observational studies and incorporated data from the other components.

The field studies and much of the analysis was structured around a comparison of two GOA study regions, eastern and western, and the connections between them (Fig. 1). These regions correspond largely to the continental shelf regions in the eastern and central GOA, respectively, but also include inshore and basin habitats. The nomenclature of spatial divisions in the GOA varies by scientific audience; in particular, "central GOA" has widely different meaning between oceanographers and fishery managers. For this reason the overall GOAIERP sampling design referred simply to eastern GOA (EGOA) and western GOA (WGOA) study regions as defined in Fig. 1, and this scheme is used in this introduction but not in all of the papers in this issue. Readers should pay close attention to the spatial terminology used in the individual papers. The research phase of the GOAIERP began in 2010, had major field years in 2011 and 2013, and ended in 2016. This was followed by a synthesis phase during 2016–2018. The first special issue produced by the GOAIERP focused mainly on physical processes. This issue is more diverse, covering fishes through all of their life stages as well as modeling, habitat studies, and other topics.

The processes of spawning, egg hatching, and larval development are crucial for determining the success of annual groundfish cohorts, and the first three papers in this issue deal with the ecology of larval fishes in the GOA. Siddon et al. (2019) present a synthesis of the ichthyoplankton data collected during the GOAIERP fisheries oceanographic surveys. Regional patterns in ichthyoplankton distribution observed in this study indicate that habitat variation, including topography and associated transport processes, is important in structuring fish distributions. Deep-water features such as troughs and canyons that bisect the shelf appear to be 'hot spots' for rockfish, sablefish, and arrowtooth flounder larvae originating from slope or basin spawning habitat. The amount of habitat available for larval gadids is greater in the WGOA relative to the EGOA, while sablefish are more abundant over the narrower shelf in the EGOA. Species-specific regional differences in the size of fish larvae likely reflected spawn timing, which is related to bloom timing and water temperature, or differences in larval growth related to prey availability and water temperature, or a combination of both factors.

Variability within individual species leads to changes in communities. Goldstein et al. (2019) describe geographic patterns in GOA larval fish assemblages, drawing on oceanographic data, adult spawning habitat, and connectivity models to identify factors that influence larval distributions. The large number of species spawning in late winter and spring leads to high spring diversity and distinct eastern versus western larval fish assemblages. By summer, reduced numbers of spawning species, ontogenetic "aging out", and oceanographic connectivity (e.g. through transport by major westward currents) have reduced the diversity and spatially homogenized the assemblage. Local conditions appear less important than broad-scale environmental factors in structuring assemblages; correspondingly, the widespread ocean warming experienced near the end of the study period led to atypical

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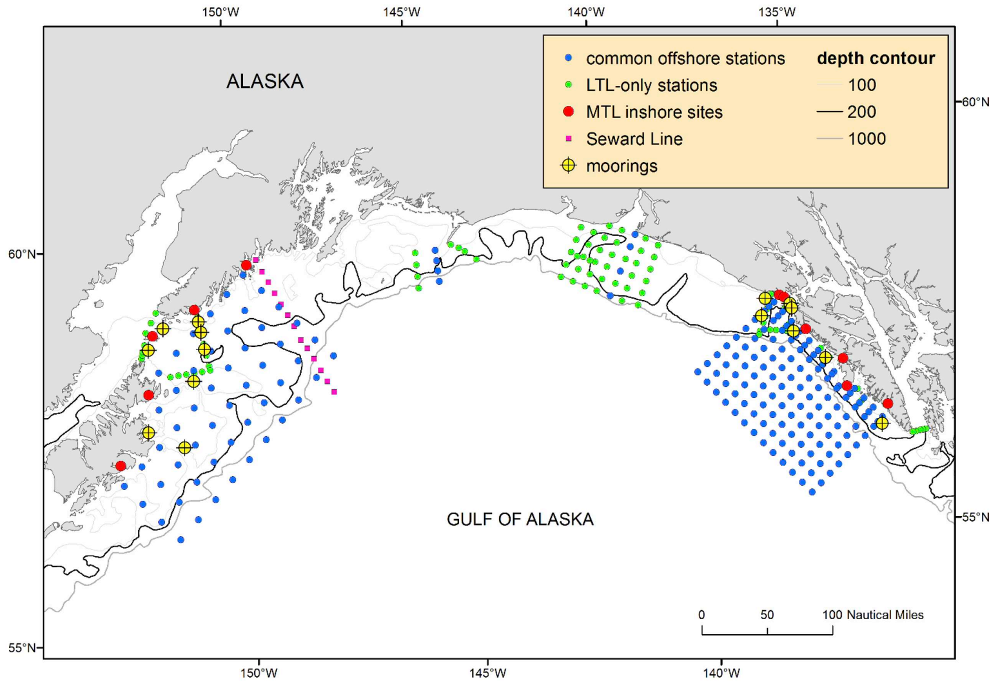

Fig. 1. General map of the GOAIERP study area. Common offshore stations (blue) were those occupied by the spring Lower Trophic Level (LTL) surveys and the summer/fall Upper Trophic Level (UTL) surveys; LTL-only stations (green) were visited only during the spring LTL surveys. Inshore sites (red) were sampled by the Middle Trophic Level Component (MTL) during spring, summer, and fall. Mooring sites (yellow) collected data throughout the year.

assemblage patterns, particularly in the western part of the study region.

The above papers emphasize the central role that seasonality plays in the ecology of fish early life stages in the GOA, and a comprehensive review of the phenology of early life stages of 23 GOA groundfish species is found in Doyle et al. (2019). A common seasonal pattern in northern oceans is that the emergence of larvae is timed to coincide with the spring phytoplankton bloom, and many species in the GOA display this strategy. However other species (e.g. arrowtooth flounder) have very different patterns, and these fishes appear to have adapted to the temporal and spatial complexity of the GOA ecosystem. The adaptations take advantage of multiple environmental factors that influence larval survival, including temperature, on-shelf transport, and food availability. At the same time, the strategies that fishes employ to navigate these factors also create different levels of sensitivity to climactic variation. For example, winter-spawned arrowtooth flounder appear to rely on colder temperatures to slow larval growth and consumption of lipid reserves until forage availability increases. As a result, larval survival may be particularly sensitive to increased winter temperatures. This paper characterizes environmental sensitivity for each species, information that will be useful for identifying ecosystem signals of relevance for individual species.

Individual-based models (IBMs), which track the fate of virtual individual fish larvae, are a powerful tool for understanding how the processes described above combine to impact the survival of individuals and cohorts. A primary goal of the GOAIERP was to create an IBM for each of the five focal species, and four of those models are described in this issue. The models used a common architecture based on the Dispersal Model for Early Life Stages (DisMELS; https://github.com/wStockhausen/DisMELS) framework, coupled to a regional ocean circulation and nutrient-phytoplankton-zooplankton model (ROMS/NPZ). The IBMs presented here were run from 1996 to 2011 to elucidate interannual variability in the connectivity between spawning areas and YOY habitats.

Stockhausen et al. (2019a) used an IBM to explore early life transport and dispersal mechanisms for POP. Results show that most individuals were unsuccessful in dispersing from continental shelf break parturition areas to inshore nursery areas. Connectivity of successful individuals was directed in a counterclockwise fashion alongshore with the most productive parturition areas in southeast Alaska and the most productive nursery areas in the central GOA. Connectivity indices were created to identify causal mechanisms for fluctuations in recruitment estimates from the stock assessment model for POP. An index of connectivity coupled with the Arctic Oscillation in a simple linear model was able to explain almost 50% of the variability in recruitment estimates, but this was considered to be an inadequate predictor of POP recruitment.

A baseline IBM for Alaska sablefish early life stages was created by Gibson et al. (2019) to explore the variability in connectivity between spawning and recruitment sites in the GOA. The IBM is used in a novel approach to generate indices of connectivity to test relationships with sablefish recruitment estimates from the stock assessment model. Additional relationships with environmental indices from the regional circulation model were also investigated. Primary results suggest that young sablefish settling in the GOA were likely spawned in the EGOA and that those individuals spawning in the WGOA were more likely to settle in the Aleutian Islands or the Bering Sea rather than the GOA. Additionally, total connectivity between all spawning sites and nursery areas was better correlated with recruitment estimates from the main stock assessment than with connections to or from specific areas. A known area of concentration for juvenile sablefish (Saint John Baptist Bay in Southeast Alaska) was not the most probable endpoint for sablefish spawned throughout the GOA model domain, suggesting that localized forcing or directional swimming may be important for the persistence of this nursery. No single correlate was strongly related to sablefish recruitment suggesting that recruitment variability arises from complex interactions.

Hinckley et al. (2019) investigated the connectivity between spawning and nursery areas for Pacific cod in the GOA using an IBM to understand transport and settlement patterns. The early life history stages of Pacific cod generally do not disperse far from their natal areas and retention of modeled individuals in areas where they were spawned was the strongest connectivity pattern seen. They also found that individuals spawned in shallower areas nearer to shore or in areas where the circulation is weaker were more likely to be retained than those released in deeper shelf areas with strong directed currents such as the Alaska Current. The model predicted that many Pacific cod that were spawned to the west of Kodiak Island were transported out of the GOA. However, many modeled individuals were also transported from the deeper shelf spawning regions to nearby nearshore settlement regions, indicating the importance of cross-shelf transport.

The IBM for arrowtooth flounder created by Stockhausen et al. (2019b) suggested that most individuals were unsuccessful in dispersing from continental shelf spawning areas to inshore nursery areas. Connectivity of successful individuals was directed in a counter-clockwise fashion alongshore with the most effective spawning areas in southeast Alaska and the most effective nursery areas in central and western GOA. Connectivity indices were created to identify causal mechanisms for fluctuations in recruitment estimates from the stock assessment model for arrowtooth flounder. Additionally, large-scale environmental drivers and regional ocean model-derived physical and biological variables were generated to correlate to recruitment. No index appeared to be strongly correlated to recruitment; however the model did not incorporate some of the submarine canyon flow dynamics discussed in other papers in this issue.

The papers described above dealt strictly with fish larval stages; two papers in this issue focused on the ecology of the subsequent age-0 stage where fishes are fully transformed and have arrived in juvenile habitats. Debenham et al. (2019) examined the effects of environmental factors on age-0 arrowtooth flounder inhabiting the epipelagic environment. This study provided information on the abundance, distribution, pelagic duration, size, growth, diet and energy content of age-0 arrowtooth flounder in the GOA. Settlement from the epipelagic zone to deeper waters was found to occur during August. Age-0 arrowtooth flounder were most abundant in cool years and were captured in higher numbers in the EGOA relative to the WGOA. Large copepods were preferred prey items and a shift in diet composition was observed between the epipelagic age-0 life stage and the demersal juvenile life stage. Energy density had little relationship with length during the early life stages suggesting that the strategy for allocating energy between structure and storage remains constant during the pelagic life phase of arrowtooth flounder. This pattern suggests that energy density does not increase prior to settlement and metamorphosis, which is believed to be a costly ontogenetic change.

Interactions among different species of juvenile fishes plays a major role in their survival. Daly et al. (2019a) investigated the potential for resource competition between age-0 marine fish and juvenile salmon in the EGOA. Age-0 groundfish and juvenile salmon have fine-scale spatial, temporal, and trophic overlap while occupying surface waters. These guilds of fish have the potential to impact one another through competition during periods of low plankton prey abundance and from predation by juvenile salmon on age-0 marine fish. Prey competition and predator/prey interaction intensity varied interannually and were related to the amount of fine-scale spatial overlap. The highest rates of diet overlap occurred between the highly planktivorous age-0 marine fish and juvenile pink *Oncorhynchus gorbuscha*, chum *Oncorhynchus keta*, and sockeye *Oncorhynchus nerka* salmon. Juvenile Chinook *Oncorhynchus tshawytscha* and coho *Oncorhynchus kisutch* salmon frequently consumed age-0 rockfishes.

Bottom-up forcing is inherent in the GOAIERP gauntlet hypothesis, and three papers in this issue illuminate key processes affecting GOA productivity and fish early life stages. The ROMS/NPZ used for the IBM work was revised and tested by Coyle et al. (2019) during the synthesis phase of the project. They used the coupled biophysical model to describe the distribution of lower trophic level biomass and production over the period 2000–2013 in the GOA. The model captured the pronounced seasonality and spatial heterogeneity characteristic of the region. Model data taken as a whole also provided evidence that the regulation of production and its trophic transfer differ substantially between spring and fall. Iron supply, although poorly constrained by data, was a key driver of production, and interannual variations in spring iron availability (here linked mainly to freshwater runoff) were the major driver of differences in spring shelf primary production. Seasonally adjusting phytoplankton carbon:chlorophyll ratios was key to allowing model replication of measured photosynthesis responses to light; modeled seasonal cycles indicate that chlorophyll is a poor proxy for primary production in the region given this C:Chl variation. Close coupling between net-sampled large copepod biomass and modeled spring production indicate a strong bottom-up regulation of these key trophic intermediates. Annual modeled primary and secondary production anomalies shifted from positive to negative after 2006, in conjunction with a shift in the North Pacific Index (NPI); the underlying mechanism may be related to changes in runoff and associated (simulated) iron supply.

To better understand lower trophic level dynamics in the coastal GOA, Strom et al. (2019) examined microzooplankton communities from the eastern and western gulf during two contrasting years: the reduced spring phytoplankton bloom of 2011, and the robust spring bloom of 2013. They found the east had lower microzooplankton biomass and a greater proportion of ciliates than the west, even in the face of basin-wide seasonal and interannual differences, likely as a consequence of the narrower shelf in the east yielding a lower productivity environment. Interannual differences in spring bloom intensity were also echoed in microzooplankton biomass, while interannual differences in taxonomic composition (ciliates vs dinoflagellates) also persisted throughout the year, with a greater representation of ciliates in 2011. They suggested ciliate dominance was favored by harvesting their prey's chloroplasts to become mixotrophic during times of prey scarcity. Microzooplankton:phytoplankton biomass ratios varied widely, with lower productivity regions (i.e. east) and seasons (i.e. summer) tending to be locations and times of reduced trophic transfer efficiency from phytoplankton to microzooplankton. With microzooplankton being the preferred prey of the dominant central GOA copepods, they concluded that multiple mechanisms conspired to reduce trophic transfer at low productivity locations and time periods.

Although the coastal GOA is a downwelling-dominated system and primary production on the outer shelf may at times be limited by iron availability, it is a highly productive ecosystem that supports large populations of fish, invertebrates, seabirds and mammals. Submarine canyons in the topographically complex shelf system around Kodiak Island have been shown to foster the exchange of nutrients across the shelf and to serve as conduits for transporting larvae of slope-spawning flatfish to their shallow nursery areas (e.g. Doyle et al., 2019). Using data from 29 moorings and results from a nested biophysical model, Mordy et al. (2019) show how cold, nutrient-rich bottom waters enter on the upstream sides of Chiniak, Barnabas and Amatuli troughs, where flow intensifies and is steered along the canyon walls. Strong tidal mixing, particularly in Chiniak Trough and downstream of Amatuli Trough, inject the cooler, nutrient-rich waters into the upper water column to sustain new production on the shallow banks around Kodiak Island throughout the summer. In addition to nutrients, the canyons also enhance the cross-shelf advection of fish larvae as they spread from the major troughs throughout the shelf regions and into Shelikof Strait from both the north and the south.

Despite the focus on a fish early life gauntlet, the GOAIERP was also a project oriented towards understanding the function of the GOA ecosystem as a whole. To this end, several investigators focused on the ecology of “forage fishes”, small fishes that provide a link between the energy contained in the plankton and larger predators such as seabirds and marine mammals. Two papers in this issue present the results of this research. McGowan et al. (2019a) describe the results of acoustic and trawl surveys conducted in the summer and fall of 2011 and 2013 to document the abundance and distribution of forage fishes including juvenile pollock. Large temporal and spatial variability in their abundance and distribution has relevance to understanding predator foraging patterns and monitoring for shifts in forage fish biomass. Changes in species composition and distribution were seen between years, seasons, and regions. Mesopelagic fishes were consistently present in summer and fall of both years beyond the shelf break. In the WGOA the forage fish community was primarily comprised of Pacific capelin *Mallotus catervarius*. Age-0 pollock were abundant over the shelf, slope, and basin in summer 2013, but were otherwise rare (fall 2013 and all seasons 2011). The apparent seasonal shift in age-0 pollock abundance in 2013 is consistent with modeled transport from offshore to nearshore waters. In contrast, the occurrence of herring *Clupea pallasii* over the EGOA shelf in fall of both years suggests herring migrate from inshore waters in summer to offshore overwintering habitat. Dense aggregations of capelin in both summer and fall over the WGOA shelf in both years suggests a non-migratory distribution. Significant differences in the vertical distribution of capelin and age-0 pollock were also observed, with capelin consistently at greater depth. This spatial separation may be indicative of interspecific differences in habitat preferences, target prey depth, resource partitioning, and/or predator avoidance.

The work on the ecology of capelin, one of the most important GOA forage fishes, was continued in McGowan et al. (2019b). In this paper, the investigators used acoustic and trawl surveys in conjunction with oceanographic data to describe the distribution of capelin, which constitutes an important trophic intermediate in GOA food webs leading from plankton to commercially important groundfish, seabirds, and marine mammals. In general, capelin distribution appeared to be dictated more strongly by prey availability than by competition or predator avoidance. In summer and fall, younger (age-1) capelin were concentrated over shallow submarine banks on the continental shelf; due to tidal mixing, these banks are ‘hot spots’ of primary production during those seasons (Mordy et al., 2019), and support high abundances of copepod prey. Older (age-2) capelin, in contrast, were concentrated in the deep troughs that cut across the continental shelf where they consume larger prey such as euphausiids.

Exploration of the inshore environment, primarily bays of varying size, was a primary component of the GOAIERP. De Robertis and Ormseth (2019) conducted a series of daytime replicate acoustic surveys at the eleven GOAIERP inshore study sites (Fig. 1; Ormseth et al., 2017) in spring, summer and fall of 2011 and 2013. The relative abundance and distribution of fish and zooplankton were measured using acoustic methods. Consistent differences were found among sites, such that the effects of site were larger than those of season or year. Findings suggest that water depth is a key characteristic in structuring pelagic communities in the inshore GOA, with fishes and large-bodied zooplankton scarce in shallow habitats, compared to adjacent deeper habitats during daylight hours. As many fishes inhabit inshore areas as juveniles, quantifying habitat use at different life history stages is critical to understanding the survival and growth of fish populations. This analysis highlights the importance of investigating the use of inshore habitats by fishes in the GOA.

Shallow inshore areas are also important nursery habitat for YOY Pacific cod, although the relative contribution of different areas to the adult stock of Pacific cod is poorly understood. Otolith elemental signatures offer a promising tool to identify nursery habitats of Pacific cod caught as adults in the fishery or surveys, given that the trace elements incorporated into the otolith matrix of juvenile fish reflect environmental conditions in their nursery habitat. Matta et al. (2019) found that the ability to assign fish to one of five known nursery areas, based on otolith elemental signatures alone, was difficult at spatial scales of a few hundred kilometers but improved at larger spatial scales. Discriminating among nursery areas was complicated by the fact that elemental signatures of fish sampled in the same location changed considerably over relatively short time scales (2 months). Otolith microchemistry may be useful in understanding the contribution of fish from GOA subregions to the overall population, but additional information is needed to quantify the contribution of local nursery habitats.

Understanding the gauntlet for young fishes requires knowledge regarding the suitability of habitats for age-0 fishes settling out of the ichthyoplankton, and several papers describe research that characterized these areas. Zimmerman et al. (2019) continued their physical analysis of the GOAIERP inshore study sites begun in the first special issue (Zimmermann et al., 2016). Their work involved using Geographic Information Systems to quantify physical descriptors of the sites, e.g. water volume, surface area, and shoreline length. They also used multivariate analysis to describe groups of sites with similar features. Size and location were the most important grouping factors. Three main groups were established (EGOA small bays, EGOA large bays, and CGOA small bays), and only two of the ten sites were distinct from these units. The clusters identified in this paper served as the basis for some of the analyses of inshore fish and oceanography, including De Robertis and Ormseth (2019) and Ormseth et al. (2017).

In this integrated program, reliable high-resolution bathymetry was essential for describing habitat (e.g. Pirtle et al., 2019; Zimmermann et al., 2016; Zimmerman, 2019) and modeling patterns of flow (Mordy et al., 2019). Zimmermann et al. (2019) detail an approach to verify the accuracy of interpolated bathymetric surfaces created by digitizing “smooth sheets”, the original National Ocean Service survey maps. They compared the smooth-sheet bathymetry to echosounder data collected during the surveys described in De Robertis and Ormseth (2019). The high resolution of the echosounder measurements allowed for multiple reference points within each 20 m resolution smooth-sheet raster cell. Interpolated depth surfaces derived from the smooth sheet bathymetry were closely correlated to echosounder depths, but smooth-sheet rasters from more recent surveys exhibited better agreement. Larger residuals were observed in areas of rapid depth transition. This analysis increased confidence in the smooth sheet bathymetry and its application to the description of fish habitat.

To explore ecosystem characteristics that regulate recruitment strength of the five GOAIERP focal species, Pirtle et al. (2019) developed habitat suitability models for early juvenile demersal stages using catch data and seafloor habitat metrics. Regional-scale maps were produced predicting the suitability of habitats in the GOA study area. This work provides the first early juvenile stage maps for GOA groundfish species that predict regional-scale habitat from settlement through to their residency in nursery areas, pointing to differences between focal species. For example, the models for sablefish suggest suitable habitat occurs in low-lying areas with low rocky structure situated within 25–300 m bottom depth. In contrast, the models for Pacific ocean perch predicted suitable habitat as rocky bathymetric rises on north-south facing slopes at depths of 85–270 m. Knowledge of these habitat covariates, which can be readily mapped at high spatial resolution, have informed further refinement of the IBMs as well as descriptions of Essential Fish Habitat used in the US federal management process.

The GOAIERP focused on five commercial groundfish species. However, Pacific salmon are a crucial component of the GOA ecosystem and support valuable commercial fisheries. The field research conducted as part of the GOAIERP necessarily yielded a large amount of information related to salmon. Analyzing data on salmon was a major goal of the synthesis phase of the GOAIERP, and the last four papers in this issue present some of this work. Chinook salmon range widely during their ocean migrations, and identifying the juvenile distribution of different Chinook stocks is important for understanding survival at a critical life stage. Van Doornik et al. (2019) used genetic stock identification techniques to determine that most juvenile Chinook captured in the EGOA study area originate from adults that spawn in the Columbia River. Juvenile abundance was also correlated with the number of adults returning to the Columbia River two years later. This study demonstrated the importance of the links between disparate ecosystems for migratory fish species and underlined the connections between the GOA and regions to the south.

Food habits and prey availability are key factors in the ocean survival of juvenile Pacific salmon species. Daly et al. (2019b) analyzed the juvenile and adult diets of five Pacific salmon species in the EGOA and CGOA during 2011–2014. The authors identified substantial variation in diets among species, age classes, regions, seasons, and years. Specialization among species in piscivory versus planktivory created the largest separation in diets, while geographic region had the least effect. The authors also discovered evidence that the low productivity and anomalous plankton conditions in 2011 described by Strom et al. (2019) negatively impacted prey availability for juvenile Pacific salmon, especially piscivorous Chinook salmon.

In contrast to other studies in this issue that are broad in spatial extent and examine multiple species, but over a limited number of years, Kohan et al. (2019) focused on one species (chum salmon) in a confined area (Icy Strait in the EGOA) over a 17-year period. This enabled them to understand how the abundance and growth of juvenile chum salmon varied under a wide variety of environmental conditions. Their study supported the hypothesis that years with a strong Aleutian Low (associated with stronger winds and warmer temperatures) favor salmon survival, but also that regional-rather than basin-scale indicators were better for predicting juvenile chum survival. Importantly, stronger freshwater discharge in spring and stronger downwelling during the preceding winter were associated with higher juvenile abundances, suggesting bottom-up forcing of the growth and survival of chum salmon.

Siwicke et al. (2019) examined the interactions between Sitka eddies and juvenile pink salmon, focusing on July when those juveniles are migrating northward along the southeast (SE) Alaska coast. They present evidence that eddies impinging on the narrow SE Alaska shelf can deflect migrating salmon offshore into poorer feeding and growth habitat; the effects of these poorer conditions were reflected in various measures of offshore juvenile pink salmon size and condition in the strong eddy summer of 2010. The frequency of Sitka eddy formation is related to broad scale climate drivers such as El Niño and the NPI. These in turn relate to changes in juvenile salmon prey abundance and composition (e.g. euphausiids versus copepods). Eddy effects on migration can be seen as one of a number of specific mechanisms, arising from broad-scale climate variation, that result in year-to-year survival and growth differences for commercially important eastern North Pacific pink salmon stocks.

Taken as a whole, this lengthy special issue effectively characterizes the breadth and complexity of the GOA ecosystem, as well as the comprehensive nature of the GOAIERP. This compilation and others recently published demonstrate that integrated research is extremely valuable; we advocate for similar approaches in other regions. A forthcoming third special issue will contain more results from the synthesis phase of the project.

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